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Advanced Reactor for Cogeneration of Heat & Electricity-R&D

Report on INDEX results

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Summary

This document contains the description of the Boudouard tests in the NACOK II facility and the experiments in INDEX. First the theoretical background of the graphite oxidation, especially the Boudouard reaction, in case of air ingress in an HTR is given. After the description of the test facility NACOK, one will get the definition of the proposed Boudouard experiments. The first experiment is done with a block geometry, in the second experiment a pebble-bed of graphite spheres is used. Additional experiments in INDEX allow a better understanding of the flow field around pebble beds.

Approval

Date	By
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31/03/2015	Norbert KOHTZ
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1 Introduction

In addition to the large-scale experiments in NACOK-II with focus on the Boudouard reaction, a few small-scale experiments are performed in the INDEX facility focussing on fluid dynamics phenomena.

The experiments using the INDEX test facility can provide detailed data about the velocity field and fluctuations above/below of a single pebble (60mm) or of pebble beds with different pebble geometries (10mm or 30mm pebbles). Pebble Beds are poorly and not easily accessible to experiments. The experimental data is useful for adequate CFD validation and necessary for CFD model enhancement for pebble bed simulations.

The knowledge of the flow field in or around a pebble bed is required in a detailed way in order to determine the energy transfer phenomena. For the most calculations of the energy flow quantities, the porous-media-concept approach is applied. For the validations of the theoretical results, the accurate information of the flow field is required, which can be for example delivered with the non-intrusive flow field measurement technique “Particle Image Velocimetry (PIV)”.

2 The INDEX test facility

Complementary to the large-scale facility NACOK the small-scale experiment INDEX is used to investigate fluid dynamics phenomena.

2.1 INDEX

The INDEX (INDuction EXperiment) facility (Fig. 1) is a glass flow channel in which a geometry of graphite can be inductively heated up. The coil is optimized for a mass of 200g graphite (one graphite sphere, d=60mm), the sample shape can be varied from a single pebble to a prismatic block like shape to a pebble bed. The geometry can be overflown with several gases like nitrogen, helium, air, carbon dioxide and their mixtures.

In the rectangular part of the flow channel a PIV (Particle Image Velocimetry) measurement system can be adapted to measure the flow field in this region. Depending on the current experimental setup, the flow field below and above the geometry can be measured. By removing the inductive coil out of sight around the pebble bed, to a certain degree, depending on the geometry also wall effects can be investigated.

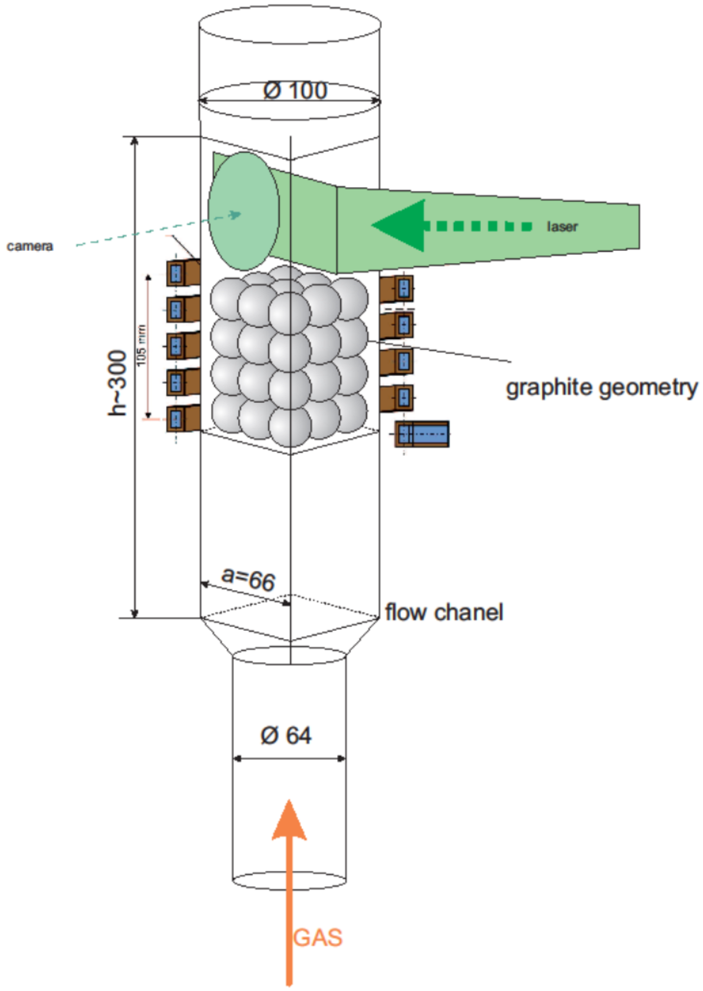

Figure 1: Schematic of INDEX

The lower part of the glass channel is a tube with an inner diameter of 64mm and a length of 1100mm. Above this cylindrical part the flow channel becomes a rectangular profile with an inner dimension of 66 x 66mm and a length of 300mm (Fig. 2). For good handling, the geometries can be inserted, using a second, inner rectangular glass channel (Fig. 3), inner dimension: 61 x 61mm, length: 300mm. The geometry is located inside this inner glass channel.

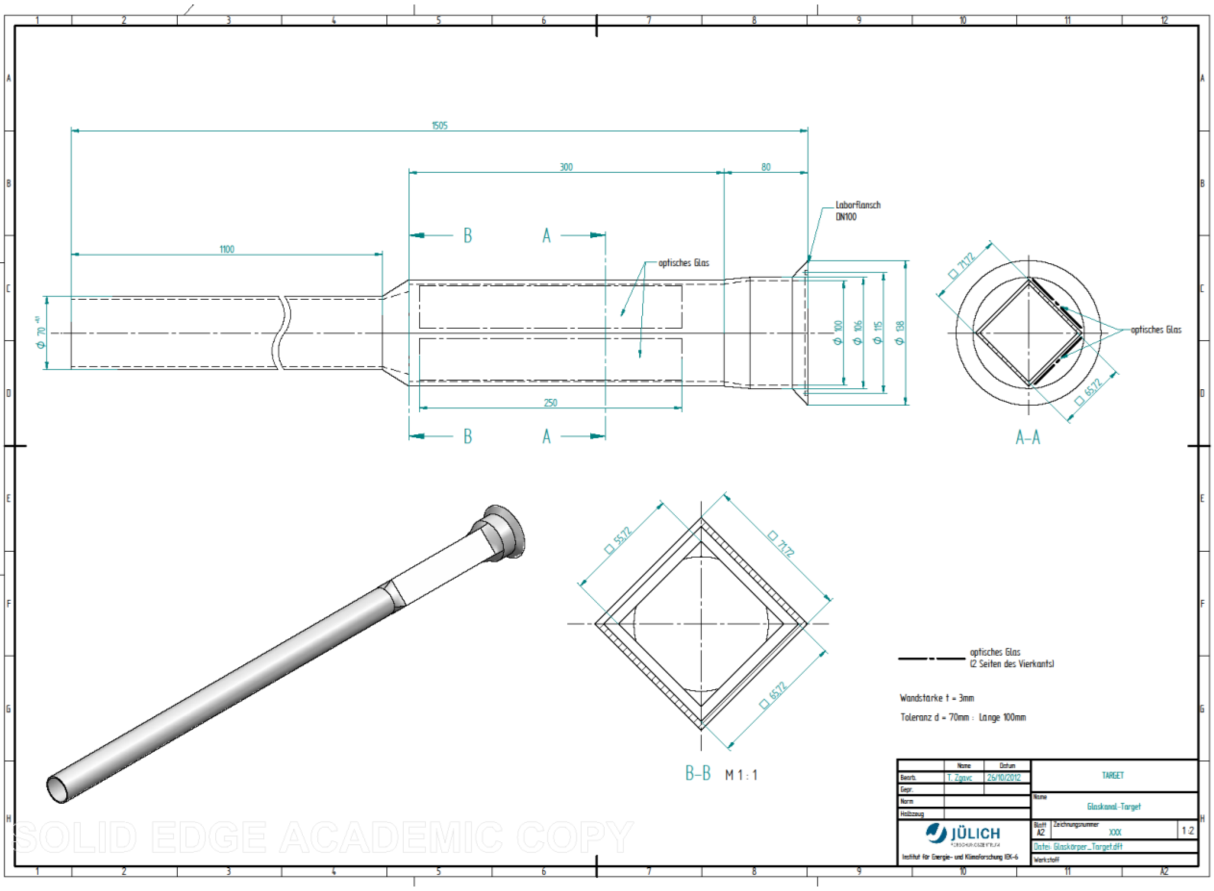

Figure 2: glass channel

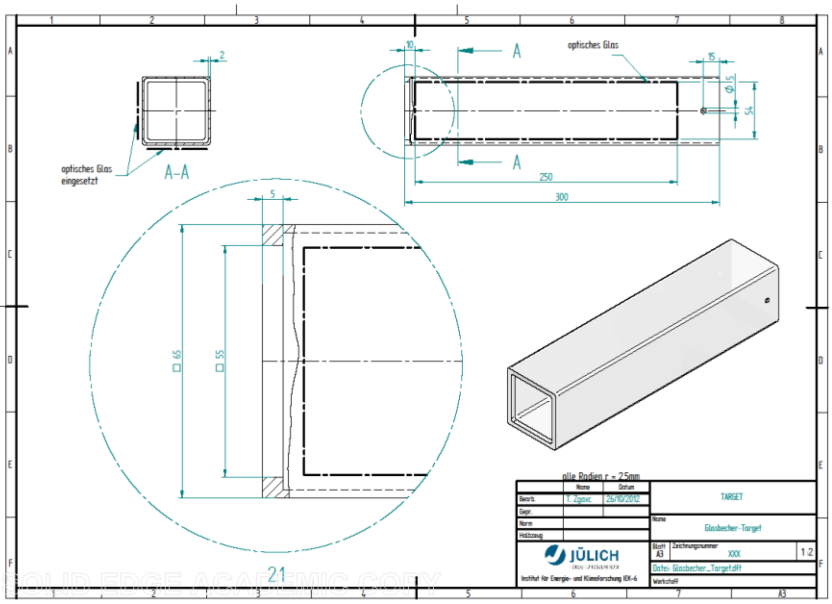

Figure 3: One of the inner glass channels

2.2 Planned Experiments

The set of experiments in INDEX consists of six experiments with different geometries at two different flow velocities, defined as following:

- **Empty channel, low velocity:**
  In the first experiment, information about the flow profile without geometry are generated

- **Pebble bed (10mm spheres, disordered), low velocity:**
  In the second experiment, the flow profile with a pebble bed of graphite spheres with 10mm diameter is investigated

- **Pebble bed (30mm spheres, disordered), low velocity:**
  In the third experiment, a disordered pebble bed geometry (30mm diameter spheres) at low velocity is used

- **Pebble bed (30mm spheres, BCC), low velocity:**
  In the fourth experiment, a sorted geometry (BCC, body centered cubic, see Fig. 4) with 30mm diameter pebbles is investigated at low velocity

- **Empty channel, high velocity:**
  The fifth experiment is in the same setup like the first experiment, but with higher velocity.

- **Pebble bed (30mm spheres, BCC), high velocity:**
  The sixth experiment is complementary to the fourth experiment (BCC geometry with 30mm diameter pebbles) at higher velocity.

