Investigating Particle Trajectory as a Parameter for Selecting the Dimensions of Cross Flow Grain Classifier

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ABSTRACT

Selection of the optimum dimensions for cross flow pneumatic classifier for grains is very essential. The study reveals the use of predicted particle trajectory in selecting the dimensions of such classifiers in the x and y planes. Drag and gravitational forces were resolved in 2D and the acceleration components integrated twice. The resulting displacement equations were solved numerically with MATLAB 3.1 software using FORTRAN 77. The plot of particle trajectory were also obtained and used as guide for selecting the length and breadth of a separation chamber.

The separation chamber was fabricated based on the particle trajectory obtained and tested with threshed cowpea discharged from a thresher unit. It was found that maximum displacement of grains under the condition of the experiment does not go beyond the boundaries of the separator unit fabricated. Also, in all the experimental cases, almost all the light materials were blown outside the separator chamber. These indicate that the theoretical particle trajectory produced from the MATLAB could be an appropriate parameter for selecting the length and breadth of a separator unit. Particle trajectory is therefore proposed as a tool for selecting the dimensions of cross flow pneumatic classifiers.

Keywords: Pneumatic classifier, particle trajectory, terminal velocity, cross flow, classifier dimensions, cowpea

1. INTRODUCTION

The solution to the motion of particles in fluid has contributed to the prediction of particle trajectory and could contribute to the selection of the dimensions of cross flow systems (Adewumi, 2005). Gorial and O'Callaghan (1991a) examined the separation of particles in a horizontal air stream and studied the effects of air velocity and feed rate on the cleaning and grading of grains. They also studied the path of grain and threshed crop material in the horizontal air stream. They observed that the separation of particle in a vertical flow could only divide mixture into two distinct fractions - heavy and light particles (Gorial and O'Callaghan, 1991b). Whereas, in many situations the separation problem is a more complicated and difficult one, requiring the separation of particles with similar aerodynamic properties. Therefore, they proposed a solution by introducing the particles into a horizontal air stream, which would subject the particles to lateral drift as they settle under gravity. Such a separation process could sub-divide a mixture of particles into several fractions, deposited at different distances from the point of feed, depending on the relationship between the tendency of particle to settle vertically under gravity and the drift horizontally under the drag force of the air stream.

The aerodynamic drag force, F_d, exerted upon the particle by the stream of air is a function of the projected area of the particle, A, the air density, ρ_a, and the relative velocity between the air and the particle, V_r, as expressed in equation 1:

$$F_d = \frac{1}{2} C_d \rho_a A V_r^2 \qquad (1)$$

For a grain assumed to have spherical shape and the projected area, A, obtained using diameter of equivalence sphere, d, as suggested by Gorial and O'Callaghan (1990), the acceleration (Acc) is given by:

$$Acc = (3C_d /4) (\rho_a/\rho_p) (V_r^2/d) \qquad (2)$$

The physical properties and drag coefficient in equation (2) suggested that separation of small and low-density grain from the bulk can be achieved aerodynamically. Hence, if two grains of different size are introduced into an air-stream, the acceleration imparted to the grains is dependent on their drag co-efficient and the velocity of the particles relative to the air stream, and inversely to their diameters and densities. Assuming the same density and drag coefficient, for same type of grain, small grains will have a greater acceleration and hence will tend to travel a greater distance in the air- stream than larger grains. A similar conclusion could be drawn for two particles of equal size but different densities.

Macmillan (1999) developed a computer program to solve fluid particle problem for single kernel drop. The program was used to analyze separation that occurs when grain and chaff are winnowed by being thrown through or dropped in wind. The program is a simulation of the traditional winnowing of grain and chaff/straw in the wind. During the process of winnowing, the lighter fractions are blown further than the grains. The program is based on numerical integration of the equations of motion. The program specified some parameters of the particles such as equivalent diameter, mass, magnitude and direction of the particle velocity (relative to the earth); and air parameters including density, viscosity, and magnitude and direction of air velocity (relative to the earth). The program provides a plot of vertical displacement (y) vs.

horizontal displacement (x) of the particles at the various time intervals (t); and x, y, t together with the magnitude and direction of the particle velocity.

