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NWRI Contribution No. 94-82

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Y.L. Lau and B.G. Krishnappan

Aquatic Ecosystem Protection Branch
National Water Research Institute
867 Lakeshore Road, P.O. Box 5050
Burlington, Ontario L7R 4A6

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MANAGEMENT PERSPECTIVE

Many contaminants are adsorbed onto fine suspended particles and transported with the flow in rivers. Therefore, information on the physical and chemical properties of these particles is required in order to understand the transport process and to develop models which can predict the fate of environmental contaminants. Particle size is one of the most important physical characteristics but is rather difficult to measure because of the fragile nature of fine sediment flocs.

A simple water elutriation apparatus has recently been proposed as a means of monitoring the in-situ particle size. This apparatus is attractive because of its simplicity and relatively low cost. In order to evaluate the performance of this system, a series of tests was carried out in a 5 m annular rotating flume. The settling suspension carried by the flow was sampled using both the elutriation apparatus and the Malvern Particle Size analyzer. Comparisons of the results show that the elutriation apparatus can be a viable field instrument.

SOMMAIRE À L'INTENTION DE LA DIRECTION

Beaucoup de contaminants sont adsorbés sur de fines particules en suspension et transportés dans l'eau des rivières. Il faut recueillir des données sur les propriétés physico-chimiques de ces particules pour comprendre le mécanisme du transport et pour développer des modèles permettant de prévoir ce qu'il advient des contaminants dans l'environnement. La granulométrie est l'une des plus importantes de ces propriétés, mais il est assez difficile de l'établir pour la simple raison que les flocs de sédiments fins sont délicats.

On a récemment proposé d'utiliser un dispositif simple d'élutriation pour contrôler *in situ* la granulométrie des particules. Ce dispositif est intéressant car il est simple et assez peu coûteux. Afin d'en évaluer la performance, on a procédé à une série de tests dans un canal rotatif de 5 m. La suspension de particules en voie de sédimenter a été échantillonnée au moyen du dispositif d'élutriation ainsi qu'au moyen du granulomètre Malvern. La comparaison des résultats montre que le dispositif d'élutriation est un instrument utilisable sur le terrain.

RÉSUMÉ

On a comparé à celui d'un granulomètre Malvern le rendement d'un dispositif simple d'élutriation qui servait à contrôler la granulométrie de particules en suspension dans l'eau de rivière. Les tests ont été faits dans un canal rotatif de 5 m de diamètre dans lequel circulait une eau transportant des sédiments en suspension. Des sédiments naturels et une eau de rivière ont été utilisés pour les tests. L'examen des résultats montre de nettes différences entre la taille des flocs en suspension *in situ* et la taille efficace de sédimentation.

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ABSTRACT

The performance of a simple water elutriation apparatus which has been used for monitoring sediment particle size in rivers has been compared with measurements made using a Malvern Particle Size Analyzer. Experiments were carried out by deploying both instruments in a 5 m diameter annular flume in which flows carrying sediment in suspension were generated. The tests were carried out using natural river water and sediment. Results obtained reveal distinct differences between in situ floc sizes and their effective sizes for settling.

INTRODUCTION

Many pollutants are transported through river systems by way of the suspended particulate matter carried by the flow. Information on the physical and chemical properties of these particles is very important for tracing the transport of pollutants through the aquatic system. Such information is required in order to understand the transport processes as well as to develop models which can predict the fate of environmental contaminants.

One of the most important physical characteristics of the suspended material is the particle size because it affects the transport and deposition, as well as the ability to adsorb, chemicals. In many cases, the suspended sediments in fluvial systems consist of fine cohesive materials which are transported in the form of flocs and aggregates. Such composite particles have physical and chemical properties quite different from those of the primary particles making up the flocs. Information on floc size is difficult to obtain owing to the fact that flocs are often very fragile and are easily broken up during sampling or handling. As a result, most of the data on fluvial sediments include information on the absolute or primary particle size distribution only and not the in situ floc size. These data cannot be used for estimating the settling velocities of the composite particles.

