THE EFFECT OF PARTICLE SIZE, SHAPE AND DENSITY ON MINIMUM PNEUMATIC SUSPENSION AND VERTICAL TRANSPORT VELOCITIES

Thesis for the Degree of Ph. D.
MICHIGAN STATE UNIVERSITY

Charles Erskine Rice

1960

This is to certify that the

thesis entitled

THE EFFECT OF PARTICLE SIZE, SHAPE AND DENSITY ON MINIMUM PNEUMATIC SUSPENSION AND VERTICAL TRANSPORT VELOCITIES

presented by

Charles Erskin Rice

has been accepted towards fulfillment of the requirements for

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Wesley F. Buchele
Major professor

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THE EFFECT OF PARTICLE SIZE, SHAPE AND DENSITY ON MINIMUM PNEUMATIC SUSPENSION AND VERTICAL TRANSPORT VELOCITIES

By

Charles Erskine Rice

AN ABSTRACT

Submitted to the School for Advanced Graduate Studies
of Michigan State University of Agriculture and
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1960

Approved Wesley F. Buchele

Fundamental information concerning the preparation of materials for pneumatic conveying has been developed during the course of the research upon which this thesis is based. Studies were made to determine the influence of size, shape and density on suspension and minimum transport velocities. Cylindrical, rectangular and equilateral triangular wooden blocks and plastic cubes were used.

The required air velocities for suspension and vertical transport were determined experimentally and showed the affects of size, shape and density. The particles with dimensions closely approaching a sphere or cube required the greatest velocity. The longer particles and thinner discs required less velocity for both suspension and minimum transport. When the maximum projected area was plotted against the ratio of $\frac{\text{area}}{\text{volume}}$, the maximum required suspension and transport velocities occurred where the line became horizontal. This was confirmed by plotting $\frac{\text{maximum projected area}}{\text{volume}}$, against the ratio of $\frac{\text{area}}{\text{volume}}$, and the maximum velocity occurred where the line turned upward.

The aerodynamic theory of the movement of a particle in a fluid was used to give the formula for determination of the velocities. The lack of information of the drag coefficient "C" (that must be used) limits the use of this formula.

Charles Erskine Rice

Formulas were developed for determining "K" for use in the velocity formula. The "K" value is used in place of the drag coefficient "C". Particle properties were used for the determination of "K".

The formulas are valid for the particles tested when the transport velocities are between 1000 feet per minute and 4000 feet per minute.

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The author expresses most sincere appreciation to these individuals and organizations and to all others who assisted in any way.

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VITA

Charles Erskine Rice

candidate for the degree of

Doctor of Philosophy

Final Examination: March 10, 1960 - 8:30 A.M. Room 218
Agricultural Engineering Building

Dissertation: The Effect of Particle Size, Shape and Density on Minimum Pneumatic Suspension and Vertical Transport Velocities.

Outline of Studies

Major Subject: Agricultural Engineering
Minor Subjects: Mechanical Engineering, Mathematics

Biographical Items

Born: March 10, 1917, Colquitt County, Georgia

Undergraduate Studies: University of Georgia 1935-1939

Graduate Studies: Iowa State College, 1939-1940

Michigan State University, 1954-1960

Experience: Agricultural Engineer, Soil Conservation Service, 1941-1942, 1946-1947.

United States Army, 1942-1945.

University of Georgia, 1947. Associate Professor and Associate Agricultural Engineer.

Member of the American Society of Agricultural Engineers.

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INTRODUCTION

Fifty percent of the agricultural man hours are employed around the farmstead in the form of chore labor. This total of approximately 8 1/2 billion man hours per year is used to a great extent in moving materials from one place to another, *i.e.*, from mill to bin, from bin to bunk. For example, 300 million tons of materials are handled by farmers every year, and this is further accentuated since some of the materials are handled several times.

This study deals primarily with those principles which use air to elevate and convey. It is known that materials can be moved at lower operating cost with other mechanical devices, however, the ease of operation and simplicity of installation have made pneumatic conveying a popular means of elevating silage, chopped hay, and grain when product damage is not of major importance.

The generally accepted pneumatic conveying rate is 50 fps (3,000 fpm) (13). In the case of vertical elevation the required air velocity must be sufficient to support the particle plus 50 fps.

The present procedure in calculating the design parameters for a pneumatic conveying system is to use handbook data collected on working systems. Usually, no allowances are made for the size and shape of the particles to be conveyed since, at the present time, no procedure has been developed to easily calculate these values. As a result conveying systems tend to be over designed. The power requirements of the conveying system could be reduced if the processing of the material permitted the selection of the size and shape of the particles.

This thesis will present methods for the determination of minimum suspension and minimum vertical transport velocities of particles. The relationship of the particle size, shape, density and the minimum velocities will be explored. Aerodynamic theory will be presented and constants determined for the critical velocities. Practical application for the formulas will be demonstrated.

REVIEW OF LITERATURE

The early work concerning pneumatic transport was conducted on silage cutters which not only cut the silage but also elevated it into the silo. In 1921 the American Society of Agricultural Engineers' Belt Machinery committee (18) suggested the following formula for rating silage cutters:

$$(1) \quad \text{Tons per hour} = \frac{\text{throat area in}^2 \times \text{cuts per min.}}{10,000}$$

The committee also standardized the silage cutter tests.

Duffee (6, 7, 8) reported on testing the efficiency of silage cutters in 1924. He found that the power requirements were 0.328 hp/ton for cutting and 0.830 hp/ton for blowing. The power for blowing was 71.72% of the total. The relationship between RPM and power requirements indicated that speeds between 500 to 600 RPM gave capacities comparable with higher speeds and required less horsepower. In his report in 1925 Duffee presented a new formula for rating silage cutters. He also studied pressures found at the bottom of the elevation pipe. In the comparison of large and small pipes it was found that, in general, horsepower requirements increased with a decrease in pipe size. For the relationship of speed and efficiency it was observed that capacity is proportional to speed and that the horsepower curve is more abrupt than the capacity curve.

In 1928, Stewart (16) calculated the volume of the pipe occupied by silage at different speeds and developed a drawing showing the results of his analysis.

In 1946 Raney (14) suggested the theory of free throw for silage blowers.

In 1949, Longhouse (11) reported on the performance characteristics of long hay blowers. He found that the fan inlet size was very important. When it is too large, efficiency is reduced and when it is too small, not enough air can enter the inlet. He also reported that the shaft horsepower varies as the cube of the speed, and that peripheral speeds of 10,000 feet per minute are needed.

In 1950 Longhouse (12) reported on the application of fluidization to the conveying of grain. He conveyed grain in a one-inch pipe seventy-five feet long. Conclusions reached as a result of the fluidization studies are as follows: 1. Grain either whole or ground can be conveyed satisfactorily as a fluid, 2. convenience and ease of operation favor fluidization, and 3. initial cost and maintenance should not be excessive.

In his text book Bainer, et al (2) gives information on the theory of the impeller blower presented by Segler.

Segler states that the material has a lower velocity than the air in the upper portion of the pipe and a greater velocity as it leaves the blades.

Raney (14) has reported that paddles loaded for a distance equal to 1/4 the radius will unload in 45°, and those loaded for a distance equal to 1/3 the radius will unload in 55°.

Duffee (9) reported that normally only 2½ to 3 inches of blade was used, and that less power was required by 4 inch blades than by 8 and 10 inch blades. Berge (1) reported that 5 inches of the blade was scored, and that the blades were unloaded at an angle of 45° with the tangent point.

Theoretically, elevation efficiency depends upon kinetic energy imparted to the particle in the cases of the impeller blower i.e., $h = \frac{V^2}{2g}$. The height elevated is always less because of friction in its various forms. Duffee (9) has stated that the power would double when the elevation height is increased from 30 feet to 100 feet. De Forest (4) worked with 4 and 8 bladed impellers and the kinetic energy imparted to the material. The kinetic energy imparted by the 8 blade impellers was 43% of input with an efficiency of 17.2%. The 4 blade impellers imparted 57% of the input with an efficiency of 22.8%.