Ogunlowo and Coble (2000) developed a mathematical 2D model for two phase motion of sugarcane (chopped components) in a vertical counter current air stream. The model considered the effects of gravity, drag, friction and collision forces. The acceleration form of the resolved force equation was integrated twice to obtain the displacement components. They obtained the trajectories of the particles by solving the final equation numerically using Adam – Bashforth and Adams – Moulton (ABM) techniques (Ogunlowo and Coble, 2000).

Cross flow classifiers have the advantage of producing more than two fractions from any particulate or granular admixtures within a short time (Wang et al., 2001; Adewumi et al., 2006a; Gorial and O'Callaghan, 1991a). Flow field in cross flow depends strongly on their geometry, which affects the cut (Wang et al., 2001). It is essential to have a procedure for selecting the dimensions of cross flow classifier. Wang et al (2001) mentioned that fluent/ UNS (now version 5) with an unstable grid was used to determine the geometry of a cross flow classifier. Bjerg et al. (2004) predicted close range ventilation spread with computational fluid dynamics. Therefore the main objectives of this study are to demonstrate the use of particle trajectory in selecting the dimensions of a cross flow classifier and provide a procedure for such selection.

2. MATERIAL AND METHODS

The vertical and horizontal dimensions of the cleaning chamber were determined using aerodynamic principles. The models proposed by Gorial and O'Callaghan (1991a) were adopted and modified for a 2-D particle trajectory in a cross flow system. Parameters such as particle injection velocity of threshed material, $V_{i,}$ air velocity, V_a, angle of air flow, θ, and terminal velocity, V_t, were incorporated into the modified equations developed during the study using the MATLAB 3.1 software.

2.1 Model Assumptions and Formulation of the Theoretical Model

The following assumptions were made in developing the theoretical model to study the particle dynamics and predict displacement (trajectory) for the cross flow system as supported by various authors (Gorial and O'Callaghan, 1991a & b):

1. The average terminal velocity in both x and y direction is equal
2. The drag coefficient of the grain is constant over the range of velocity considered for the study.
3. The air flow rate is uniform
4. Only drag and gravitational forces are responsible for the movement of material
5. Particle flow is two dimensional (2D)
6. Materials are closely packed and there is free fall and no tangling.
7. Pressure drop is negligible across the system

8. Magnus effect is negligible since material shall not be feed to clogging situation.
9. The effect of temperature and environmental condition are negligible
10. The grain tend to a spherical shape
11. Influence of acceleration on drag coefficient is negligible.

Drag and gravitational forces were assumed to be the main factors responsible for materials movement in the system. Therefore, the total forces (F_T) acting on the material is the sum of drag (F_d) and gravitational (F_g) forces and,

$F_T = F_d + F_g$ (3)

Where,

$F_d = C_R V_p^2$ (4)

$C_R = C_d (3/4d) (\rho_a /\rho_p)$ (5)

$F_d = (3C_d /4) (V_p^2 /d)(\rho_a /\rho_p)$ (6)

$V_p = V – V_a$ (7)

For a 2D situation, equation 6 could be re written as stated below:

In y – direction,

$M \partial v/\partial t = C_R (V – V_a)^2 + Mg$ (8)

$\partial v/dt = C_R/M (V – V_a)^2 + g$ (9)

In the x –direction,

$M \partial u/\partial t = C_R (U – U_a)^2$ (10)

$\partial u/\partial t = C_R/M (U – U_a)^2$ (11)

Having developed the model, the 2-D trajectory of the threshed materials injected into the cleaning unit in the x and y directions were also plotted using the MATLAB software for the following practicable and applicable boundary conditions (Gorial and O'Callaghan. 1991a & b; Adebayo and Anjorin, 2000; Ademosun, 1993; Aheneku et al., 2003; Gummert, Kutzbach et al., 1992; Kashayap and Pandya, 1986; Ogunlowo and Adesuyi, 1999):

