# A Mercury Displacement Method to Measure Fish Feed Density

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# A Mercury Displacement Method to Measure Fish Feed Density

Huriye Ariman Karabulut and Ilhan Yandi
Department of Aquaculture, Faculty of Fisheries, Rize University, 53100 Rize, Turkey

**Abstract:** In order to advance a theoretical approach to settling velocity one must know density of the feed pellets. In this study a device to measure fish feed density was constructed. The device measures buoyancy force applied to the feed in the mercury and from the known density of mercury the volume of the feed pellet is calculated. The mass of the pellet is accurately measured with a precision scale and density is calculated from mass and volume data. The device is tested by measuring densities of some steel spheres with the device and Sartorious Density Measurement Kit. Both measurements agree within 0.1% which proves that the device is working well. The density of fish feed pellets is different for each pellet. As an example to the use of this device on fish pellets, we investigated density distribution of standard trout feed (6 mm) produced by Trouw company.

**Key words:** Fish feed density, mercury displacement method, feed pellet, settling velocity, scale, Turkey

## INTRODUCTION

Effects of uneaten fish feed in fish cage farms on benthic environment is an important field of study. There are computer programs such as MERAMOD and DEPOMOD (Cromey *et al*., 2002) used for this purpose. Such programs require data on settling velocity of fish feed pellets in water to perform their calculations. There are few measurements of settling velocity of feed pellets in the aquaculture literature (Findlay and Wattling, 1994; Elberizon and Kelly, 1998; Chen *et al*., 1999; Sutherland *et al*., 2006; Vassallo *et al*., 2006; Piedecausa *et al*., 2009). There is also considerable literature on settling velocities of objects with different shapes in different fluids in chemical engineering literature (Chhabra *et al*., 1999; Loth, 2008). In particular, Gabitto and Tsouris (2008) investigate settling velocities of cylindrical object similar to fish feed pellets.

When a pellet is dropped in water with zero initial velocity it starts accelerating. As the velocity increases the drag force on it increases until the weight of the pellet is balanced by the drag force and buoyancy force combined. The velocity remains constant after reaching this terminal velocity. The chemical engineering literature expresses the drag force in terms of velocity and physical and geometrical parameters such as viscosity, diameter and length of the pellets. There are various empirical equations in chemical engineering to express the drag force in terms of dimensionless numbers. In order to use these formulae to obtain settling velocities both the mass and the volume of the pellets must be known accurately. Since the mass is easy to measure accurately with an analytical balance we must be able to measure the volume or equivalently the density accurately.

The main objective in this study was to apply the methods already known to chemical engineering community to settling velocity of fish pellets and provide practical formulas for settling velocities. We submitted a research (Karabulut and Yandi, 2011) that discusses existing formulae in chemical engineering literature and compares them to settling velocity data in aquaculture literature.

As an example to settling velocity formulae consider the Isaacs and Thodos formula (Isaacs and Thodos, 1967; Gabitto and Tsouris, 2008).

$$V = 1.005 \left(\frac{\rho_P}{\rho_f}\right)^{0.06} E^{0.04} \sqrt{\frac{\pi g}{2}\frac{(\rho_P - \rho_f)}{\rho_f} d_C}$$

Where:

$\rho_p$ = The density of particle
$\rho_f$ = The density of water
$d_c$ = The diameter of pellet
$\mu$ = The viscosity of water
V = The settling velocity

The symbol E denotes aspect ratio which is defined as height/diameter. This formula is accurate for relatively larger pellets and E>1. The velocity depends density difference $\rho_p$-$\rho_f$. Usual densities for pellets are about

**Corresponding Author:** Huriye Ariman Karabulut, Department of Aquaculture, Faculty of Fisheries, Rize University, 53100 Rize, Turkey