Figure 4: BCC geometry

The gas of interest is helium, so all experiments are done in helium atmosphere. Four of the experiments have been done at room temperatures, the experiments with the BCC-geometry were executed at temperatures above 200 °C. Additionally, the maximum feasibility of INDEX regarding the temperatures that can be achieved in the BCC-geometry is shown.
The BCC geometry is of special interest for the CFD code validation at NRG, so this design is investigated at two gas velocities. The BCC geometry is manufactured, containing defined points of contact, so this geometry can later be modelled in CFD (Fig. 5).

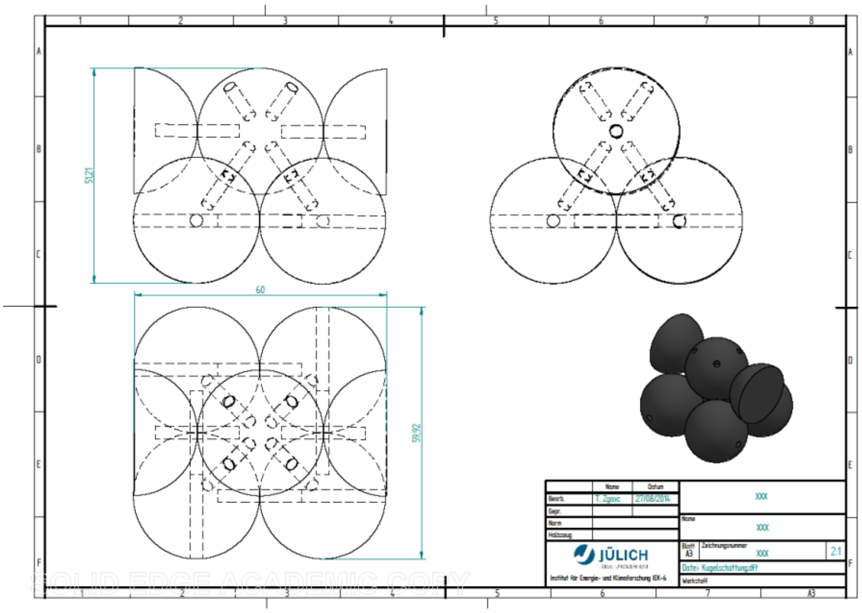

Figure 5: BCC geometry, defined points of contact

2.3 Experimental Setup

As mentioned above 6 Experiments were planned in INDEX for Characterization of the flow fields.
The first Experiment was executed in the empty channel without any geometry to view the Flow field above the hole-plate, that is located in the inner glass channel. For the experiments a shorter glass channel was used, of almost the same geometry as the inner channel mentioned above in 3.1. In order to differentiate the shorter inner glass channel from the longer inner glass channel, this shorter glass channel is called “glass cage”. That means the specimen (pebbles) are put in the glass cage and the glass cage is put in the glass channel. Although the inner glass cage is only shorter than the above-mentioned inner glass channel, the effects that are to be measured, the same. There are 36 holes (5mm) in the hole-plate that is used to make the flow laminar. Besides of this effect, there has to be a surface where the pebble bed can be put on. Such a plate with the inner glass channel can be seen in the figure 6.

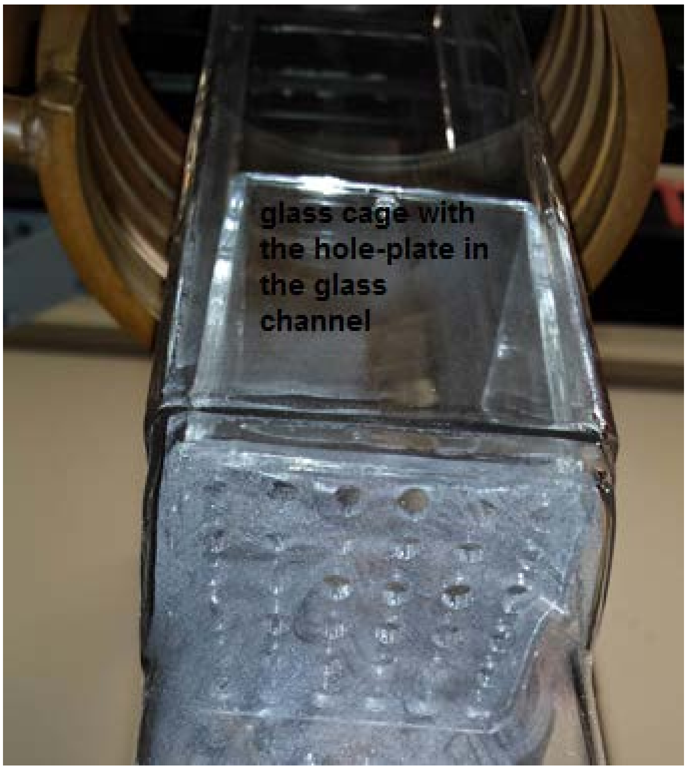

Figure 6: Configuration of the glass cage with the hole-plate in the glass channel

It was located in the glass channel and PIV-System with the Laser, light sheet optics and the camera was setup, as shown in figure 7. The laser beam illuminates the graphite particles (tracer particles) from the side and at the angle of 90° the camera is located to detect the reflected laser light. The particles were generated with a particle generator that was self-made. It had the purpose of generating the particles in the glass channel for the measurement of the flow field.
By trying out the reasonable Volume rate for the measurement which will be related to low Reynold Numbers, a Volume rate of 1.3 till 1.5 m^{3N}/h was suggested. This would correspond to a laminar zone with the mean velocity of 0.137m/s and a Reynolds Number of 63.
The gas helium and the graphite particles were injected separately in the glass channel, where they got mixed together in the cylindrical section and then in the quadratic section.

During the measurements there was a negative effect from the particles observed. After a short period of time, deposition of the particles on the glass was observed. Because of these depositions on the glass walls the measurement time was limited to roughly 10 minutes, which on the other hand resulted in high effort for the execution of the experiments. Following steps had to be repeated in a monotonous way:

- Setup the whole experiment
- Execute the PIV-Measurement
- Remove the bender
- Remove the glass cage
- Clean the glass channel and the glass cage
- Put the cage back in the glass channel
- Assembly the bender with the glass channel

Many pre-experiments had to be done in order to find the correct volume rate and the correct delta T, i.e. the time between both laser shots. This resulted in 10-15 minutes experimental time and up to 30 minutes time for the disassembly, cleaning and assembly of the whole setup.

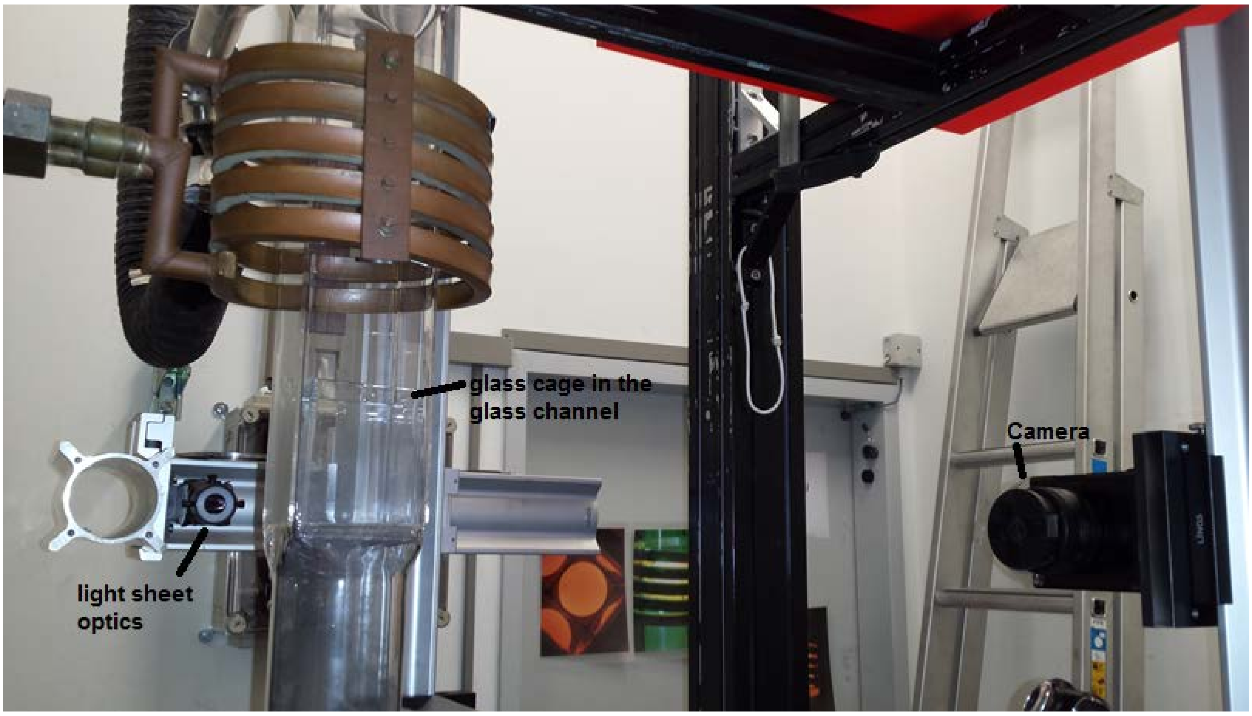

Figure 7: Experimental Setup

Before starting any measurement a calibration has to be done, in order to calculate the correct velocities. For achieving this a foot rule was illuminated by the laser sheet and focussed with the camera. For a 2-D measurement it is enough to hold anything in the measuring point as long as the distance between two points of the object is known. Only for 3-D measurements the information of the depth is required and the calibration becomes really sophisticated and requires more effort. It is to be mentioned, that without any calibration, the "correct" flow field can never be characterized.

The calibration delivered a value of 65.48 µm/Pixel. With this information and the laser impulse time, it is relative easy for the software to calculate the velocity. The empty glass channel with the inner glass cage is shown in the figure 8. In this figure the illuminated plane by the laser light sheet is shown, synchronized with the camera. The particles were injected from the bottom cylindrical section and entered the glass cage, respective the quadratic section through the hole-plate.

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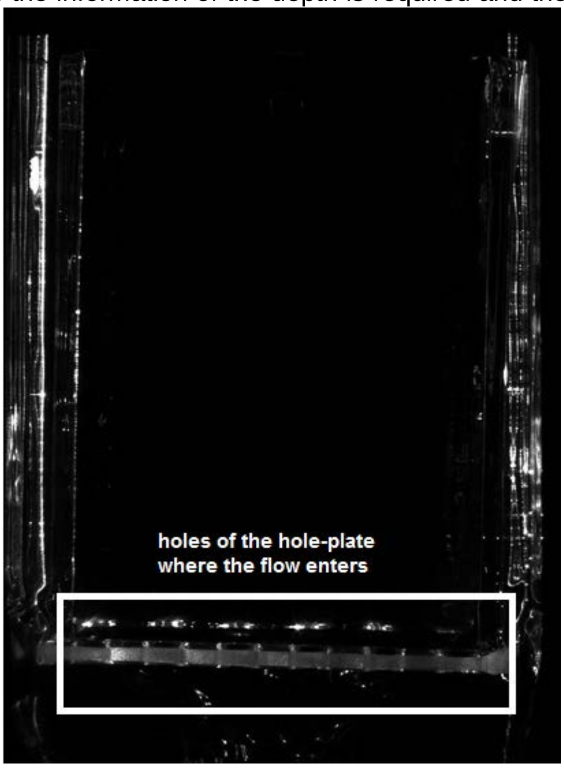

Figure 8:Rotated view of the camera on the measuring section

2.4 Process of the Evaluation

In order to evaluate the frames few steps have to be done:

- *Set the calibration (has to be done only once, if the laser sheet and the camera are always fixed)*
- *Pre-Processing:-mostly contains two steps:*
  -Generate a background Image
  -subtract all the frames from the background image in order to only have moving objects
  The procedure of background subtraction is not necessary, but it improves the results of the characterization of the flow field as only the moving objects are “moved” to the foreground. If there are elements like thermocouples or any other objects that do not move and disturb the evaluation, then this method is highly recommended.
- *Put a “mask”:*
  Putting a mask can be helpful if for example the flow field around any objects has to be characterized, then a put can be put “on” this object. While performing the evaluation, the objects that are put in the mask are neglected and not evaluated. An example of the set mask is given in the figure 9. In the figure a mask above the pebble bed was set, in order to only evaluate the sections above the pebble bed.
- *Processing:*
  After the Pre-Processing the “correct” algorithm for the Processing has to be set. This is not described here in detail, as there are many existing software that use different modifications of the calculating algorithms and there is no “the” algorithm that can be applied on all PIV-Measurements. It is only mentioned, that the TSI-Software INSIGHT4G was applied.
- *Post-Processing:*
  Post-Processing can be helpful in order to eliminate spurious vectors or fill any holes, etc.

