PHYSICAL PROPERTIES OF STRAWBERRIES AS RELATED TO PNEUMATIC SORTING

Thesis for the Degree of M. S.
MICHIGAN STATE UNIVERSITY
JOSSE G. DE BAERDEMAEKER
1972

ABSTRACT

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by

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The need for cleaning and sorting of the harvested crop arises in machine harvesting of strawberries. The possibility of using an airstream for this sorting operation was investigated in this study.

The terminal velocity of individual strawberries was determined using the air velocity required for flotation. A linear regression analysis showed that the terminal velocity was primarily a function of the square root of the weight with the shape of the strawberry producing a variation in terminal velocity for any particular weight. Density and stage of maturity did not have significant influence on the terminal velocity.

A method for studying the feasibility of pneumatic sorting of strawberries was formulated in terms of a sorting matrix and a field maturity matrix. The sorting matrix which gives the percent of strawberries removed by a specific airstream velocity was calculated from the weight-terminal velocity data. A field sample was divided into weight and maturity groups and the composition of the product after using an airstream at certain velocities was calculated. It was concluded that complete pneumatic sorting of green

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strawberries cannot be accomplished without losing some of the ripe product. A sizeable amount of the ripe strawberries would be lost if the field sample contains green strawberries of the same weight as the ripe ones. This results because pneumatic sorting is really another form of sorting by weight.

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A THESIS

Submitted to

Michigan State University

in partial fulfillment of the requirements

for the degree of

MASTER OF SCIENCE

Department of Agricultural Engineering

1972

G78908

ACKNOWLEDGEMENTS

The author would like to express his appreciation to Dr. Larry J. Segerlind for his guidance throughout the research program.

Appreciation is also expressed to the University of Leuven, Belgium for allowing the author to pursue his studies here, to the Department of Agricultural Engineering of Michigan State University and to the Commission for Educational Exchange between the United States and Belgium for their financial support.

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I INTRODUCTION

Mechanical Harvesting of Strawberries

The introduction of mechanical harvesting in the traditionally labor intensive fruit and vegetable production is often based on the once-over harvesting concept. The human harvester searches the crop, decides which to pick and which not, handles it carefully and often also grades the harvested fruit. Once-over machine harvesting needs devices which will obtain a final product of acceptable quality for processors and consumers. The availability of, or the possibility to develop these devices, their quality of operation and their economic feasibility are some of the factors which determines the success of mechanical harvesters.

In the case of strawberries, decreasing availability of harvest labor and competition from imported lower-cost Mexican strawberries dictates a need for mechanical harvesting (Larsen, 1968). Booster et. al. (1968) concluded that the state of art has been sufficiently developed to demonstrate that strawberries can be harvested by mechanical means, but unless equipment can be developed to cap, sort and grade the fruit, the advantages offered by mechanical harvesting will be lost. Therefore, current efforts are directed towards further improvement of a mechanical picker as well as to the development of equipment to perform sorting, grading and capping operations.

Experimental harvesters are capable of separating the fruit from leaves and other foreign material (Nelson and Kattan, 1967). Another desirable property is the separation of machine harvested strawberries into groups according to maturity, since once-over harvesting of present varieties results in berries with varying degrees of maturity. Nelson and Kattan (1969) reported that maturity seems to be a function of berry size. They constructed a tapered-finger sizing device that permits the fruit to be separated in groups according to maturity. While the machine performed quite well, they concluded that hand-sorting would still be required to obtain complete maturity sorting.

A very limited amount of data taken at Michigan State University in 1970 indicates that it may be possible to sort strawberries by passing them through an airstream. The following objectives for this study were established: a) investigate aerodynamic properties of strawberries, more specifically the terminal velocity as related to the maturity; b) determine physical properties of strawberries such as dimensions, weight, volume and density; and c) investigate the feasibility of pneumatic separation of strawberries into maturity classes.

II REVIEW OF LITERATURE

Moving air in combination with other mechanical devices has long been used for cleaning and sorting of grains and seeds. Although this application is widely adopted in current grain harvesting and handling equipment, continuing investigations of the interaction of air and materials are aimed towards the design of more efficient and economical equipment (Uhl and Lamp, 1968; Kashayap and Pandya, 1966; German and Lee, 1969). There also has been increasing interest in airstream applications for harvesting and handling of fruits and vegetables, especially for picking, conveying and sorting. Crowther and Gilfillan (1959) and Hallee (1972) investigated physical and aerodynamic properties of potatoes and stones that would be important in the design of an aerodynamic separator. Tiwari (1962) studied physical and aerodynamic properties of dry beans and associated materials in relation to separation. Aristizabal et. al. (1969) showed that an airstream can be used for maturity and quality separation of peanuts. In another investigation, Soule (1970) tried to link the aerodynamic behavior of blueberries to the aerodynamic behavior of common geometrically shaped objects. Such documentation would have enabled him to use the published fluid-dynamic data to design more efficient harvesting and processing systems. However, from the results of the data collected and calculated he concluded that the behavior of blueberries in a turbulent airstream differed significantly from that of spheres under the same conditions. Idell et. al. (1971) experimented with an air suspension-vibration strawberry harvester. They found that the overall average drag coefficient for strawberries is 1.15 to 1.38 depending on air velocity but independent of berry size. Igbeka and Sagi (1971) investigated pneumatic separation of dropped citrus flower particles. They concluded that complete separation cannot be achieved by air alone.

III AERODYNAMIC THEORY RELEVANT TO THE PROBLEM

Drag Force

Consider the fluid flow about an immersed object, then the forces acting on that body can be represented by the resultant force F_1 (Figure 1). The component of this force in the direction of the fluid flow is the drag force F_d, the component orthogonal to the fluid flow is the lift F_l. The relationship between these forces and the fluid and body characteristics are given by (Lapple, 1956) where C_d and C_l are the drag coefficient and lift coefficient

$$F_l = C_l A_p \rho f \frac{V^2}{2} \qquad (1)$$

$$F_d = C_d A_p \rho f \frac{V^2}{2} \qquad (2)$$

of the object. For particle motions in general applications it is not necessary to separate the force in two components since the body is usually free to assume its own random orientation and no permanent lift can act (Lapple, 1956). The net resistance force F_r can be given in terms of an overall drag coefficient C as:

$$F_r = C A_p \rho f \frac{V^2}{2} \qquad (3)$$

Where: F_r = drag force (lbs.)

C = overall drag coefficient

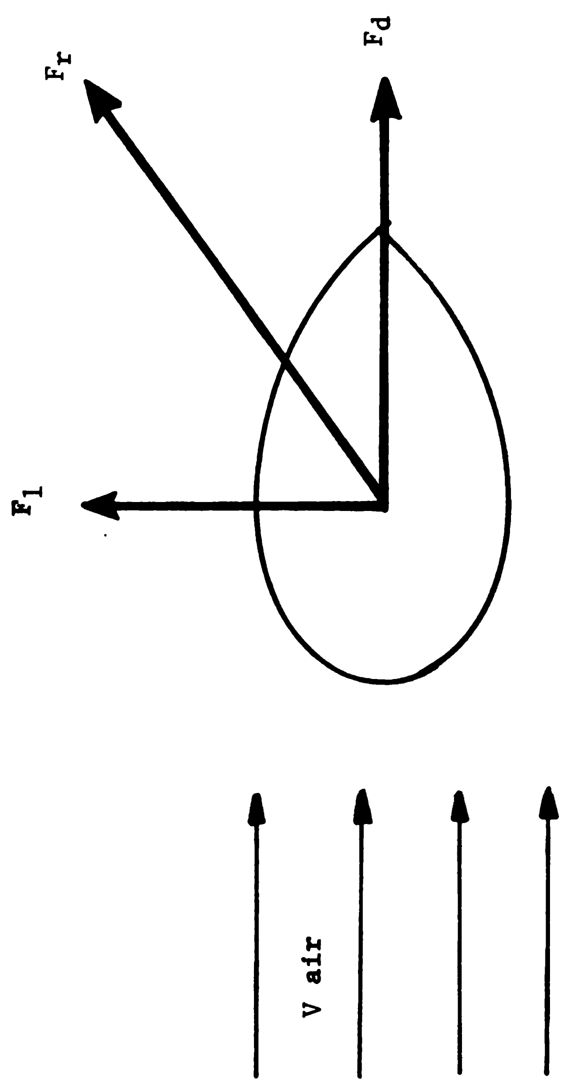
A_p = projected area normal to direction of motion (Ft.^{2})

ρf = mass density of the fluid lb-sec^2/ft-ft^3

V = relative velocity between undisturbed fluid and object (ft/sec)

Figure 1

Forces Acting on a Body in an Airstream



Terminal Velocity

Consider a particle moving in a vertical airstream. The forces acting on it are the drag force and the gravity force, and the equation of motion is:

$$M \frac{dV}{dt} = F_r - mg \qquad (4)$$

When F_r = mg the velocity difference between fluid and particle is constant and called terminal velocity V_t. From (3) and (4) it follows that:

$$Vt = \left[\frac{2W \quad (\rho p - \rho f)}{\rho p \quad \rho f \; A_p \; C} \right]^{\frac{1}{2}} \qquad (5)$$

where W is the weight and ρp is the density of the particle.

