[1.]Elijah G. IKRANG, [2.]Precious O. EHIOMOGUE, [1.]Unwana I. UDOUMOH

HYDRO AND AERODYNAMIC PROPERTIES OF FRUITS AND VEGETABLES: A REVIEW

[1.]Department of Agricultural and Food Engineering, Faculty of Engineering, University of Uyo, NIGERIA
[2.]Department of Agricultural and Bioresources Engineering, Michael Okpara University of Agriculture, Umudike, NIGERIA

Abstract: Hydro and aerodynamic properties of the material to be processed are fundamental and continue to be a challenge for researchers to design a machine appropriately. Mechanical damages to seed at harvesting, transporting, and threshing are major concerns form farmers and farming experts. All the processes of wing transfer, floatation and seed removal from seed mixture and the stalks and husks depend on the behaviour of the seeds in the wind flow. Therefore, it is crucial to determine the physical and aerodynamic properties of various crops to analyzing their behaviour during transport, processing, and precise design of farm equipment and machines to minimize wastes. Physical and aerodynamic properties of agricultural products have been used to precision design of the machinery and different postharvest operations. In this review, hydro and aerodynamic properties of selected agricultural products have been reviewed. Therefore this paper presents highlights and reviews of studies related to the measurements of hydrodynamic and aerodynamic properties of some selected agricultural products. The objective is to study methodologies used and identify future research directions to get a more accurate result. Several papers search from various search engines for scientific articles that are available online. Some keywords and a combination of keywords used in the search process are "hydrodynamic properties", "aerodynamic properties" of fruits and vegetables. The result of the search showed that terminal velocity and drag coefficient of agricultural products have been extensively studied for the designing of air/hydro conveying systems and separation equipment. The result also showed that computer vision and image processing has also been used to detects defects, quality control, classification and sorting of agricultural products.
Keywords: Terminal velocity, Grading, Aerodynamic, Fruits and Vegetables, Sorting

INTRODUCTION

Grading by farmers are usually by experience or through to select either grading by size or by weight (Mokhtar and Firdaus, 2014). This manual sorting techniques will generate some problems such as error in grading, delaying task for sorting because humans cannot work continuously and if there is so many tons, farmers will pay more workers to do the job. The need to develop efficient automated grading system cannot be over emphasize. However this is not without limitation due to irregular shape and sizes of fruits and vegetables. Fruit graders that employ near infrared technologies are expensive and more importantly the calibration and maintenance requirement remain outside the skills of packing house staff (Jordan and Clark, 2004).

The food industry has long utilized air and water to transport products from one location to another, especially raw products. Likewise, a gas or fluid can be utilized to separate a desirable product or products from undesirable materials. When designing systems to work with a specific food material, one must know about the aero and hydrodynamic characteristics of the material. The characteristics, or primary properties, that govern the product behavior in air or water are the drag coefficient and the terminal velocity (Fletcher, 1975).

Terminal velocity and drag coefficient of agricultural products are important and required for the designing of air/hydro conveying systems and the separation equipment (Jalgaonkar *et al.*, 2017).

Terminal velocity is a complex function of fruit shape, fruit size, both water and fruit temperature, and density (Garavand *et al.*, 2010; Kheiralipour *et al.*, 2010; McGinley and Brigham, 1989)

The physical properties such as density, shape size, are required for calculating the terminal velocity and drag coefficient of the agricultural produce (Garavand *et al.*, 2010).

Terminal velocity of fruits is a maximum velocity that each fruit can reach in specific medium (Mohsenin, 1986). Terminal velocity of any falling object is reach when the net force in the downward direction (net body force) is balanced by air resistance (drag force) (McGinley and Brigham, 1989)

As world market for fruit and produce become more sophisticated and technology continues to provide means to measure product quality, there is a corresponding market pull for produce with higher quality levels. Demand from consumer for quality produces, consistent behaviour of machines in comparison with humans, the insufficiency of labour and an attempt to reduce labour costs are the main motivations of automated packing and sorting system in the past decades (Bally, 2006)

According to Jordan and Clark (2004), the right approach to fruit sorting is to use the terminal velocity fruit moving in a fluid that has a density above or below the target density. Density, a good indicator of fruit dry matter thus become an interesting tool for fruit quality sorting because of its inherent lower cost and simpler operation (Richardson *et al.*, 1997). Sorting product based on density is not new, potato, citrus, blueberries and tomatoes have been sorted by floatation techniques for quality or defects (Bajema, 2001; Jordan and Clark, 2004; Wilson and Lindsay, 1969).