1.1 g $cm^{-3}$. Density of water is about 1.0 g $cm^{-3}$. Suppose 2% error is made in measurement of density of pellet. This means we measure 1.08 g $cm^{-3}$ instead of 1.1 g $cm^{-3}$. Then the density difference $\rho_p$-$\rho_f$ is measured as 0.08 g $m^{-3}$ instead of 0.1 g $cm^{-3}$. A much larger 20% error in density difference $\rho_p$-$\rho_f$. The settling velocity will be in 10% error at least. As this example shows a 2% error in particle density is unacceptable. The settling velocity sensitively depend on accuracy of particle density. In fact this sensitivity increases for lower particle densities. For example if $\rho_p$ = 1.05 then a 2% error in particle density gives 40% error in density difference and about 20% error in settling velocity. The point to these examples is that density must be measured very accurately in order to predict settling velocity from such formulae. This behavior is not unique to Isaacs and Thodos formula. Any formula for settling velocity will have such sensitivity to particle density uncertainty because particle density and density of water are so close and their difference is 10-20 times smaller than their absolute magnitude. It is the density difference $\rho_p$-$\rho_f$ that enters all the settling velocity formulae from chemical engineering literature. Therefore it is not possible to avoid this problem by changing formulae.

In order to derive better correlations (empirical relations) for settling velocity and to test existing correlations against measured settling velocities we need a method of measuring density of the pellets accurately. The acceptable error is <1%. Preferably as low as 0.1%. Therefore as the first phase of experimental part of this project we constructed a device to measure density of pellets with acceptable accuracy and speed. This study reports this device.

The standard devices for measuring volume (and hence density) of small particles are pycnometers (Dismuke and Stone, 1967; ASTM, 1982; Snel, 1984; Yamagishi *et al*., 1984; Yamagishi and Takahashi, 1992). But pycnometers take about 10 min to make one measurement. In order to measure density profile of various feed pellets one needs to make hundreds of measurements and long measurement times is a problem. The device constructed in this study has a much shorter measurement time (about 2 min) and comparable accuracy. The device is based on Mercury Displacement Method (MDM). This study describes how this device works and how it was constructed. The pellets have air bubbles inside them due to production processes and hence density of each pellet is different. As an example to use of the device density distribution of one kind of pellets produced by Trouw company was measured.

## MATERIALS AND METHODS

**Description of the device:** Consider a mercury cup standing on a precision balance. The balance measures the mass of mercury and the cup (denoted as M). If a pellet is inserted in the mercury there will be lifting force on the pellet as:

$$F_b = V\rho g$$

Where:

V = The volume of the pellet
$\rho$ = The mercury density
g = The gravitational acceleration on earth

The pellet must be pushed into the mercury with a stick. The force needed to apply to the stick to keep the pellet in the mercury is $F_b$-mg where m is the mass of the pellet. This force adds to the total weight (M+m) g applying to the balance and the balance shows Mg+V$\rho$g force. The precision balance measures the force in grams, therefore it actually measures M+V$\rho$. The weight increase V$\rho$ (in grams) is measured with 0.1 mg accuracy. Since the density of mercury ($\rho$) is known with a great accuracy, the volume V and the density m/V of the pellet can be measured accurately.

A cage must be attached to the stick to hold the pellet (otherwise the pellet will float on the mercury). There will be some lifting force applied to the cage and stick too. In order to account for this force the stick and the empty cage must be inserted in mercury and the balance should be set to zero. Next the stick and the cage with the pellet in it is inserted in mercury and the force on the balance is measured. If the stick is inserted exactly at the same depth in both cases, the lifting forces on the stick and the cage will cancel and net increase of weight (in grams) will be V$\rho$.

The cage must be built such that there should be no air bubbles trapped under the cage when it is inserted in mercury. If some air bubbles are trapped under the cage the results will be wrong. The first cage we built had this problem. The results were erratic and repeated measurements gave different results. When we built a better cage the problems disappeared and the repeated measurements gave the same results with about 0.1% uncertainty. Figure 1 shows some cages we tried.

