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Experimental determination of spatial distribution of granular fractions in flow of bimodal mixture

Štěpán Zrostlík[1,*], *Tomáš* Picek [1], *Lukáš* Svoboda[1], and *Václav* Matoušek[1]

[1]Czech Technical University in Prague, Faculty of Civil Engineering, 166 29 Prague 6, Czech Republic

Abstract. The contribution deals with the determination of the ratio of volumes of particles of individual fractions in flows transporting bimodal granular mixtures. The spatial distribution of the ratio is obtained by analyzing images collected by video recording. The measuring method and post-processing analysis are demonstrated on experiments in our new recirculating fluidization cell. The tested bimodal mixture is composed of two granular fractions of different colors – black and white. The analysis is based on a local identification of particles and their background in the collected images. More precisely, the identification of individual particles is based on the grayscale screening of the images. The method allows to identify both the instantaneous and time-averaged spacious distribution of the grain volume ratio. The experimental results reveal that the measuring method is successful if constant light condition is secured and the medium carrying particles is sufficiently transparent. The method is applicable to laboratory flows with sediment transport no matter whether sediment particles are transported as bed load or as suspended load.

1 Introduction

Transport of solid particles by flowing carrier fluid is common in many industries including mining, dredging, chemistry or food industry. Usually, the transported solids contain particles of different sizes and various investigations have been conducted to look at the effect of the particle size on the transport phenomenon. For instance, Berstein (1962) used the x-ray technique to evaluate the influence of the particle size on solids transport. When it comes to bimodal mixtures, it is preferable to identify the ratio of the individual fractions in the transported bimodal mixture directly during transport. However, the biggest problem associated with such monitoring that the used method should be non-invasive and mostly continuous.

For example, video analysis is a non-invasive method. However, it requires a transparent section of a pipe conveying the mixture, as used by e.g., Mena et al (2005) for an identification of the shape and size of air bubbles. The video was used to identify the flow through the particles by Simon (2005) and Surý (2006). Video can be used for an identification of the total volumetric concentration of solids in flowing mono-size mixture as showed by Spinewine et al (2011) and Krupička et al (2018).

Hlom (2018) used video recordings to determine the ratio of volumes of particles of individual fractions in flows of bimodal granular mixtures composed of a black fraction and a white fraction in open channel flow. The thesis by Hlom summarizes advantages and disadvantages of this method and points out the necessity of constant light conditions.

In this paper, we investigate and further analyse video recordings for a bimodal mixture. Contrary to previous works, the method is tested for the condition of turbulent suspension of particles in which it has not been used yet.

2 Methods

The bimodal suspension experiments were carried out in our new fluidization cell in the Water Engineering Laboratory of the Czech Technical University (CTU) in Prague.

2.1 Materials

Two different solids fractions were used in the tested mixture. Both fractions were plastic grains of similar density and they differed in size and shape. They also differed in colour to make visual observations of the individual fractions in the bimodal mixture more recognisable. Properties of the fractions and the bimodal sediment are summarized in Table 1. Plastic grains of the finer fraction (Hostaform, HSF3) are white, its shape is ellipsoidal, the equivalent sphere diameter d_e = 3.18 mm and the density ρ_s = 1359 kg.m^{-3}. Plastic grains of the coarser fraction (Tiulit, TLT50) are black and of a cylindrical shape with the equivalent diameter d_e = 5.41 mm and the density ρ_s = 1307 kg.m^{-3}.

[*] Corresponding author: stepan.zrostlik@fsv.cvut.cz

Table 1. Properties of sediments.