A simple water elutriation apparatus has recently been proposed as a means of monitoring the in situ particle size (Walling and Woodward, 1993). The system consists of four cylindrical settling chambers, linked by glass and PVC tubing. Water is drawn from the river and discharged into the first chamber at the bottom. It then passes out from the top of the chamber and discharges near to the bottom of the next chamber. The peristaltic pump which moves the water is located after the last settling chamber so as not to cause any disruption of the flocs. With each successive chamber doubling in diameter, the upward flow velocity decreases four-fold from one chamber to the next. Therefore, the settling velocity of those particles which deposit in one chamber should also be four times larger than that in the next chamber. As the settling

[1] Research Scientist, National River Research Institute, Burlington, Ontario, Canada, L7R 4A6.

velocity of spherical particles increases with the square of diameter according to Stokes Law, the particles which settle in one chamber should be twice the diameter of those settling in the next larger chamber. In this manner, the elutriation apparatus fractionates the suspended sediment into different size classes.

Walling and Woodward (1993) used the elutriation apparatus in the River Exe basin in the U.K. and obtained particle size distributions which appeared very reasonable. This apparatus looks promising as a simple, cost-effective means of monitoring suspended sediments. However, it is useful to validate the performance of this apparatus against other instruments. The Malvern Particle Size Analyzer ,which operates on the principle of light diffraction, has been used by several investigators to measure in situ floc sizes (Bale and Morris, 1991; Krishnappan and Engel, 1994). The performance of the elutriation apparatus can be evaluated by deploying both instruments simultaneously in the same flow system to obtain particle size measurements. This paper describes such a study and its results.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

The Flume

The experiments were carried out in the rotating annular flume in the hydraulics laboratory of the National Water Research Institute at Burlington, Ontario, Canada. The flume is 5.0 m in mean diameter, 28 cm wide and 30 cm deep and sits on a rotating platform. An annular top cover fits inside the channel and makes contact with the water surface. By rotating the top cover and the platform in opposite directions, a two-dimensional shear flow can be generated. Complete details of the flume and the measurements of flow characteristics can be found in Krishnappan (1993).

Sediment Measurement Equipment

Figure 1 shows a sketch of the elutriation apparatus. The whole assembly was located on the rotating platform and the water-sediment suspension was pumped into the apparatus from an intake tube located on the centre-line of the flume at approximately mid-depth. The suspension then discharged into the bottom of the smallest settling chamber which has an inside diameter of 25 mm. The suspension then exited near the top of the chamber and was released into the bottom of the next chamber. Each subsequent chamber is twice the diameter of the previous one. Particles which deposited were collected in transparent rubber tubings at the base of the chambers. The finest material which was unable to deposit in any of the four chambers was collected in glass carboys with the outflow of the pump. The glass and PVC tubing transporting the suspension all have 4 mm inside diameter.

Continuous in situ measurements of the floc sizes were made using the Malvern Particle Size Analyzer which was mounted on the rotating platform so that the flow-through sensor was located directly below the centre-line of the flume. The suspension was drawn continuously from the flume by gravity through a 5 mm diameter tube. The end of the tube was bent at a right angle so that the intake faced directly into the flow at approximately mid-depth. The sample flowed

