REVIEW OF THE AERODYNAMICS AND PARTICLE DYNAMICS FOR COFFEE SEPARATION

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ABSTRACT

The importance of agriculture in mitigating the effects of overdependence on crude oil export to boost Nigeria economy cannot be overemphasized. Coffee is an important foreign exchange earner and Nigeria has vast potential to resuscitate production, processing and export. An important first step to earn a premium on coffee is to ensure quality post-harvest practices which include cleaning sorting and classification which at present is either lacking or inadequate, given the poor price coffee of Nigeria origin currently attracts. This study reviewed a few notable research works on the aerodynamic of coffee and other notable works on its particle dynamics and related studies in agriculture. The subject of particle dynamics for coffee separation was lacking, hence the need to undertake detailed study on the subject the outcome of which would be to obtain particle trajectories of coffee beans and components as a basis to select the dimensions of a cross flow system to classify coffee beans which is a major requirement in coffee trade worldwide.

Keywords: aerodynamics, particle dynamics, coffee

INTRODUCTION

Particle dynamics is essentially the dependence of the motion of a single material particle on the external forces acting upon it, particularly electromagnetic and gravitational forces. Fluid-particle interactions have long been informally observed by humans. For instance seeds were dispersed by wind and soil materials are also being carried in water. Further observations of these phenomena generated the questions of why some materials are been carried farther than others. Such observations have led humans to explore fluid particle interactions to beneficial effects such as manually broadcasting seeds in the field with the aid of the wind, winnowing to separate chaff from grains in the wind and the separation of one mineral material from another in a natural or constructed water stream. Early machine development based on fluid-particle interactions included the hand cranked winnowing machine used to separate chaff from wheat. Field machines were later developed to harvest seeds by cutting and stripping and later fed to a separate winnowing machine to separate the chaff from the wheat. The separate harvesting and winnowing or cleaning equipment were later combined into a single mobile unit thus giving rise to the working principle and elements of modern combine harvesting machines (Mcmillan, 2008). Studies conducted on the earlier machines having one or more units employing fluid-particle interactions involved practical studies of field performance in order to determine the optimum parameters for effective calibrations and settings rather than providing a formal basis for the design of the machines.

The predictive studies on particle dynamics relating to agriculture began with one dimensional study of aerodynamics involving terminal velocity and associated drag coefficient. These studies are usually associated with separation in a vertical air stream. The fundamental parameters of cleaning and separation processes were investigated by studying the behaviour of materials in a vertical air stream. An example of the application of the study is to improve the design of cleaning systems involving one or more sieves by aerodynamically removing a significant proportion of the light materials to improve sieve performance. However the observations of the human and natural situations stated above could be effectively described using the two dimensional approach which sufficiently addresses the puzzle "why some materials are carried farther than others in the wind". The analysis of particles dropped or projected into the horizontal airstream would enable the prediction of crop and machine parameters relevant to the design of a horizontal tunnel or cross flow systems.

One dimensional study: Aerodynamics of coffee and other related studies

Experimental studies of the aerodynamic of agricultural materials as a preliminary to and often in conjunction with more detailed studies on fluid-particle interactions cannot be over emphasized. Although works on the study of aerodynamic properties of coffee are sparse a few notable investigations have been undertaken.

Olukunle and Akinnuli (2012) noted that coffee processing, harvesting and handling were still manually undertaken despite its huge potential as a highly valued commodity crop, the need to develop mechanical equipment to handle the aforementioned operations was stressed. As a necessary first step, some engineering properties of coffee seeds and beans were investigated to ascertain if existing machines can be used to undertake some to the processes being manually undertaken especially pulping which was still done with mortar and pestle. The properties were determined for the seeds and beans at moisture content at 10.7%. The properties measured such as the axial dimensions, geometric mean diameter, angle of repose on mild steel, coefficient of static friction were comparable to values obtained for some other crops investigated by other researchers. It was thus concluded that existing machines could handle the aforementioned handling and processing needs of coffee.

Aerodynamics of coffee cherry and beans were studied for (Afonso Junior *et. al*., 2007) for *Coffea canephora* and *Coffea arabica* for moisture range 9-54% wb and 8-56% wb. Increase in moisture content and true density affected the aerodynamic properties of the product by promoting an increase in the terminal velocity and a reduction in the drag coefficient. The value of the terminal velocity of the dry processed coffee cherries did not exhibit significant changes for the analysed cultivars. Values of the drag coefficient for both coffee cherries and beans slightly changed during the dry process. The study did not however state whether the wet processed coffee were in parchment or hulled during the sample preparation. Wet processed coffee is preferably stored with the parchment prior to export. This is necessary so that the coffee beans do arrive at the destination with moisture content above the safe value owing to moisture migration. Furthermore a comprehensive study of the aerodynamic properties of coffee of Nigeria origin is highly essential as coffee grown at different altitudes exhibit remarkably different characteristics.