When an airstream is used for sorting purposes, the terminal velocity of the particles to be separated will determine the range of air-velocities useful for separation.

The difficulty in calculating the theoretical terminal velocity lies in obtaining reasonable values for C. For spherical and other regular shaped particles Lapple (1956) discusses how the drag coefficient is a function of the Reynolds number, and how terminal velocities can be calculated from the drag coefficient-Reynolds number relationship through a trial and error solution.

Data on drag coefficients for irregular particles are not very complete or conclusive. In some cases they are calculated by approximating the shape as a sphere using an equivalent diameter derived from the volume or from averaging the dimensions in different directions. Torobin and Gauvin (1960) give a detailed discussion of the effects of particle shape on the drag coefficient and the attempts that have been made to relate irregular shapes to spheres.

From the equation of motion (4) for an object falling in still air, the relationship between displacement, time and terminal velocity is derived as (Bilanski et. al., 1962).

$$S = \frac{Vt^2}{g} \ln \cosh \frac{g}{Vt} t \qquad (6)$$

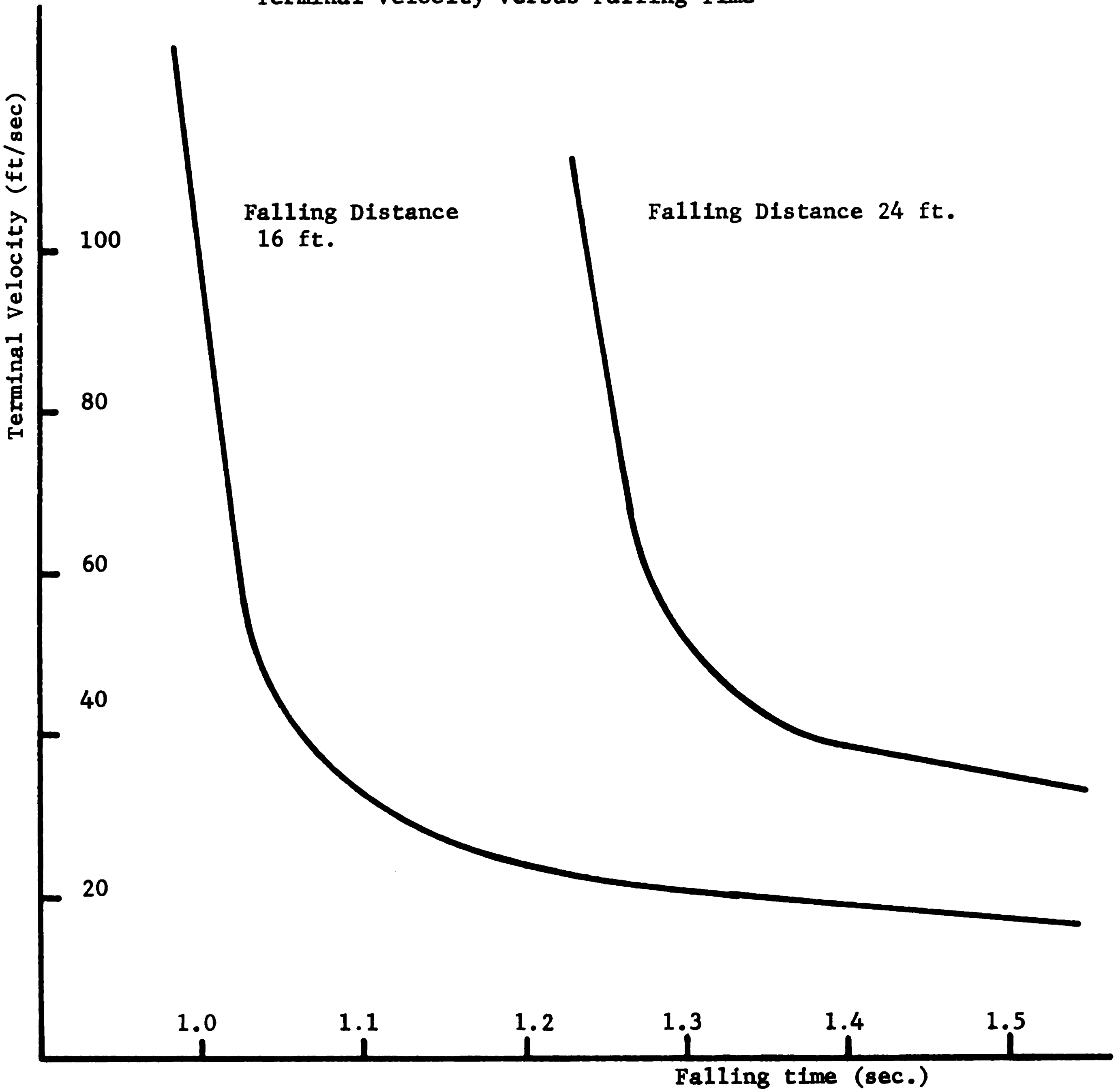
If one measures the time for an object to fall over a distance S, then the terminal velocity can be calculated from (6) or read from a terminal velocity versus falling time graph for a particular distance as in Figure 2. Figure 2 shows that the accuracy in measuring the falling time is very important for objects with high terminal velocities. Improvement could be sought from using a higher falling distance but unreasonable heights are required to obtain dependable results once the terminal velocity exceeds fifty to sixty ft/sec.

Another way to obtain more accurate values for the terminal velocity is to drop the object in an airstream opposite to the falling direction and measuring the falling time and the air velocity. The velocity calculated from equation (6) is then added to the measured air velocity to obtain the terminal velocity.

Other methods have been used to determine terminal velocities of agricultural products. Perhaps the most important is the one in which the object is floated in an airstream, the velocity of which then is measured. The main difficulty with this method is to get the object flotating because of the rotation resulting from an irregular shape.

Figure 2

Terminal Velocity Versus Falling Time



IV EXPERIMENTAL PROCEDURE

The terminal velocity of strawberries was initially determined in the dropping test and compared with the results from the flotation method. The dropping test did not give consistent values for terminal velocity because the terminal velocity of strawberries is too high. It lies in that part of the curve (Figure 2) where small time errors give large velocity variations. The dropping method was thus abandonned and terminal velocities were determined from flotation.

The equipment used to determine the terminal velocity is shown in Figure 3. It consists basically of a motor to drive the fan, a vertical cylindrical plexiglass tunnel connected to a plenum chamber which in turn was connected to the inlet of the fan. generating the airstream by aspiration. The air velocity was controlled by changing the outlet cross-sectional area of the fan. A flow straightener was mounted at the entrance of the tunnel and a wire screen was mounted about six inches above the straightener. The strawberries were placed on the wire screen at the start of the test. Higher in the tunnel was another wire screen to prevent the loss of strawberries once they were lifted. The strawberries were placed in the tunnel through an opening in the side which then was carefully closed in order to minimize any disturbance of the airstream due to leaks or surface irregularities at that place.