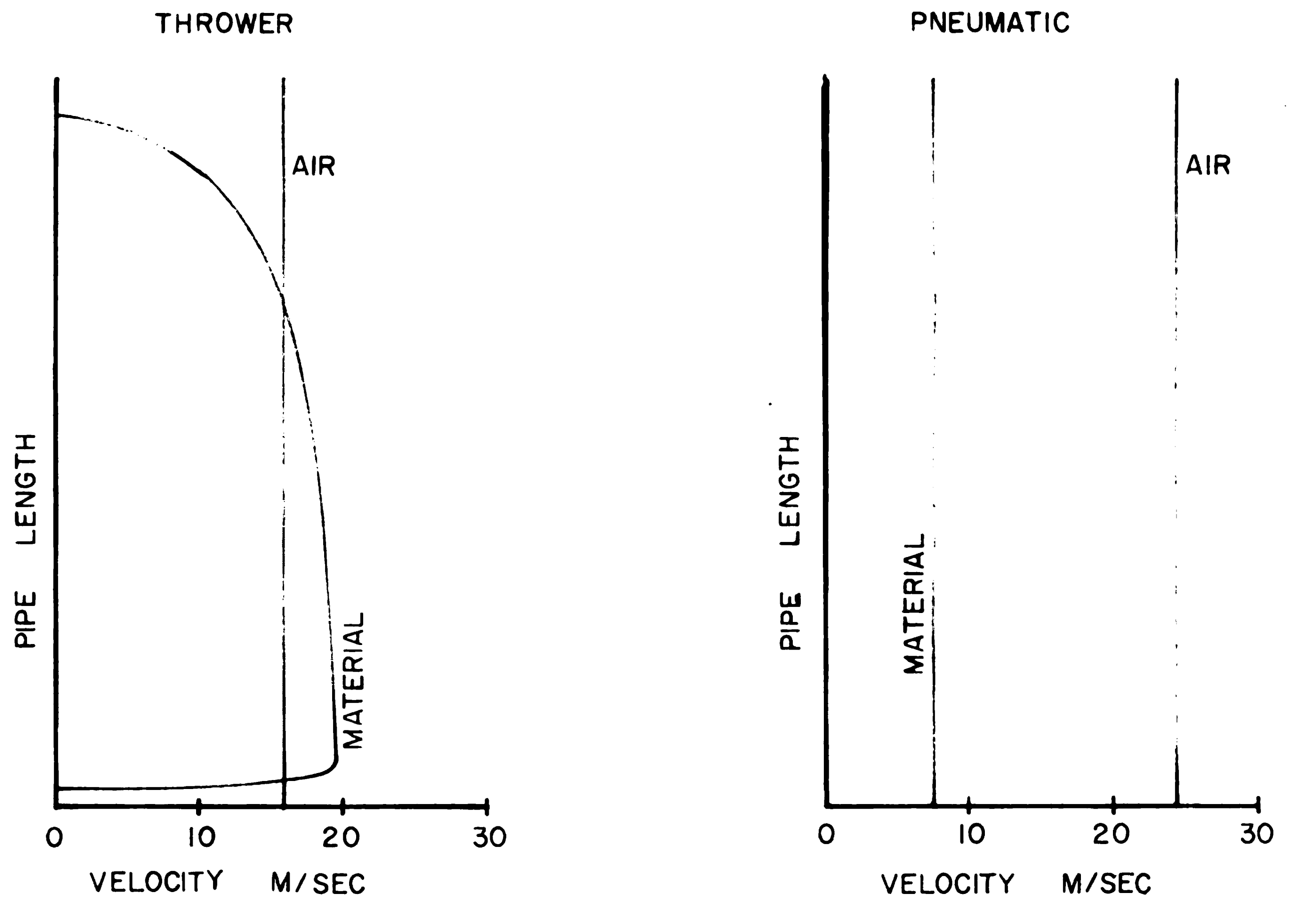
The actual height that blowers should be operated is 40% of theoretical height according to Duffee (9). They are often operated, however, at lower percentages of the theoretical height. Power operation data normally used for impeller-blowers indicate that most of them operate with efficiencies running from 5 to 10 percent (14).

Segler (14) has done considerable work on pneumatic conveying and on impeller blowers. He states that there is not sufficient experimentally determined data available for determining the coefficient for chaff and chopped straw conveying. Segler recommends an elbow of 8 diameters for conveying, and the use of a diffuser which gave a 10% capacity increase.

Henderson (5) gives the methods for injection of material into pneumatic conveying systems such as the bucket wheel, screw and the injector. To these can be added the direct entrance into the fan housing. The bucket wheel can be used for higher pressures than the screw. The bucket wheel and screw both give excellent air flow efficiencies of approximately 100% because of very low pressure loss. The injector intake which operates on the principle of the injector pump is of simple design and is suited for the entrance of most materials. The air stream coming from the blower is restricted in the nozzle and transferred to a high velocity. The resulting velocity pressure in the conical expansion is transferred into static pressure.

Segler (13) has shown that in an impeller blower, the material velocity is greater than the air velocity during the first part of movement and that its velocity drops below the air velocity very rapidly towards the final part of movement (Figure 1). The material velocity is always below the air velocity in a pneumatic system.

The Buffalo Forge Company (13) has published data



AIR AND MATERIAL VELOCITY IN THE CASE
OF THROWER AND PNEUMATIC CONVEYORS

Figure 1. Air and material velocity in the case of thrower and pneumatic conveyors.

on generally used conveying air velocities. These are shown in Table 1.

The Buffalo Forge Company (13) uses an expression developed from tests by M. Gasterstedt to determine the pressure loss resulting from the pressure of material in the air stream. They use a vertical resistance twice that for horizontal movement for moderate lifts (approximately fifty feet or less).

The energy required to accelerate the material from zero to the conveying velocity is significant. The pressure loss resulting from the introduction of the materials into the stream of moving air may be estimated by the following expression:

(2) $A = 2.25\ RP_V$

A = Pressure loss, inches of water

R = Ratio, pounds material per pound air

P_V = Velocity pressure, moving air

Crane (3) developed theoretical equations for determining pressure drops in a pneumatic system conveying solids in a straight section of pipe under steady state conditions. Friction factors for air and the solid and the design specification are required for the solution of these equations which were verified by experimental work. Some of the conclusions Crane drew from his work are:

1. Pressure drop due to solids increase as pipe

TABLE 1

AIR VELOCITY FOR CONVEYING MATERIALS

Materials	Feet per Minute
Castor beans	5000
Corn	5600
Cotton	4500
Oats	4500
Paper	5000
Rags	4500
Sand	7000
Sawdust	3000
Shavings	3500
Wheat	5600
Wool	5000
Vegetable pulp dry	4500

inclination increased.

2. Pressure drop due to solids increased as air velocity decreased and the pipe angle increased.

3. Pressure drop due to the solids increased as flow rate increased for any given air velocity and pipe inclination.

The horsepower required for conveying with both impeller and pneumatic systems has been determined by many research workers. They also studied pressure drop in conveying systems. This literature survey revealed little information concerning the effect of size and shape of the material being conveyed upon horsepower and efficiency of the system.

OBJECTIVES

The Review of Literature has shown considerable work on total power required for handling forages by the use of blowers. Little work appears to have been done on the effect of particle size, shape and density on required suspension, lifting and transporting velocities. The objectives of this study are as follows:

1. Determine the effect of size, shape and density upon the velocity required to suspend the particle.
2. Determine the effect of size, shape and density on the minimum transport velocity 50 fps.
3. Apply the aerodynamic mathematical theory of particles suspended in a moving fluid to determine velocities.
4. Develop equations for the calculations of constants which can be used in the theoretically developed equation for determination of minimum suspension velocities, and minimum transport velocities.

EQUIPMENT

The study required the development of experimental equipment and the assembling of standard test equipment.

Development of Variable-Area Meter

A device was needed to determine the air velocity required to suspend a particle in space with only an air stream opposing the forces of gravity. Commercial equipment available did not have the required characteristics. The requirements set up for this equipment were as follows:

1. It should permit use of a range of air velocities at any one time.
2. It should be transparent to permit observation of the action of the particle.
3. The diameter should be comparable to pipe diameter used in pneumatic conveying.

The variable-area meter (Figures 2, 3 and 4) were designed and constructed to permit measuring of the air velocity required to suspend or float a particle. The tapered portion is 30 inches long, 3 inches in diameter at the small end and 4 inches at the large end. Several additional feet of plastic tubing were used to convey the air. The air was introduced at the small end. This resulted in decreasing air velocities as it approached the large end. The tapered portion was constructed by heating the plastic tubing in oil and stretching over a turned wood form. Since the form had

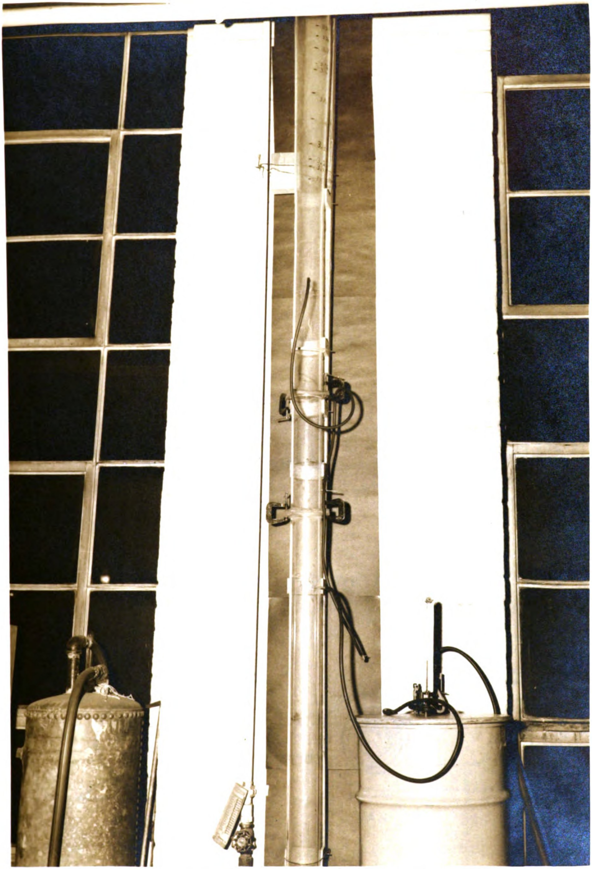


Figure 2. Apparatus used in determining suspension velocitie

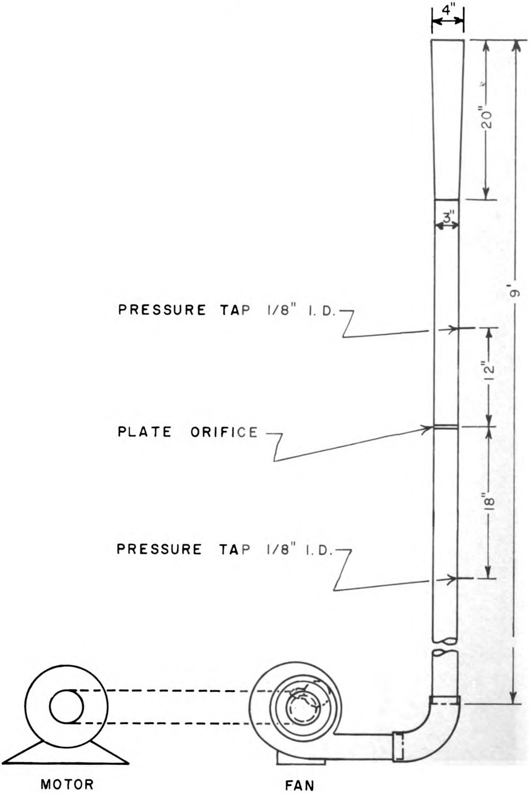


Figure 3. Variable-area Meter.