One novelty of the device is the method used to insure that the stick is inserted at the same depth in each measurement. A needle running parallel to the stick is attached and a voltage difference applied between them. (Both the stick and the needle are metal). When the needle touches the mercury, the mercury conducts electricity and a LED lights up. During the measurement, the stick with the empty cage is inserted until the LED lights up. Next

Fig. 1: Some of the cages we tried

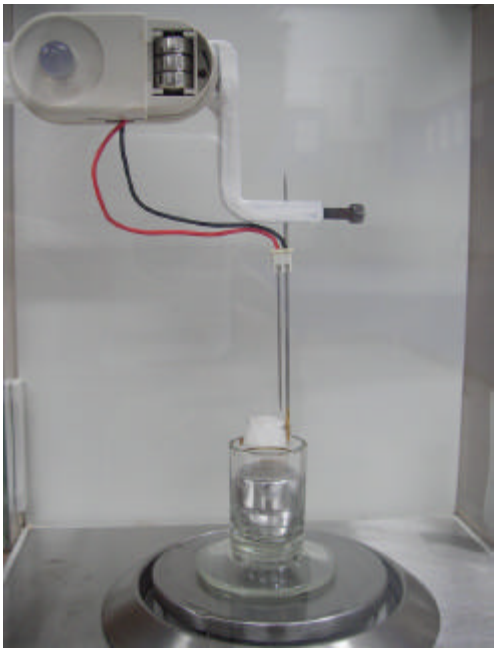

Fig. 2: The batteries, the LED, the needle and the stick attached to the cage mounted on the arm

the cage with the pellet is inserted until the LED lights up. This insures that the stick is at the same depth with an uncertainty of about 0.1 mm in each measurement. Figure 2 shows the LED and the batteries, the stick, the needle and a couple of wires connecting them.

As the final piece of the equipment a mechanism to move the stick and the cage up and down is needed. The mechanism must be able to move the stick within a small fraction of a millimeter. There must be a gross adjustment knob and fine adjustment knob of altitude. As a practical solution we used mechanism of an old microscope. Gross adjustment of the microscope lifts the stick 2.5 cm and fine adjustment can move 2 mm in ten turns. This is enough

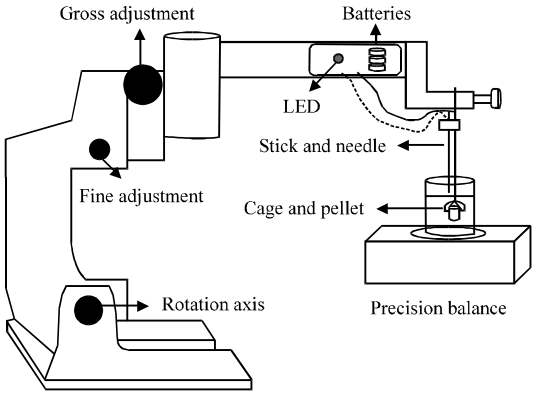


Fig. 3: A schematic description of the setup

Fig. 4: The set up during a measurement. The arm enters the housing of the precision balance while the body of microscope remains outside. The mercury cup is shown on the balance. We move the cage and the stick and the needle up und down by using gross and fine adjustment knobs on the microscope

range of movement for the device. If further lifting is necessary there is an axis on the base of microscope to rotate entire upper part of microscope as shown in Fig. 3. An arm is attached to the microscope which holds the stick with the cage and needle. Batteries and LED are mounted on the arm. The arm is needed to deliver microscopes altitude changes to the stick in the precision balance housing. Figure 4 shows the system during a measurement; the microscope and the arm attached to it carrying the LED and batteries, the stick and the needle. Figure 3 shows the entire setup schematically.