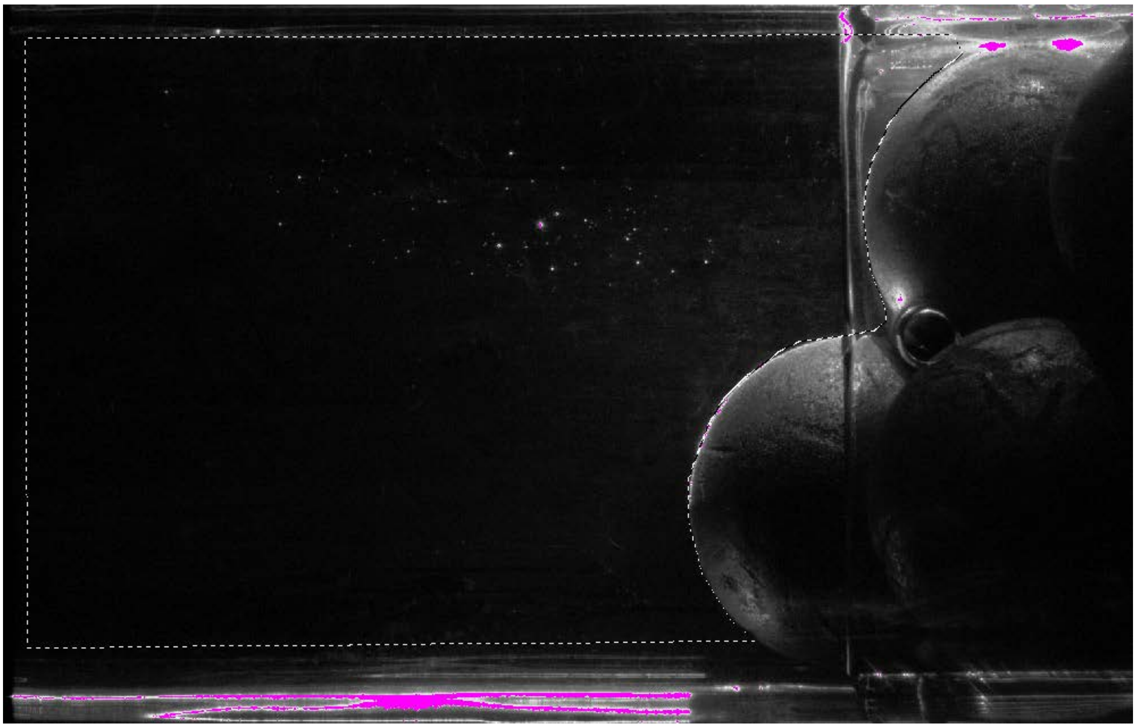

Figure 9: Example of the Mask: the pebbles will be neglected for the Evaluation

3 Experimental Results

3.1 Empty channel with low velocities

In the first experiment the flow of the empty channel with the empty glass cage was characterized.
The empty glass cage is shown in the figure 8. Only the glass channel with the inner cage is to be seen. Behind the cylindrical part of the glass channel the quadratic section begins, where the glass cage is sitting. Same glass channel with the glass cage is illustrated in the figures 10-14. It is to be mentioned that the view is rotated due to the setup of the camera, which had to be rotated at 90° in order to fix it on the Linos stand. So the flow is actually coming from the bottom and flowing upwards, but the camera sees it from right to left.

At the transition part (cylindered section to the quadratic section), the holes of the hole-plate can be seen, where the aerosol enters the quadratic section.
The entrance of the flow is shown in the Figures 10-14. As it can be seen from the figure 12 the particles flow through the hole plate with parabola shape, which was expected, as the flow is laminar. It can be clearly seen with the camera, how the particles enter the glass channel through the hole-plate. The shape of the flow is a parabola, where the velocity in the middle of the flow is the "highest" and reducing to the corners to another smaller value.

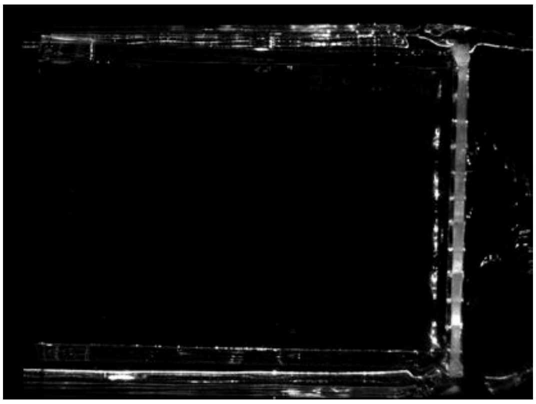

Figure 10: empty glass cage

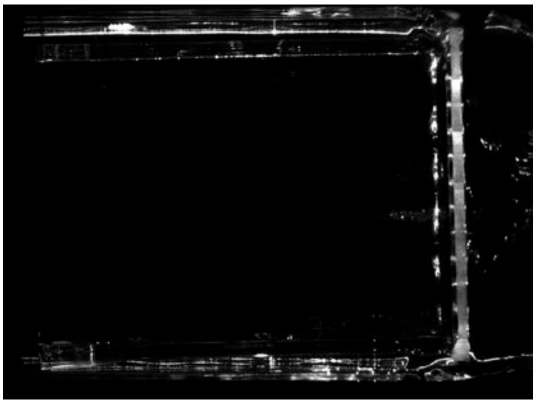

Figure 11: Flow entering in the glass cage from bottom

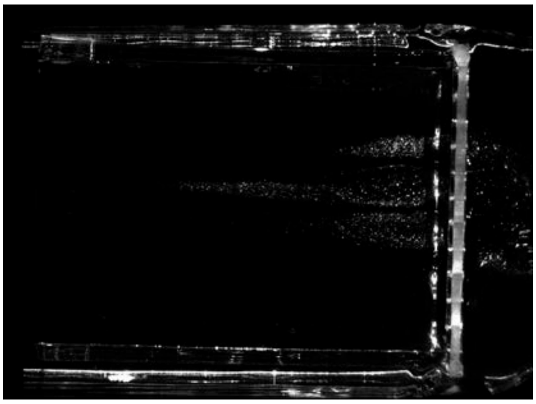

Figure 12: Flow with the parabola shape

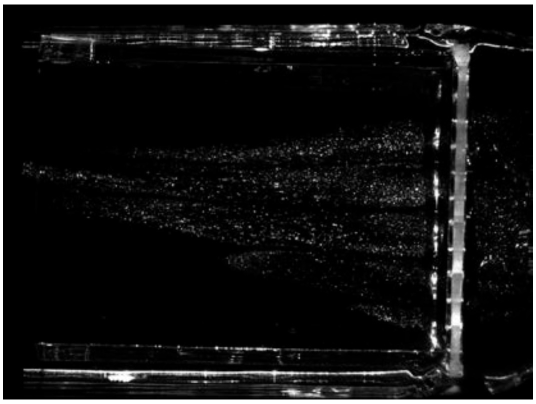

Figure 13: Flow with the parabola shape

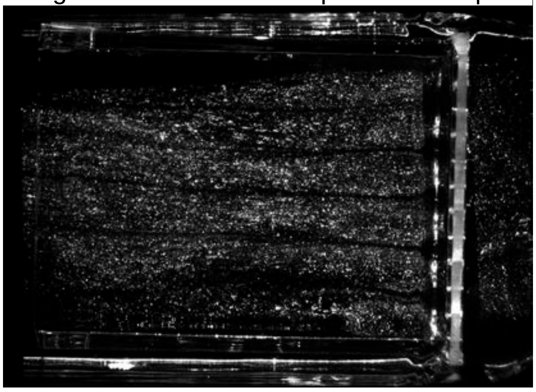

Figure 14: Flow distribution in the glass cage

In the following figures 15-18 the evaluation of this flow is given. The x- and the y-axis show the area of interest that was evaluated (the mask).The different colours show the calculated local velocity of the flow field with the TSI-Software. The evaluation shows the particles entering from the middle of the glass channel, with the highest velocity in the middle. After few microseconds the aerosol enters through the other holes and distributes to the sides, with a velocity, that is lower than the velocity from the middle of the flow. After a short period of time the whole channel is filled with particles with a parabola distribution of the flow. The results of the evaluation may not be perfect yet but they do show a congruence with theoretical distribution of the flow that can be calculated with the Bernoulli-Equations. Above all the last figure demonstrates this fact clearly. The red colour in the middle corresponds to high velocity and yellow/green colours correspond to lower velocities.

