# **CHAPTER 205**

# GRAIN-FLUID INTERACTION IN COUETTE FLOW

by

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1. ABSTRACT.

This paper is a continuation of the papers of Bakker & Van Kesteren (1986) and Bakker et al. (1988). In this paper the results are presented of ring shear tests on mixture of oil and spheres with the same density (880 kg/m<sup>3</sup>). In order to study in detail the behaviour of a sand water mixture at high concentrations in a Couette like shearflow in the viscous regime the graindiameter and viscosity are enlarged by a factor 100: respectively 15 mm and  $10^{-4}$  m<sup>2</sup>/s. The test are executed in the so called grain carrousel with shear rates up to 75 s<sup>-1</sup> (Bagnoldnumber N=240). The experimental set up is such that only constant volume test could be performed.

The test results indicate that at concentration below 30% (vol.) no dispersive stresses are generated. At higher concentrations the generated dispersive stresses increases with concentration and shearrate. From videofilms it was observed that the grains are moving in layers with only small mutual exchange (grainswop).

2. SCOPE OF PAPER.

This paper reports on a continuation of a study on the bottomboundary layer in oscillatory flow. This series started with a paper of Bakker (1974) on suspended sediment in a horizontally uniform oscillating flow. After considering the near bottom velocity field more into detail (Bakker and Van Doorn, 1978; Bakker and Van Kesteren, 1984) the study proceeded with a closer investigation of the sand transport mechanism at the bottom under sheetflow conditions (Bakker and Van Kesteren, 1986, 1987: Bakker, Van Kesteren and Yu, 1988).

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# GRAIN FLUID INTERACTION

In the last-mentioned paper experiments in a grain Carrousel and measurements in nature were mentioned. The present paper gives more data and some analysis concerning the Carrousel measurements. New prototype data, measured with the Harp during the Lohengrin project are reported on in the subsequent paper (Yu, Niemeyer and Bakker).

In a reliable mathematical model on sheetflow as well the shear stresses between shearing layers of grains as well as the normal stresses should be well reproduced.

With the theory of Bagnold (1954,1956) and a simple analytical model it is possible to reproduce concentration profiles and intrusion depth in sheetflow reasonable well, however, velocity profiles and shear stress distribution found in this way are based upon too primitive assumptions and thus do not match nature very well (Bakker and Van Kesteren, 1986, fig.6 and 7).

Furthermore, Bagnold's theory is designed for stationary flow.

In a numerical model (Bakker and Van Kesteren (1986)), in which layers of grains (with a rigid rectangular structure) are sliding over each other , it was not possible to reproduce Bagnold,s dispersive stress in the case of a Couette shearflow at constant volume. Because the model is based on viscous motion, squeezing pressures found when the grains move to each other are cancelled by equal tensile forces when the grains move from each other.

Thus the questions arise:

- a. if rigid layers are shearing over each other, will there be dispersive stress?
- b. which are the stresses, when two grains from different layers nearly touch each other?
- c. is it reasonable to schematize a Couette flow of grains with a layer model?
- d. under which circumstances will dispersive stress be created?

This leads to the following aims of the experiments planned:

insight in the physical background of the Bagnold stresses;
 visualisation of the grain motion during grain-grain interaction.

3. EXPERIMENTAL SET-UP.

A ring shear apparatus ("Carrousel") has been developed (fig.1, Bakker and Van Kesteren, 1986). Detailed description of experiments accuracy and calibration has been given by Klomp (1990). Between two plan-parallel rings placed in a circular flume (diameter in the center 1.13 m; internal width 0.07 m) a Couette like shear flow of a mixture of polypropene spheres (diameter D=14 mm; Young's modulus 1300 N/mm<sup>2</sup>), immersed in oil (medical oil Shell code M.W.0.95 or V7047) with the same density (oil: 889 kg/m<sup>3</sup>; spheres:  $860\pm30$ kg/m<sup>3</sup>) is generated by rotating the upper ring, where the lower ring is fixed. The level of the upper ring is adjustable. Both rings have a spacing in the circular flume of 1 mm on both sides.



Fig.1 Carrousel.