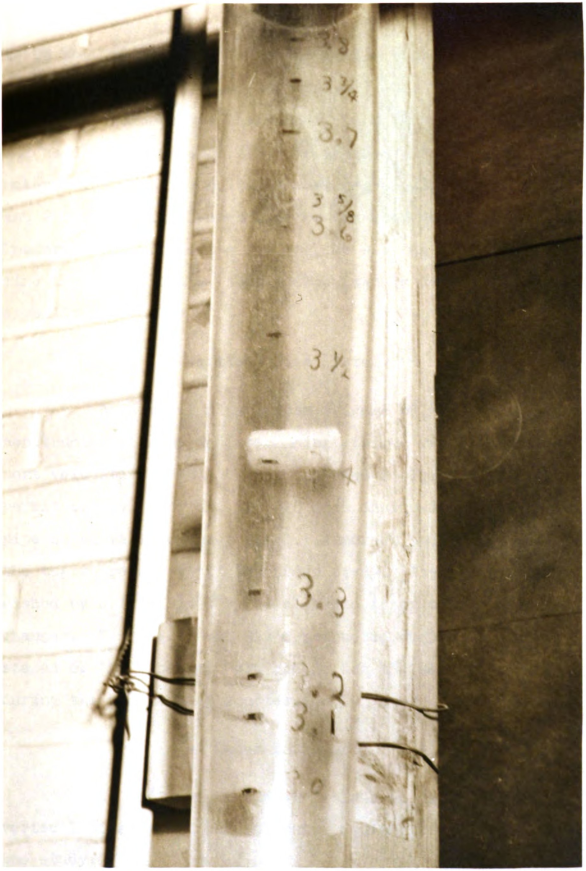


Figure 4. View of rotometer with a cylindrical particle suspended.

to be removed before the plastic cooled there were slight variations in the tapered sections.

Square edged orifices (Figure 5) were constructed and used in the plastic air line ahead of the variable-area meter. The diameter of the square edged orifices were $1\frac{1}{2}$ and 2 inches. The 2-inch orifice was used during the tests. The pressure drop across the orifice was measured to determine the air velocity. The method used is set forth in the appendix.

Vertical Pipe System

A vertical pipe system (Figure 6) was designed and constructed for use in determining minimum vertical transport velocities. This system included a plastic section, to permit observation, and a 3 7/8 inch inside diameter vertical pipe of galvanized sheet metal. A screen spout was used on the top to return particles under study. The air was furnished by a fan driven by an electric motor through a speed changer. This equipment was constructed during the final stages of the research work and is not the same as was used during the preliminary studies.

Other Equipment

In addition to the variable-area meter, and the vertical pipe system the following equipment were used in the study:

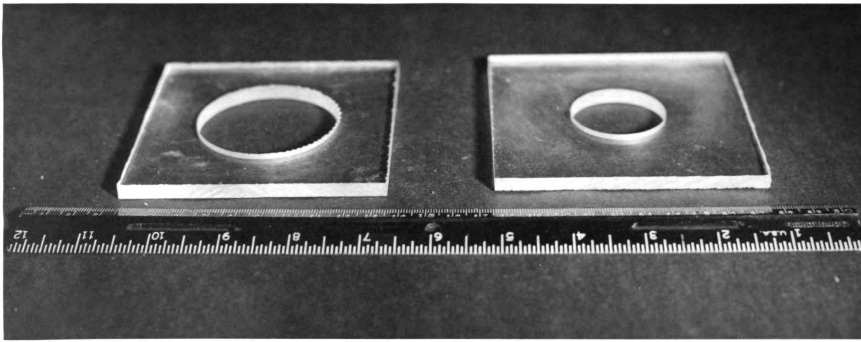


Figure 5. Two of the square edged orifice plates used in measuring air.

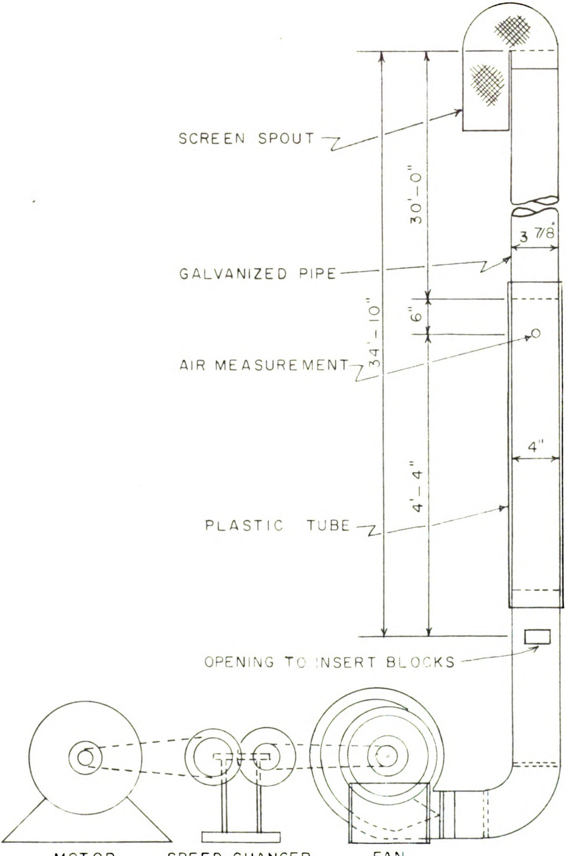


Figure 6. Apparatus used in making minimum transport velocity determinations.

a. Manometer. Micro-Manometer.

b. Hot wire anemometer. Anemotherm Air Meter Model 60.

c. Blower. Buffalo Forge #22, Buffalo Forge Co., Buffalo, New York.

d. Pitot Tube.

SELECTION OF MATERIALS

Several types of materials were tested before the materials used in the experiment were selected. Soft material such as corn pith broke down rapidly, and was not suited for repeated tests using the same particles. The following five types of wood and plastic particles were selected for use in the tests:

1. Wood cylinders. These cylinders (Figure 7) were made from maple dowels having a density of 43 pounds per cubic foot. Diameters used varied from 1/8 inch to 1¼ inch, and lengths from ¼ inch to 2 inches. These particle dimensions are similar to the stalk section dimensions found in silage.
2. Wood rectangular particles. These particles (Figure 8) were made from Douglas Fir having a density of 33 pounds per cubic foot. The side dimensions ran from ½ inch to 2 inches, and lengths from ¼ inch to 2 inches. The overall dimensions are similar to the stalk sections of silage and have different shape relation than the cylinders.
3. Wood equilateral triangular shaped particles. These particles (Figure 9) were cut from Douglas Fir with a density of 33 pounds per cubic foot. The particles used varied in side dimensions from ½ inch to 1-7/8 inches,

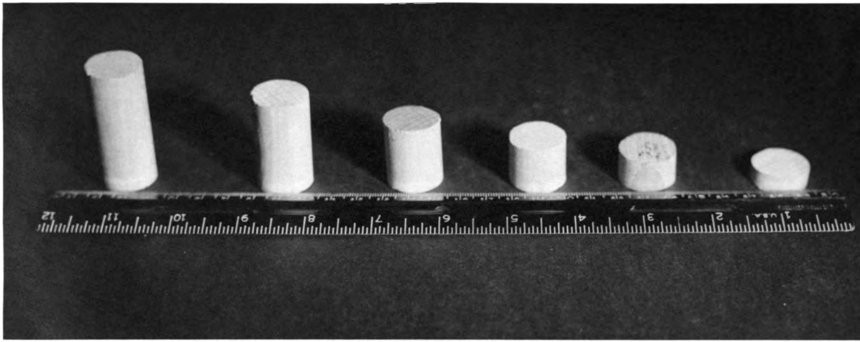


Figure 7. Some sylindrical particles used in the tests.

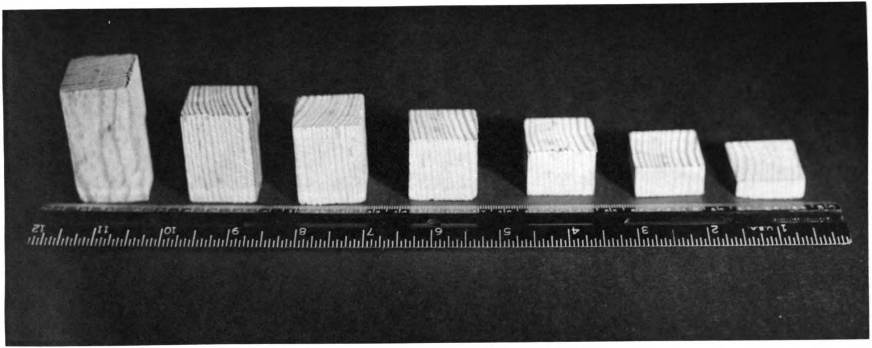


Figure 8. Some retangular particles used in the tests.

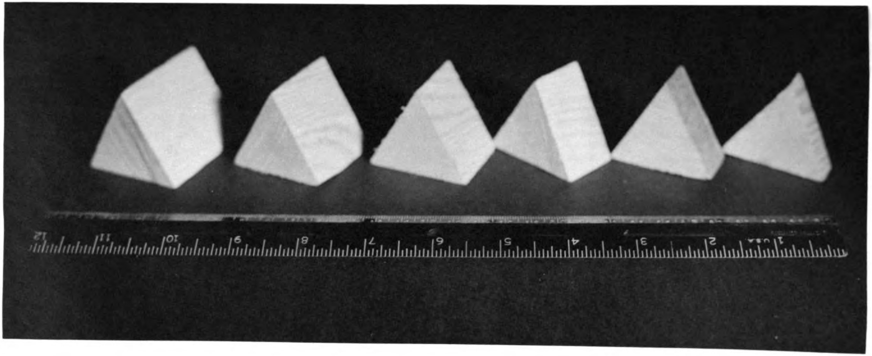


Figure 9. Some equilateral triangular shaped particles used in the tests.

and in length from 1/8 inch to 2 inches. These particles are similar in size to others selected but they have different shape relations than the cylinders and rectangular particles.