$0.05 \leq V_i \leq 0.25 \text{ m s}^{-1}$

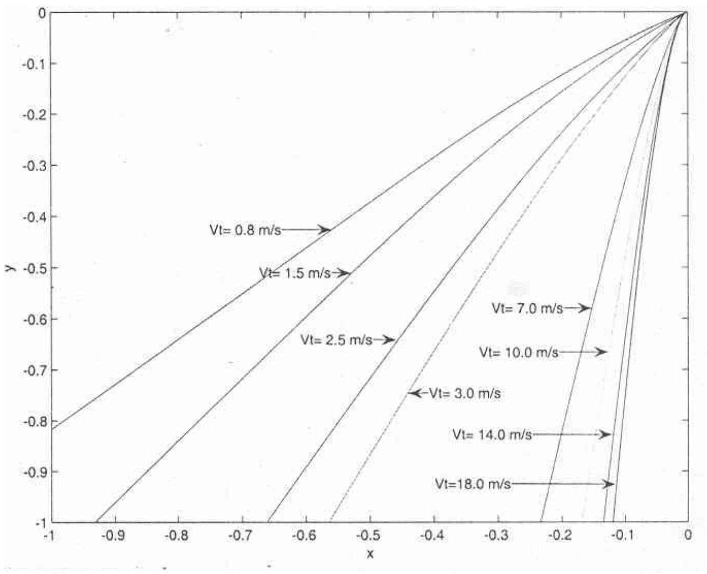
$3.6 \leq V_a \leq 7.5 \text{ ms}^{-1}$

$0.08 \leq V_t \leq 18 \text{ ms}^{-1}$

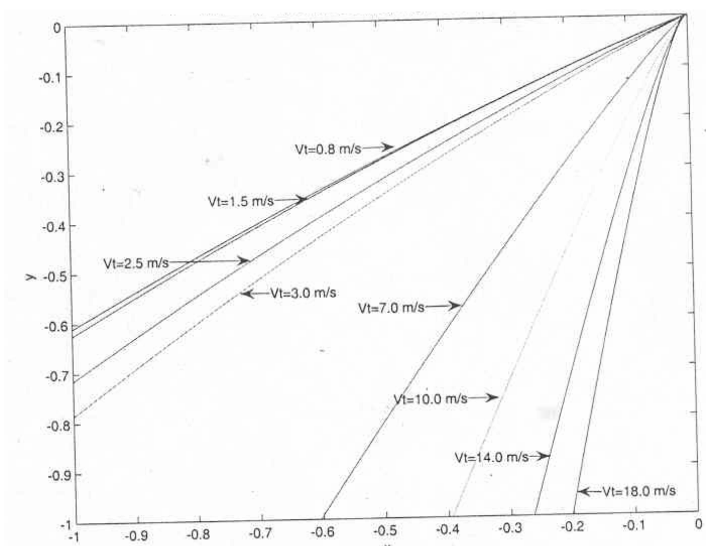
$60 \leq \theta \leq 120^0$

Equations 9 and 11 were solved numerically. Fortran 77 was used to prepare the program used to solve equations. The numerical solution involves iteration at 0.01 second until a steady state was achieved. Iterative schemes are accepted numerical method for trajectory studies because of the associated high accuracy (Kahl, 1996; Seibert, 1993).

Figs. 1-3 show the trajectory plots for fan angle of inclinations of 60, 90 and 120^0 respectively for particle inlet velocity of 0.25 m s^{-1} and air velocities of 3.6 and 7.5 m s^{-1}, and maximum x and y value of 1 m. From the trajectory plots, particles with $V_t \leq 3.0$ ms^{-1} represent light materials