The precision balance measures masses up to 220 g with 0.1 mg precision. Since density of mercury is very high, at most 10-15 mL of mercury can be used. The mercury cup is a test tube of 2.5 cm diameter. The depth

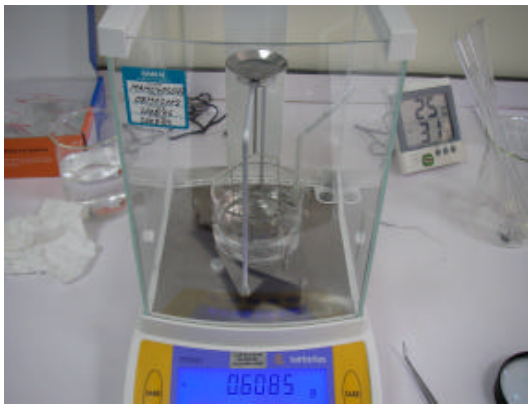

Fig. 5: Sartorious density determination kit

of mercury column is only about 2.5 cm. Therefore, the part of the test tube above the mercury level is cut. A mercury column of 2.5 cm width and 2.5 cm height is enough for measurement since the pellets are shorter than 1 cm and the cage is about 1.5 cm wide.

**Testing the device:** Before using the device for actual measurements of density the device had to be tested. Some steel spheres with different radii (hence different mass) were collected and their densities were measured using density measurement kit of Sartorious precision scale (CP224S Model plus YDK01 density determination kit and the components, Sartorius AG, Germany). A picture of this device in operation is in Fig. 5. This instrument for density measurements gives accuracy of about 0.1%. After that the same spheres were measured with the device and the results were compared. It was concluded that both measurements agree within 0.1% and the device is working well. Table 1 shows a list both measurements and their differences. Figure 6 shows a scatter plot of the measurements for steel spheres. From the Table 1 we calculated Root Mean Square (RMS) percent difference by the formula:

$$\text{RMS (\%error)} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\varepsilon_i^{\,2}}$$

where;

$$\varepsilon_i = \frac{x_i - y_i}{y_i} \times 100$$

Where:

$x_i$ = The density measurement ith. The sphere with mercury displacement device

$y_i$ = The density measurement ith. The sphere with Sartorious device

Table 1: The results of measurements with the device and Sartarious density measurement kit for a variety of steel spheres

| Mass (g) | MDM measurement (g cm$^{-3}$) | Sartarious density kit measurement (g cm$^{-3}$) | Percent difference ε |
|---|---|---|---|
| 0.439 | 7.598 | 7.615 | -0.22 |
| 0.699 | 7.725 | 7.729 | -0.05 |
| 0.699 | 7.735 | 7.737 | -0.03 |
| 0.699 | 7.760 | 7.753 | 0.09 |
| 0.699 | 7.742 | 7.746 | -0.05 |
| 0.699 | 7.699 | 7.702 | -0.03 |
| 0.699 | 7.717 | 7.722 | -0.06 |
| 0.699 | 7.747 | 7.750 | -0.05 |
| 0.857 | 7.663 | 7.673 | -0.13 |
| 0.857 | 7.701 | 7.723 | -0.28 |
| 0.873 | 7.756 | 7.753 | 0.03 |
| 0.877 | 7.836 | 7.859 | -0.29 |
| 0.879 | 7.676 | 7.689 | -0.17 |
| 2.043 | 7.746 | 7.755 | -0.12 |
| 2.043 | 7.698 | 7.707 | -0.12 |
| 2.043 | 7.732 | 7.742 | -0.14 |
| 2.044 | 7.748 | 7.759 | -0.14 |
| 2.044 | 7.738 | 7.753 | -0.20 |
| 2.045 | 7.728 | 7.734 | -0.08 |
| 3.523 | 7.733 | 7.748 | -0.19 |
| 3.539 | 7.857 | 7.867 | -0.12 |
| 3.542 | 7.784 | 7.787 | -0.03 |
| 5.543 | 7.744 | 7.754 | -0.12 |
| 5.552 | 7.741 | 7.728 | 0.17 |
| 5.562 | 7.725 | 7.744 | -0.25 |
| 8.281 | 7.739 | 7.743 | -0.06 |
| 8.282 | 7.748 | 7.733 | 0.19 |
| 8.290 | 7.750 | 7.756 | -0.08 |
| 13.974 | 7.716 | 7.745 | -0.37 |
| 16.251 | 7.711 | 7.737 | -0.34 |
| 16.256 | 7.721 | 7.749 | -0.36 |
| 0.439 | 7.598 | 7.615 | -0.22 |
| 0.699 | 7.725 | 7.729 | -0.05 |
| 0.699 | 7.735 | 7.737 | -0.03 |