4. Rectangular cubes. These cubes (Figure 10) are 1 inch cubes, but are made up of plastic and wood such that all have different densities.

With the exception of the rectangular cubes, the particle sizes were selected to furnish a range of shapes, sizes and lengths.

Figure 10. Some retangular shaped particles of same size but different densities used in the tests.

PROCEDURE

Suspension Velocities

The method used to determine the effect on minimum suspension velocities caused by size, shape, density and number of the particles required the use of the variable-area meter.

The flow of air through the variable-area meter was adjusted by trial until the approximate range of velocities were obtained that would suspend the particle in the variable-area meter. The test particle was then injected into the top of the variable-area meter. The position the particle occupied in the variable-area meter, and the flow of air through the square edged orifice permitted the calculation of the air velocity at the point where the particle was suspended. Some of the particles floated evenly and gave uniform results and other particles varied widely in their suspension velocity due to the position they assumed in the air stream.

The experimental design used was the randomized block. Preliminary tests were run to determine the number of replications that would be required. Based on the above tests twenty replications were run and used in the analyzation of the data.

The particles were injected one at a time for determination of the effect of size, shape and density upon the velocity of air.

Vertical Transport Velocities

The method used to determine effect on minimum transport velocity caused by size, shape and density of the particle on minimum transport velocities called for the use of the vertical pipe system. The experimental design used was the randomized block. Preliminary tests were run to determine the number of replications that would be required. As a result of these tests eight replications were used in analyzing the data.

The fan speed was adjusted to furnish air at a velocity below the anticipated minimum transport velocity of the particle under test. The test particle was injected through the port opening and then the port was closed. The speed of the fan was then adjusted until the particle became visible in the plastic section, and then the speed would be increased in increments equal to approximately 20 feet per minute of air velocity until the particle would be transported up the vertical pipe system, and out the top of the system. One minute was allowed between increment increases to permit stabilization of the particles.

The air velocity in the vertical pipe system at which the particle was transported was determined by a traverse of the pipe with a hot wire anemometer, and checked by the use of a pitot tube.

The time allowed for the particle to be elevated 34 feet was 1 minute. A reasonable estimate for the average time would be 30 seconds. This results in an average velocity of 69 feet per minute for the particles. However, this average would include the several reversals in direction. The velocities of the particles leaving the top of the pipe would be much greater than the average velocity.

AERODYNAMIC THEORY

The aerodynamic properties of a particle depends upon the physical characteristics of the particles, the properties of fluid in which it is located, and the applied force. The fluid considered in this study was air.

Lapple and Shepherd (10) developed a mathematical analysis which handles the relations of these properties.

$$(3) \quad M \frac{dV}{d\theta} = (v_p \rho_p - v_p \rho) - F$$

$$= Mg \left(\frac{\rho_p - \rho}{\rho_p} \right) - F$$

By definition:

$$(4) \quad F = C \frac{V^2}{2g} \rho A$$

$$(5) \quad \frac{dV}{d\theta} = \left(\frac{\rho_p - \rho}{\rho_p} - C \frac{V^2 \rho A}{2g M} \right) g$$

A = projected area of particle. Square feet.

ρ = fluid specific weight. Pound per cubic foot.

ρ_p = particle specific weight. Pounds per cubic foot.

v_p = particle volume. Cubic feet.

C = particle aerodynamic drag coefficient, dimensionless.

V = relative velocity. Feet per second.

F = force. Pounds

N = particle mass.

W = particle weight. Pounds

θ = time. Seconds.

Re = Reynolds number.

D = average particle diameter. Feet

A particle allowed to fall with only fluid resistance will reach a maximum velocity, in a downward direction if the particle density is greater than the fluid density, and this is referred to as the steady state velocity. To suspend a particle, the air velocity in the upward direction must balance the steady state velocity of the particle in the downward direction.

The particle would have no acceleration or velocity and the velocity of the air would also be the relative velocity of the air stream to the suspended particle.

Since the particle has no acceleration.

$$(6) \quad \frac{dV}{d\theta} = 0$$

We will substitute $\frac{dv}{d\theta} = 0$ into equation: (5)

$$(7) \quad 0 = g \frac{\rho_p - \rho}{\rho_p} - g\, C \frac{V^2}{2g^2} \frac{\rho A}{M}$$

$$\frac{C}{2g^2} \frac{V^2 \rho A}{M} = \frac{\rho_p - \rho}{\rho_p}$$

$$V^2 = \frac{2g^2\, M}{C\, \rho\, A} \left(\frac{\rho_p - \rho}{\rho_p} \right)$$

$$(8) \quad V = \sqrt{\frac{2g^2\, M}{C\, \rho\, A} \left(\frac{\rho_p - \rho}{\rho_p} \right)}$$

$$V = 45.5\sqrt{\frac{M(\rho_p - \rho)}{C\rho A\rho_p}}$$

This equation can be simplified since the density of the particle is much greater than the density of air.

$$(9)\quad V = 45.5\sqrt{\frac{M\rho_p}{CA\rho\rho_p}}$$

By using the weight mass relationship the formula can be reduced to:

$$(10)\quad V = 0.63\sqrt{\frac{W\rho_p}{CA\rho\rho_p}}$$

$$(11)\quad C^{\frac{1}{2}}V = 0.63\sqrt{\frac{W\rho_p}{A\rho\rho_p}}$$

The drag coefficient "C" and the velocity can be determined but cannot be separated into values for each.

The physical properties of the particles influence the value of the drag coefficient. The value of "C" can be determined if the velocity is known. The results of the velocity experiments will be used to develop a formula for a constant that can be used in equation (11) instead of the drag coefficient "C" for a limited range of velocity. The calculated constant will be referred to as "K", and will be determined by the relationship of the physical properties of the particle.

RESULTS

Test Results on Suspension Velocities

The experimental design used in the tests was the randomized block. Twenty replications were used to determine if there was a significant difference in the air velocity required to suspend particles varying in only one dimension from the initial or check particle of that shape and density. The "F" test was used at the 5 percent level to determine if a difference was shown by the experimentally determined data.

The data obtained experimentally by the suspension of particles in an air stream were used to plot several graphs to determine the relationship between size, shape, and density of particle and the required suspension velocity.

When the required suspension velocities for different length particles of the same diameter or equivalent dimensions were plotted against a ratio of $\frac{\text{area}}{\text{volume}}$, (Figures 11, 12 and 13) the graphs consistently showed that the suspension velocity maximized when the dimensions of the particle approached that of a sphere or cube. When the maximum projected area of rectangular particles was plotted against the ratio of $\frac{\text{area}}{\text{volume}}$, the maximum required suspension velocity occurred where the line became horizontal (Figure 11), *i.e.*, maximum projected area stabilized for the particle. The same results were obtained by plotting $\frac{\text{maximum projected area}}{\text{volume}}$ against the ratio of $\frac{\text{area}}{\text{volume}}$ (Figure 12). The point of maximum velocity was indicated by the place at which the

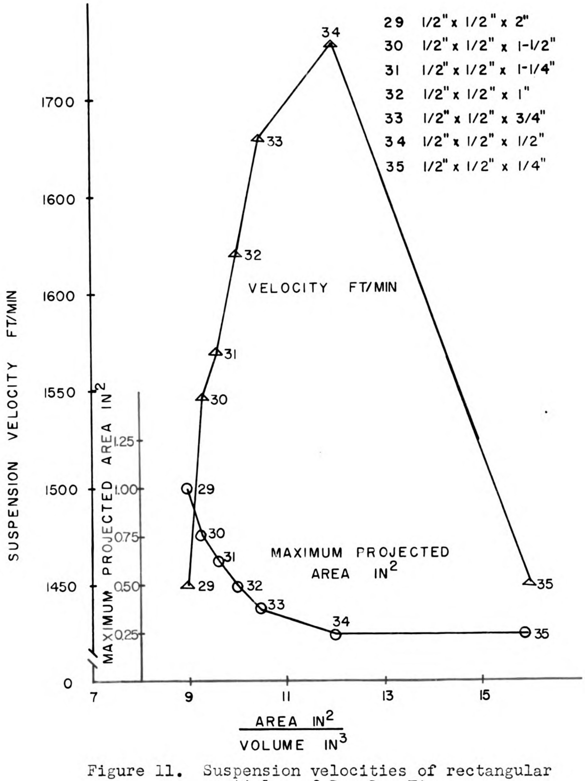


Figure 11. Suspension velocities of rectangular particles of Douglas Fir.

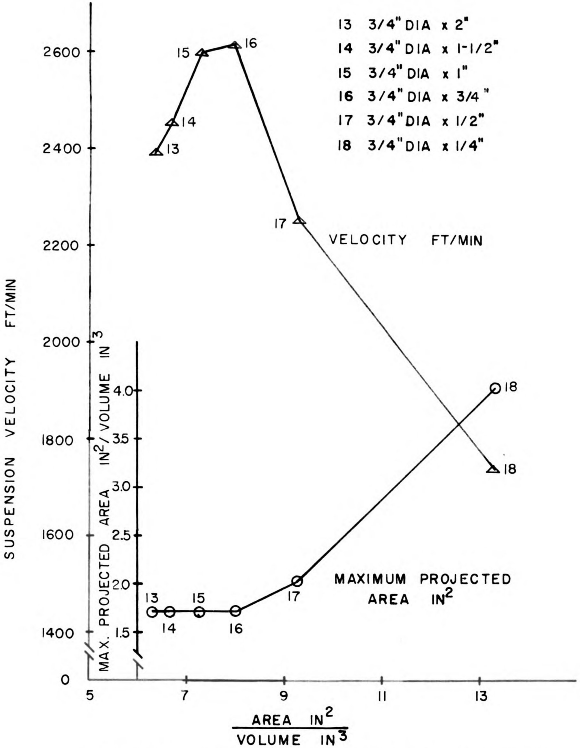


Figure 12. Suspension velocities of cylindrical particles of Maple.

curve turned upward.