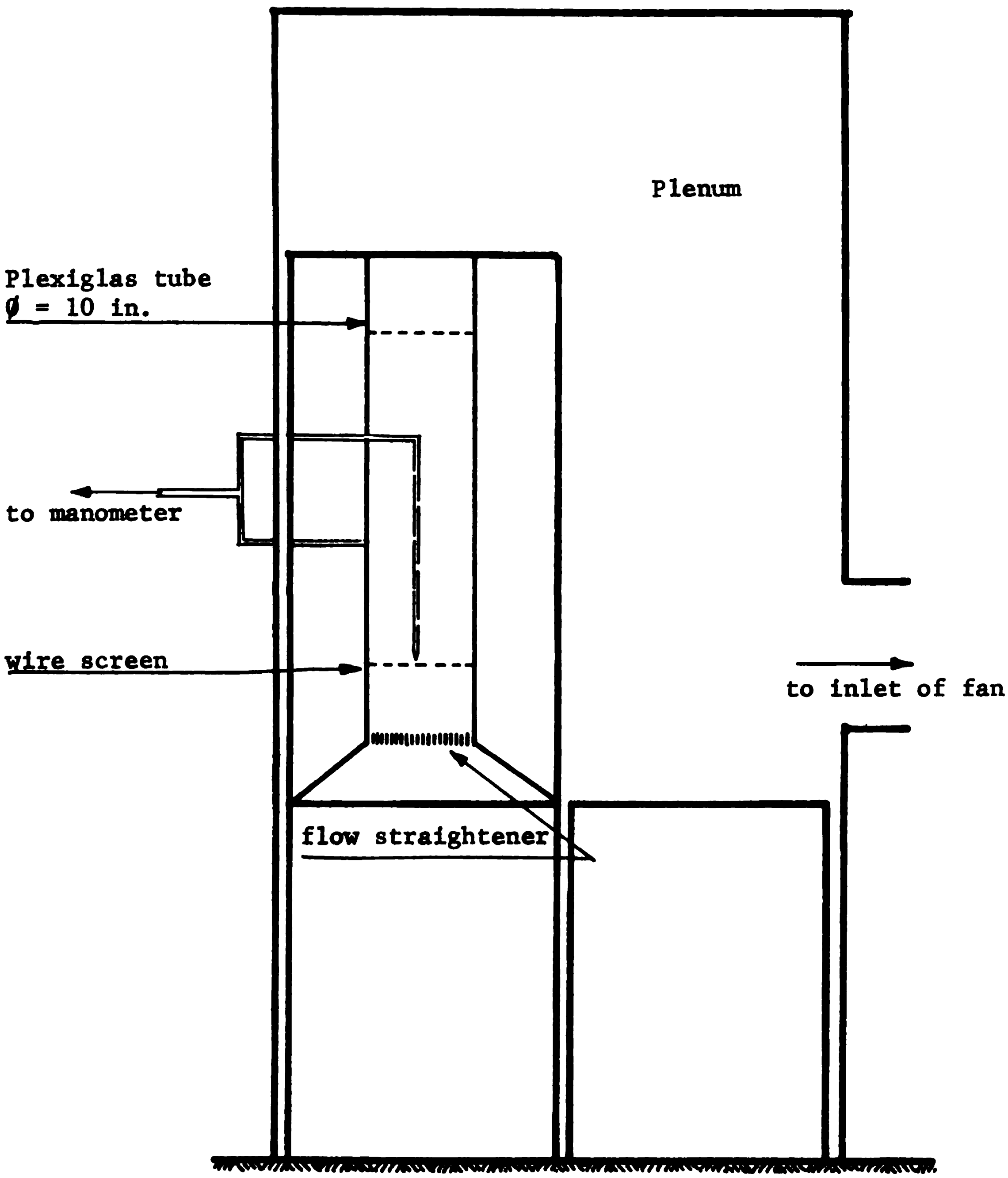


Figure 3

Aerodynamic Properties Testing Apparatus

The air velocity was calculated from static pressure readings. Therefore, a thin tube with small holes was vertically mounted in the middle of the tunnel and connected to a micromanometer in parallel with another small hole in the tunnel wall to average the static pressure in the tunnel. Pressure losses due to the straightener and the friction with the tunnel wall were neglected. The air velocity was calculated using Bernouilli's equation

$$\frac{p_o}{\gamma_{air}} + \frac{V_o^2}{2g} = \frac{p_1}{\gamma_{air}} + \frac{V_1^2}{2g} \qquad (7)$$

Where: p_o and p_1 are the static pressure outside and inside the tunnel respectively,

V_o and V_1 are the air velocities outside and inside the tunnel respectively, and

γ_{air} is the density of the air.

Since $V_o = 0$ at a distance far removed from the tunnel (7) reduces to

$$\frac{V_1^2}{2g} = \frac{p_o - p_1}{\gamma_{air}} \qquad (8)$$

The equation for the manometer reading is

$$p_o - p_1 = h\,\gamma_{fluid} \qquad (9)$$

Where: γ_{fluid} is the density of the manometer fluid and h is the manometer reading (inches). Substitution of (9) into (8) gives the flotation velocity as

$$V_1 = \sqrt{2g\,\frac{\gamma_{fluid}}{\gamma_{air}}}\,\sqrt{h} = 66.75\,\sqrt{h} \text{ ft/sec.} \qquad (10)$$

The smallest division on the manometer scale was .05 inch with possible interpolation to .01 inch.

The terminal velocity of the strawberries was determined on an individual basis. A strawberry was placed in the tunnel and the air velocity was increased until the strawberry started flotating. The manometer reading at the initial flotation was recorded.

Other physical parameters useful in classification of strawberries which were recorded are:

1. Color, five color groups visually distinguished, green, white, pink-white, pink, red.
2. Weight and volume.

   A METTLER balance type P1200 was used to measure the weight of the strawberries in air and the weight of the displaced water. The volume and specific gravity were then calculated as (Mohsenin, 1970):

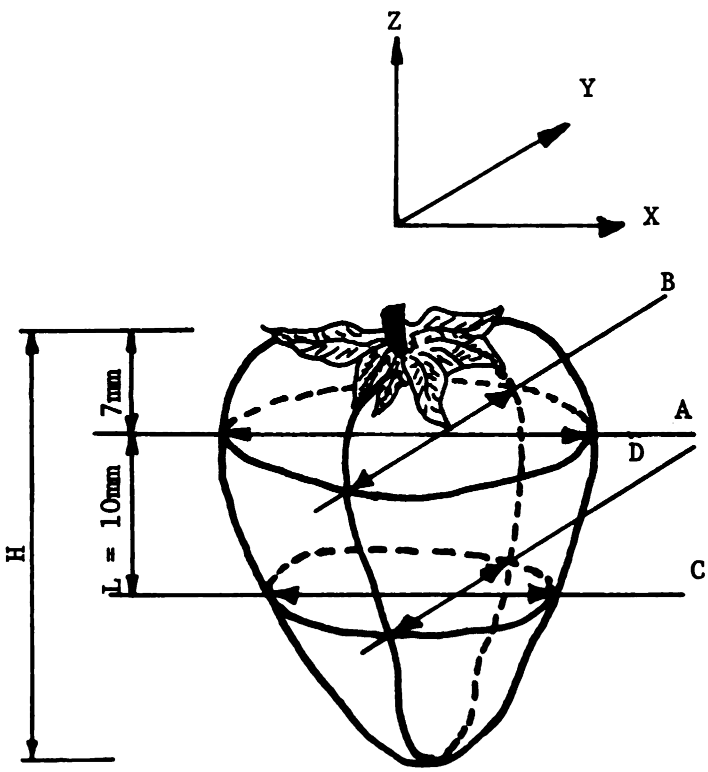
   $$\text{volume} = \frac{\text{weight of displaced water}}{\text{weight density of water}}$$

   $$\text{specific gravity} = \frac{\text{Weight in air x specific gravity of water}}{\text{weight of displaced water}}$$

   The specific gravity for each color group is given in Table 1.
3. Dimensions. The height and two orthogonal diameters at two different locations on the strawberry were measured with a caliper as indicated in Figure 5.

Figure 4

Measured Dimensions of Strawberries



V EXPERIMENTAL RESULTS AND DISCUSSION

Terminal Velocity

The terminal velocity of 568 strawberries was determined with approximately 100 strawberries in each color group. The strawberries were all of the Midway variety. Very small strawberries (less than one gram) were not included.

A statistical analysis of the data was performed using the LS-Stat routines of the Michigan State University, Agricultural Experiment Station. The first regression analysis was performed using the linear model

$$V_t = a_o + a_1 W + a_2 SG$$

Where: V_t is the terminal velocity, W is the weight of the strawberry and SG is the specific gravity.

Beta-weights of 0.707 and 0.006 were obtained for the weight and specific gravity variables respectively. (Beta-weights are used as a means of indicating the contribution of each independent variable above that accounted for by its mean). Consequently, the density was omitted in the second analysis which used a linear model

$$V_t = a + b W$$

A summary of the results for this model is given in Table 2. The equations are represented in Figure 5.

Equation (5) indicates that the terminal velocity is a function of the square root of the weight, therefore, the data were also analyzed using the model:

$$V_t = a_1 + b_1 W^{\frac{1}{2}} \qquad (11)$$

The coefficients for this model are given in Table 3. The equations for the different color groups are also shown in Figure 6. The correlation coefficients indicate that using the square root of the weight does result in a more accurate model. Also comparing the equations for each color group with the equations for the total group as in Figure 6 shows that the terminal velocity of strawberries can be satisfactorily expressed as a function of weight while disregarding the color. However, the multiple correlation coefficients of .8205 indicate that a fairly large amount of the variation of the terminal velocity is caused by factors other than the weight.