Casanova *et. al*. (2016) conducted experiments to study the aerodynamic behaviour of clones of *Coffea canephora* fruits during drying. The terminal velocities and drag coefficient for each clone were determined at different moisture levels. The vertical wind tunnel was used to determine the terminal velocity while the subsonic wind tunnel was deployed to determine the drag coefficient. A common model for each of terminal velocity and drag coefficient was developed for the coffee clones at different stages of maturation. The model developed could be deployed in commercial coffee processing plants where there could be need to separate the desirable ripe coffee fruits from the unripe ones. This may to an extent take care of indiscriminate manual or mechanical harvesting of ripe and unripe coffee fruits in the field. However for good quality coffee it is a widely acceptable practice to selectively pick only fresh ripe coffee berries or fruits.

Numerous investigators had studied the aerodynamic properties of other agricultural products such as grains, legumes and oilseeds. Majority of the research works studied the effects of moisture content of the agricultural materials on the terminal velocity and drag coefficient, both of which are important aerodynamic properties. The studies were often accompanied with the measurement of physical parameters and solid flow properties of the materials. Some of the investigators who determined terminal velocity as a function of moisture content included Joshi *et. al*. (1993); Suthar and Das (1996); Gupta and Das (1997); Nimkar and Chattopadhyay (2001) and, Dursun and Dursun (2005). However, relatively earlier studies indicated the variation of terminal velocity with some other product parameters such as the mass, volume, form and superficial area (Uhl and Lamp, 1965; Mohsenin, 1986; Haffar and Van Ee, 1990). Other factors which significantly influence terminal velocity are the interaction between several particles and the turbulence of the airflow. Pinheiro (1995) reported a significant reduction in terminal velocity in a particle stream when compared to that of a single particle subjected to airflow. The effect of turbulence on terminal velocity was mentioned by Tabak and Wolf (1998). A decrease in terminal velocity and an increase in drag coefficient was recorded for cotton seed subjected to increasing airflow turbulence (Kilickan and Guner (2006).

In order to determine the terminal velocity and drag coefficient for different agricultural products Gorial and O'Callaghan (1990) and Song and Lichfield (1991) volume shape factors were proposed for spherical and non-spherical particles. The drag coefficient was also represented as a function of Reynolds number. The study also revealed that the orientation of the particle immersed in the airflow affected the product terminal velocity, a finding which was also corroborated by Bilanski and Lal (1965), who found that particle rotation reduced the values of the terminal velocity and increased drag coefficient.

Ayman Hafiz Aimer Eissa (2009) investigated the aerodynamic and solid flow properties of flaxseed as a function of moisture content of the seeds. The bulk density, true density and porosity were found to decrease as the moisture content increased. The angle of repose and terminal velocity increased as the moisture content increased. The static coefficient of friction on various surfaces also increased with moisture content. The result of the investigation was used as a guide to optimize some engineering parameters of separation equipment. Consequently, pneumatic separating equipment was manufactured and tested under different combinations of air stream velocity, feed rate and sample moisture content.

An interesting practical application where the different behaviours of particle components in a mixture moving in a stream of air was exploited to beneficial effects is the separation of stones from potatoes. Carey *et. al*. (1981) reported that when potato – stone mixture was carried over an upward moving air stream, intended to float potatoes from stones, flat stones floated as easily as potatoes- even though their specific gravity is about twice grater- due to the ratio of the stones mass to its projected area. This relationship among other factors could be particularly germane in the specification of parameters to effectively separate components of coffee such as the parchment, pulp and other foreign matter from whole coffee beans.

Two dimensional studies: Horizontal air separation

Although the foundation for fluid particle interaction was laid by Newton *et. al*. (1803), the publication of a general solution for the prediction of particle trajectories was provided by Lapple *et al*. (1940) in the context of chemical engineering. This enabled the application of the general fluid particle theory to the two dimensional analysis of a wide range of processes and arrangement that are of interest in agriculture. The work of Lapple *et. al*. (1940) which was a general solution for the prediction of particle trajectories involved hand calculation which was a tedious task to undertake at inception. The cumbersome manual calculation was initially replaced by the analogue and later the digital computer (Macmillan, 2008). Although not much has been done to apply the fluid particle theory to predict the trajectory of coffee and components in two dimensional systems in order to classify coffee into different size grades meeting stipulated international standards, a few researchers have undertaken significant studies for different crops. Such investigators include Kashayap and Pandya (1965); Gorial and O'Callaghan (1991); Adewumi *et. al*. (2006) and Mcmillan (2008).

Kashayap and Pandya (1965) developed a qualitative approach to the problem of winnowing. The study was based upon two dimensional motion of a particle in a gravitational field. The equations of motion are stated below.