It is possible to show this point of maximum suspension velocity even more clearly by adjusting the scale and plotting both the maximum projected area and the ratio of $\frac{\text{maximum projected area}}{\text{volume}}$ against the ratio of $\frac{\text{area}}{\text{volume}}$ (Figure 13). In Figure 13 the scales were so adjusted that the two lines crossed where the maximum projected area line became horizontal and the rate of the $\frac{\text{maximum projected area}}{\text{volume}}$ line turned upward.

This combination was used to show the location of the maximum required suspension velocity as a point on the graph rather than the break in the line as shown in Figures 11 and 12.

The effect of the L/D ratio was investigated in two ways. Figure 14 gives the required suspension velocities for different shaped particles with a common L/D = 1. The density of the cylinders was corrected to that of the other particles. This graph indicates that with common L/D ratio, cylinders require greater air velocities than the rectangular and triangular particles. Figure 15 compares the required air velocities for suspension of different shaped particles with common L/D ratios. The maximum suspension velocity occurred with an L/D = 1 except for the triangular particles. The required suspension air velocity goes up as the L/D ratio decreases to 1 and decreases as L/D decreases from 1 with the exception of triangular particles shown. Figure 16

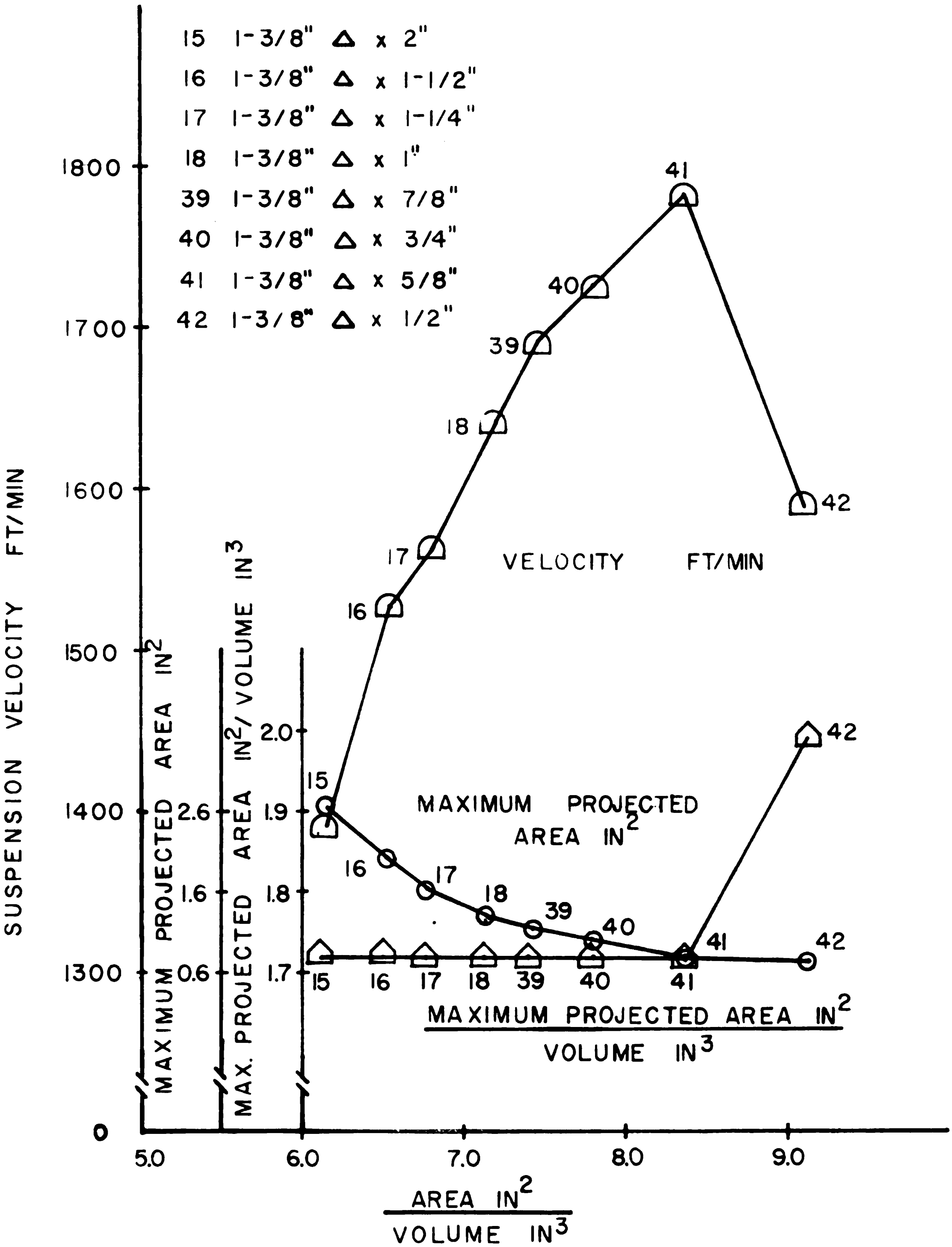


Figure 13. Suspension velocities of equilateral triangular particles of Douglas Fir.

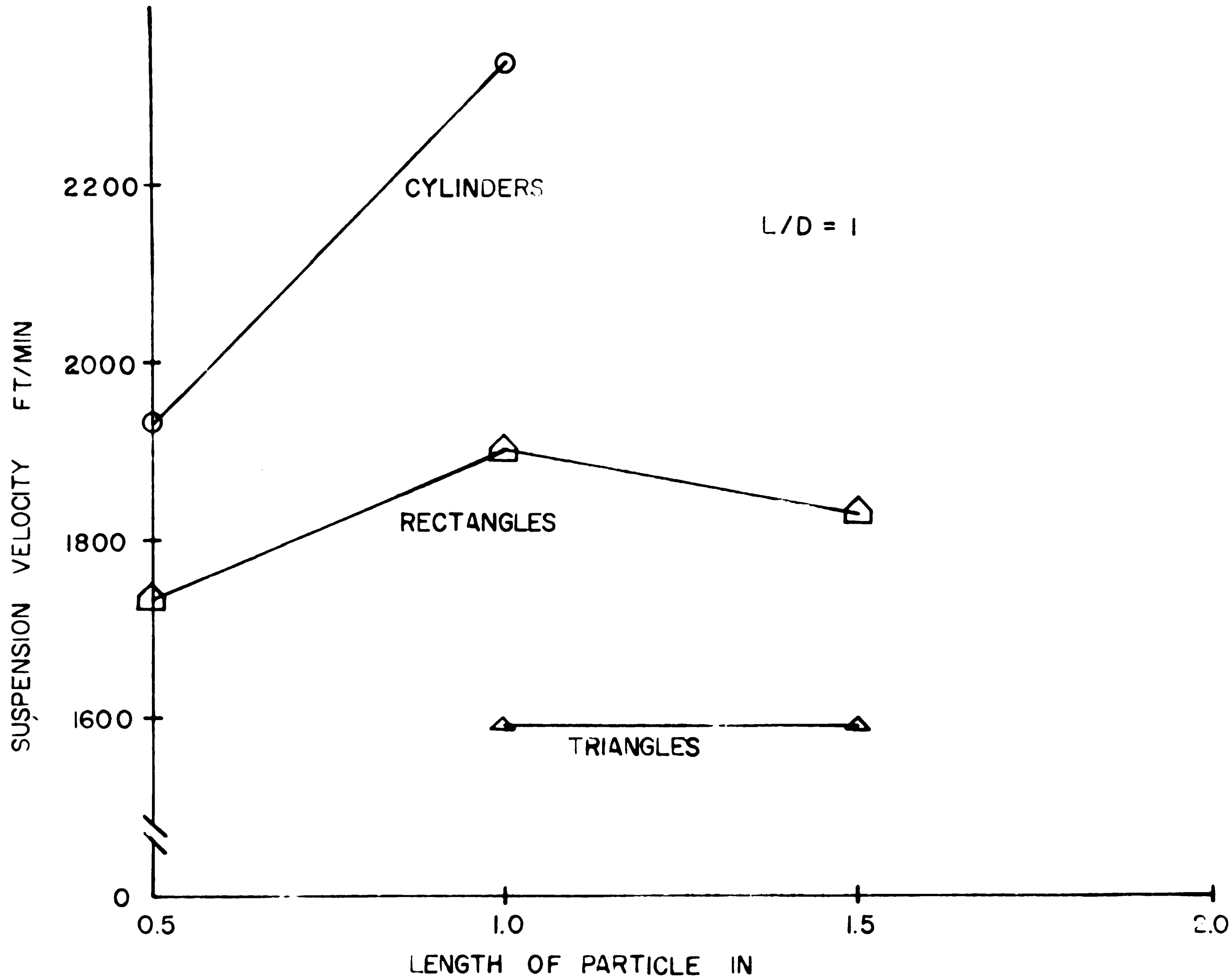


Figure 14. Comparison of suspension velocities for different shapes.