The viscosity of the oil is  $10^{-4}$  m<sup>2</sup>/s at a temperature of 20° Celsius. It has been chosen in this way, that the shear Reynold's number (see ch.7 eq.2) in the tests was of the same order of magnitude as occurs in oscillating sheetflow in the prototype. The bottom ring rests on three supports (under a mutual angle of 120° with respect to the center of the flume), provided with strain gauges, which all measure normal force, where one of those measures the tangential force. The other

two supports are provided with a skirt-like construction to prevent transducing of any shear stress. After mounting a static and dynamic calibration with and without oil was performed. Elaborate accuracy analysis with respect to the gap width between the rings is given in Klomp (1990) and Bakker et al.(1990).

On upper- and lower ring each 4 rows of 199 hemi-spheres are glued in a regular pattern. For visual observation, three glass windows with a length of 29 cm each were made in the carrousel. Sampling occurs with a frequency between 60 and 540 per second, depending on the experiment.

4. EXPERIMENTS.

Five series of experiments have been carried out:

- NO: no interjacent spheres;
- SOME: half a row of interjacent spheres (100 spheres)
- ILR: (about) one layer of interjacent spheres (510 spheres)
   3LR: three to five layers of interjacent spheres (36)
- 3LR: three to five layers of interjacent spheres (3641 spheres).
- VIS: Visual observations, using ca. 3600 grains

Going from series NO to series 3LR the probability of dispersive stress increases, which forms the motivation of these succession of series of tests.

The experiments are determined by the distance between the rings and the turning period of the upper ring. The following table 1 gives the schedule. The table consists of combinations of 2 columns indicating resp. the variables "height between rings" (h) and "revolution period" (T). The mean velocity gradient or shearrate S is given by:

 $S = 2 \frac{\pi R}{T h}$ ; R = (central) radius ring = 565 mm (1)

Series:	height between				rir	ngs	[ mm ]				revolution [sec]					period	
NO	14.9 16 17	18	20	25		50					3	4	5	7	10	20 20	?
SOME				25	35	50					3		5		10	20	
1LR					35	50		65			3		5		10	20	
3LR						51 53 55	60	65	75		3	4 4	5 5	7 7 7	10 10 10	20 20 20 20	
VIS						48	60		78		2.	4	5	7.	10. 8 9.5	3	

Table 1. Experiments carried out.

For each of the indicated heights of the rings tests have been carried out for all of the revolution periods, mentioned on the same line.

Other combinations, which could be imagined have not been carried out because of practical disadvantages: too large forces on the gauges or the destruction (loosening) of the hemispheres on upper and lower ring. The blanks in table 1 show the limits of the possibilities because of blocking.

For instance: during the firstmentioned experiment (of series NO) the distance between upper and lower ring has been reduced as much as possible, up to 14.9 mm. Although according to the schedule still a gap width of 0.9 mm should exist, accuracy analysis made clear, that the utmost extruberance of the upper ring could easily "hit" the utmost extruberance of the lower ring. The experiment had to be stopped soon, in order to avoid destruction, and therefore the revolution period has not been measured accurately.

Mind, that it was possible to carry out experiments with h=25 mm (less than 2D, where D is the grain diameter) in the series SOME; however, this was not the case in the series lLR, although technically all spheres used in series lLR could find a place in one layer.

Using a distance between the rings of 3.6 D (51 mm) during the series 3LR, it was only possible to measure with a slow revolution period of 20 sec. Here the allowable forces on the measuring system were used as criterion. During the visual tests the force measuring device was blocked and

the allowable torque on the Carrousel (with respect to the motor) could be used as criterion, which gives the opportunity to reduce the distance to 3.44 D (48 mm).

With respect to the series VIS (table 1), as well as in series 3LR the grains have been dumped randomly in the Carrousel. Paradoxally, this gave less blocking than an initially arranged order of the grains in a similar way as the one of the hemispheres on both rings. In the arranged order the initial spacing was rather large, which gave freedom for disorder.

Apart from the measurements, photographs in a succession of 0.04. seconds were made from series SOME, and video-films from series VIS. These photographs were analyzed by Bakker, Van Kesteren and Yu (1988; ch.3). The analysis of the video's will be treated in ch.6.

## 5. GEOMETRIC CONSIDERATIONS.

If it is assumed that in 3 adjacent grainlayers resp. 5, 4 and 5 rows of loose spheres are stacked (in closest packing) in the Carrousel. and the layers would be perfectly flat, only 3548 grains could be stacked. However, when the layers show a certain "waviness" (wave length 2 grain diameters; amplitude 1.5 mm), all 3641 grains can be stored. This waviness occurs anyway, as the lowest loose grains will partly be situated in the hole between 4 hemi-spheres, partly will have their center point in the cross-section perpendicular to the flume through the center of the hemispheres. This gives a variation in height of the center points of those loose spheres (with respect to the lower ring) between 7.83 and 12.12 mm. Thus 4\*10=40 mm is considered the minimum distance for storing the grains in the Carrousel (conc.=62.7%).