The shape of the strawberries cannot be overlooked as a factor causing the previously discussed variation in terminal velocity. Indeed, Hallee (1972) in his potato studies and Soule (1970) for blueberries found that terminal velocity can be related to the ratio weight/projected area. However, the projected area varies with orientation and with shape. Since orientation is difficult to exactly determine, the projected area was not calculated. However, some shape parameters and their variations were calculated from the dimension measurements of about 80 strawberries. The ratio of the maximum thickness in two orthogonal directions, the thickness versus height ratio and the slope of the cone are given hereafter in Table 4 (see also Figure 4). These shape

Table 1

Specific Gravity of Strawberries

Color	Specific Gravity	Standard Deviation
Green	.886	.0562
White	.898	.0409
White-Pink	.907	.0769
Pink	.918	.0367
Red	.921	.0405

variations would have to be combined with the variation in orientation to make an estimation of the projected area possible.

Another factor is the presence of the cap. How this affects the terminal velocity of different sizes of strawberries was not investigated in this experiment.

Strawberries initially laying horizontally on the wire screen slowly moved into a vertical orientation with increasing air velocity and remained in this position (Figure 7). The air velocity had to be increased by about 25 to 47 feet per second before the strawberry was lifted which happened so suddenly that no flotation could be observed. The strawberry was usually found in a horizontal position against the top wire screen. A possible explanation of this phenomenon is that as soon as the strawberry is lifted it starts rotating and assumes an orientation such that the terminal velocity is less than the actual air velocity. It was found that this problem in determining the flotation velocity could

Table 2

Regression Analysis of Terminal Velocity V_t Versus Weight W
Model $V_t = a + b W$

Color Group	No.	Weight, (Grams) Minimum	Maximum	Mean	a	b	Standard Error of a	Standard Error of b	Multiple Correlation Coefficient
Green	107	1.15	10.65	3.96	53.46	2.63	.919	.209	.775
White	98	1.85	12.32	5.50	58.01	2.35	1.166	.196	.774
White-Pink	117	1.70	14.15	6.51	59.36	2.08	1.209	.173	.754
Pink	112	2.27	15.85	7.35	62.36	1.73	1.046	.132	.781
Red	139	2.60	18.45	7.83	65.36	1.44	1.068	.123	.709
Overall	568	1.15	18.65	6.35	58.83	2.10	.475	.067	.796

Table 3

Regression Analysis of Terminal Velocity V_t Versus Weight W
Model $V_t = a_1 + b_1 W^{\frac{1}{2}}$

Color Group	No.	Weight, (Grams)			a_1	b_1	Standard Error of a_1	Standard Error of b_1	Multiple Correlation Coefficient
		Minimum	Maximum	Mean					
Green	107	1.15	10.65	3.96	62.29	11.15	1.681	.865	.789
White	98	1.85	12.32	5.50	45.22	11.19	2.110	.899	.786
White-Pink	112	1.70	16.15	6.51	46.33	10.63	2.183	.856	.764
Pink	112	2.27	15.85	7.35	69.67	9.64	1.957	.722	.786
Red	139	2.60	18.65	7.83	53.23	8.56	1.980	.709	.718
Overall	568	1.15	18.65	6.35	44.76	11.22	.828	.329	.821