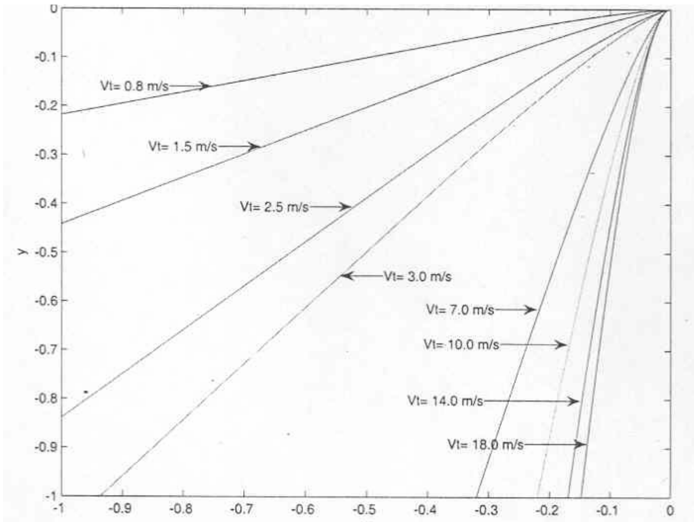
(a) Air velocity of 3.6 ms^{-1}



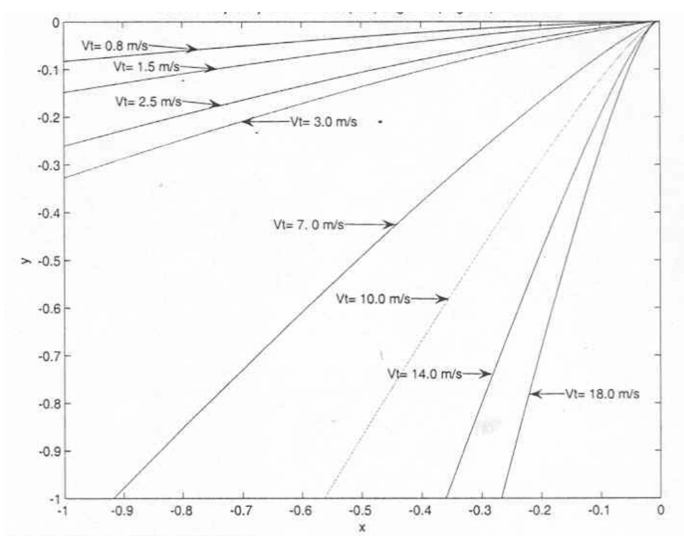
(b) Air velocity of 7.5 ms^{-1}

Fig. 1: Particle trajectory produced from the 2D model at fan inclination of 60^0 and inlet velocity of 0.25 ms^{-1}

while particles with $V_t \leq 7$ ms^{-1} represent heavier materials (grains) The heavier materials are expected to have a maximum lateral displacement of 0.9 m while the lighter materials are blown off, far ahead. Also the lighter particles are expected to have a maximum of 0.6m vertical displacement. Hence, a lateral axis greater than 0.8m and a vertical axis greater than 0.6m are adequate for the separation unit.