When the distance between 2 layers of grains becomes more than 12 mm, theoretically those layers should have the probability to slide with respect to each other. Thus a slide plane can occur when the distance between the rings exceeds 42 mm (conc.59.7%).

The effect of the waviness of the layers on the shearing resistance is not quite clear. As the undulating layers can reshape each other during the shearing process, the effect will be less than the one of a fixed roughness. Still, the extra 2 mm allowing for shearing anyway will be a minimum. The minimal distance between the rings when 3 layers of 5 rows in simple cubic piling turn around in the Carrousel becomes 48 mm (conc.=52.2%). This asks for a distance of 2(D+10) mm (the center of the grains of the lowest layer are 10 mm above the lower ring, as in the former case). If all layers are fully occupied, 3801 grains are needed, i.e. more than available. Mind, that 48 mm was the minimum distance for which the upperring of the Carrousel was able to rotate in test VIS.

### 6. VISUAL OBSERVATIONS; GRAIN SWOPS.

From Bakker, Van Kesteren and Yu (1988), ch.3, especially the theoretical and phenomenological aspects of the "centering effect", mentioned in that paper should be remembered (photo 4 a,b,c of that paper).

When there is enough space between the various loose spheres in the same row (in series SOME somewhat more then a grain diameter) the grains move to a central position between the rings and turn around in a stable position, having half the velocity of the upper ring. Furthermore these rotate around their axis.

When the distance between the rings increases or the velocity decreases the effect becomes less distinct (photo 4a of Bakker, Van Kesteren and Yu (1988)); then doublets of spheres can be formed, which can tumble around as a unit (Vand, 1948; Batchelor and Green, (1972)).

During the series lLR (about one layer loose grains) the centering effect turned out to be not large enough to enable a small distance between the rings. A single grain blocking between the hemi-spheres of upper or lower ring could disturb already the order, after which total blocking was just a matter of time.

During experiments in the series VIS carried out with a height between the rings of 60 mm or less, 3 layers were to be distinguished; in the other 2 experiments (h=78 mm) 5 layers were observed. In fig.2 the horizontal and vertical velocities of the centers of the visible spheres are shown for the test with a height of 48 mm and a revolution time of 5s (S=14.8 s<sup>-1</sup>). The vertical coordinate is the position of the spheres with respect to the fixed bottom ring. The velocities are obtained from the digitized videofilm.

The figure shows clearly that the grains move in layers: the vertical position of the centers of the grains is concentrated at three different (grainlayer) levels. Also it must be concluded that the



Fig.2 Grain velocities testserie VIS (height h=48 mm, period 5 s)

velocity gradient is not constant over the height: in the lower half the velocity gradient is about half the installed velocity gradient. In the upper half of the Carrousel concentration is less than in the lower half, notwithstanding the fact, that the grains are as an average very slightly buoyant and concentrate on the upper part in the starting position. Apparently, the same shear stress can be transmitted with high velocity gradient and low concentration as well as with low velocity gradient and high concentration. Although only some tests have yet have been elaborated in the present way, it is the impression that relative low concentrations occurred on the topside of the Carrousel in all tests. Reason for deviation from symmetry can be: the walls, remaining at rest or relatively large shear stresses near the top ring during the initiation of motion.

A certain grain, emerging in a certain layer on the lefthand side of one of the windows, was followed with the eye until it disappeared on the right hand side. It was registered, whether this grain was at that moment in the original layer, or one or two layers higher/lower. Fig. 3 shows the probability of grain swop in various tests; on the first line for the tests where the grains divided themselves in 3 layers, on the second one for the tests, where 5 layers could be observed. Vertically the various layers are indicated; horizontally the percentage of observed grains, found in this layer at the end of the observation time. With an arrow the layer is indicated, in which the grains emerged on the lefthand side of the window. These observations have been elaborated in the following way.

Call a "grain encounter" the event, that two grains of adjacent layers "meet" each other, i.e. (nearly) come into contact with each other.