Properties	HSF3	TLT50
d_e (mm)	3.18	5.41
v_t (m.s^{-1})	0.131	0.149
ρ_s (kg . m^{-3})	1359	1307
color	white	black

2.2 Fluidization cell

An experiment in a fluidization cell is a suitable way to test a method for the measurement of solids concentration under controlled conditions (Spinewine et al., 2011, Krupička et al., 2017). Recently, we constructed a new fluidization cell based on our previous experience with other cell used previously. The main improvement is a possibility of the recirculation of particles or keeping particles in suspension without recirculation. The fluidization cell has two parts of the same height of 1.4 m. The first part is built from a circular pipe and a propeller was placed into the pipe. The propeller is driven by an electric drilling machine. The second part of the cell has a rectangular cross-section of 20 cm x 11 cm and has transparent walls (Fig. 1). Water flows downstream through the circular part and then upstream through the rectangular part. During our experiments, mixture of water and suspended particles recirculated in the system.

The flow was observed in the upstream part of the setup by a camera Photron Fastcam 1024PCI. This camera has colour resolution. The constant lightness condition was guaranteed by the couple of led lights using daylight shading. The locations of the camera and lights are shown in figure 1. A system of shutters close to the bottom of the rectangular part operated inflow of water and helped to ensure the uniform distribution of flow velocity. Circulation of the mixture through the setup is driven by the propeller.

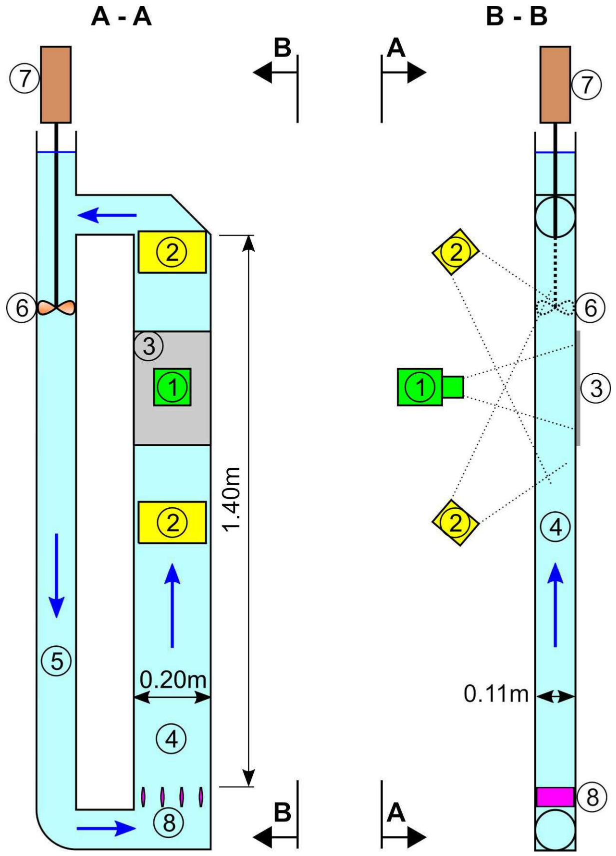

Fig. 1. Schematic sketch of fluidization cell; 1) camera, 2) light, 3) background 4) transparent part of fluidization, 5) pipe part, 6) propeller, 7) electric drilling machine, 8) shutter.

2.3 Experimental work

The experiments were carried out in two series of experiment. The first series started with filling of the cell with black plastic particles only and their recirculation in the mixture driven by the propeller. The total volumetric concentration *c* was approximately 4%. After some time spent for mixture homogenization, video recordings were carried out. The recorded area was 123x70 mm with resolution 768x432 pixels applied to this area. The high-speed camera was used in a slow regime of 50 fps for the recordings. Each 5th frame was selected for further processing. The reason for this procedure was the guaranties of different picture by its moving. The total record time was more than 30s and the number of analysed frames was 600.

The next step was to change the tested conditions by adding the white-particle fraction to the mixture and to record the new flow conditions. This was recorded with three different modes of shading of background (experiments 2, 3, 4). The middle shade was selected for further experiments.

The addition of white particles and recording of videos continued until the equilibrium between the volumetric concentration of white particles c_w and concentration of black particles c_b was reached (experiments 4-11). At the end of the series all particles were removed from the cell.

The second series was carried out in a similar way, but only white particles were introduced to the cell at the beginning of the experiment 12. Then black particles were gradually added (12 – 15). Figure 2 shows the order of experiments and the proportion of the concentration of the white particles to the total concentration.