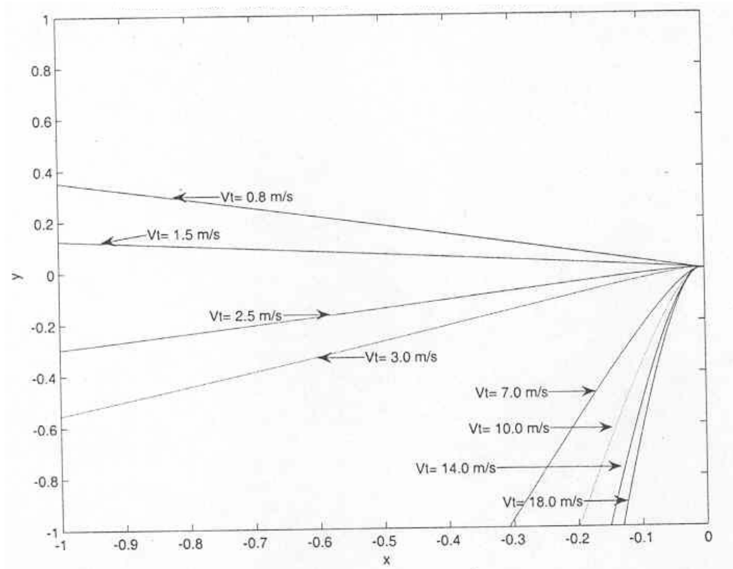


(a) Air velocity of 3.6 ms^{-1}

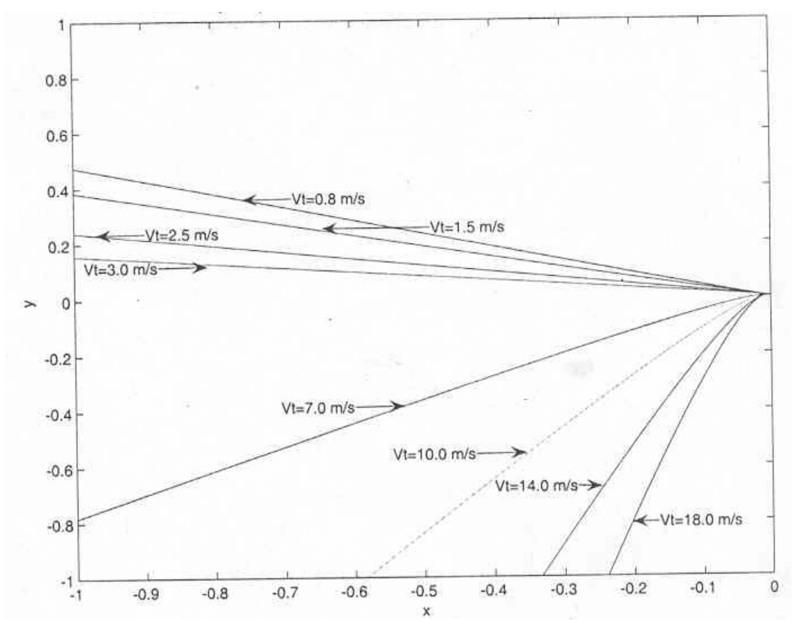


(b) Air velocity of 7.5 ms^{-1}

Fig. 2: Particle trajectory produced from the 2D model at fan inclination of 90^0 and inlet velocity of 0.25 ms^{-1}



(a) Air velocity of 3.6 ms^{-1}



(b) Air velocity of 7.5 ms^{-1}

Fig. 3: Particle trajectory produced from the 2D model at fan inclination of 120^0 and inlet velocity of 0.25 ms^{-1}

2.2 Fabrication and Testing of the Cross Flow Classifier

A practicable dimension of 0.99 x 1.3 m was selected for the cleaning unit, considering the space requirements for free fall of the materials (Kashayap and Pandya, 1986; Fernando and Hanna, 2005). A thresher-cleaner with cross flow classifier was fabricated at the Department of Agricultural Engineering, Federal of Technology, Akure, Nigeria and described in Adewumi (2005); Adewumi et al. (2005; 2006b). Fig. 4 shows the diagram of the classifier while Fig. 5 shows a sketch of material flow in the cross flow chamber. The classifier was tested with cowpea discharged from the thresher unit at a pod moisture content of 14.0%, grain moisture content of 15.3%, fan angles of inclination of 60, 90 and 120^0, and fan speeds of 900 and 1500 rpm. Materials fed into the classifier are a mixture of whole and damaged/ broken grains, and whole and broken pods. The materials were collected in a collector partitioned at 12.5 cm intervals. About 65% of materials loaded into the classifier were pod while 35% was grain. The materials collected in each of the trays were classified into 8 groups, as shown on Table 1. Experiments were conducted in triplicates and the mean value is used for the discussions