$dU_h = (P_f\, C_d A U U_h / 2M)\, dt$ -------------- 1

$dU_v = (32.2 - P_f\, C_d A U U_v / 2M)\, dt$ -------------- 2

Where

U = velocity of the particle relative to the airstream, ms^{-1}

U_h and U_v = the horizontal and vertical components of U respectively, ms^{-1}

C_d = drag coefficient

A = projected area of the particle, m^2

M = mass of the particle, Kg

P_f = density of air, Kgm^{-3}

t = time, s

Equations 1 and 2 above were solved by a method of incremental approximation. The process was simplified for a digital computer by making the time interval much smaller (0.001s) so that in one step final values of velocity increments at the end of the time interval were obtained. From the velocity components at the end of the time interval the distances moved by the particles in the respective directions were calculated thus completely describing the trajectory of the particles in the airstream. The particle trajectories obtained showed the effects of various parameters on air velocity requirements for winnowing operations.

Gorial and O'Callaghan (1991) observed the difficulty of dividing bulk grains into more than two fractions in a vertical air stream. Consequently a grain particles was introduced into a horizontal air stream where the effects of air velocity and feed rate on cleaning grading. The path of grain and threshed crop material in the horizontal airstream was also studied. As the particles were introduced into the horizontal airstream they were subjected to lateral drift as the settled under gravity. A separation process deployed in this manner has the potential to subdivide a mixture of particles into several fractions deposited at different distances from the point of feed. How far individual particles are transported from the point of feed depends on the relationship between the tendency of a particle to settle vertically under gravity and to drift horizontally due to the effect of drag.

Adewumi *et. al*. (2006) investigated particle trajectory as a parameter for selecting the dimensions of a cross flow grain classifier. The particle trajectory was obtained by the resolution of drag and gravitational forces in the horizontal (x) and vertical (y) directions. The equations are presented below. The model assumed among other factors that only drag and gravitational forces acted on the particle and that the drag coefficient is constant.

$\partial v/\partial t = C_R / M\, (v - v_a)^2 + g$ --------------------- 3

$\partial u/\partial t = C_R / M\, (u - u_a)^2$ --------------------- 4

Where

v, u = resultant velocity of air in y and x direction respectively, ms^{-1}

v_a, u_a = velocity of air in vertical and horizontal directions respectively, ms^{-1}

C_R = coefficient of resistance

M = mass of the particle, Kg

g = acceleration due to gravity, ms^{-2}

Equations 3 and 4 were solved numerically using FORTRAN 77 software. The computer program

developed to solve the equation numerically was iterated at 0.01s until steady state was achieved. The trajectory plot was obtained using MATLAB 3.1 software.
Based on the particle trajectory obtained a separation chamber was fabricated. Threshed cowpea was used to test the effectiveness of cleaning and classification in the chamber. It was found that the grains displaced did not go beyond the boundaries of the chamber fabricated for separation. Almost all the light materials present in the threshed cowpea was blown out of the classifying chamber thus achieving effective cleaning. Thus the deployment of the trajectory theoretically obtained from the MATLAB software to size the separating chamber was validated.
In an attempt to develop a general solution which would solve a variety of problems related to agriculture, Macmillan (2008) developed a computer program based on the theory of a particle moving relative to a fluid under the action of gravitational and fluid forces only. It enables the user to specify conditions for a fluid and initial condition for particle, both moving in any direction. It plots the trajectories for up to 10 particles and gives the final values at a user defined end line. The program furnishes a graphical user interface (GUI) and could be deployed on a window based computer. The validation of the trajectory plotting system (TPS) rests with the users who are encouraged to use it and report any observations.
The application of fluid particle interaction to achieve a desirable end is demonstrated in the fishing industry. When fish are cut in the natural water bodies different species are inevitably found in the lot, hence it is necessary to separate fish species for commercial purposes. The usual practice of separating the fish species by hand apart from being labour intensive is also very costly. To achieve this objective therefore, a mechanical system was developed to automatically separate flat fish from round fish by utilizing their differences in projected area and aerodynamic properties. A continuous stream of mixed fish is moved along a belt conveyor at a rapid rate, and upon discharge, each fish is subjected to a blast o high velocity air. Differences in shape and ratio of projected area to weight of flat fish and round fish are sufficient to alter their trajectories and thereby enable their separation. Experimental result indicated that the system is a practical method to sort fish by shape either at sea or at shore (Carey *et. al*., 1981).

CONCLUSION

Coffee export could be resuscitated to provide foreign exchange earnings for Nigeria. Poor premium currently placed on coffee of Nigeria origin is due to poor post-harvest processing and grading. The cleaning and grading problems could be economically resolved by combining the cleaning and grading operations in a single machine unit. The potentials for separating a mixture of particles into different size fractions in horizontal air stream have been exploited to varying degrees of success over the years. The trajectory of coffee components could be effective means of sizing the classification unit of the proposed grading equipment to be developed to grade coffee of Nigeria origin. To this end as a preliminary investigation a comprehensive study of the aerodynamic properties of Nigeria coffee is imperative to obtain important parameters of the trajectory model to be developed for coffee. The assumption of sphericity of particles assumed by the majority of existing models shall be modified to incorporate the shape factor. The effect of buoyant forces shall also be considered especially for coffee in parchment.

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