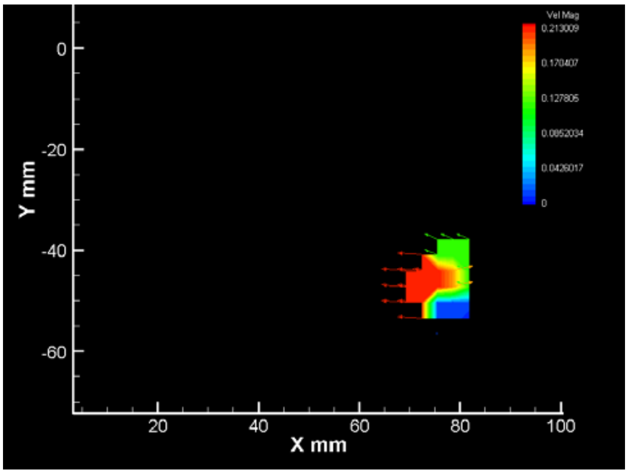

Figure 15: Characterization of the entering flow

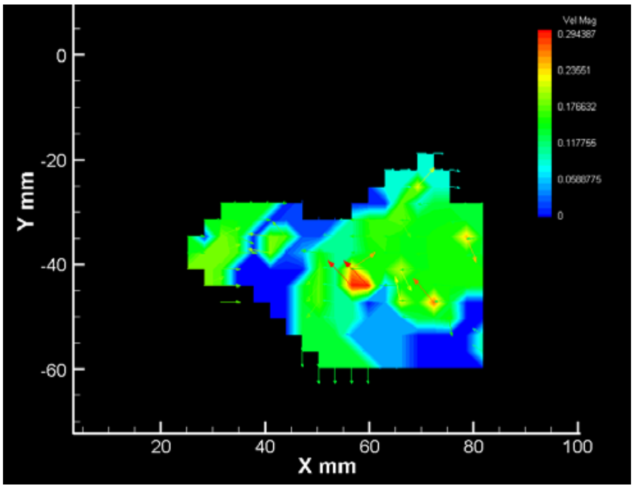

Figure 16: Characterization of the entering flow

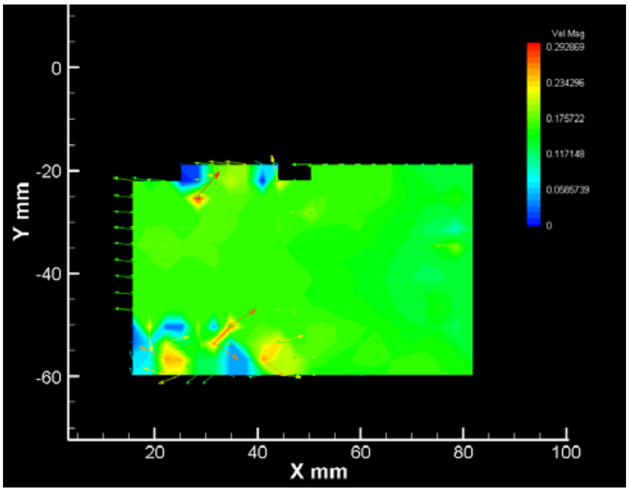

Figure 17: Characterization of the flow

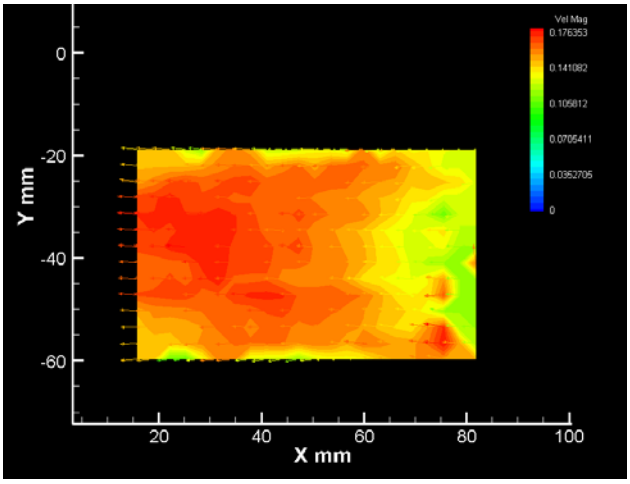

Figure 18: Parabola shape of the flow with the highest

3.2 Empty channel with high velocities

As the particle generator does not work quite well at the moment and the particle density fluctuates too much, it was decided to use 12 m^3/h, where the particle density is appropriate for the PIV. Also here, the flow was laminar, with the Reynolds Number of 511. There has to be a minimum density for the PIV, such as 10 Particles (average, experience value) in an "interrogation window". Because of the poor quality of the frames, which resulted in poor quality of the evaluation, only the evaluation is given here. The figure 19 shows such an evaluation of the flow entering the glass cage. The green parts in the evaluation are the result of different particle size distribution of the graphite particles. Depending on the particle size, the smaller respective bigger size particles are accelerated differently. This results in wrong velocity vectors, which are indicated with the green spots upstream of the hole-plate. All in all, it can be said, that the velocity at the volume rate of 12 m^3/h is homogenously distributed in the glass cage (light blue colour).

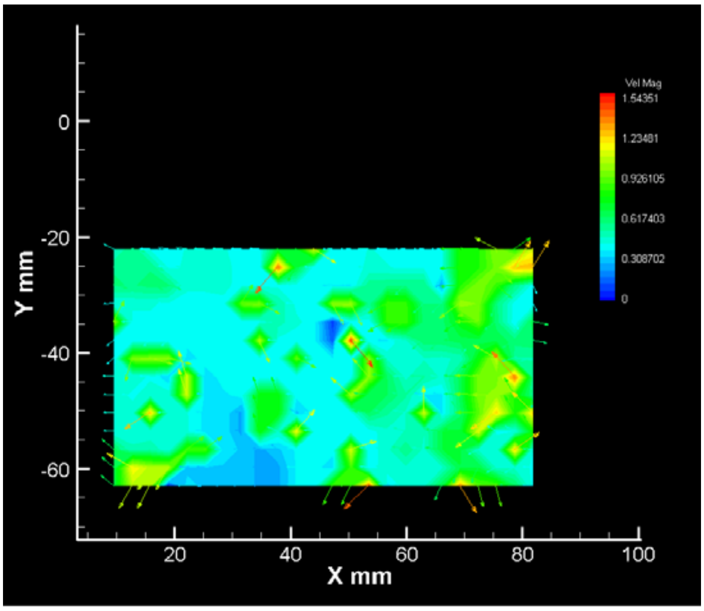

Figure 19: Evaluation of the flow field in the empty glass cage with high velocities

3.3 10 mm pebble-bed with low velovities

The inner glass cage was filled till the top with the 10mm-pebbles and the flow were characterized above the pebbles bed, as there is no chance of illuminating the pebble bed from inside. This is the reason why only the flow field from above was characterized. Figure 20 shows the pebbles with the glass cage. This picture was taken after the experiment and illustrates also the depositions on the pebbles and at the inner wall of the glass cage, which restricts the view of the camera after few minutes.

Figure 20: glass cage with the 10mm-pebbles

The raw images of the flow above the pebbles are demonstrated in the figures 21, 22. It is to be mentioned that the illuminated layer was in the middle of the pebble bed. The section of the measurement is smaller than of the other experiments, because the coil was blocking the view of the camera, respective the laser light. At the time of these measurements, the coil could not be removed because few malfunctions with the device control of the linear-engine occurred, that moves the coil up and down.

By considering the both raw frames, one can see that on the first raw frame there are lesser particles to be seen than on the second. This was observed continuously during the measurement and also visualized in the evaluated results, figures 23, 24. The evaluated results are little poor, because of the smaller particle density above the pebble bed. The conditions for this experiment were the same as for the empty channel. But due to the depositions in the pebble bed, the particle density was unwillingly reduced. Nevertheless, still the flow can be evaluated and delivered this new cognition for flows in pebble beds.

The flow finds free spaces in the pebble bed and takes the "easiest" path to discharge from the pebble bed. The path that is chosen by the particles is the glass cage`s wall, where through the contact of the pebble with the wall bigger empty spaces are located than in the middle of the pebble bed. This is the reason why in the evaluated frames, the faster regions are located at the sides and the slower in the middle of the measured section. At the outer parts of the pebble bed, there are more “free” paths for the aerosol to flow.

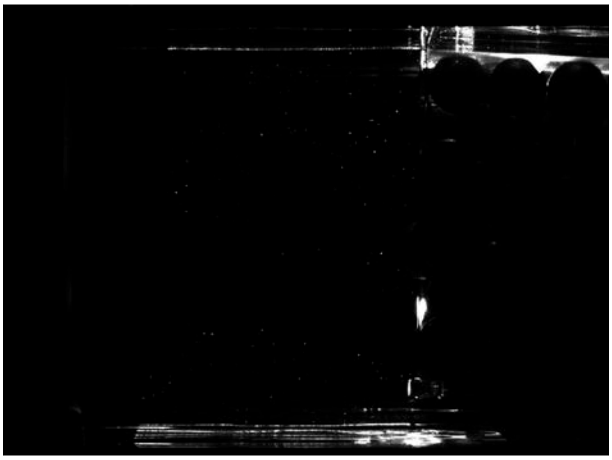

Figure 21: uncharacterized flow above the pebble bed

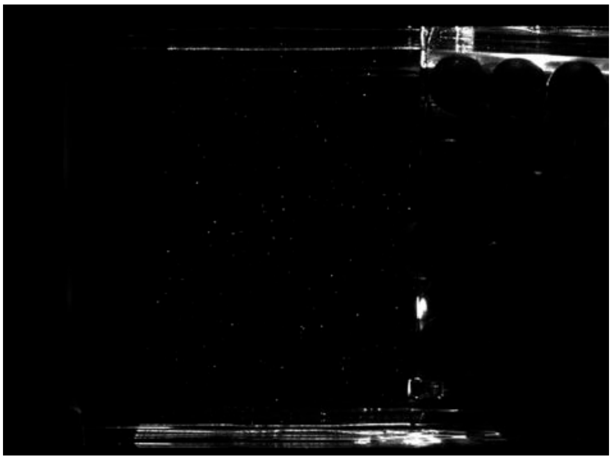

Figure 22: uncharacterized flow above the pebble bed

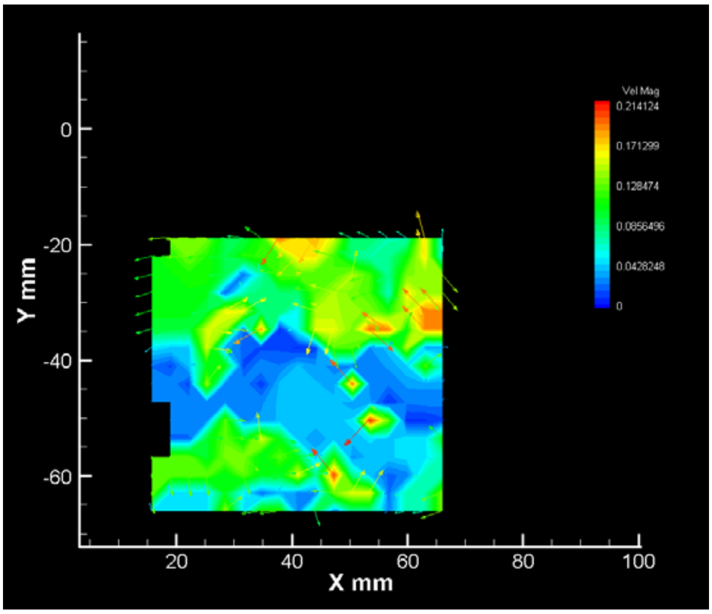

Figure 23: Flow field above the pebble bed

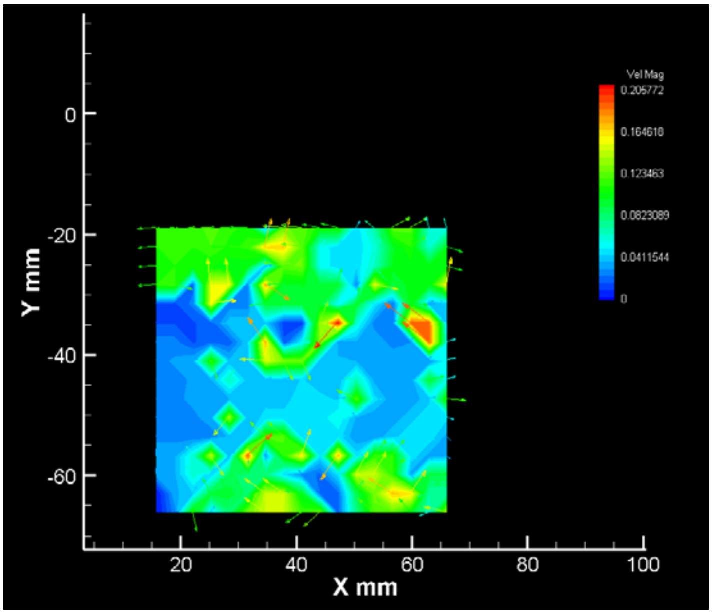

Figure 24: Flow field above the pebble bed

3.4 30 mm pebble bed with low velocities


Figure 25: Pebble bed of 30mm pebbles

It is also interesting to view the flow field around 30 or above 30 mm pebbles. For this purpose 30 mm pebbles were put in the glass cage, shown in the figure 25. As the pebbles are big, the idea was to measure the flow between the free spaces in the pebble bed. But unfortunately after illuminating the pebbles, the pebbles reflected the laser light too strong, that no measurements between the "free" spaces could be done. There were no particles to be located by the camera due to the strong reflection at the pebbles. This is the reason why the flow can only be characterized above the pebbles.