Fig. 4: FUTA Thresher - Cleaner

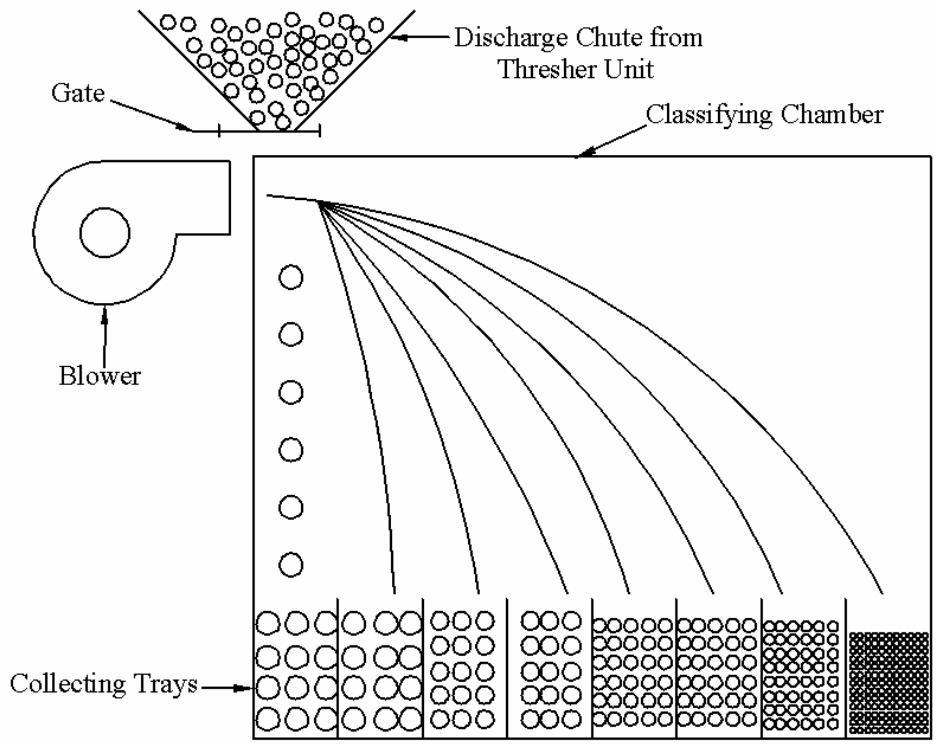


Fig. 5: Sketch of the Experimental Set up and Material Flow in the Classifier

Table 1: Classification of material loaded into the cleaning chamber

Material	Specification	Size range (mm)
Cowpea (Whole Seeds)	Big size	$7.00 \leq x \leq 10.00$
	Medium size	$5.00 \leq x \leq 7.00$
	Small size	$3.80 \leq x \leq 4.99$
Cowpea (Damaged Seeds)	Broken seeds	< 5.00
	Infested seeds	$3 \leq x \leq 10.00$
	immature seeds	≤ 3.00
Pods	Unthreshed	$40 \leq L \leq 120$
	Whole size	$100 \leq L \leq 120$
	Medium size	$40 \leq L \leq 99$
	Small size	$5 \leq L \leq 39$

3. RESULTS AND DISCUSSION

Tables 2 to 6 show the mean of the material distribution in the trays under the specified conditions. Material discharge is not single kernel drop. Therefore, force and material interactions simultaneously occurred as materials dropped in the separation chamber. The materials are therefore spatially distributed in the trays with most of the heavier materials deposited closer to the air inlet and the lighter once displaced further.

Tray 1, 2, 3, 4, 5, 6 and 7 corresponds to a horizontal distance of 12.5, 25.0, 37.5, 50.0, 62.5, 75.0 and 82.5 cm respectively from the point of drop. At a fan speed of 900 rpm, the maximum displacement of grain was 62.5 cm away from the point of drop (Tables 1 and 2). But, grains were dragged further to a distance of 82.5 cm at a fan speed of 1500 rpm (Tables 4 to 6). Almost all the 65% pod loaded into the cleaning chamber were blown out and recovered outside the chamber, except in the case at $\theta = 90^0$ and $V_f = 1500$ rpm where whole pod was collected at a distance 75.0 cm from the inlet point, closest to the exit of the cleaning chamber. The maximum displacement of grains under the condition of the experiment does not go beyond the boundaries of the separator unit fabricated. These are indications that the predicted trajectory is an appropriate tool for determining or selecting the length and breadth of a cleaning chamber.

It is essential to skillfully use the procedure developed and the respective trajectory plots from the MATLAB software to appropriately select classifier dimensions. The desired or prevailing conditions of air velocity, fan angle of inclination and material inlet velocity should be input into the programme for plotting the trajectories of the representative materials (indicated by the terminal velocities), especially under limiting conditions. The plots should thereafter be studied to determine the optimum dimensions of the classifier as demonstrated in Figs. 1-3. Considerable values of x and y of up to 3 m each should be used for the initial plots in order to have a good picture of the flow field of the materials before the selection of appropriate classifier dimensions.

Table 2. Mean material distribution within trays 1-7 at θ = 90^0, V_F = 900 rpm

		Quantity	of	material	collected	in	the	trays	(g)
SN	Materials	1	2	3	4	5	6	7	Total
1	Big seeds	5.9	4.0	2.4	0.7	0.1	0.0	0.0	13.1
2	Medium seeds	0.4	1.1	0.4	0.2	0.0	0.0	0.0	2.1
3	Small seeds	0.0	0.2	0.0	0.3	0.1	0.0	0.0	0.7
4	Damaged seeds	6.5	3.6	2.1	1.6	0.1	0.0	0.0	14.0
5	Whole pods	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	Medium pods	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	Small pods	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	Unthreshed pods	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Total	12.9	8.9	4.9	2.9	0.4	0.0	0.0	29.9