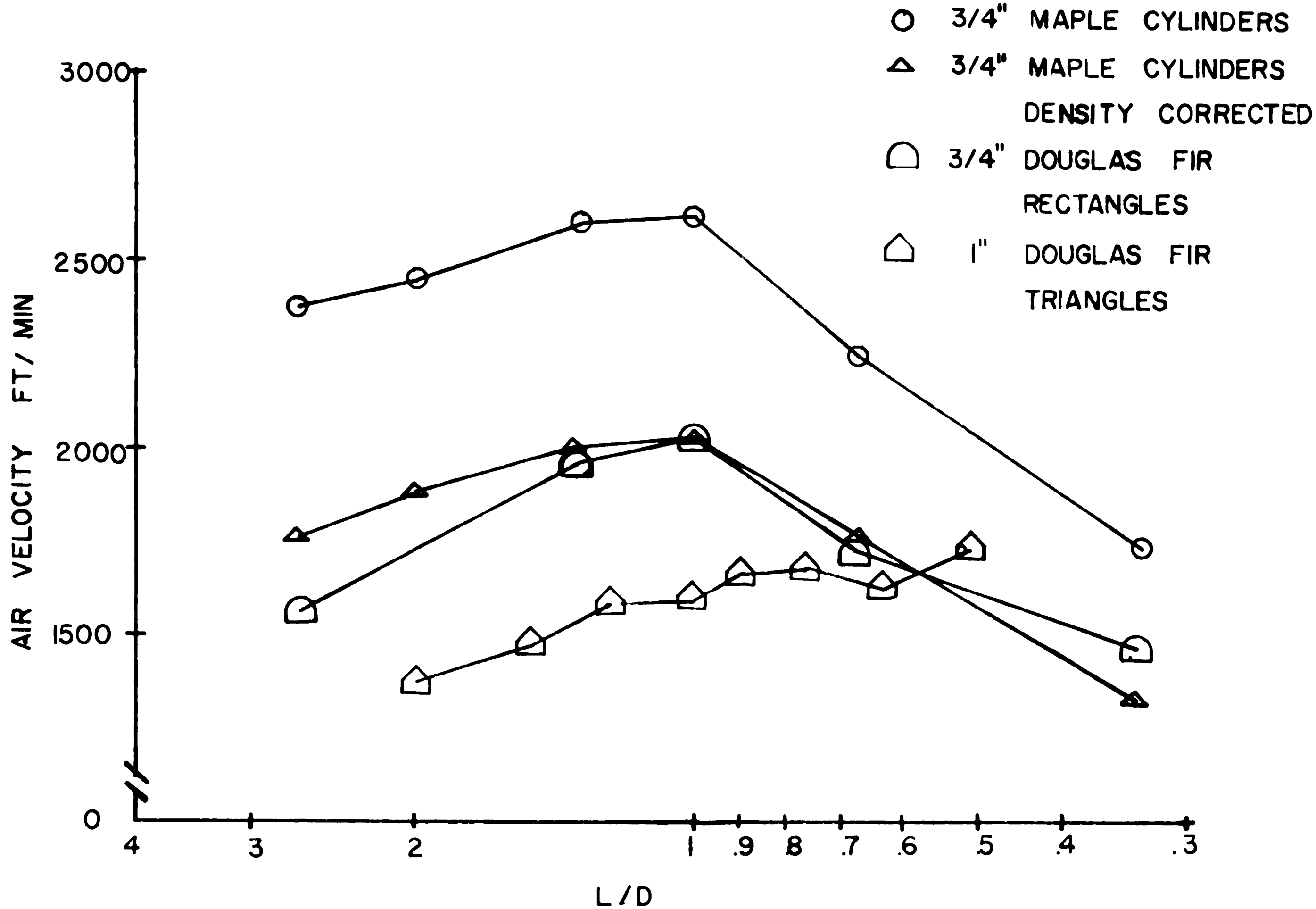


Figure 15. Air velocities required for different shaped particles with common L/D ratios.

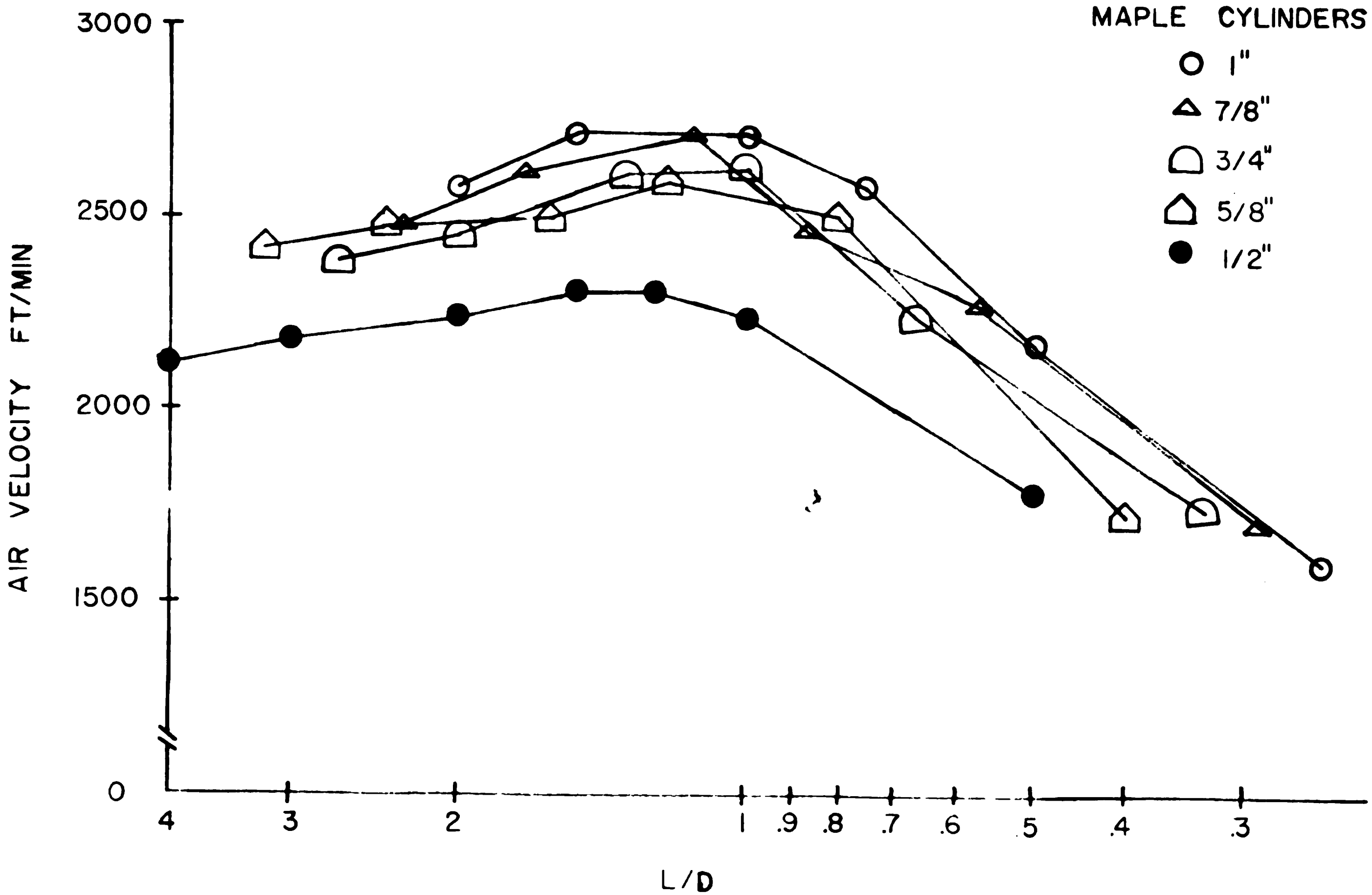


Figure 16. Air velocities required for cylinders with common L/D ratios

shows air velocities required for cylinders with common L/D ratios.

Comparisons of required air suspension velocities of the same shape but of different size particles are given in Figures 17, 18 and 19 (plotted on inverse semi-log paper). The maximum velocity for each size is of the same magnitude, but occurs at a different volume. The maximum occurs in the region where L/D is approximately 1 and the velocity decreases with a decrease in volume as the L/D ratio goes down.

The data obtained in determining the suspension velocities for cubes of the same size but different densities were used to calculate the suspension velocity of the heaviest particle using the assumption that the velocity would be proportional to the third power. The average of the values calculated from experimental data for the suspension of the heaviest particle was taken as the best estimate of the required suspension velocity of the particle. It was used as a basis for calculating suspension velocities for each group of particles. The values obtained were plotted as a line on the same graph with the experimental values (Figure 20). The calculated curve, and the experimental curve, are similar.