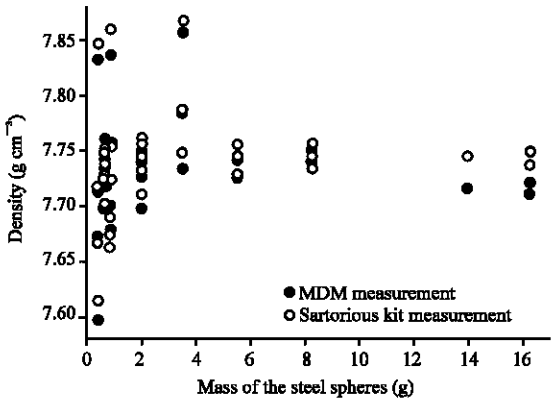


Fig. 6: Densities of the reference steel spheres comparing MDM measurement (●) versus Sartorious density measurement kit (○)

The symbol N is the number of measurements and N = 34 in this data set. The result of this calculation is that average (RMS) error is 0.17%. But as can be observed from the table most of the $\varepsilon_i$ values has negative sign. This means that most of the error in the measurements are some kind of systematic error. Random

errors would have zero average approximately. The fact that most errors have negative sign indicate that true random errors is a small part of the observed error.

## RESULTS AND DISCUSSION

We measured density distribution of Trouw's 6 mm extruded trout pellets. In the production of extruded pellets air gaps remain in the pellets and density of each pellet is slightly different. But when you consider large number of pellets there should be a distribution of densities. It is desired that pellets sink slowly so the fish can catch almost all of them. This means that density must be slightly more than the density of water. In order to produce a rough density distribution we must measure densities of about hundred pellets and plot a bar graph. We made 153 measurements for 6 mm pellets.

Figure 7 shows density distribution of 6 mm extruded pellets. The first thing to observe is that densities of most of the pellets fall in the 1.00-1.10 g $cm^{-3}$ interval. The average density of 6 mm pellets is 1.0936 g $cm^{-3}$ and the peak value is about 1.09 g $cm^{-3}$. The peak is not very sharp. The standard deviation is 0.0520 g $cm^{-3}$.

There are few pellets (four in the measurements) with densities <1.0 g $cm^{-3}$ and these pellets do not sink immediately. They absorb water and raise their densities above density of water in a matter of seconds to minutes and they sink eventually. Since the densities are different for each pellet the settling velocities should be different and there should be a distribution of settling velocities. Papers on settling velocities give single value of settling velocity for each type of pellets. These should be taken as the average values and should not be interpreted as settling velocity of all the pellets.

In order to use a theoretical approach to settling velocities the volume and the density of pellets must be measured first. One of the widely used methods to measure density is hydrometric methods (displacement method) based on measuring buoyancy force in a liquid. In case of feed pellets a liquid that will not wet and diffuse into the pellets must be used.

Mercury is an ideal liquid in this respect because it does not stick and wet the pellets. Mercury is a poisonous liquid metal and one should be careful when working with it. The mercury vapor in the air should be less then some value to avoid health hazards.

Winter (2003) discussed evaporation of mercury drops and estimating mercury vapor in the air. The device uses 10-15 mL mercury and since the measurement time is short the health risks are minimal during the measurements. Of course one should be careful not to spill the mercury since spilling 10-15 $cm^3$ mercury can cause serious health risks in the laboratory if not cleaned thoroughly.