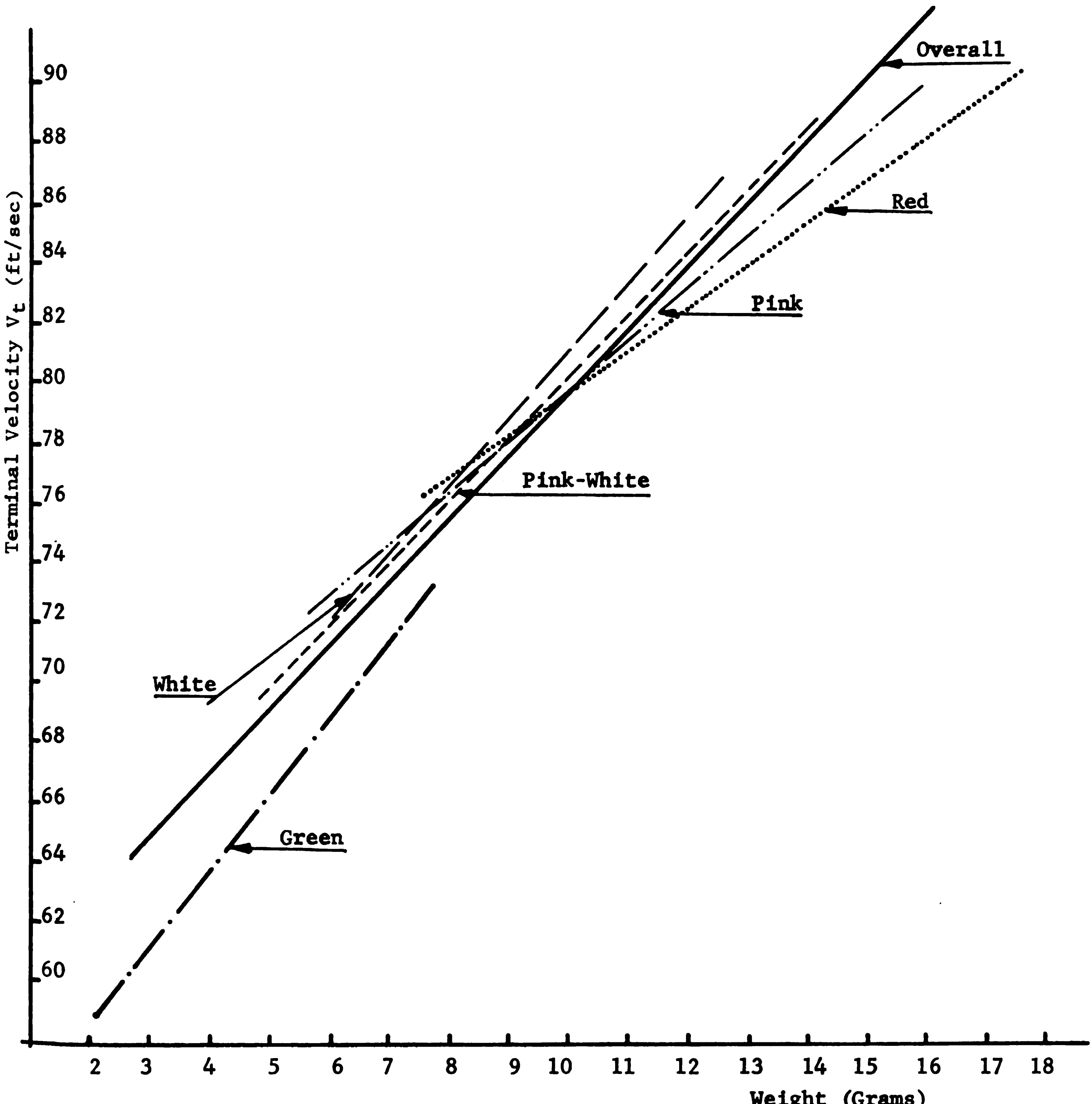


Figure 5

Terminal Velocity vs Weight: Linear Model
$V_t = a + b\,W$ for each Color Group

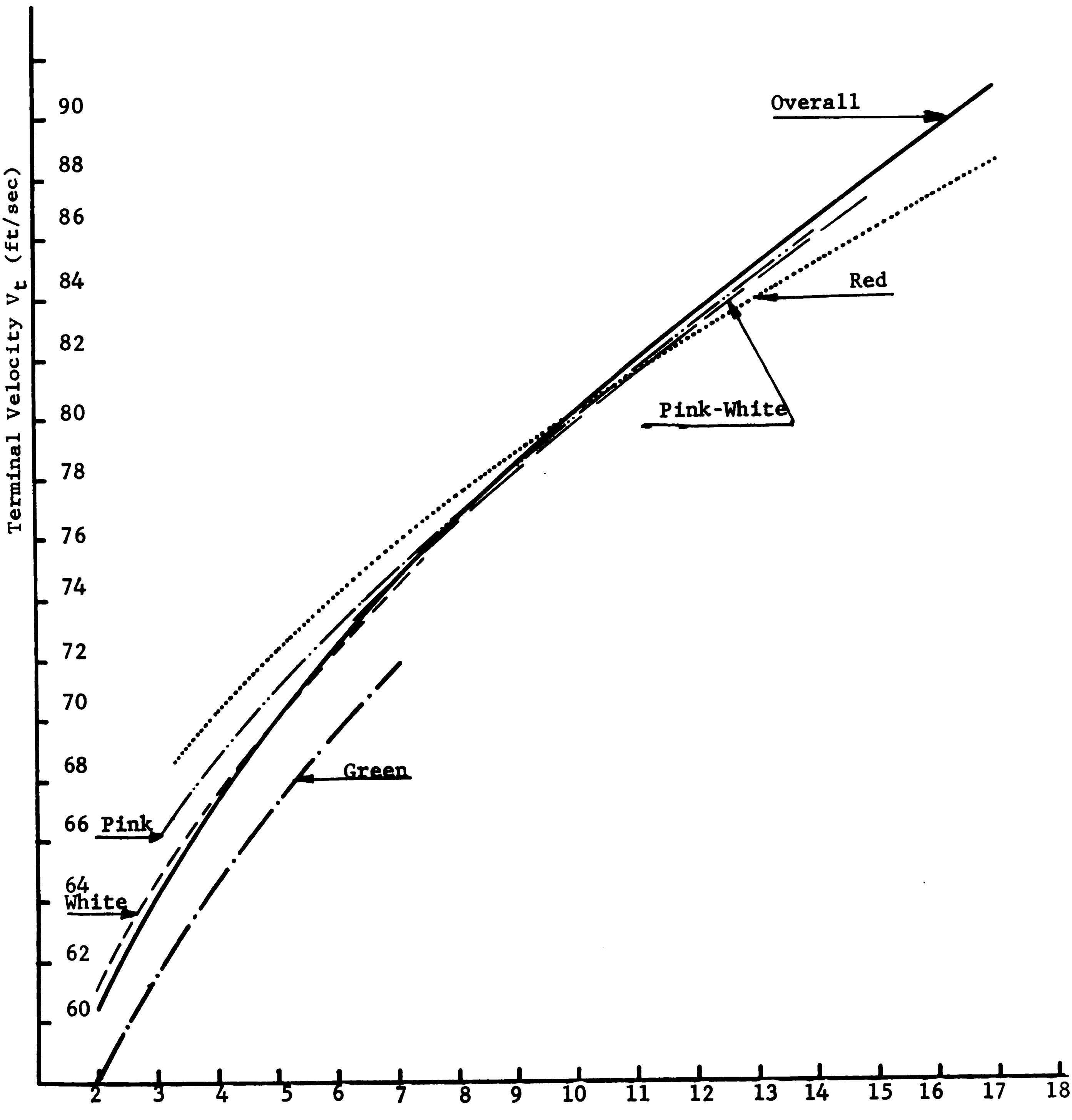


Figure 6

Linear Model $V_t = a_1 + b_1 W^{\frac{1}{2}}$ for each Color Group

Table 4

Ratio's of the Dimensions of Strawberries in Different Directions (For Symbols see Figure 5)

Ratio	Mean	Standard Deviation
$\frac{B}{A} = \frac{\text{Dmax Y}}{\text{Dmax X}}$	.928	.0693
$\frac{A}{H} = \frac{\text{Dmax X}}{H}$	.771	.0879
$\frac{A-C}{L} = \frac{\text{Dmax X-Dmin X}}{2L}$	.198	.113
$\frac{B-D}{L} = \frac{\text{Dmax Y-Dmin Y}}{2L}$	.210	.111

be overcome by slightly vibrating the tunnel such that the strawberry did not stay in the same position but was moving across the wire screen.

The orientation of a flotating strawberry varied with the shape. The more a shape approximated a sphere, the more likely the strawberry would remain vertical. With shapes approaching cones more rotation about a vertical and horizontal axis was observed, and usually the axis of the cone would make an angle with the vertical. If the cross section was not circular but elliptical it seemed that the largest diameter of the cross section was oriented normal to the direction of the airflow.

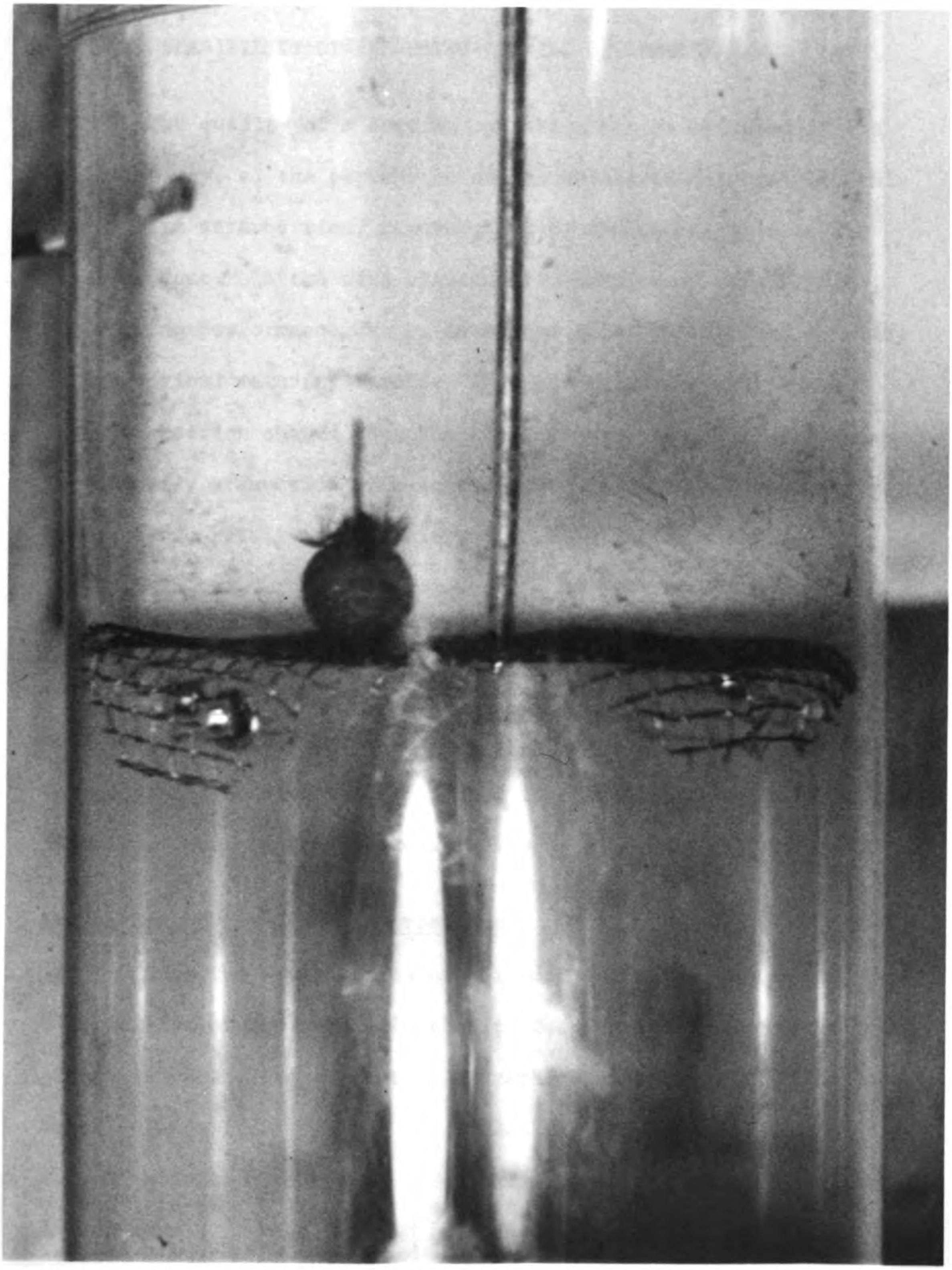


Figure 7

Strawberry Orientation before Lifting

VI FEASIBILITY OF PNEUMATIC SORTING OF STRAWBERRIES

The quality of a sorting operation can be measured in the following way, a) the percentage of the undesired material, in this case unripe strawberries, removed, and b) the composition of the final product. In the case of pneumatic sorting of strawberries, the sorting performance can be estimated from the terminal velocity of the various maturity levels. The regression analysis in the previous section showed that the terminal velocity of strawberries is primarily a function of weight. Other factors such as density, shape, etc., result in a velocity distribution for a particular weight. In this study the strawberries were divided in discrete weight groups, each covering one gram. The velocity distribution for the 4-5 gram weight group is given in Figure 8 along with the cumulative distribution. The cumulative distribution is also the percent of the weight group that is lifted at a certain velocity. Note that discrete values were also used for the velocity.