Minimum Transport Velocities Test

The data obtained in the tests to determine

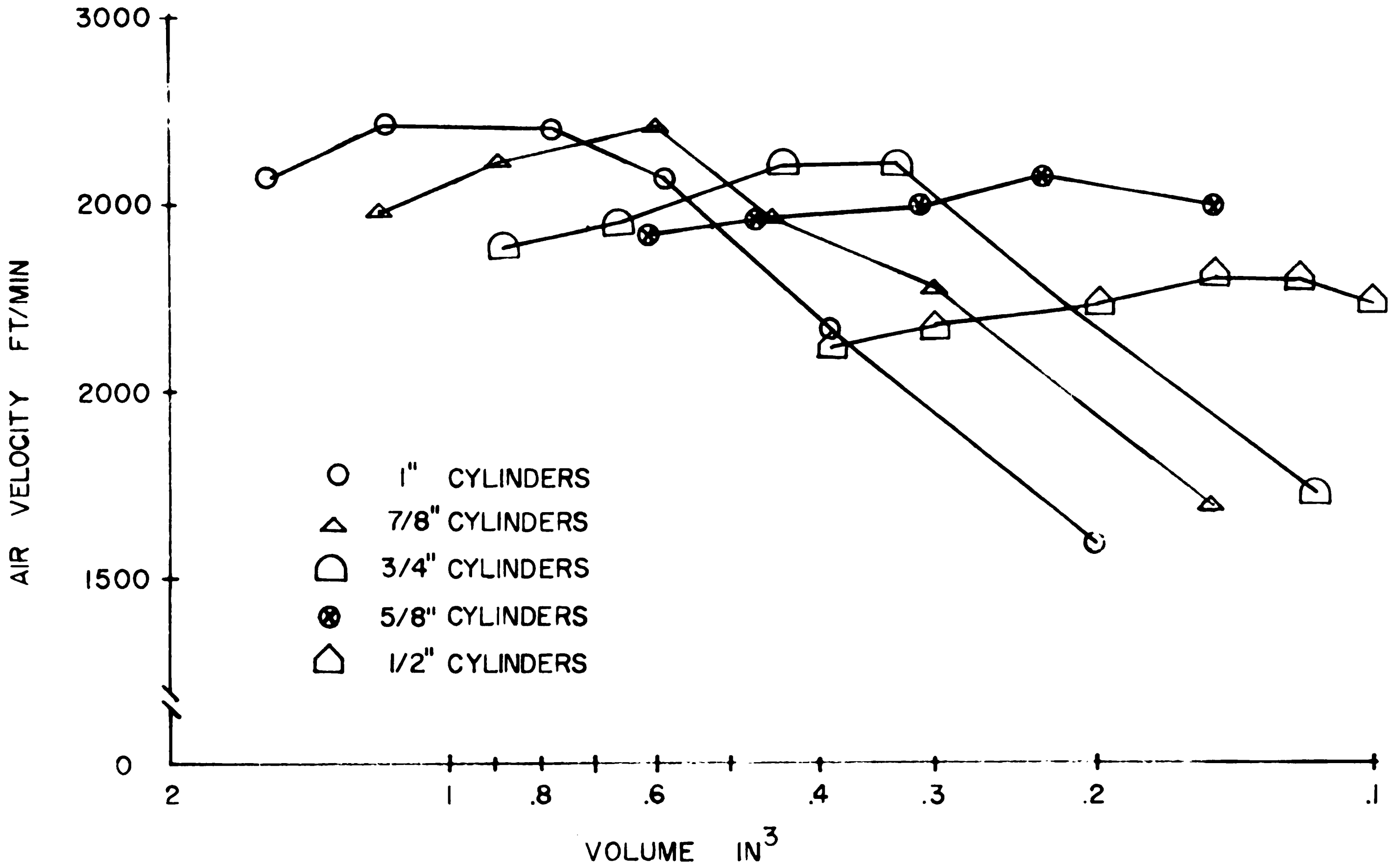


Figure 17. A comparison of dimension effect on Maple Cylinders.

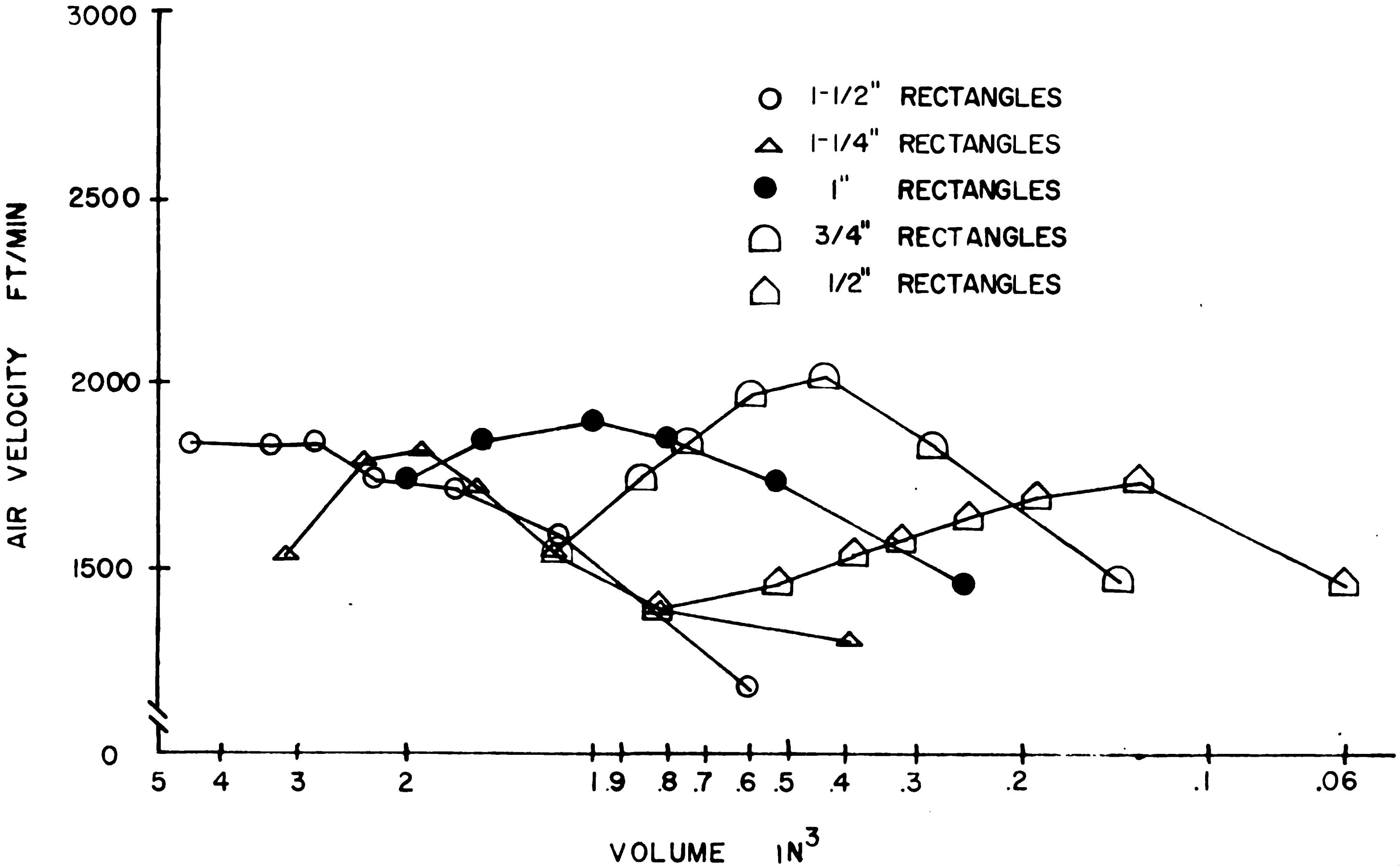


Figure 18. A comparison of dimension effect on Douglas Fir rectangles

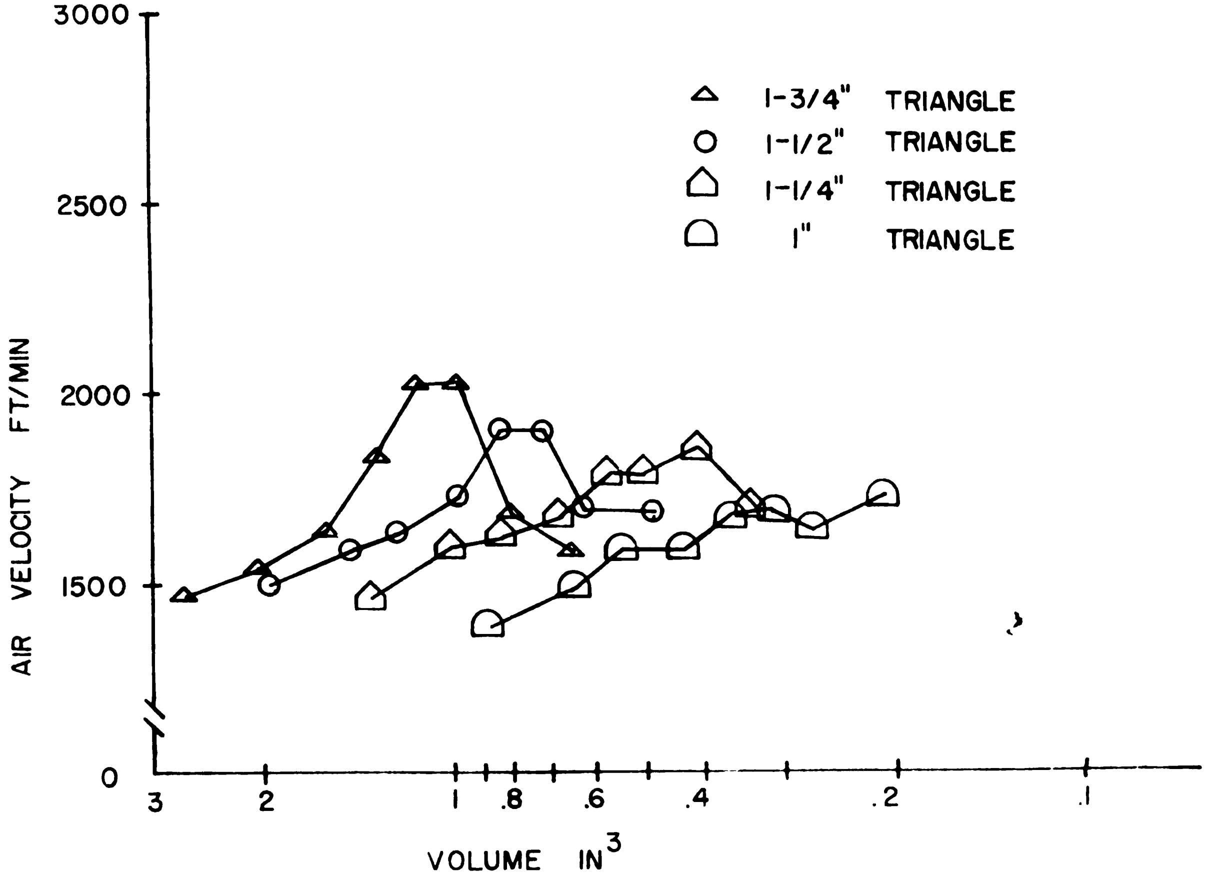


Figure 19. A comparison of dimension effect on Douglas Fir triangles.