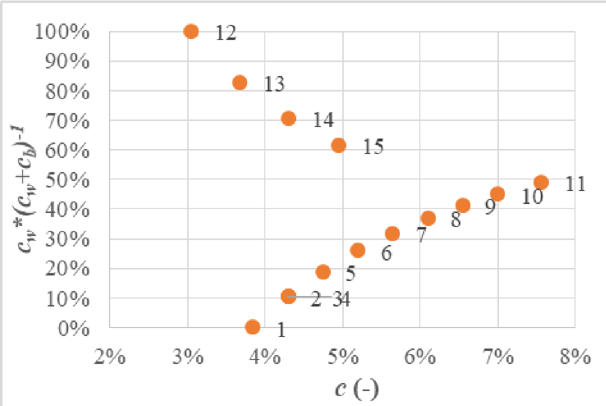

Fig. 2. Order of experiments and proportion of concentration of white particles and total concentrations, numbers in description are order of measurement.

Table 2 summarizes all experiments and gives the volumetric concentration of each particle fraction, the total concentration and the relative concentration of white particles.

Table 2. Cell experiments.

ID	c_b	c_w	$c_w.(c_b+c_w)^{-1}$	c
1	3.85%	0.00%	0.00%	3.85%
2	3.85%	0.45%	10.47%	4.30%
3	3.85%	0.45%	10.47%	4.30%
4	3.85%	0.45%	10.47%	4.30%
5	3.85%	0.90%	18.96%	4.75%
6	3.85%	1.35%	25.97%	5.20%
7	3.85%	1.80%	31.87%	5.65%
8	3.85%	2.25%	36.90%	6.10%
9	3.85%	2.70%	41.24%	6.55%
10	3.85%	3.15%	45.02%	6.99%
11	3.85%	3.70%	49.06%	7.55%
12	0.00%	3.04%	100.00%	3.04%
13	0.63%	3.04%	82.81%	3.67%
14	1.26%	3.04%	70.66%	4.31%
15	1.90%	3.04%	61.62%	4.94%

3 Analysis

The main task of the analysis of video images is to determine the ratio of particle occurrence. As mentioned previously, colour images were taken by the camera. The first step in processing the images was to convert the images to the grey scale. Each pixel has a value between 0 and 255. This number represents the value between white and black. The total white colour is 0 and black is 255.

The analysis consists in identifying the particles and filtering the background in the image. The analysis itself consists of two steps. The first is to find a grayscale boundary where white particles are captured in the image, when black is visible, and when the background of the cell is seen through the mixture. The boundary between the black particles and the background was named the boundary of black b_b and the boundary between the background and the white particles was the boundary of white b_w. The boundaries are illustrated in figure 3.

Fig. 3. Range of shade in image and boundary of white and black particles.

An example of the results of the analysis is shown in figure 4. The part a) shows the cut out from raw images for an analysis. The part b) shows identified particles. In the figure, the particles are coloured for a better illustration. White particles are shown as yellow, black particles stay black and background is coloured to red.

The part c) quantifies the relation of white particles to total concentration obtained using the equation

$$c_{relative} = c_w.(c_b+c_w)^{-1} \tag{1}$$

The relation is computed for every column of the analyzed area. In this way, the actual ratio of particles through the flow profile can be determined. The relation for the whole picture is computed as the mean value of values for individual columns. By averaging the values for individual images, we get the value for that experiment.

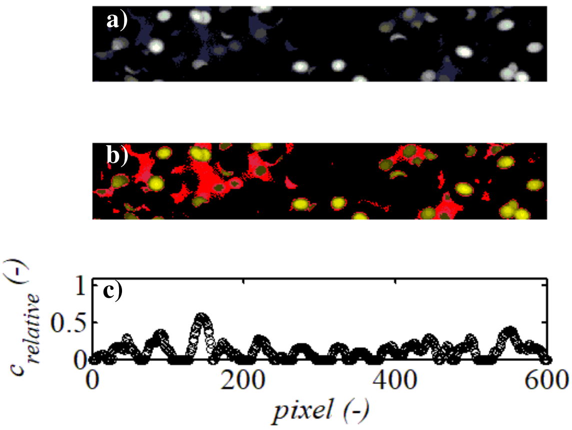

Fig. 4. Example of analyse part of image; a) raw image, b) recognizing area, c) relation of white particles to total concentration in each column of picture.