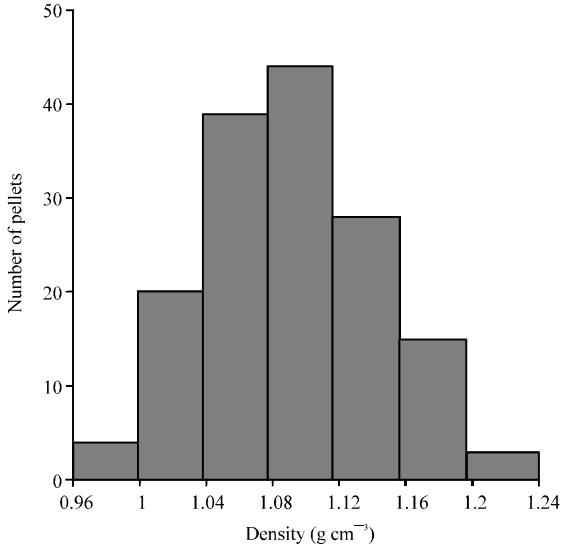


Fig. 7: Density bar graph for ext 6 mm

A novel feature of the device is the method used to insure that the stick always dives to the same depth exactly each time thus eliminating errors from volume of the stick remaining in the mercury. Because mercury is a conducting liquid metal when the needle touches the mercury the mercury completes the circuit over the stick and an LED lights up. Combined with a precise fine adjustment of altitude the microscope has this enables us to make density measurements with a 0.1% error.

Precision of the microscopes fine adjustment knob is crucial to obtain this accuracy. It is possible to adjust the altitude of the stick such that the needle is just barely touching the mercury. When the needle is just barely touching the mercury, the LED starts flickering because of the the small vibrations on the surface of the mercury keeps turning the LED ON and OFF. In fact you can observe the vibrations of a person walking nearby from the rapid flickering of the LED.

The Mercury Displacement Method (MDM) of the type we used was also employed by Knight (1983) and Franzini and Lezzerini (2003). Knight and Heymsfield do not have a precise method to insure that stick is inserted in the same depth in each measurement. Franzini and Lezzerini has a similar method to insure the same stick depth. Both Franzini and Lezzerini and Knight and Heymsfield measured much larger objects and hence they had different experimental setups. Their setups are not suitable to measure small object like fish feed pellets but the physical principles are the same.

We tested the device by measuring some steel spheres with the device and the Sartorious density measurement kit. The results agree within 0.1% accuracy.

Of course one can ask if we have the Sartorious kit why we bother to construct another device. There are two reasons for this. The Sartorious kit works with water. The physical principles of measurements are similar for both devices. When measuring the fish feed pellets, the pellets immediately starts absorbing water and density changes during the measurements. Mercury does not have this problem. Secondly the device has a shorter measurement time which is a considerable advantage when you need to make hundreds or thousands of measurements.

Actually one can argue that during the settling the pellets absorb water and change their densities and therefore, it is better to measure density in water rather than mercury. First of all, settling columns in settling velocity experiments are rather short (about one meter) and the pellets cross this distance in a few seconds. Therefore they don't have enough time to absorb significant amount of water and the relevant density for measured settling velocity is the dry pellet density. Secondly, the water absorption effect is a secondary effect that must be investigated separately. About two pellets, one that is soaked in water for some time and the other that is dry will settle with exactly the same velocity if they have the same size and densities. Therefore the soaking effect on density and the size of pellets should be investigated separately and should be combined with the kind of theoretical formulae described by Karabulut and Yandi (2011).

## CONCLUSION

In the study, as an application of the device we measured a rough density profile for one kind of pellet from Trouw company. There are dozens of different feed pellets and each company's pellets are expected to have different density profiles. Even if we limit of the study to pellets of one company this still means measuring many different kind of pellets and each kind of pellets requires hundreds of measurements for an accurate density profile. Therefore a systematic study of density profile of existing commercial pellets requires thousands of measurements. This study reports a method of measuring pellet densities and it is not a systematic study of existing commercial pellets. Therefore, measurements on one kind of pellet as an example to what can be done with this device is presented.

A final point about the measurement is that density of mercury changes considerably with temperature. Therefore, the temperature of the medium should be measured and the corresponding density must be used in calculations. The device, mercury and mercury cup and pellets should be kept at the room temperature until they reach thermal equilibrium.

## ACKNOWLEDGEMENTS

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