Note, θ = angle of inclination of fan and V_F = fan speed for Tables 2 to 6

Table 3. Mean material distribution within trays 1-7 at θ = 105^0, V_F = 900 rpm

		Quantity of material collected in the trays (g)							
SN	Materials	1	2	3	4	5	6	7	Total
1	Big seeds	9.1	5.7	3.4	2.4	1.3	0.0	0.0	21.8
2	Medium seeds	0.0	0.0	0.0	1.0	0.0	0.0	0.0	1.0
3	Small seeds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	Damaged seeds	1.7	3.0	1.3	0.3	0.0	0.0	0.0	6.4
5	Whole pods	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	Medium pods	0.3	1.7	1.0	0.0	0.0	0.0	0.0	3.0
7	Small pods	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	Unthreshed pods	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Total	11.1	10.4	5.7	3.7	1.3	0.0	0.0	32.3

Table 4. Mean material distribution within trays 1-7 at θ = 120^0, V_F = 1,500 rpm

		Quantity of material collected in the trays (g)							
SN	Materials	1	2	3	4	5	6	7	Total
1	Big seeds	0.6	1.7	0.6	1.9	3.9	3.6	2.6	14.9
2	Medium seeds	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.7
3	Small seeds	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.2
4	Damaged seeds	0.0	0.0	0.1	0.3	0.2	0.8	1.5	3.0
5	Whole pods	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	Medium pods	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	Small pods	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	Unthreshed pods	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Total	0.6	1.7	0.7	2.4	4.8	4.4	4.2	18.8

Table 5. Mean material distribution within trays 1-7 at $\theta = 105^0$, V_F = 1,500 rpm

		Quantity of material collected in the trays (g)							
SN	Materials	1	2	3	4	5	6	7	Total
1	Big seeds	0.1	1.9	2.9	2.2	2.4	1.6	0.7	11.9
2	Medium seeds	0.0	0.4	0.6	1.0	0.7	0.3	0.1	3.2
3	Small seeds	0.0	0.3	0.1	0.0	0.0	0.4	0.0	0.9
4	Damaged seeds	0.0	0.2	0.0	0.0	0.0	0.1	0.6	0.9
5	Whole pods	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	Medium pods	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	Small pods	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	Unthreshed pods	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Total	0.1	2.8	3.7	3.3	3.1	2.5	1.5	17.0

Table 6. Mean material distribution within TRAYS 1-7 at θ = 90^0, V_F = 1,500 rpm

		Quantity of material collected in the trays (g)							
SN	Material	1	2	3	4	5	6	7	Total
1	Big seeds	0.0	0.9	1.8	3.3	3.0	1.3	1.6	11.9
2	Medium seeds	0.0	0.8	0.2	1.5	1.5	0.2	0.8	3.8
3	Small seeds	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.4
4	Damaged seeds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	Whole pods	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0
6	Medium pods	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
7	Small pods	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	Unthreshed pods	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Total	0.0	1.7	1.9	4.9	4.5	2.0	2.4	16.2

4. CONCLUSION

It can be inferred from the study that the plots of the 2D trajectories of materials discharged into a cross flow classifier using MATLAB 3.1 are useful tools for simulating/ predicting the lateral and longitudinal dimensions of the classifier under the various applicable conditions of grain inlet velocity, air velocity and fan angle of inclination. Therefore, the procedures discussed and the resulting trajectories plots are useful tools for selecting cross flow classifier dimensions.

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Nomenclature

$\frac{\partial^2 x}{\partial t^2}, \frac{\partial u}{\partial t^2}$ = Acceleration in x-direction, ms^{-2}

$\frac{\partial^2 y}{\partial t^2}, \frac{\partial v}{\partial t^2}$ = Acceleration in y-direction, ms^{-2}

A = Projected area, m^{-2}

C_d = Drag coefficient

C_R = Coefficient of resistance

D = Diameter of equivalent sphere, m

F = Force, N

F_d = Drag force, N

F_f = Frictional force, N

F_w = Weight or gravitational force, N

g = Acceleration due to gravity, ms^{-1}

M = Mass of particle, kg

V, U = Resultant velocity of air in y & x-direction respectively, ms^{-1}

V_a, U_a = Velocity of air in y & x-direction respectively, ms^{-1}

V_i = Injection velocity of particle, ms^{-1}

Vp = Particle velocity, ms^{-1}

V_t = Terminal velocity of particles, ms^{-1}

V_{ry}, U_{rx} = Relative velocity of particle to air in y & x-direction respectively, ms^{-1}

ρ_a = Air density, kgm^{-3}

ρ_p = Particle density, kgm^{-3}