Fruit with different terminal velocities will reach different depths after flowing a fixed distance in a flume and may be separated by suitably placed dividers. This approach could use water as a sorting medium, which provides huge advantages in terms of the resulting low corrosion and disposal difficulties, and the fact that it does not need any density adjustment. Moreover, this approach allows purely mechanical setting of the separation threshold by adjusting the divider positions and no change in fluid density is required. Garavand *et al.* (2010) model the terminal velocity of tomato in water column to determine if there was a potential for terminal velocity methods as a practical approach that could be used in sorting unit operation in tomato processing.

The result showed that fruit density created a considerable influence on terminal velocity while the parameters such as fruit volume, shape factor had small effect on the terminal velocity. It was concluded that in any sorting systems, difference in terminal velocity of tomatoes could be addressed as a crucial factor for designing sorting systems. Drag coefficient is used to quantify drag or resistance of an object in a fluid environment such as air or water. Drag coefficient is associated with surface area.

SEPARATION TECHNOLOGIES

Fruits with approximately constant volume and different densities have different terminal velocities and can be used in separation technology (Mirzaee *et al.*, 2008). Several non-destructive methods are available to improve the quality assessment of fruits and vegetables after harvest.

X-ray, accelerometer, electronic nose, nuclear magnetic resonance, and near-infrared spectroscopy are some of the non-destructive available quality assessment technology (Costell and Duran, 2002; Nordey *et al.*, 2019). X-ray is used to measure the size, shape colour, and external defects by image analysis (Lakshmi *et al.*, 2017).

The limitation of using terminal velocity and drag force is that they do not detect the inner quality of the fruits and vegetable. Another limitation and challenges is the fact that the shapes and sizes of fruits and vegetables varies greatly from one to another. The above limitation can be overcome by the use of computer vision and image processing.

COMPUTER VISION AND IMAGE PROCESSING

The detection of defects, quality control, classification and sorting of the product are some of the major applications of machine vision system. Computer vision and image processing systems not only recognize size, shape, colour, and texture of objects, but also provide numerical attributes of the objects or scene being image. Image processing and image analysis are recognized as being the core of computer vision (Krutz *et al.*, 2000). Computer vision system generally consists of five basic components: illumination, a camera, an image capture board, computer hardware and software (Wang and Sun, 2002). Figure 1 shows computer vision system for the by Bio-inspired Vision Fusion for Quality Assessment of Mango.

The vision system directly measures the fruits without physical contact with it. Unfortunately this method will not be suitable for small and medium growers because the system is very expensive (Wang and Sun, 2002).

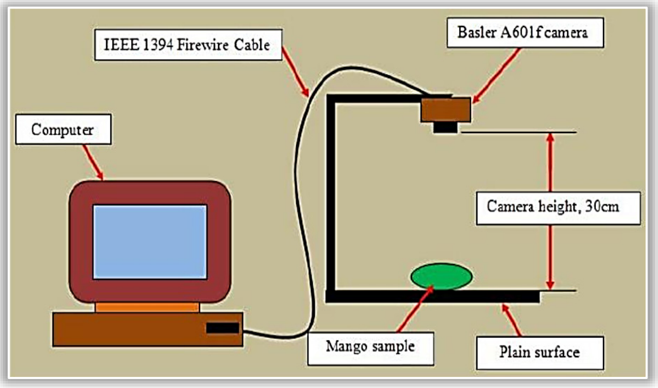

Figure 1: Elements of machine vision system by Bio-inspired Vision Fusion for Quality Assessment of Mango