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The number of grain encounters during the observation time (the time during which the grain is visible in the window) can be calculated from the (expectation of the) increment in velocity of a higher layer compared to the one of the adjacent lower layer. It also depends on the distance between the grains in one layer, which can be approximated as  $(1 + 1/\lambda)D$  ( $\lambda$ =linear concentration according to Bagnold (1954)) and of the length of the observation time, which is smaller for the higher layers than for the lower layers. Thus is found (Bakker, 1989) that the number of grain encounters during the observation period equals  $\lambda L/{(\lambda+1)kD}$ , where L is the length of the window (29 cm) and k the number of the layer (counting from downwards to upwards).

During each encounter the two grains involved can either remain in the layer in which they are, either exchange position. This last event will be called a "grain swop". Let p be the probability of a grain swop per encounter. For the upper or lowest layer thus the probability Pr that a grain still is in the same layer in which it started equals:

 $Pr = (1 - p) \frac{\lambda L / \{(\lambda + 1) k D\}}{k}$ 

This under the assumption, that the probability can be neglected, that a grain returns to its former layer after swopping to another layer.

If a layer is enclosed by two adjacent moving layers grain swop can occur to two sides and "1-p" in (2) should be replaced by "1-2p". From the results, depicted in fig. 3, with the aid of (2) the probability p of a grain swop per encounter has been calculated as function of the linear concentration  $\lambda$  and the shear Reynolds number Re<sub>g</sub>, where Re<sub>g</sub> is defined as:

 $Re_{g} = r^{2}S/v$ 

(3)

(2)

Here S is the velocity gradient, v the kinematic viscosity and r the radius of the grain (i.e.D/2).

Fig. 4 shows the result with its confidence limits. The probability of grain swops tends to decrease with increasing velocity gradient and increasing concentration.



Fig.4 Probability of grain swop as function of  $\lambda$  and Re  $_{_{\rm S}}$ 

Bakker (1989) calculated the increase in shear stress caused by momentum transfer from one layer to another. Only the direct transfer - a grain with its momentum comes suddenly in the next layer - has been calculated (the effect of the whole process of blocking and collision, during which a grain could transfer as well the momentum of other grains in its layer to the adjacent layer has not been taken into account). It was found, that the increase of viscosity, caused by this process is proportional to Re and p; for the present tests

this increase only amounts to 10 % of the viscosity of the oil.

# 7. PREVIEW OF THE RESULTS OF THE MEASUREMENTS.

The measured normal forces on the bottom ring in the tests NO showed the occurrence of a propagating pressure wave in phase with the revolution of the upper ring. In the shear force data these fluctuations were absent. Putting separating screens in the space of the carrousel below the lower ring, in order to attenuate these waves, gave some improvement, but not enough.

Using Fourier analysis, the signal with the revolution period has been filtered away and a mean normal pressure time series during a period of encounter between two hemispheres of resp. upper and lower ring could be determined. The result, a nearly symmetrical curve with its confidence limits, is shown in fig.5.

Fig 6 shows the tension/pressure in one pressure gauge as function of time in the case of nearly-touching (the first-mentioned experiment of series NO; see table 1 and text ch.6). A very large pressure peak is followed by a small peak of tension. Cavitation could be the cause.







Fig.6 Tensile force in test NO (nearly touching hemispheres.

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# 8. ELABORATION OF THE MEASUREMENTS.

By averaging over an integer number of revolutions, summation over the number of supports (i.e. 3) and by division over the area of the lower ring  $(0.23 \text{ m}^2)$  the normal forces are converted into pressures (or tractions). The shear stress can be found by direct division by the area of the lower ring.

Data will be presented as function of the shear Reynolds number (eq.(3)) and in the dimensionless Bagnold parameters N and  $G^2$ , defined by:

$$N = 4 \sqrt{\lambda}. Re_{g}$$
(4)

$$G^{2} = \tau/\tau_{0} \quad \text{or } p/p_{0} \quad \text{with } \tau_{0} = p_{0} = \rho \cdot v^{2} \cdot \lambda/D^{2} \tag{5}$$

Here S is the velocity gradient, v the kinematic viscosity,  $\rho$  the common specific density of grains and fluid, r the radius of thegrain and  $\tau_0$  ( $p_0$ ) is a reference shear stress (pressure). Mind that G<sup>2</sup> according to Bagnold entails one of two variables; it is rather a dimensionless way of presenting  $\tau$  and  $\rho$  than a variable. Furthermore  $\lambda$  is the linear concentration  $\epsilon/r$ , where  $\epsilon$  is half the smallest distance between two adjacent grains. It thus may be found from:

$$\lambda = \{ (c_{\max}/c)^{1/3} - 1 \}^{-1}$$
(6)

where c is the maximum concentration.