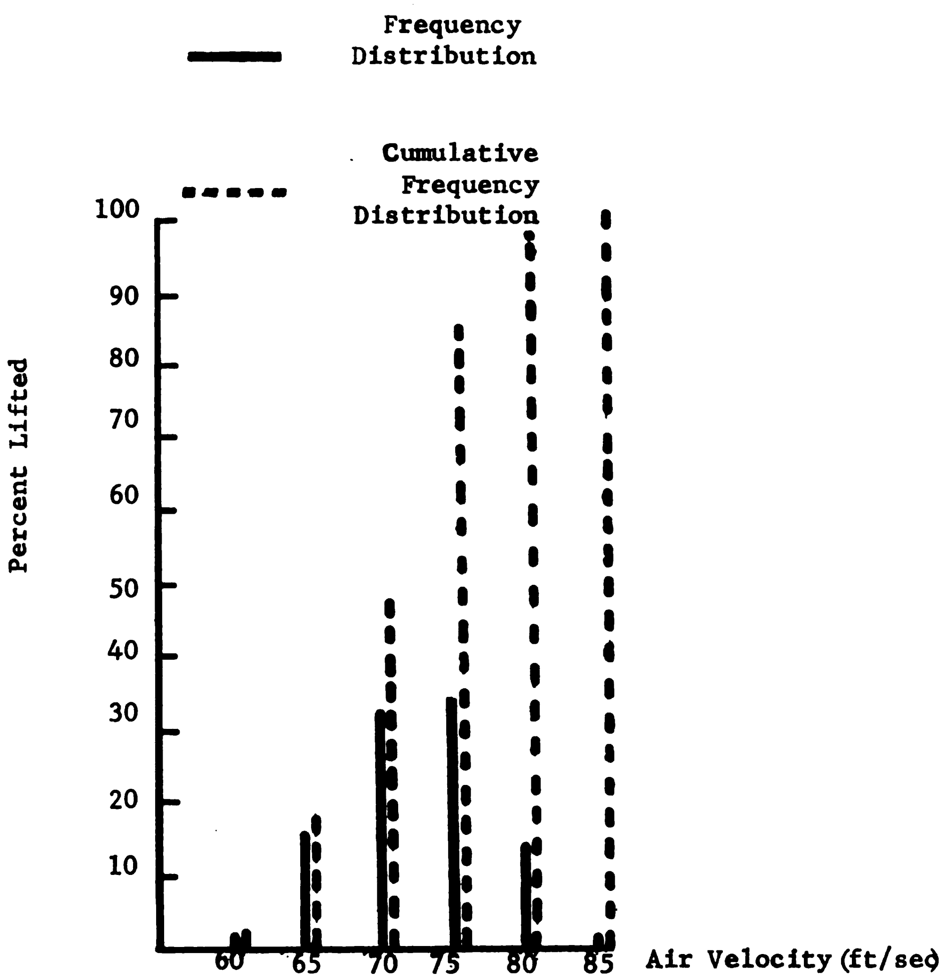
Estimation of the Removal Percentages

Once the strawberries are divided in weight groups and the distribution of the terminal velocity for the different weight groups is known, the percentage of each maturity that is lifted can be calculated from:

$$\begin{bmatrix}\text{Percent of one}\\ \text{maturity level}\\ \text{lifted at a}\\ \text{certain air}\\ \text{velocity}\end{bmatrix} = \sum_{\substack{\text{weight}\\ \text{groups}}} \begin{bmatrix}\text{Percent of the}\\ \text{maturity level}\\ \text{in each weight}\\ \text{group}\end{bmatrix} \times \begin{bmatrix}\text{Percent of that}\\ \text{weight group lifted}\\ \text{at a certain}\\ \text{velocity}\end{bmatrix}$$

Figure 8

Frequency Distribution and Cumulative Frequency Distribution of Strawberries Lifted at Different Air Velocities (4-5 gram weight group)



This can also be written in matrix notation as:

$$\{R\} = [A]\ [B]\ \{V\} \quad (12)$$

Where: $\{R\}$ gives the percentage of each color group removed at a certain velocity

$[A]$ relates the color group (rows) to the weight groups (columns) for a field sample. A coefficient a_{ij} is the percent of the i^{th} color group which fall in the weight group j. For example, if green is the first color group and 4-5 grams is the fifth weight group then a_{15} is the percent of green strawberries weighing between four and five grams.

$[B]$ contains the percentage of each weight group (rows) lifted at different air velocities (columns)

$\{V\}$ is a triggering matrix, i.e. all the coefficients are zero except the velocity under investigation which has a value of one.

The color levels used are 1=green, 2=green-white, 3=white-pink, 4=pink, and 5=ripe. The weight groups were 0-1, 1-2, etc., up through 19-20 grams.

The determination of $[A]$ and $[B]$ is discussed in detail later in this section.

The Composition of the Final Product

The maturity distribution of the final product can be estimated from:

$$\begin{bmatrix}\text{each color-}\\ \text{group in}\\ \text{percent of}\\ \text{total remaining}\\ \text{after using a}\\ \text{certain velocity}\end{bmatrix} = \frac{\displaystyle\sum_{\substack{\text{weight}\\ \text{groups}}} \begin{bmatrix}\text{Number or total}\\ \text{weight of berries}\\ \text{in a weight group}\\ \text{that have that}\\ \text{maturity}\end{bmatrix} \text{X} \begin{bmatrix}\text{Percent of}\\ \text{that weight}\\ \text{group not}\\ \text{lifted at}\\ \text{the given air}\\ \text{velocity}\end{bmatrix}}{(\text{total number or weight remaining at that velocity})}$$

This can again be written using matrix notation as:

$$\{F\} = \frac{[C]\,[M]\,\{V\}}{\sum [C]\,[M]\,\{V\}} \qquad (13)$$

Where: $\{F\}$ is the maturity distribution of the final product after passing through an airstream with a given velocity

$[C]$ contains the total number or weight of each color group in each weight group as obtained from dividing a field sample in color groups and weight groups. A coefficient c_{ij} is the number (or total weight) of the strawberries with color i that are in the j^{th} weight group.

$[M]$ contains the percentage of each weight group (rows) not lifted at different air velocities (columns). The relationship between m_{ij} and b_{ij} is

$$m_{ij} = 1 - b_{ij} \qquad (14)$$

$\{V\}$ again is the velocity triggering matrix.

Evaluation of the Removal Matrix $[B]$

The air velocities at which the sorting performance will be evaluated range from 55 ft/sec up to and including 100 ft/sec in steps of 5 ft/sec. The percentage of strawberries in each weight group that has a lifting velocity below a given air velocity was

Table 5

Sorting Matrix [B] from Experimental Data:Cumulative Percentages by Number

Weight Group (Grams)	Air Velocity in (Feet Per Second)								
	55	60	65	70	75	80	85	90	95
0-1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1-2	.333	.867	.933	.933	1.000	1.000	1.000	1.000	1.000
2-3	.058	.462	.885	.942	1.000	1.000	1.000	1.000	1.000
3-4		.077	.415	.785	.985	.935	1.000	1.000	1.000
4-5		.012	.174	.500	.849	.988	1.000	1.000	1.000
6-7			.016	.143	.698	.952	.984	.984	1.000
7-8			.014	.068	.438	.849	.973	.986	1.000
8-9				.049	.293	.707	.927	1.000	1.000
9-10				.037	.148	.593	.926	1.000	1.000
10-11				.087	.174	.522	.826	1.000	1.000
11-12						.286	.929	1.000	1.000
12-13						.200	.400	.900	1.000

Table 5 (continued)

13-14	.400	.800	1.000	1.000
14-15		0.000	.800	1.000
15-16		.200	1.000	1.000
16-17			1.000	1.000
17-18			.500	1.000
18-19			.500	1.000
19-20				1.000

Table 6

Sorting Matrix [B] from Experimental Data: Cumulative Percentages by Weight

Weight Group (Grams)	Air Velocity in (Feet Per Second) 55	60	65	70	75	80	85	90	95
0-1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1-2	.320	.860	.935	.935	1.000	1.000	1.000	1.000	1.000
2-3	.048	.442	.882	.939	1.000	1.000	1.000	1.000	1.000
3-4		.079	.410	.781	.983	.983	1.000	1.000	1.000
4-5		.012	.169	.497	.845	.987	1.000	1.000	1.000
5-6		.024	.048	.308	.788	.950	1.000	1.000	1.000
6-7			.015	.141	.697	.953	.985	.985	1.000
7-8			.013	.069	.441	.849	.974	.987	1.000
8-9				.051	.291	.710	.925	1.000	1.000
9-10				.036	.149	.593	.926	1.000	1.000
10-11				.089	.177	.522	.827	1.000	1.000
11-12						.284	.928	1.000	1.000