TERMINAL VELOCITY AND DRAG COEFFICIENT IN POSTHARVEST PROCESSING

Understanding the aerodynamic properties of agricultural produce such as the terminal velocity and drag coefficient, is important for the design of structures and equipment used in operations such as pneumatic and hydraulic transportation of agricultural products; grains classification and cleaning, grain spreading equipment used in storage bins and grain drying (Binelo et al., 2019a). The terminal velocity and drag coefficient of different seeds and other food products have been studied by different authors. Terminal velocity has previously been determined as a function of moisture content from a number of aerodynamic tests with different agricultural products. However, some studies showed that terminal velocity of an agricultural products also changes according to the mass, form, volume and superficial area of the product (McGinley and Brigham, 1989). As reported by Mirzaee *et al.* (2008), noted that the interaction between several particles in airflow causes a significant reduction in terminal velocity, when compared to that of a single particle. Mohsenin (2020) mention that another factor influencing the determination of the terminal velocity is the intensity of turbulence of the air flow. A decrease in the terminal velocity and an increase in the drag coefficients of cotton were recorded with increasing airflow turbulence intensity. Gürsoy and Güzel (2010), studied the physical and aerodynamic properties of wheat, barley, chickpeas and lentil seeds. They performed experiments and use mathematical models to define the terminal velocity and the drag coefficient of each seed type. Although the complete modelling of airflows around the seeds can offer more detailed and realistic results, its implementation, considering a system with movement and interaction among many seeds, becomes impracticable. As an alternative, if the drag force coefficient of a seed is known, it is possible to incorporate the effect of a simple air stream into the seed flow simulation, thereby providing a considerable improvement in the accuracy of the models a relatively low computational cost. The drag force coefficient can be obtained by obtaining the terminal velocity. There are two main methods to measure the terminal velocity, the free fall method and the fluidized bed method. The free fall method is not very practical, since it requires the grain to fall from a high height, requiring precise equipment to measure the seed fall speed and fall time. the fluidized bed method is more practical. In this method, the seed is subjected to an ascending air stream, which is gradually increased until the grain starts to be suspended. The velocity of the air stream necessary to suspend the seed is equal to the seed terminal velocity (Mohsenin, 1986).

Drag is a hydrodynamic force acting opposite to the movement of a body through a fluid. Drag force is generated by the interaction of the body surface and the fluid medium both at different velocities and can be expressed as:

$$F_d = \frac{1}{2} C_d \rho_f A V^2 \quad (1)$$

where F_d is the drag force, C_d is the drag coefficient, ρ_f is the fluid density, A is the projected area perpendicular to the movement vector, and V is the relative velocity between the body and the fluid.

A body freely falling through a fluid will accelerate under the influence of gravity but since drag is proportional to the square of velocity, it will limit the fall velocity until it becomes constant at the so-called terminal velocity.

A body reaches its terminal velocity when the drag force becomes equal to its weight

$$F_d = mg \quad (2)$$

where m is the mass of the body and g is acceleration due to gravity. By substituting equation 2 in 1

$$mg = \frac{1}{2} C_d \rho_f A V^2 \quad (3)$$

Rearranging, the terminal velocity is defined as

$$V_\infty = \sqrt{\frac{2mg}{\rho_f C_d A}} \quad (4)$$

Furthermore, if the terminal velocity of the body is known the drag coefficient C_d can be derived by

$$C_d = \frac{2mg}{\rho_f A V_\infty^2} \quad (5)$$

— Seed Orientation and Projected Area

The project area A is a parameter that depends on the body shape and its orientation. Seeds have irregular shapes, making them difficult to accurately represent it in a simple mathematical model

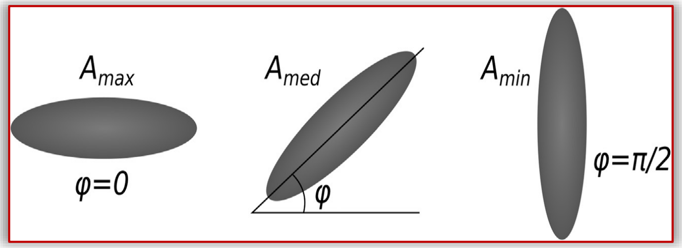

Figure 2: Seed orientation and projected area.
Source: Binelo *et al.* (2019).

Khatchatourian and Padilha (2008) developed algorithm that is used to detect the contours of each seeds, the contours are then processed and each seed is identified, as seen in Figure 3.