Here at the rate of 1,5 m^3/h a straight flow on one side of the upper section and on the other a "dead" zone above the pebble was observed, shown with their characterizations in the figures 26-29. By looking at the right part of the glass channel a flow can be seen that is moving upwards, visualized by the particles. While looking at the left part, there are no particles, depicted with the "no particle" spot. As the flow of the particles continues, more and more particles get dragged in the "dead" zone and a vortex is built up right

above the upper pebble. As more and more particles get dragged in the dead zone, the “no particle zone” vanishes.
The results of the evaluation are not perfect because there are always few particles or spots, which run out of line and do not deliver correct results in the evaluation. But nevertheless the above mentioned observations of the illuminated particles with the camera can also be seen after the evaluation of the frames, figures 27, 29. Here again, the frames were added to generate a background image that was subtracted from the other images in order to only have the “moving” objects i.e. particles in the foreground. In the first images of the evaluation a jet stream to the right side is to be seen and not on the left side, no evaluation can be done, as there are no particles. In the further images more and more particles get drag in the dead zone and make a vortex that could be evaluated with the software.

Figure 26: Flow field above the 30mm pebble bed with a "no particle" zone

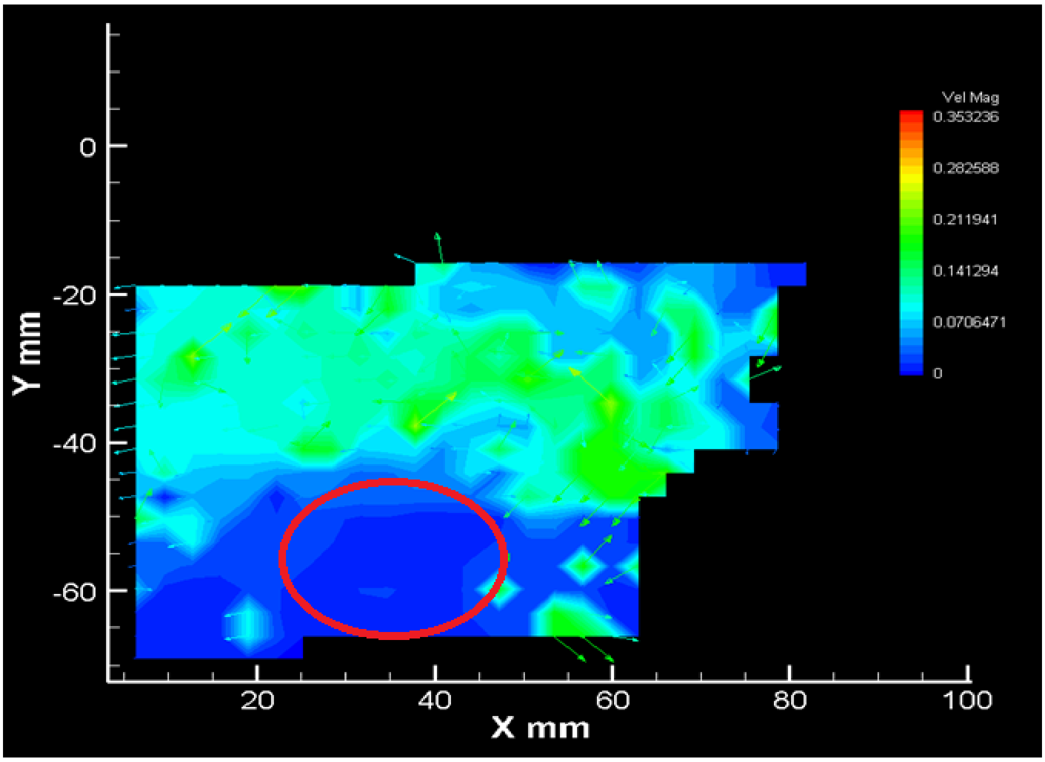

Figure 27: Evaluation of the flow field

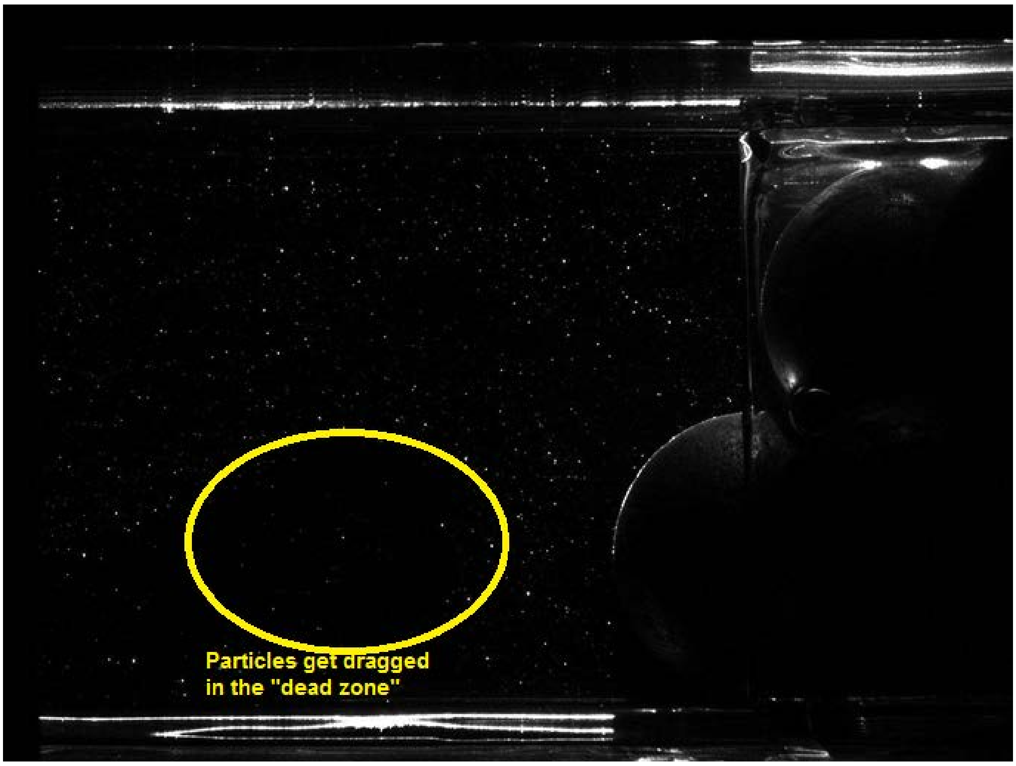

Figure 28: Flow field above the 30mm pebble bed – particles get “dragged” in the dead zone

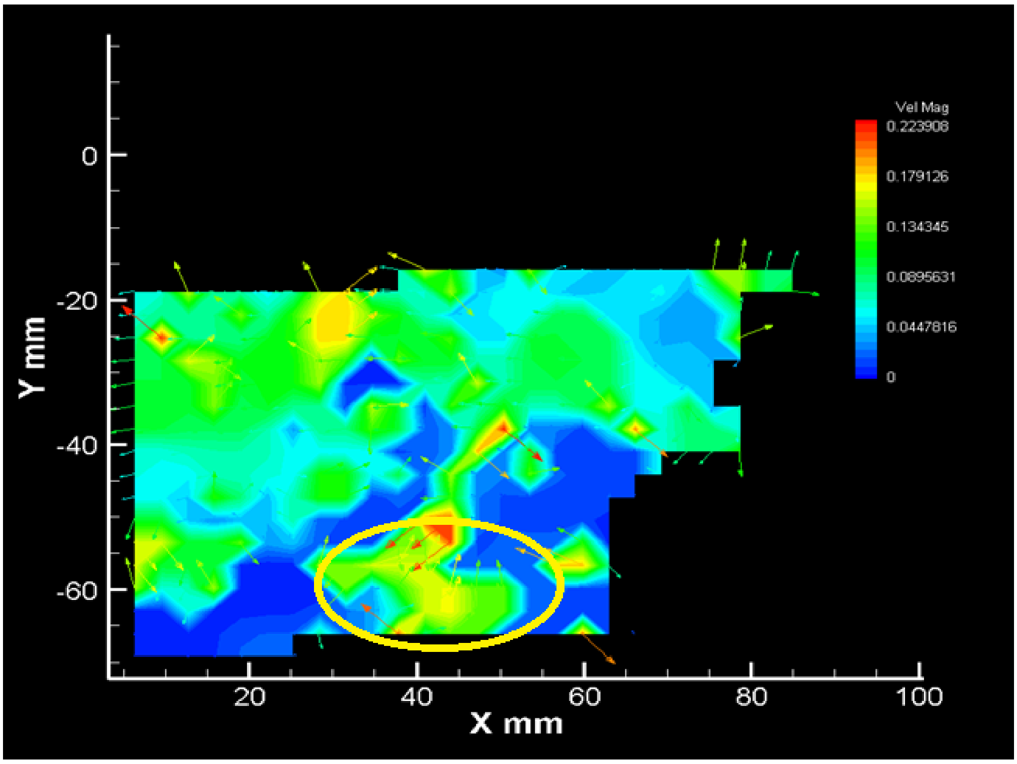

Figure 29: Flow field above the pebble bed

3.5 BCC-Geometry with low velocities

The structured "Body Centred Cubic (BCC)" consists of three layers:
1st layer: 4 complete pebbles
2nd layer: 1 complete and 4 half pebbles
3rd layer: 4 complete pebbles
The aim is to improve models for porous approaches to simulate complete pebble beds. The first approach started with a simple idealized structured bed with idealized conditions, which with more and more theory and experimental data should be enhanced to the reactor scale/conditions.

As mentioned in 2.1 and indicated in the Figure 5, the BCC is connected with small cylindrical sticks to enhance the "contact" area between the pebbles which leads to higher induction heat in the pebble bed. It is to be noticed that there is no connection between the 1st, 2nd and the 3rd layer among each other.

The configuration of the thermocouples and the laser beam are given in the Figure 30. The BCC-pebble bed was positioned in the inner glass channel with three thermocouples to measure the temperatures downstream, upstream and of the pebble bed (only 1 pebble to be exact).