Pictures have resolution 768x432 pixels. The analysis was carried out at a little smaller area as shown in Figure 5. The analysis itself was preceded by the optimization of boundaries. This was done on an even smaller area, which is also shown in the figure. This area follows from results by Hlom (2017). The minimum size is 6 particle sizes in the direction of flow and more than two thirds of the picture (100x400) was used in the perpendicular direction. The reason for the selected smaller area for optimization was the speed of calculation. Details of optimization are described in the next chapter.

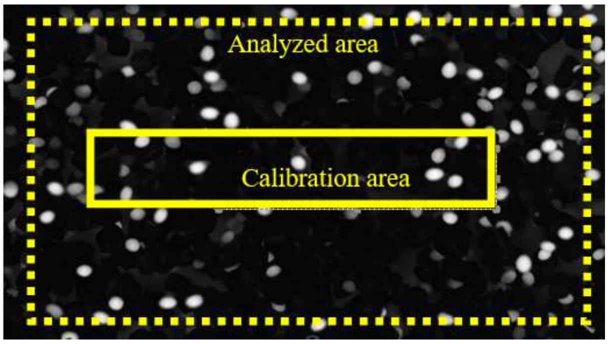

Fig. 5. Example of observed area.

3.1. Optimization of trashed value of boundaries

Two boundaries had to be optimized: the boundary of black and the boundary of white. The reason why the boundaries need to be optimized is the diminishing intensity of light penetrating through the mixture and at the same time the small differences in shades of particles of the same material.

The optimization starts by handling the analysis of darkness of pixels representing each area. It was found that the boundary of black has a smaller scatter on the shade scale. It is in an agreement with the conclusion by Hlom (2017). Based on this finding, the boundary of black to was set to 20.

The range of shade for white particles was wider and the border had to be examined more carefully. The limit value was gradually chosen and the concentration of individual fractions was calculated. Figure 6 shows the result of an optimization for the experiment No. 4. The optimal boundary of the white particles is determined by the point of intersection of the two lines in the plot.

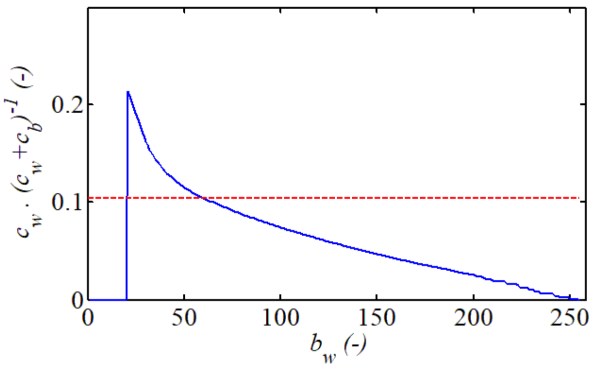

Fig. 6. Result of optimization for experiment No. 4. Blue line is the number of white particles during optimization, red doted line is the measured number of white.

This analysis was done for each mixture experiment and the result of the optimization is plotted in figure 7. It shows how the boundary of white varies with the total concentration. Results for the experiments No. 12 to 14 are missing because no optimum value between value 21 and 255 was found. The solution to this problem is to optimize the boundary of black particles instead of the boundary of white.