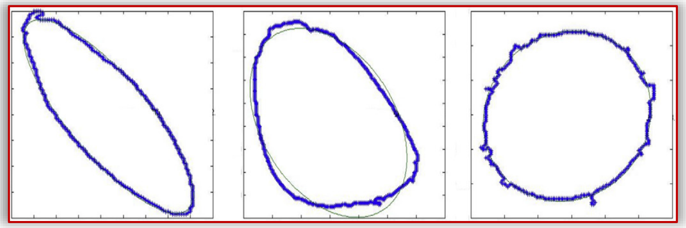

Figure 3: Eclipse approximation

Gürsoy and Güzel (2010) studied the physical and aerodynamic properties of wheat, barley, chickpeas and lentil seeds. Experiments was performed and mathematical models to define the terminal velocity and the drag coefficient of each type of seed. To theoretically define the terminal velocity, equations, with a correction factor based on the form of each seed, were used. To obtain the drag coefficient, variations of grain orientation, and the consequent change in projection area relative to the fluid flow were considered. The average experimental terminal velocity was found to be in the range of 7.52 to 8.14 m/s for wheat varieties, 7.04 to 7.07 m /s for barley varieties, 7.72 to 7.78 m/s for lentil varieties and 11.15 to 12.01 m/s for chickpea varieties. The drag coefficients of seeds according to projected areas in different positions and equivalent spheres were calculated. The drag coefficient in the position of the lowest projected area for all the grain varieties was higher than that in the other position.

Ghamari *et al*. (2011) conducted fluidized bed experiments in order to determine the terminal velocity of chickpeas, rice and lentil seeds. The obtained results showed that terminal velocity for chickpeas ranged from 11.5 m/s to 15.08 m/s, rice terminal velocity ranged from 4.24 m/s to 5.01 m/s, and lentil terminal velocity ranged from 5.08 m/s to 6.41 m/s, according moisture content levels.

The terminal velocity is affected by the density, shape, size and moisture content of samples. Therefore, it is necessary to determine the aerodynamic properties as a function of different factors such as moisture content. Many valuable research works have been carried out about the aerodynamic properties of agro-food materials such as pistachio nut and its kernel (Razavi *et al*., 2007). Figure 4 shows some pistachio nuts and kernels.

Figure. 4: Pistachio nuts and kernels.
Source: Kashaninejad *et al.* (2006).

Kashaninejad *et al.* (2006) determine some physical and aerodynamic properties of pistachio nuts and its kernel in order to design processing equipment and facilities. Several experiments were performed to investigate the moisture-dependent of aerodynamic and physical properties of pistachio nut and its kernel. Physical properties such as dimensions, sphericity, splitting, unit mass, bulk density, true density, porosity, static friction coefficient on various surfaces and terminal velocity were determined. The range of moisture content was selected from 4.10 % to 38.1 % (w.b). Terminal velocity increased from 6.45 to 7.32 m/s and the coefficient of static friction increased linearly against all the tested surfaces as the moisture content increased.

— Aerodynamic Properties of Coffee Beans

Knowledge of the aerodynamic properties of coffee cherries and beans is fundamental to the designing of the machines used in coffee production (harvesting, sorting, cleaning, drying, storage, processing and classification of the product) (Binelo et al., 2019b; Júnior *et al*., 2007). Most of the equipment uses either air or water to transport or separate the desirable and high quality product from either the impurities or lower quality materials. This knowledge may also be used in the improvement of those operations related to the handling and different processing stages of the material.

— Computation Fluid Dynamics for Modelling Terminal Velocity of Agricultural Granular Materials

Computational fluid dynamics uses powerful computers and applied mathematics to model fluidflow situations (Xia & Sun, 2002). The yardstick of success is how well the result of numerical simulation agree with experiment in cases where careful laboratory experiments can be established, and how well the simulations can predict highly complex phenomena that cannot be isolated in the laboratory.

Computational fluid dynamics has received extensive attention throughout the international community since the advent of the digital computer. Since the late 1960s, there has been considerable growth in the development and application of computational fluid dynamics. However, it is only in recent years that computational fluid dynamics has been applied in food processing (Scott, 1992). Computational fluid dynamics as a tool of research for enhancing the design process and understanding of the basic physical nature of fluid dynamics, can provide benefits to the food processing industry in many areas, such as drying, sterilization, mixing, refrigeration and other applicable areas. In the past few years' great development has taken place in these areas (Scott, 1992).