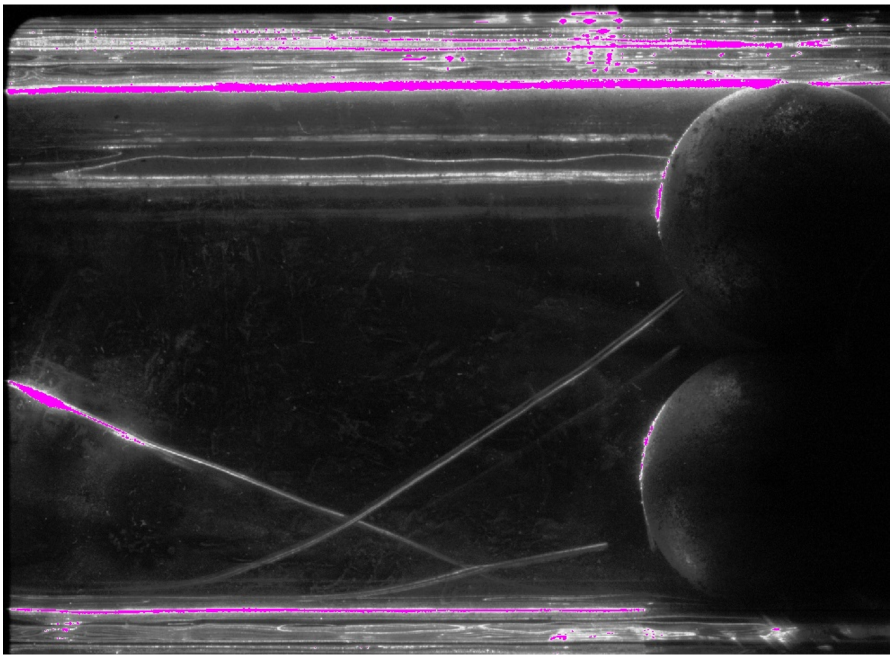

Figure 30: Laser sheet, thermocouples and the section above the pebble bed

Due to the larger dimensions of the BCC-geometry, the larger inner glass channel instead of the glass basket was used for the bedding of the pebble bed. The particles and the preheated gas were injected separately in the glass channel, as the particle generator cannot be operated at high temperatures. The gas was preheated with a heating sleeve and a heat exchanger. Another heating sleeve was wrapped around the glass channel to reduce the heat losses in the channel. The seeding particles were injected from the bottom where they mixed up in the preheated gas and purged through the pebble bed. The temperature profile of the interesting section is given in the Figure 31. The volume rate was set at 2 m^3N/h for the preheated gas and 1 m^3N/h for the aerosol flow. The average volume rate below the pebble bed would be due to the density differences ~5.2 m^3/h, which leads to an average velocity of ~0.44 m/s at the entrance of the pebble bed. This would correspond to a Reynolds Numbers of 104, which indicates a laminar flow before the pebble bed. The fluctuations in the temperatures are due to the setting on /off of the particle generator, which is only put in operation, when the PIV-measurements are to be executed. The reason for this procedure is the limited time that is available for the measurements due to the depositions on the wall, which restricts the view of the camera.

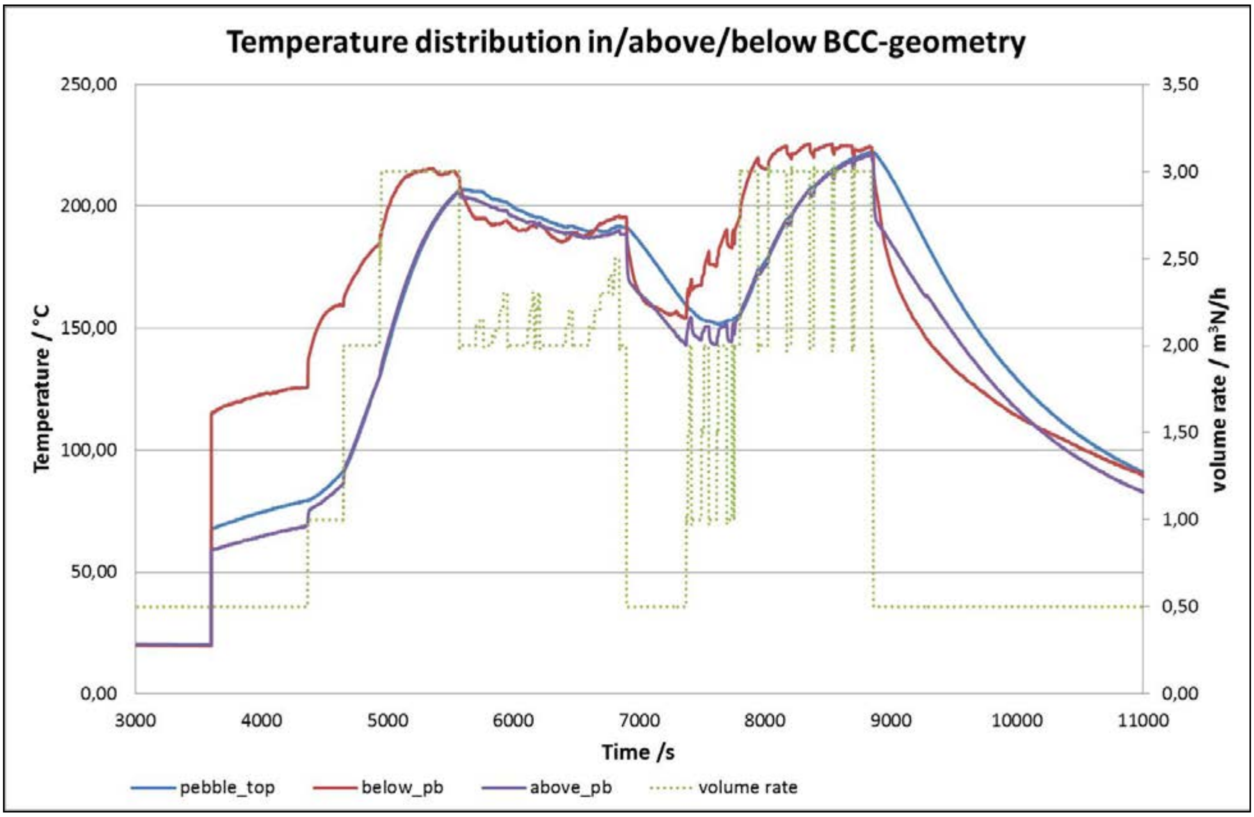

Figure 31: Temperature distribution of the pebble(s) and the gas; volume rate

The Figures 32 and 33 show the mask of the relevant section and the results of the PIV evaluation. The flow was characterized from the top of the pebble bed, as it was not possible to record any particles between the pebble bed. The relevant parts of the measurement section are unfortunately hidden between the pebbles in front or the reflection of the pebbles is so strong that no measurement in a pebble bed is possible.

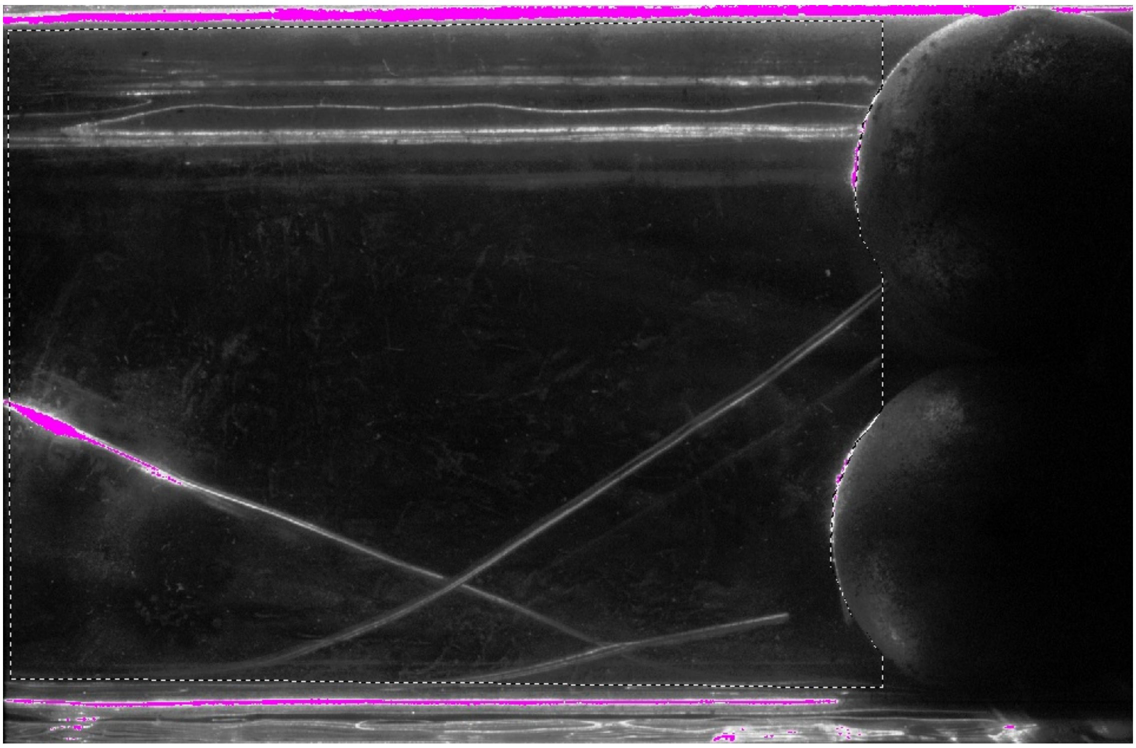

Figure 32: Mask for the evaluation

The flow above the front pebbles was characterized which is shown in the Figure 33. As it can be seen there are two vortices, one above the right pebble and one above the left pebble, which move in the opposite directions and eliminate each other, which results in a very low velocity zone right above both vortices. Another zone where the flow velocity is very low can be seen above the left vortex. The particles change their direction and follow the fluid to the right, which indicates that the flow is diverted to the right. Above this path there is again a flow (particles) to be seen which is probably coming from another direction. On the top right side a particle/velocity free zone is built up, which was consistently seen during all the measurements. The whole evaluation shows a mixing of the fluid above the pebble bed, which could be due to the different empty places where the fluid exits the pebble bed.

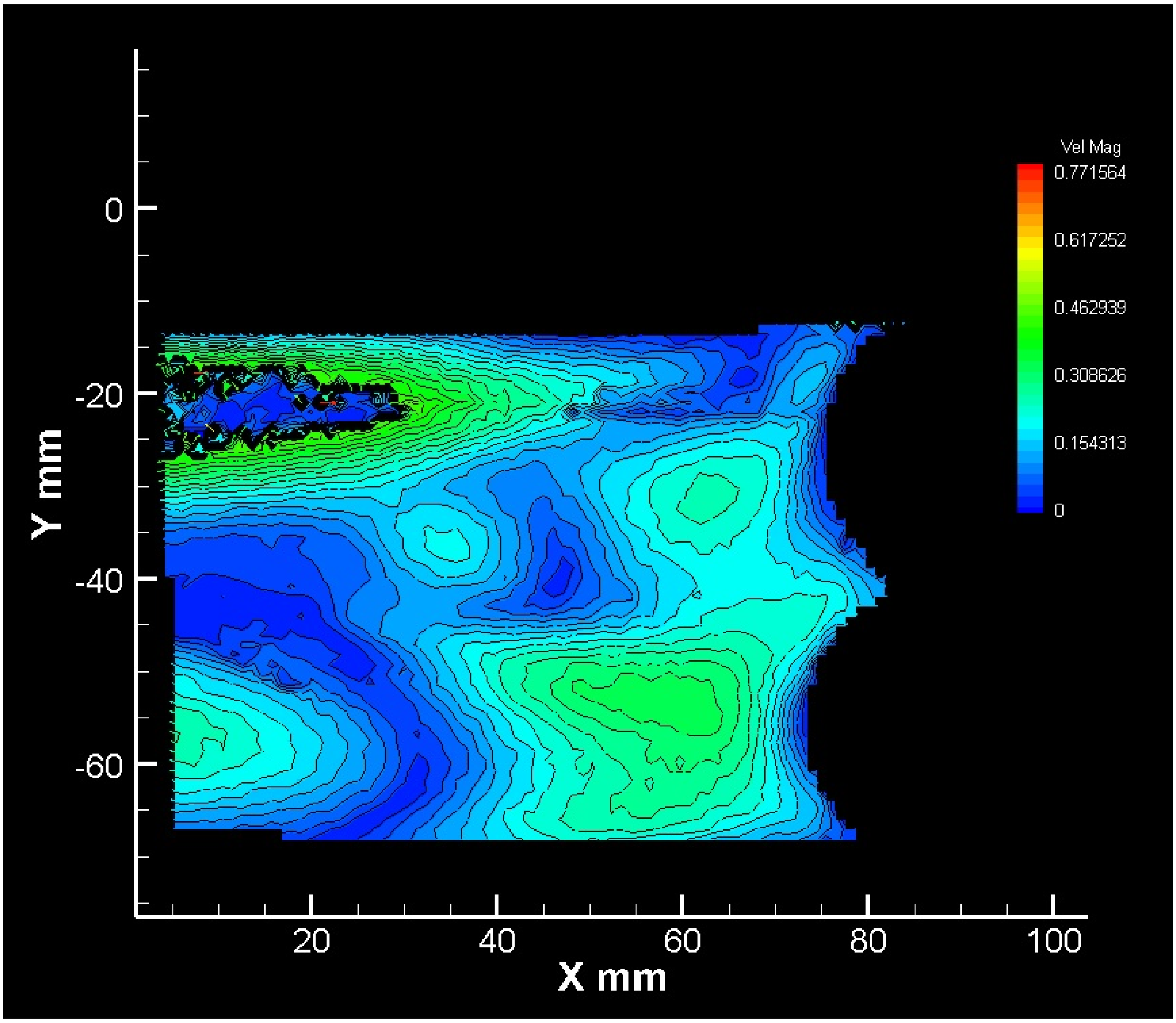

Figure 33: PIV-evaluation above the pebble bed

After the measurements, the heating sleeves and the induction generator were put off and the facility was cooled which takes few hours. The facility was dissembled in order to clean the inner glass channel for another experiment for higher velocities.