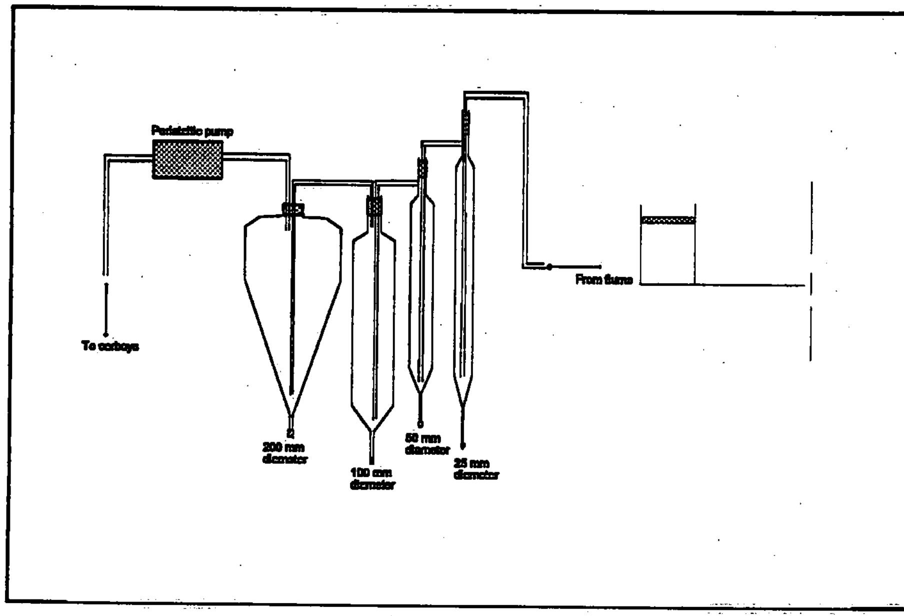

Figure 1. Sketch of elutriation apparatus as designed by Walling and Woodward (1993).

through the sensor and then was pumped back into the flume.

Test Procedure

The tests were conducted using water and sediment collected from the Fraser River in British Columbia. The sediment consisted of fine material, with a median particle size (dispersed) of about 13 µm, that had deposited on the gravel river bed. The flume was filled with 500 L of sediment-free water. Before beginning a test, a measured amount of sediment slurry was added to the flume and the water-sediment suspension was thoroughly mixed with a mechanical mixer to break up any existing flocs. The top cover was then lowered so that it penetrated the water surface by about 3 mm to ensure proper contact between it and the water surface. The water depth below the cover was 12 cm. The platform and top cover were then rotated at close to maximum speeds to ensure that the suspension was well mixed. After twenty minutes, the system was slowed down to the chosen test speeds. Samples for concentration measurement were withdrawn from the flume at 5 minute intervals during the first hour and every ten minutes thereafter. Each sample was filtered, dried and then weighed to obtain the total sediment concentration.

Five tests were conducted, with different values of bed shear stress and initial sediment concentration. In two of the tests, a certain quantity of effluent from a pulp mill on the Fraser River was added to the flume as part of a test to investigate the effects of the effluent on floc characteristics. The test conditions are summarized in Table 1.

Monitoring with the Malvern began when the system was rotating at high speed. The elutriation apparatus was filled with the same sediment-free water from the Fraser River. While the flume was running at high speed, the peristaltic pump was started to pump water through the apparatus from a separate container. When the flume was brought down to the testing speed, pumping from the flume began. Each experiment usually ran for three hours.

The peristaltic pump was adjusted to produce a flow rate of 105 ml/min through the elutriation apparatus. At this flow rate, the velocities in the settling chambers were such that the effective diameters of the material collected were >63, 63-32, 32-16 and 16-8 μm respectively.

Materials which were deposited in the settling chambers and the carboys were filtered, dried and weighed to obtain the mass collected.

TABLE 1. SUMMARY OF TEST CONDITIONS

Test No.	Shear Stress N/m^2	Initial Concentration mg/L	Concentration of Pulp Effluent % by volume
1	0.121	200	0
2	0.169	200	0
3	0.121	250	0
4	0.121	250	3
5	0.213	250	3

RESULTS AND DISCUSSION

The decrease in concentration with time for three of the tests is shown in Figure 2. Results for the other two tests are very similar. The concentrations decreased more rapidly in the beginning and then levelled off to their equilibrium values. This is typical of the deposition of cohesive sediments as found in earlier studies by other investigators (Partheniades and Kennedy, 1967; Metha and Partheniades, 1975; Lick, 1982). Tests no. 3 and 4 were conducted under the same hydraulic conditions. The settling velocity appears to be slightly larger for Test no. 4 which had the addition of the pulp mill effluent. It is possible that the chemicals in the effluent enhanced the flocculation process, leading to a more rapid settling. Test no. 5 was conducted at a higher shear stress and, as expected, produced a higher equilibrium concentration.