— Aerodynamics property in Drying of Agricultural Produce Using Computational Fluid Dynamics

The drying rate is a strong function of air flow or air velocity. Therefore, it is of great importance to know the airflow and velocity in the drying chamber, thus leading to know the areas of adequate air velocities for proper drying. However, air flow and air velocity are difficult to measure during operation because several sensors are needed to be placed at various directions of air flow and locations. Since there are some difficulties in modelling the complex phenomena, especially the gas turbulence. Computational fluid dynamics is a powerful tool to aid the prediction of drying process. Computational fluid dynamics has been used to predict the air flow and velocity during drying. Mathioulakis *et al.* (1998) used computational fluid dynamics to simulate the air movement inside an industrial batch-type tray air drier. Dry test of several fruits were performed and the results showed that the degree of fruits dryness depended on its position within the drier. Determination of pressure profiles and air velocity by computational fluid dynamics showed that the main cause of the variations in drying rates and moisture contents was lack of spatial homogeneity of air velocity within the drier. Mirade (2003) studied velocity fields in a modern sausage drier in order to provide the information on air circulation inside the drier, which showed that computational fluid dynamics was able to predict the effects of filling level on air flow patterns and also to identify measurement errors in areas where the main air flow direction was horizontal.

Computation fluid dynamics has also been use to investigate the performance and the design of spray dryers in the food industry. Spray dryers are used to produce products such as milk and coffee powder, as well as detergents. However, the design of spray dryers for the food industry is difficult because the performance of spray dryers is heavily influenced by the complexity of air and spray flow patterns inside the dryers.

— Measuring Aerodynamic Properties of Agricultural Products

Two commonly used methods of measuring the terminal velocity experimentally are the suspension and drag methods. The suspension method allows a particle to be suspended in a vertical duct by blowing air in a duct and measuring the air speed at a moment when the particles is suspended. Under these conditions the weight of the particle becomes equal to the drag force (Gharekhani *et al*., 2013; Mohsenin, 1986). The drop method involves dropping the particle from a certain height whereby the particles will reach their terminal velocity after dropping a certain distance. Terminal velocity can be taken from the distance versus time curve where it begins to become linear. The advantage of the drop test for particles with lower terminal velocities is that it is less difficult to use than the suspension method (Gorial and O'callaghan, 1990; Gupta *et al*., 2007; Gürsoy and Güzel, 2010; Razavi *et al*., 2007).

CONCLUSION

Review of the terminal velocities and drag coefficients revealed the following: increase in moisture content and true density affect the aerodynamic properties of the product leading to increase in terminal velocity and a reduction in drag coefficients for different agricultural products. One of the impressive factors of optimizing the harvesting of cereals is terminal velocity and its variation regarding the ambient conditions. Computational fluid dynamics is a validated method that can simulate the phenomenon and help with a prediction of some characteristics. The result can be basis for simulating the transfer of granular material in food processing devices. Biological materials that are consumed as food or feed undergo various unit operations right from the harvesting and postharvest processing. Designing and selecting tools as well as equipment's requires knowledge of the hydro and aerodynamic properties of agricultural materials. Undesirable materials such as light grains, weeds seeds, chaff, plant leaves and stalks can be removed with air flow when grains, fruits and vegetables are mechanically harvested. In addition, agricultural materials are routinely conveyed using air stream in pneumatic conveyors. If these systems are not used properly, they could cause problems.

For example, in a combine harvester, if the air speed is low, the materials would not be separated from each other and there will be extra foreign material with the product. If air speed is high the product will be exhausted along with extra materials and product loss will increase. For conveying agricultural material, the range of proper air streams should be used. With low air speed, there is stagnation in the system, or with high air speed, there will not only be energy lost but also grains may be broken.

The proper air speed can be determined from aerodynamic properties of agricultural materials. These properties are terminal velocity and drag coefficient. Knowledge of aerodynamic properties in agricultural products is of vital importance. In order to design efficient equipment for the harvesting and post-harvesting of agricultural materials, it is necessary to know its aerodynamic behaviour. Knowledge of hydro and aerodynamic properties of agricultural foods and products are important for designing the equipment for processing, transportation, sorting, separation and storing. Designing such equipment without taking these into consideration may yield poor results. The major moisture-dependent physical properties of biological materials are shape, size, mass, bulk density, true density and porosity. Aerodynamic properties such as the terminal velocity of agricultural products are important and required for the design of air conveying systems and the separation equipment. Physical properties such as density, shape, and size, need to be known for calculating the terminal velocity and drag coefficient for separating the desirable products from unwanted materials. Aerodynamic properties such as terminal velocity and drag coefficient are needed for air conveying and pneumatic separation of materials (Gupta *et al.*, 2007). The two commonly used methods of measuring terminal velocity experimentally are the suspension and drag methods.

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