The configuration of the setup for the higher velocities was identical to the setup for low velocities with only two differences that the thermocouple below the pebble bed was removed as it takes a high effort to put it on the correct position and the other change was the usage of the induction generator from the beginning to heat up the pebble bed. In few pre-tests an appropriate volume rate (between 6 – 8 m^3N/h) for the measurement was detected. At these volume rates the particle density is sufficient, above 8 m^3N/h the particle density is too low for the evaluation. The Figure 34 shows the result of the PIV-evaluation. For the evaluation the interrogation windows were chosen to be larger than for low velocities because of the smaller particle density. Still the results are usable for the understanding of the flow at relative higher velocities. 6 to 8 m^3N/h correspond to a volume rate of 9 – 13 m3/h before the pebble bed and with it a velocity range of 0.77 – 1.2 m/s which indicates the laminar regime with the Reynolds-No of 285. The evaluation shows two vortices above both pebbles, both moving in opposite directions. By considering the middle section of the flow, it seems that another bigger vortices starts to build up from both directions, which meets up in the middle and moves upwards. Through the impact from each side the flow looses energy and moves upwards with a lower energy and probably also lower velocities. To verify these speculations another camera and light sheet optics would be required in order to span out a laser sheet and recording the flow above this measuring section, which would also enhance the measurement section.

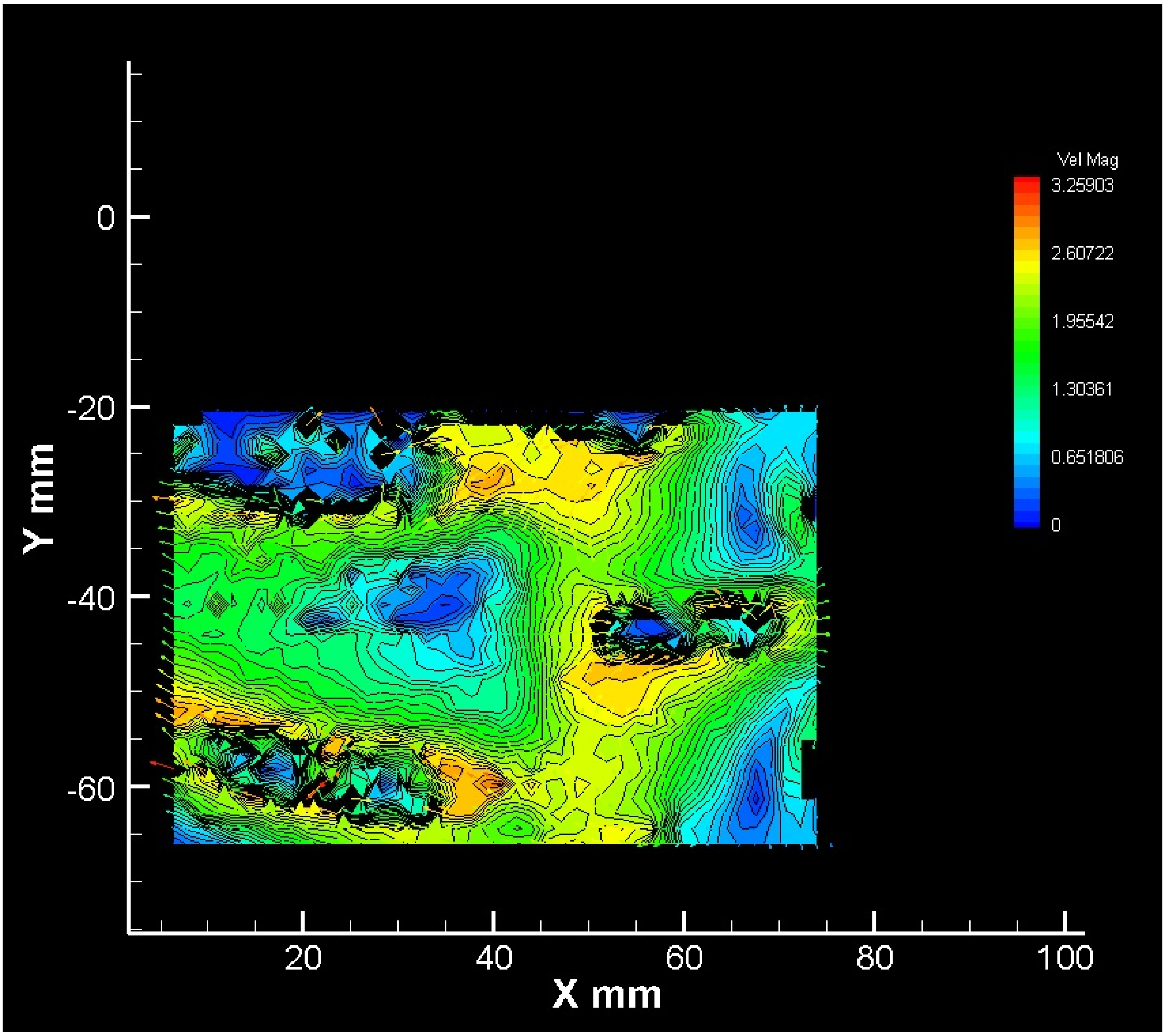

Figure 34: PIV-evaluation above the pebble bed for higher velocities

The limits of the experimental facility INDEX regarding the temperature distribution in the **BCC-geometry**:

In another experiment, with the same conditions and setup (without cleaning) the BCC pebble bed was heated up with the induction coil to deduce the maximum temperatures that can be reached in the pebble bed. For this purpose the induction generator was put in operation and after a short period of time the pebbles reached a maximum temperature of almost 700 °C (with the maximum induction power). At this temperature the pebbles began to glow, which can be seen in the Figure 35. The temperature of 700 °C was measured with a thermocouple that was "touching" the pebble. As only one pebble-temperature was measured and all the pebbles were glowing, this temperature was assumed for the other pebbles as well.

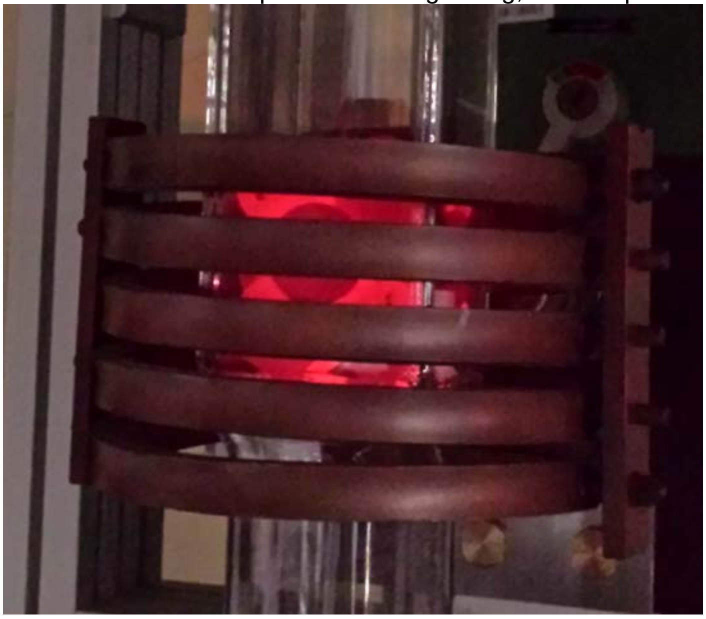

Figure 35:The induction coil heats up the pebbles till 700 °C

An increase in the temperature was not seen. The gas temperatures at the entrance of the glass channel and the temperatures below, in and above the pebble bed are indicated in the Figure 36. The preheating of the gas was put off, in order to check the induction performance only. At the downstream of the pebble bed the gas temperature was measured with a thermocouple and reached almost 580 °C, which could be the effect of the radiation emission from the pebbles. This results in that the actual gas temperature may be lower than 580 °C. To determine the "correct" gas temperature and the influence of the radiation of the thermocouple is not the subject of the work.

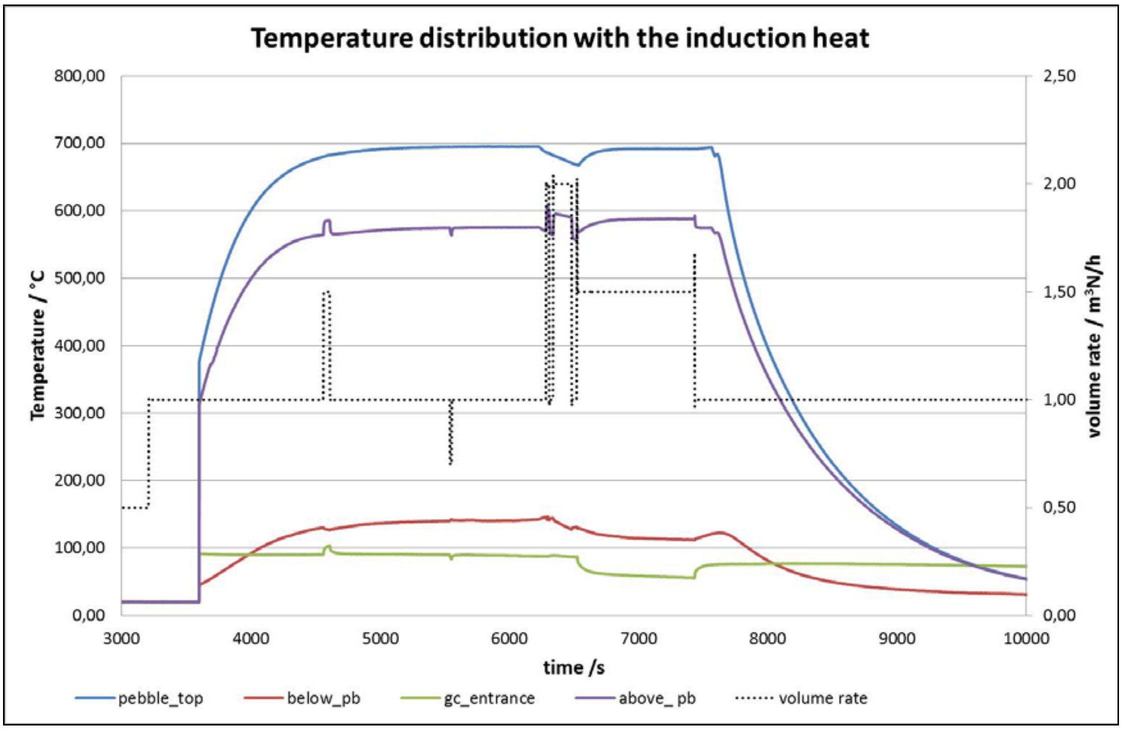

Figure 36:Heat generation in the pebble bed by induction coil

Between 6000 and 7000s the temperature sank to another smaller value, which was the result of the linear displacement of the induction coil. The coil was moved to the bottom to execute PIV-measurements above the pebble bed, see Figure 37.