Presenting the data on the way of Bagnold thus has no other meaning than presenting the shear stress (c.q. normal stress) versus the velocity gradient at a certain, by Bagnold described dimensionless way. If one wants to compare with Bagnold's results, it should be kept in mind, that Bagnold starts from the conception, that shear stress can be divided into shear stress, acting on the fluid and shear stress acting on the grains, where the present idea is: an integral shear stress, acting on the fluid only and transmitted via the fluid on the grains. It must be kept in mind, that the "correction" of the shear stress for fluid shear stress is not applied in this paper.

# 9. PRESENTATION OF RESULTS.

#### Shear stress:

A plot of the shear stress according to Bagnold ( $G^2$  versus N) of the NO-series (fig 7) shows, that the slope of the line follows Bagnold's theory; however, the shear stress is an order 2 lower than Bagnold predicts. Similar results were found in the series SOME (shown in Klomp, 1990 and Bakker et al., 1990) and ILR (fig.8) apart from one



of velocity gradient; series NO



Fig.9 Shear stress as function of velocity gradient; 3LR.



Fig.8 Shear stress as function of velocity gradient; lLR



Fig.10 Relative apparent viscosity vs. concentration.

test with smallest distance between the rings in series SOME and two tests with the same conditions in series lLR, giving a shear stress being orders higher, which can be attributed to blocking.

In series 3LR (fig 9) each concentration gives a different line in the Bagnold graph, being especially for higher concentrations somewhat flatter than the Bagnold line. For high concentration the shear stress is orders of magnitude larger than Bagnold predicts, probably due to the boundary condition of no dilatation and the rigid boundary of hemispheres at the rings in the present tests. Mind (fig.8) that given a relatively high concentration (17.4% in series SOME, 19.1 % in series LLR) no blocking occurred at relatively high velocity gradient.

In fig.10 the relative apparent viscosity (determined from the experiments) as function of concentration is compared with the theory of Bagnold, Einstein and the numerical theory (Bakker and Van Kesteren 1986). For high concentrations the numerical theory predicts quite well the increase of the apparent viscosity with increasing concentration. The blocking during the series SOME and 1LR appear clearly in this figure.

#### Normal stress:

In the series NO,SOME and 1LR under some circumstances traction forces on the lower ring are registered instead of pressure, as Bagnold predicts. This makes a presentation impossible according to the Bagnold way, implying a logarithmic plot of the pressure. For





series 3LR, always pressure forces are found; the Bagnold plot of this series is given in fig. 11. Linear plots of fig.11 (Klomp, 1990; Bakker et al.1990) show dispersive pressure and shear stress build up, approximately linear with the velocity gradient. However, the linear relation has a zero-shift: one gets the impression that in the "soil mechanics region" (neglegible motion, nonneglegible strains and stress field) shear stresses and pressures build up, which are enhanced during the motion in the viscous region. The relation between shearstress and normal stress is depicted in fig.12 including the stress points, determined by extrapolation, corresponding to a zero velocity gradient. It appears that the results for different concentrations together form a single unique relation similar to failure envelopes in soil-



mechanics. From this relation it can be concluded that the same stress point (shear stress - normal stress) can occur at a high velocity gradient and low concentration or at a low velocity gradient and high concentration.

## 10. CONCLUSIONS.

- a. Dispersive stresses are found in the grain carrousel, when the concentrations exceed 30%.
- b. Probably because of the rigid boundaries (fixed hemispheres, no dilatancy allowed) the dispersive stresses in these cases are (especially at high concentrations) much higher than those found by Bagnold.

A much stronger relation between dispersive stress and concentration was found than according to Bagnold's theory.

- Most probable reason of this dispersive stress is blocking c. (although no straight-forward theory can yet be given concerning the mechanism). In the case that no blocking occurs (series NO and the most experiments of series SOME and ILR) only for small shear Reynolds number a minimal dispersive pressure is found; for larger shear Reynolds number even traction forces between the layers are measured. If no blocking occurs, the shear stress found is about 2/3 of the value predicted by Bagnold.
- d. The grains in a high-concentrated mixture move generally in layers. Only a small percentage of grain swops occur.
- e. When the grain motion is not blocked (exp. series NO,SOME and lLR) the spheres tend to move in a central position between the rings. This can be explained by the centering force acting on grains, moving between two plates (Bakker et al., 1988).

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