Figure 3 shows the concentration distributions for test no. 5 at various times after settling started. These are obtained from the size distribution curves given by the Malvern. The Malvern actually produces much more detailed size distributions but, for the purpose of comparison, only the five size classes differentiated by the elutriation apparatus are used. It can be seen that the size distributions remained relatively constant so that the proportion of flocs in the various sizes did not change a great deal from the beginning to the end of the test. Flocs in the >63μm size predominate, making up more than 70 percent of the total volume. The next smaller size class contributes only about 10 percent, while the three smallest sizes each occupies only about 5 percent.

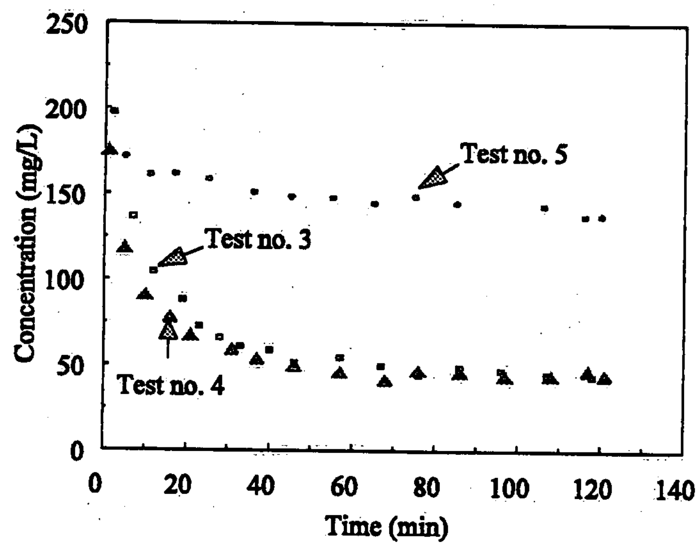

Figure 2. Changes in total suspended sediment concentration with time.

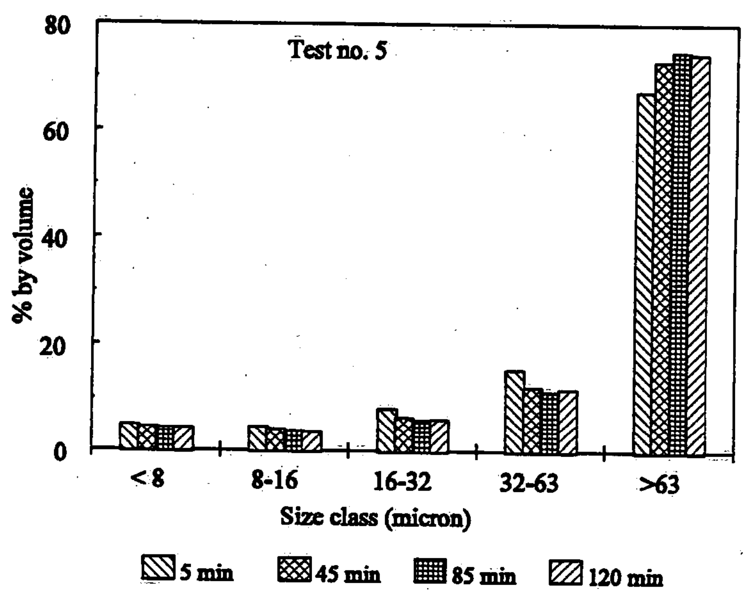

Figure 3. Size distributions obtained from the Malvern at various times from start of settling.

Results obtained from the elutriation apparatus for the same test are shown in Figure 4 in terms of the percentage of the total mass occurring in each size fraction. This distribution is quite different from that given by the Malvern. While the Malvern results indicate that the highest percentage (> 70%) is in the >63μm class, the elutriation results produce the lowest percentage (< 2%) for that class. The majority of the material (over 45%) is in the 32-63 μm class and the proportion of material in the three smallest sizes is also larger than what the Malvern indicates.