Table 6 (continued)

12-13	.202	.402	.900	1.000
13-14	.402	.803	1.000	1.000
14-15		0.000	.798	1.000
15-16		.196	1.000	1.000
16-17			1.000	1.000
17-18			.494	1.000
18-19			.502	1.000
19-20				1.000

Table 7

Mean and Standard Deviation of the Weight and the Terminal Velocity of the Different Weight Groups

Weight Group (Grams)	No. of Strawberries	Weight (grams) Mean	Weight (grams) Standard Deviation	Terminal Velocity Mean	Terminal Velocity Standard* Deviation
1-2	15	1.74	.236	56.72	4.939
2-3	52	2.48	.298	60.98	4.343
3-4	65	3.52	.259	65.88	4.498
4-5	86	4.49	.300	69.57	5.041
5-6	80	5.50	.275	71.60	4.941
6-7	63	6.49	.277	73.64	4.728
7-8	73	7.53	.317	75.67	4.497
8-9	61	8.55	.325	77.71	4.465
9-10	27	9.62	.298	79.33	4.015
10-11	23	10.47	.239	80.19	5.714
11-12	16	11.52	.258	81.51	2.750
12-13	10	12.69	.222	85.26	4.255
13-14	5	13.59	.284	81.55	4.330
14-15	5	14.28	.293	88.03	2.068
15-16	5	15.41	.407	86.91	1.811

*Average standard deviation for group 1-2 through 9-10 is 4.607

calculated as shown in Figure 7. These percentages are b_{ij} can be expressed either as a percent by number or as a percent by weight. Tables 5 and 6 give the coefficients of the sorting matrix as calculated from the experimental data. Table 5 gives the percentage by number while Table 6 gives the percentage by weight.

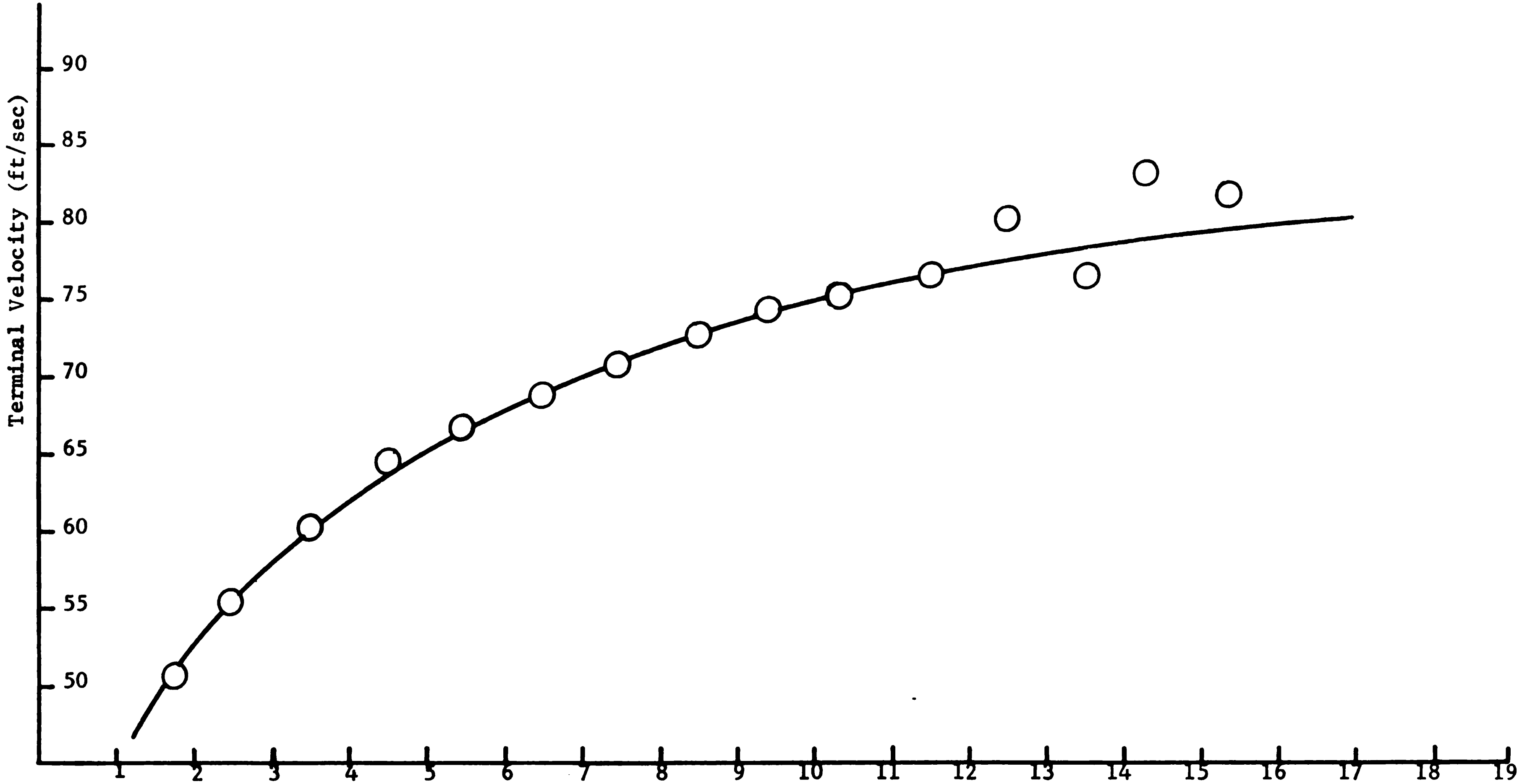


Figure 9

Terminal Velocity--Weight Relationship Obtained from the Mean of the Terminal Velocity for each Weight Group

Table 8

The Calculated Sorting Matrix $\left[B \right]$: Cumulative Percentages

Weight Group (Grams)	Terminal Velocity (feet per second)											
	55	60	65	70	75	80	85	90	95	100	105	110
0-1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1-2	.483	.851	.983	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2-3	.104	.431	.819	.970	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
3-4	.011	.115	.457	.836	.980	1.000	1.000	1.000	1.000	1.000	1.000	1.000
4-5		.023	.181	.569	.896	.990	1.000	1.000	1.000	1.000	1.000	1.000
5-6			.064	.332	.743	.958	.997	1.000	1.000	1.000	1.000	1.000
6-7			.024	.187	.577	.899	.990	1.000	1.000	1.000	1.000	1.000
7-8			.010	.104	.431	.819	.977	1.000	1.000	1.000	1.000	1.000
8-9				.057	.309	.721	.953	.997	1.000	1.000	1.000	1.000
9-10				.028	.205	.603	.911	.992	1.000	1.000	1.000	1.000
10-11				.013	.125	.474	.846	.982	1.000	1.000	1.000	1.000
11-12					.070	.348	.756	.962	.998	1.000	1.000	1.000

Table 8 (continued)

12-13	.036	.237	.644	.927	.994	1.000	1.000	1.000
13-14	.017	.149	.517	.870	.987	1.000	1.000	1.000
14-15		.086	.389	.789	.971	1.000	1.000	1.000
15-16		.045	.272	.683	.941	.996	1.000	1.000
16-17		.022	.175	.560	.892	.989	1.000	1.000
17-18		.010	.104	.431	.819	.977	1.000	1.000
18-19			.057	.309	.721	.953	.997	1.000
19-20			.028	.205	.603	.911	.992	1.000

These tables have some inaccuracies for higher weight groups due to the small number of strawberries in these groups. The terminal velocity data available for lower weight groups was used to extrapolate coefficients of the sorting matrix for the higher weight groups. The mean and the standard deviations of the weight and of the terminal velocity V_t for each weight group was calculated (Table 7). A graph of the terminal velocity versus weight was plotted using the calculated means (Figure 9). The terminal velocity for the midpoint of each weight group was determined from Figure 9. The standard deviation of the velocity in each weight group was assumed equal to the average standard deviations for the weight groups one through nine. Cumulative distributions at the air velocities previously mentioned were calculated from the normal distribution of the terminal velocity of a weight group. Table 8 gives the results of these calculations which are also the coefficients b_{ij} of the removal matrix $[B]$. For example, 12.5 percent of the strawberries weighing between 10 and 11 grams are removed by a lifting velocity of 75 feet/second. Since $[B]$, Table 8 is based on the midpoint value of the weight groups, the coefficients are both a percentage by number and a percentage by weight. Therefore, $[B]$ can be used in calculating removal both by number and by weight.