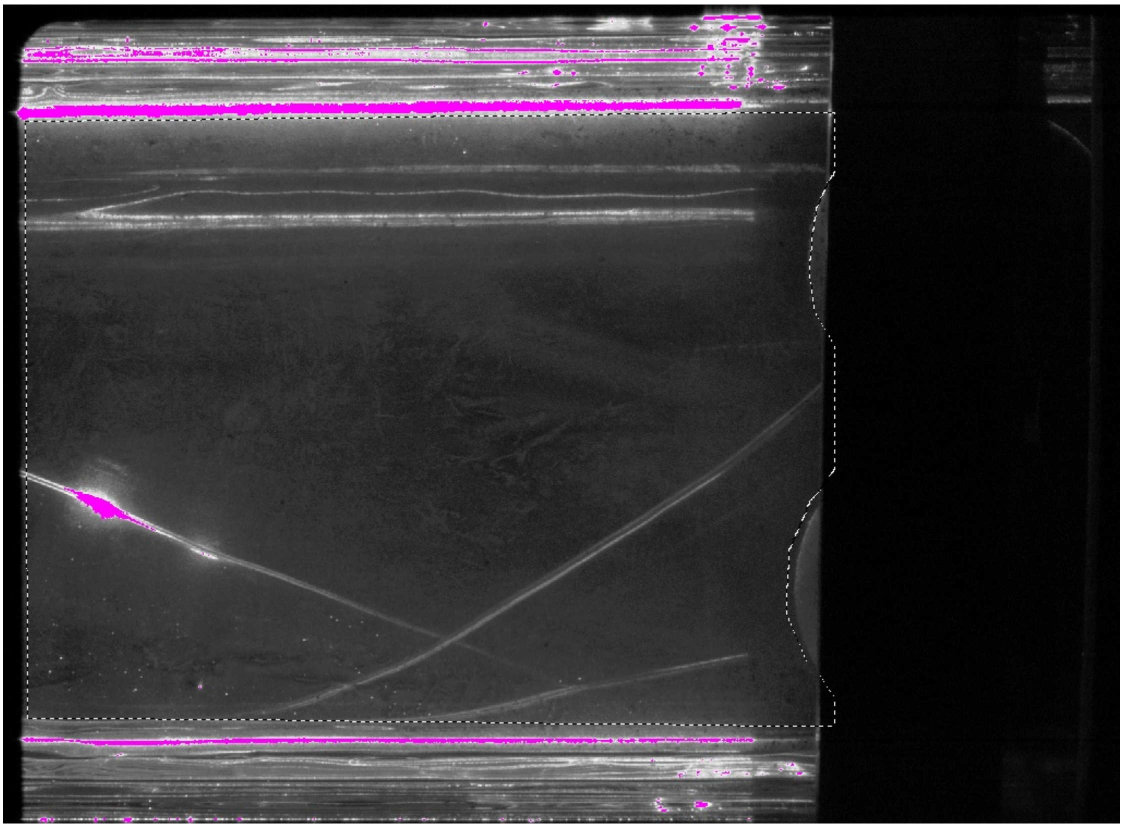
Figure 37: Pebbles hidden by the upper induction coil winding

The evaluation of this short experiment is indicated in the Figure 38. As the particles suffer from the thermophoretic force, they deposit on the cold areas of the glass channel and unfortunately this (negative) effect limits the time of the measurement. But nevertheless, still few measurements could be done, indicated in the Figure 38. It can be seen that right above the pebbles the velocity is relative slow which is the result of the thermophoretic force due to the high temperature of the pebbles. This only indicates that the particles are "moved" away from the hot areas of the pebbles, which results in higher velocities in the centre of the measurement section. This necessarily does not mean that there is no flow above the pebbles, it just cannot be illustrated with the particles as the gas temperature below the pebble bed was much lesser than the pebbles bed temperature. In order to measure the flow directions correctly the gas temperature probably has to be the same as the pebble bed, which is not possible. The maximum gas temperature in the glass channel at the position of the pebble bed can only reach 400 °C at the volume rate of 5 m^3N/h. To reach the turbulent regime at the temperature of 400 °C one would need to set a volume rate of 197 m^3/h (i.e. 86 m^3N/h) in the cylindrical glass channel, which is blatantly not possible in the facility. Even at cold conditions a volume rate of roughly 41 m^3/h would be required in the glass channel. This volume rate is generally possible but the particle density would never be sufficient for the PIV-measurements.

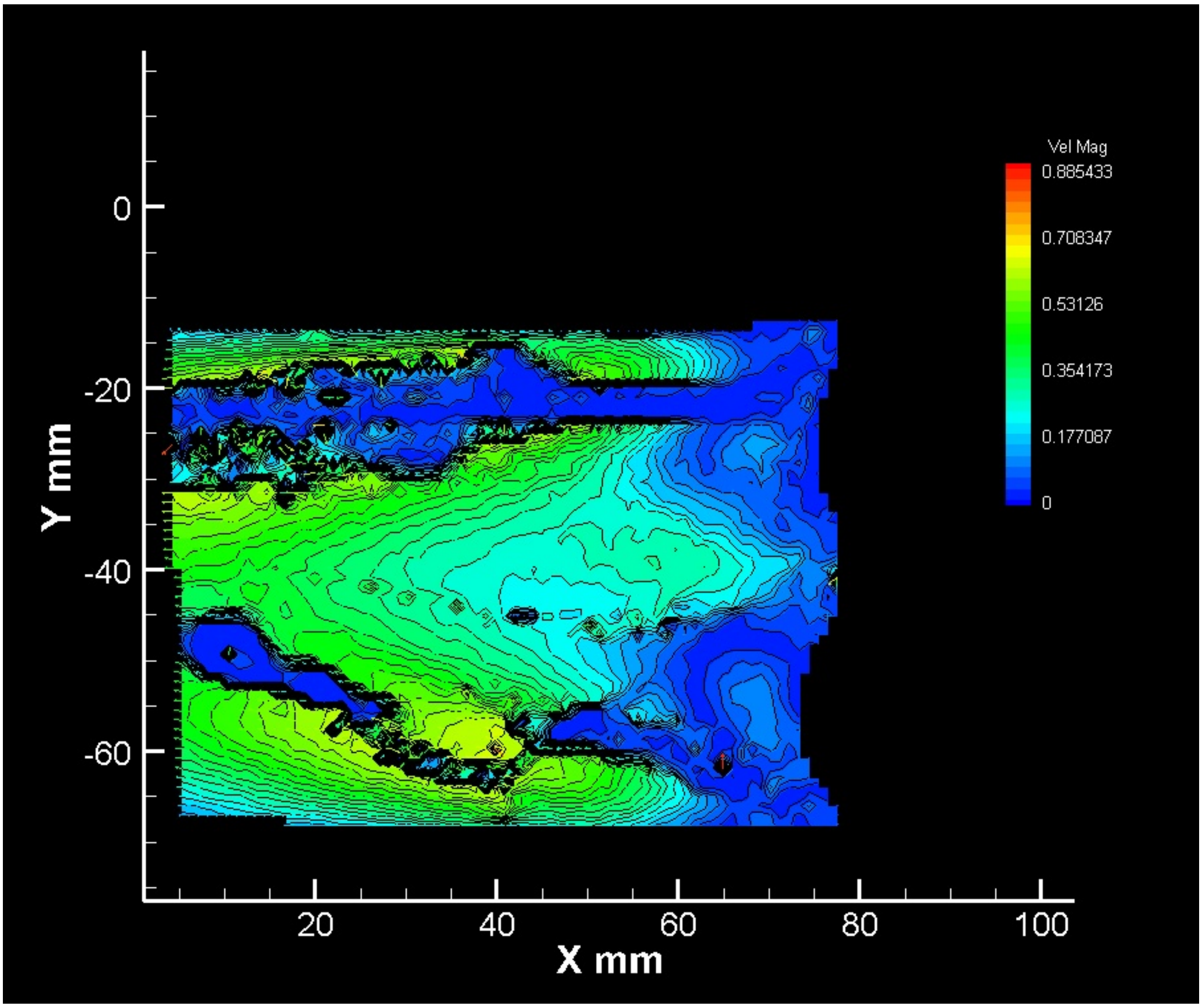

Figure 38:Evaluation of the flow field above the heated pebbles with the induction coil

Flow at the boundary layer of the pebble bed:

As mentioned above the flow characterization in the pebble bed is not possible due to the high refractive index of the pebbles and “hidden” positions of the path that the flow takes. But nevertheless, fortunately it can be characterized qualitatively by viewing the inner glass channel where the pebble bed was located. By considering the Figure 39, one can see how the fluid purged through the pebbles bed, respective at the boundary layer of the pebble bed. Attention: The flow lines only illustrate the flow at the boundary (cold areas). Through viewing this pattern, one should not have any conclusions on the whole flow in the inner glass channel.

Figure 39: Flow field at the boundary layer

4 Summary & Outlook

In the empty channel the observation and evaluation was in relative good agreement with the expected theoretical results. For the first experiments with the PIV-System the evaluation can be considered as good results, but of course there can be always improvements in the measurements and in the settings of the evaluation, which could deliver better results. Because of the deposition of the particles on the wall there is a limitation of experimental measurement time with the PIV-system. As the channel has to be cleaned and assembled again, it is very difficult to set the same conditions, such as setting the camera exactly at the degrees of 180° with respect to the glass channel. More important for the measurements are not the exact position of the camera and the glass channel but the camera recording the reflected laser light of the seeding particles at the angle of 90°. This condition was always ensured during all the measurements by using and fixing the laser (laser-sheet) and the camera with LINOS-profiles, which were purchased for these purposes. This is why, the results obtained are reproducible, as for example in a 10mm pebble-bed, only the order of the pebbles is changed, but the observations above the pebble bed stay the same.

There was no possibility to view the flow field between the pebble bed, as the graphite pebbles reflected the laser light too much. The reason for the "good" reflection is the relative high index of refraction n which is for graphite roughly $n=2$. For this reason no particles between the free spaces were visible, even with a wavelength Filter (that was on the camera for all measurements) it was not possible to reduce the reflected laser light from the pebbles. This is also why the flow layers of the above part of the pebble bed were analysed.

For further studies a sophisticated 3D-PIV-System can be setup with 2 cameras, so that the depth information can also be measured or a 2D-measurement with two cameras, which can be located above each other and measure a larger area of the flow. Measuring with two cameras can also deliver information of the transition area of the flow, where the flow transfers from laminar into turbulent flow.