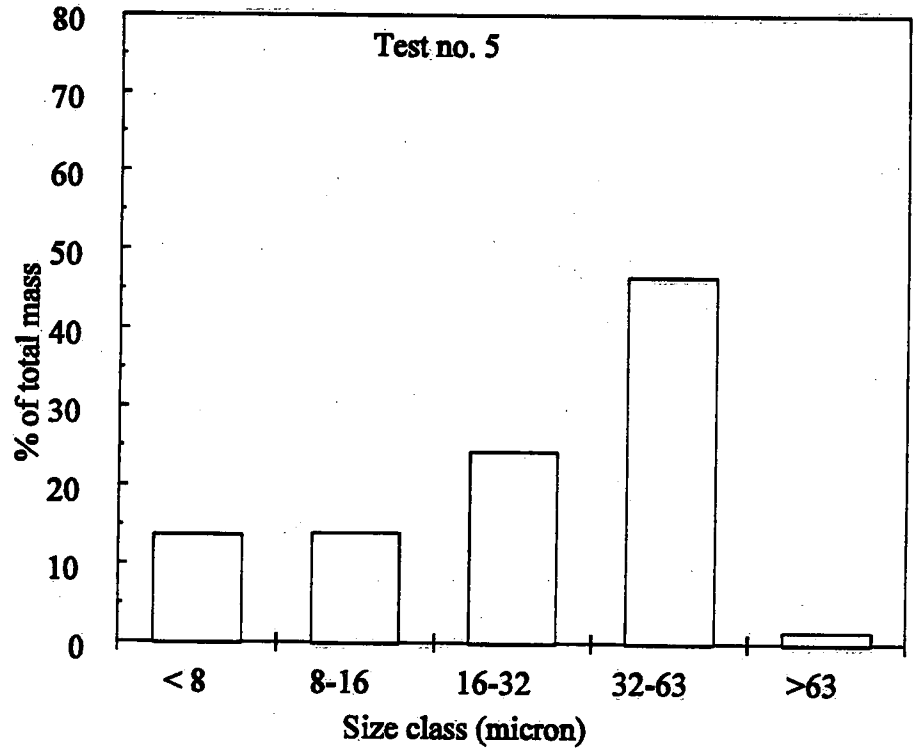

Figure 4. Size distribution obtained from elutriation apparatus.

Similar results are obtained for all the other tests. In each case, the Malvern produced the highest percentage in the >63μm size while the elutriation system showed minimal quantities in that class.

Although the two sets of instruments produced different size distributions for the same suspension, the results are not necessarily contradictary. The Malvern measurements give information on the in situ floc size distribution, based on the volumes of the different sizes of flocs. Those results show that flocs bigger than 63 μm in size make up more than 70 percent of the total floc volume. The detailed Malvern distributions actually show that the median size is about 85 μm, with approximately twenty percent of the material being larger than 140 μm. Thus a significant number of large flocs existed in the suspension. The elutriation apparatus, on the other hand, collects material which posseses a certain settling velocity and assigns a diameter to it based on Stokes Law. The elutriation results show that very little material had settling velocity as large as that of a 63 μm particle settling in Stokes flow. Looking at these two sets of results together, one can conclude that the large flocs must have settled with much smaller settling velocities than what their diameters would indicate. The small settling velocity is probably caused by the fact that these flocs are very porous and have densities only a fraction of that of the parent material.

Various studies have shown that as flocs increase in size, their porosity increases and their density decreases. Size-density relationships which have been proposed are all empirical in nature (Gibbs, 1985; Lagvankar and Gemmel, 1968) . Many of these relationships have the form:

$$\rho_f - \rho_w = a\, d_f^{-m} \qquad (1)$$

in which d_f = floc diameter, ρ_f = floc density, ρ_w = water density and a and m are empirical constants. These relationships can usually be fitted to experimental data over a certain range of sizes but they will probably have significant errors at the very small or very large sizes. Ideally, the density function should produce a floc density equal to that of the parent material when d_f is very small and a density approaching that of water when d_f is very large. The expression

$$\rho_f - \rho_w = \rho_s \exp(-b d_f^c) \qquad (2)$$

in which ρ_s = density of the parent material and b and c are empirical constants, can produce this type of variation in floc density. Equation(2) was applied to the size distributions from the Malvern to obtain the percentage of the total mass residing in different sizes of flocs. The results are shown in Figure 5 together with the elutriation data.