<u>The Field Data</u>

A sample of machine harvested strawberries was divided into color groups and each individual strawberry was weighed. The matricies $[C_n]$ and $[C_w]$ were obtained, where the subscripts n and w indicate that the coefficients c_{ij} are the total number or total weight in the color group i and weight group j. The weight distributions per color group, c_{ij}, were calculated in percentages both by count and by weight giving the matrices $\left[A_n\right]$ and $\left[A_w\right]$, where the subscripts n and w indicate that a_{ij} are percentages by count and by weight respectively. The matrices $\left[A_n\right]$ and $\left[A_w\right]$ are given in Tables 9 and 10. For clarification, a_{15} in Table 9 is the percent (10.3) by number of the greens in the 4-5 gram weight group while a_{15} in Table 10 is the percent (15.9) by weight of the greens in the 405 gram weight group. The matrices $\left[C_n\right]$ and $\left[C_w\right]$ are shown in Tables 11 and 12.

Results

Tables 13 and 14 summarize the results of the estimation of the percent of material removed in an airstream and the composition of the final product. Tables 13 and 14 are in percentages by number. Tables 15 and 16 are in percentage by weight.

The initial composition of the field sample was, in percentages by number; 47.7 green, 12.6 white-pink, 9.2 pink, and 30.5 ripe. After using an airstream with a velocity of 70 ft/sec, the composition of the remaining product, Table 14 is 16.3 percent green, 17.1 percent white-pink, 12.2 percent pink and 54.4 percent ripe. Table 12 shows that in this sorting process 85.5 percent of the greens were removed but also 26.3 percent of the ripe strawberries were lost. Sorting performances by weight are shown in Tables 15 and 16.

It is clear that both Tables 13 and 14, or 15 and 16 are necessary to evaluate a sorting performance. They show that

Table 9

Weight Distribution Per Color Group of a Field Sample:
Matrix $[A_n]$ (Percentages by Number)

Color Group	Weight Groups (Grams)																			
	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20
Green	.071	.271	.245	.239	.103	.032	.032		.006											
White-Pink		.166		.122	.146	.166	.098	.220	.073	.024			.024							
Pink			.200	.067	.100	.300	.133	.033	.067			.100								
Red		.020	.020	.091	.101	.091	.121	.081	.101	.081	.051	.091	.030	.030	.020	.010	.010	.020		.030

Table 10

Weight Distribution Per Color Group of a Field Sample:
Matrix $[A_W]$ (Percentages by Weight)

Color Group	Weight Group (Grams) 0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20
Green	.021	.169	.223	.293	.159	.063	.072		.019											
White-Pink		.038		.078	.119	.150	.116	.292	.111	.063			.055							
Pink			.093	.062	.080	.282	.155	.065	.098			.203								
Red		.005	.006	.037	.055	.060	.094	.073	.105	.092	.064	.126	.046	.050	.035	.018	.020	.042		.071

Table 11

Field Sample Divided into Weight and Color Groups by Number: Matrix $\left[C_n\right]$

Color Group	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20
Green	11	62	38	37	16	5	5		1											
White-Pink		6		5	6	6	4	9	3	1			1							
Pink			6	2	3	9	6	1	2			3								
Red		2	2	9	10	9	12	8	10	8	5	9	3	3	2	1	1	2		3

Table 12

Field Sample Divided into Weight and Color Groups
by Weight: Matrix $[C_w]$

Color	Weight Group (Grams)																			
Group	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20
Green	9.18	64.44	96.81	127.0	69.13	27.41	31.33		8.20											
White-Pink		8.63		17.61	26.83	33.86	25.89	66.14	25.01	9.80			12.42							
Pink			16.01	7.22	13.72	48.37	26.50	7.78	16.83			34.81								
Red		3.89	5.11	30.8	45.47	49.13	77.37	59.95	86.50	75.32	52.30	103.78	38.19	60.83	29.02	15.03	16.20	34.94		58.48

Table 13

Strawberries of each Color Group Sorted out at Different Air Velocities (Percentage by Number)

Air Velocity (ft/sec)	Green	White-Pink	Pink	Red
55	.230	.072	.022	.013
60	.437	.142	.096	.039
65	.669	.240	.235	.106
70	.855	.426	.438	.243
75	.958	.685	.697	.454
80	.993	.894	.883	.685
85	.999	.979	.969	.854
90	1.000	1.000	1.000	.941
95	1.000	1.000	1.000	.981
100	1.000	1.000	1.000	.997
105	1.000	1.000	1.000	1.000

Table 14

Composition of the Final Product after Using an Airstream at Different Velocities (Percentages by Number)

Air Velocity (ft/sec)	Green	White-Pink	Pink	Red
55	.420	.134	.103	.344
60	.356	.144	.111	.389
65	.265	.161	.118	.456
70	.163	.171	.122	.544
75	.079	.156	.110	.655
80	.029	.108	.887	.776
85	.007	.052	.056	.885
90	.000	.015	.020	.965
95	0.000	.003	.003	.994
100	0.000	0.000	0.000	1.000
105	0.000	0.000	0.000	1.000

Table 15

Strawberries of each Color Group Sorted out at Different Air Velocities (Percentages by Weight)

Air Velocity (ft/sec)	Green	White-Pink	Pink	Red
55	.119	.019	.010	.003
60	.282	.044	.047	.012
65	.519	.110	.133	.044
70	.758	.280	.305	.128
75	.918	.569	.570	.298
80	.983	.838	.804	.533
85	.998	.963	.942	.745
90	1.000	.995	.992	.881
95	1.000	1.000	1.000	.959
100	1.000	1.000	1.000	.992
105	1.000	1.000	1.000	.999
110	1.000	1.000	1.000	1.000

Table 16

Composition of the Final Product after Using an Airstream at Different Velocities (Percentage by Weight)

Air Velocity (ft/sec)	Green	White-Pink	Pink	Red
55	.240	.139	.106	.515
60	.207	.144	.109	.540
65	.155	.150	.110	.585
70	.095	.148	.108	.649
75	.046	.124	.094	.736
80	.016	.079	.073	.832
85	.003	.036	.043	.917
90		.011	.014	.976
95		.002	.002	.996
100				1.000
105				1.000
110				0.000
Initial Composition	.262	.137	.104	.497

sorting of the machine harvested strawberries under investigation is not possible without the loss of the major part of the ripe strawberries. However, these results depend on the actual maturity stage of the strawberries, the uniformity of ripening. This information would be required for determining the optimum time for machine harvesting as well as for estimating the pneumatic sorting performance.

The sorting matrix $\left[B\right]$ in Table 8 gives the percentages of each weight group lifted at different air velocities. The obtained results are an estimation of the size of strawberries that are sorted out. The decision to work with a certain air velocity depends upon how desirable small ripe strawberries are and what labor is required to remove remaining bigger green strawberries.

VII CONCLUSIONS

The objectives of this study were to obtain information on aerodynamic properties of strawberries and to investigate the feasibility of pneumatic sorting. The conclusions are:

1. The terminal velocity V_t of strawberries is primarily a function of the square root of the weight W. Terminal velocity and weight can be related by a regression equation of the form $V_t = 44.74 + 11.22\ (W)^{\frac{1}{2}}$.
2. There is no indication that green and red strawberries with the same weight have different terminal velocities.
3. The feasibility of pneumatic sorting is highly dependent upon the color and weight distribution of the strawberries in the machine harvested product. Since the probability of having only small green and large red strawberries is low, complete sorting of the color groups is unlikely.
4. It was observed that some strawberries can be oriented in an airstream before they are lifted. These strawberries generally were conical in shape.

SUGGESTIONS FOR FURTHER WORK

1. The terminal velocity was determined for each strawberry individually. It would be desirable to know how strawberries behave in a group and if the sorting performance would be the same.
2. Information on how the shape of strawberries changes with maturity could improve the sorting matrix since the shape affects the range of the terminal velocity in a specific weight group.
3. The influence of the cap on the terminal velocity of different sizes of strawberries and the behavior of strawberries still in a cluster needs attention.
4. Information is needed on how color and weight distribution in the field evolves during the ripening and how this is reflected in the machine harvested product.

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