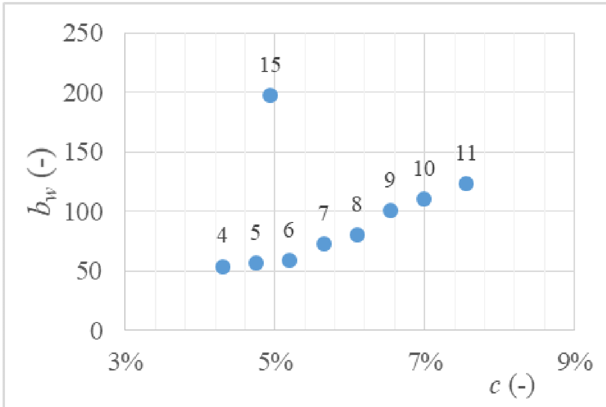

Fig. 7. Optimized boundary of white dependent on concentration.

4 Result and discussion

Since the results of the optimization show that it is not possible to use only one white border value, we discuss how the use of the only one border for white particles influences an evaluation of the other experiments for which the value was not optimized.

For clarity, figure 8 shows the result of relative concentration of white particles for three border values of white. Experiments Nos. 2 and 3 were processed with different colour of background. The effect of the background is shown on the parts of the curves where the experimental values deviate considerably from the curves.

The middle part shows a relatively good match always with better agreement in the area where the limit value was optimized. In general, the method works well in areas with a larger number of black particles when the black border value is not optimized.

The problem with non-optimized values of the boundary of black are at the end of curves where the curves start to deviate from the real values.

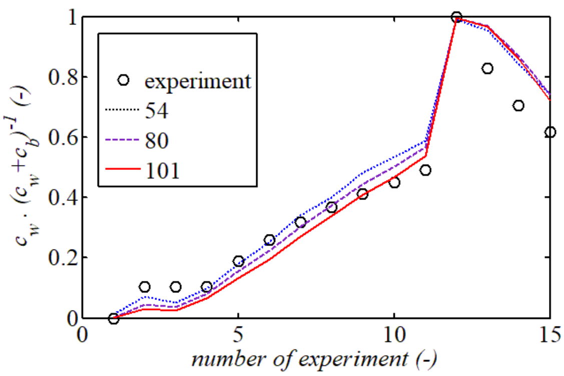

Fig. 8. The result of relative concentration of white particles for three values of boundary white and invariable value for boundary of black.

In order to show the accuracy of the method of determining the volumetric ratio in the mixture, the following figure 9 show parity plot between real value of relative concentration from measurement and evaluate concentration from video. From plot is seen the accuracy of method is with deviation o 10% in area with higher contain of white particles. The maximum deviation is to 20 % in area where there are more black particles than white.

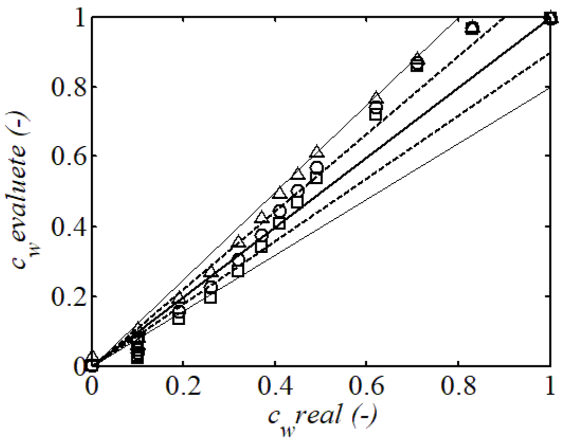

Fig. 9. Parity plot of relative concentration by experiment and by evaluation. Legend: square – evaluation for b_w 101, circle – evaluation for b_w 80, triangle – evaluation for b_w 54, thick line – perfect fit, dash line – deviation 10%, thin line – deviation 20%.

5 Conclusions

A series of experiments was performed to verify the possibility of using video analysis for an identification of the ratio of the local volume concentrations of individual particle fractions suspended in a bimodal mixture.

Previous work suggested that the black border may not be optimized. However, the results of the here presented work indicates that even this boundary must be given due attention.

In general, the method works well in areas with a larger number of black particles when the black border value is not optimized.

The method of determining the ratio has been shown to be suitable for determining the actual or average ratio of particles across flow profile or over time. Assuming a smaller variation in the particle ratio, it can be said that the maximum deviation can be a maximum of 10%.

Acknowledgments

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