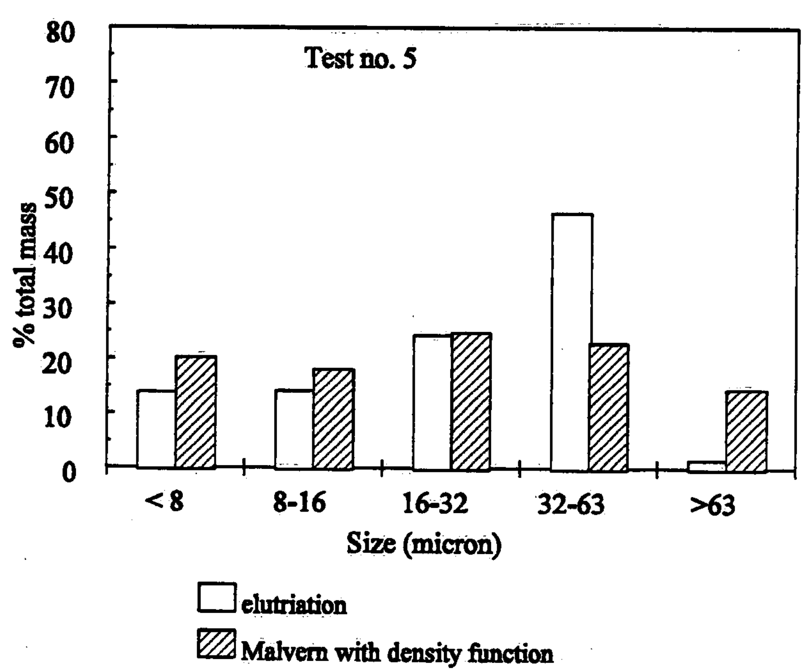

Figure 5. Mass distribution obtained using Malvern data with a density function.

The agreement between these distributions is much better than those shown previously. The comparisons for the four other tests are shown in Figure 6. The empirical constants in all the five tests were the same ($c = 1.7$; $b = 0.0015$).

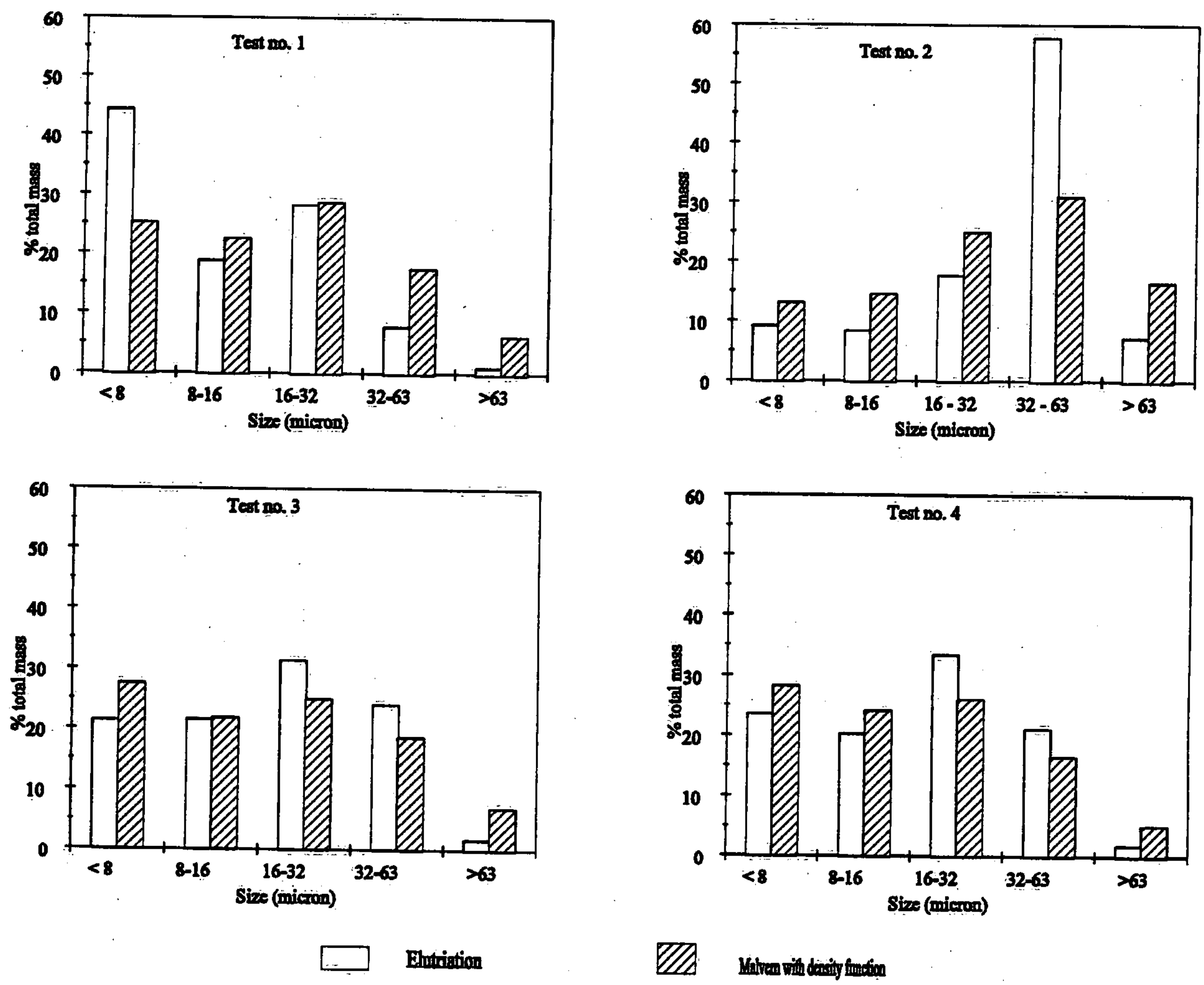

Figure 6. Comparison of elutriation and Malvern results.

Considering that the two instruments operate on two different principles(Malvern operates on the principle of light diffraction and gives a measure of the surface area of the flocs in terms of an equivalent sphere while the elutriation apparatus uses the settling velocity to calculate an equivalent spherical diameter from Stokes Law), the agreement seen in Figs. 5 and 6 can be considered as reasonable. Furthermore, differences between the two meaurements could also have been due to possible floc modification that occurred as the sample was drawn through the two instruments. In the case of Malvern, the sample passes through a small length of tube (about 15 cm) before reaching the sample cell whereas in the elutriation apparatus, the sample has to pass through all four settling cylinders where the flow characteristics are considerably different from the flow inside the annular flume.

Comparision of the size distributions from the two instruments was facilitated by the use of the density function given by equation 2. The form of the equation guarantees the correct variation of the floc density at the lower and upper limit of the floc sizes. However, the general validity of this expression has to be verified by other independent studies.

The elutriation apparatus, in addition to providing the size distribution data, can also serve as a fractionation apparatus for suspended sediment. This feature is especially useful for analyzing contaminant concentration on different fractions of sediment and to determine the active fraction for contaminant loads. However, it does not provide information on the actual, in-situ floc size which may be important for the investigation of chemical adsorption and desorption. It also cannot provide information on any changes which may occur during the sampling period.

From the limited comparisons presented in this paper, one can conclude that the elutriation apparatus can be a viable instrument for size distribution measurement and for size fractionation of suspended sediment in natural river systems.

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