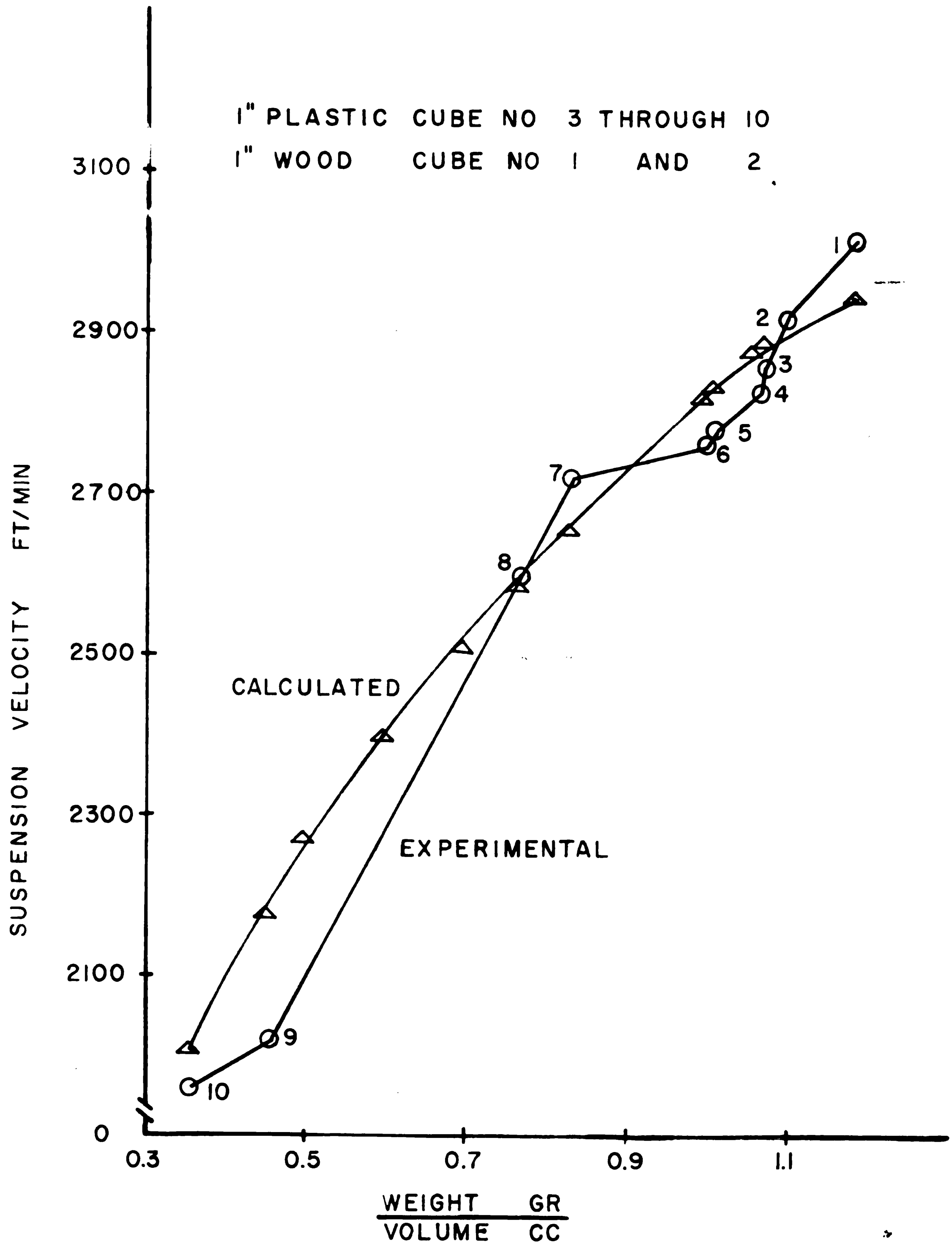


Figure 20. Suspension velocities of cubes of the same size but of different densities. Calculated and experimental values are shown.

minimum transport velocities were plotted in the same manner as the data from the suspension velocity tests. The nature of the curves was the same. The values obtained and the analysis were comparable to the results on the required suspension velocities. (Figure 21).

The particles with dimensions approximately those of a sphere or cube required higher suspension and higher minimum transport velocities (Figure 22).

Figure 23 shows some of the test particles. The corn pith had to be dropped from the tests because it disintegrated before the required number of replications could be made.

Figure 24 shows the transport and suspension velocities required for 3/4 inch diameter maple cylinders. The transport values are higher than the suspension velocities. According to Segler (15) the particle velocity would be about one third the increase in air velocity.

Comparison of Experimental Results with Theory

The velocities were calculated for particles tested and the value of "C" determined that could be used in formula (11) and obtain the same velocity.

$$(11) \quad C^{\frac{1}{2}}V = 8.03\sqrt{\frac{W}{A}\,\frac{\rho_p}{\rho\,\rho_p}}$$

These experimentally obtained "C" values were

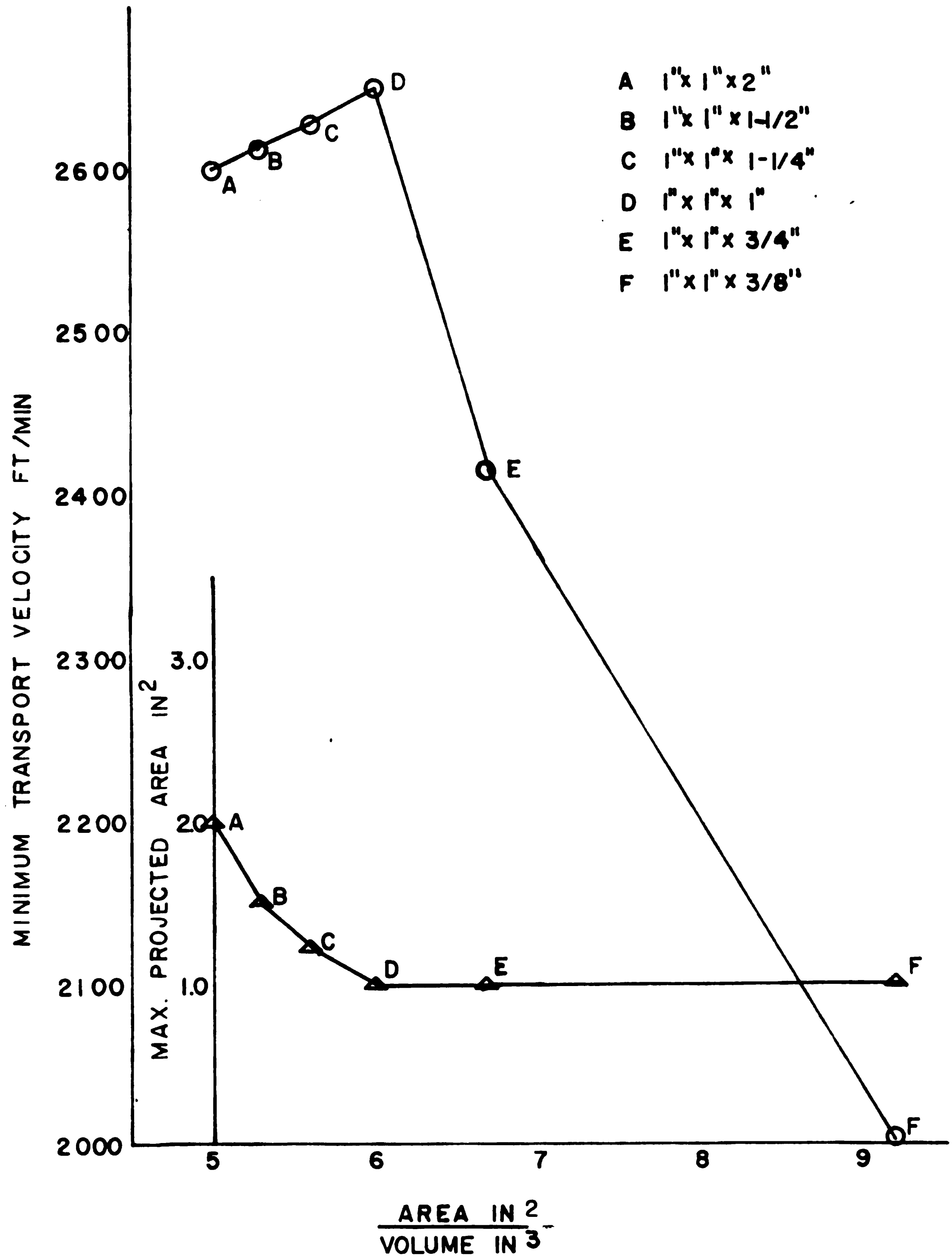


Figure 21. Minimum transport velocities for rectangular particles of Douglas Fir.

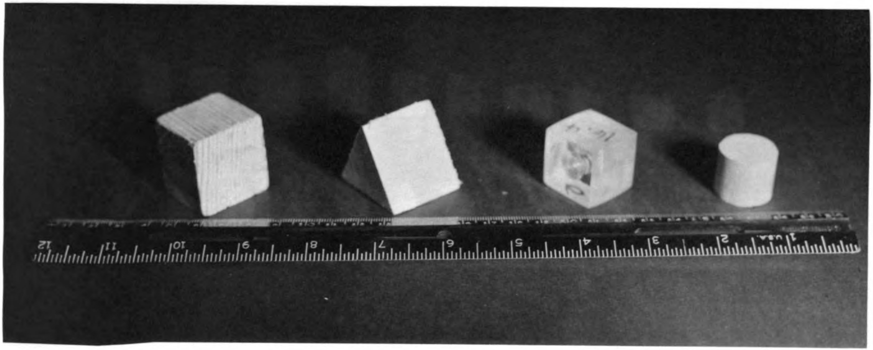


Figure 22. A group of particles that tend to require high suspension velocities.

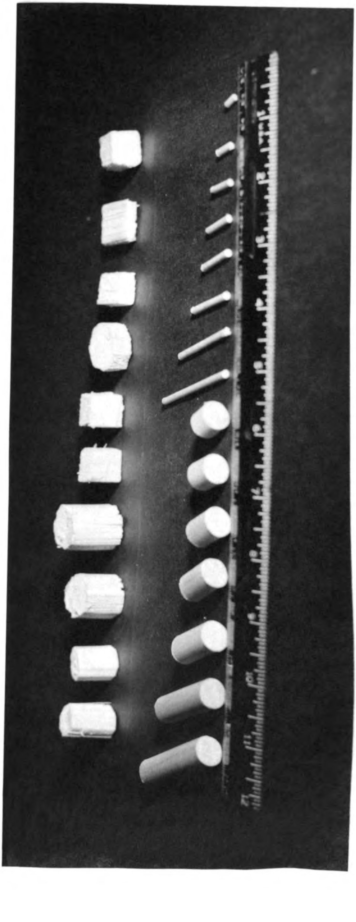


Figure 23. Some of the particles on which tests were run.

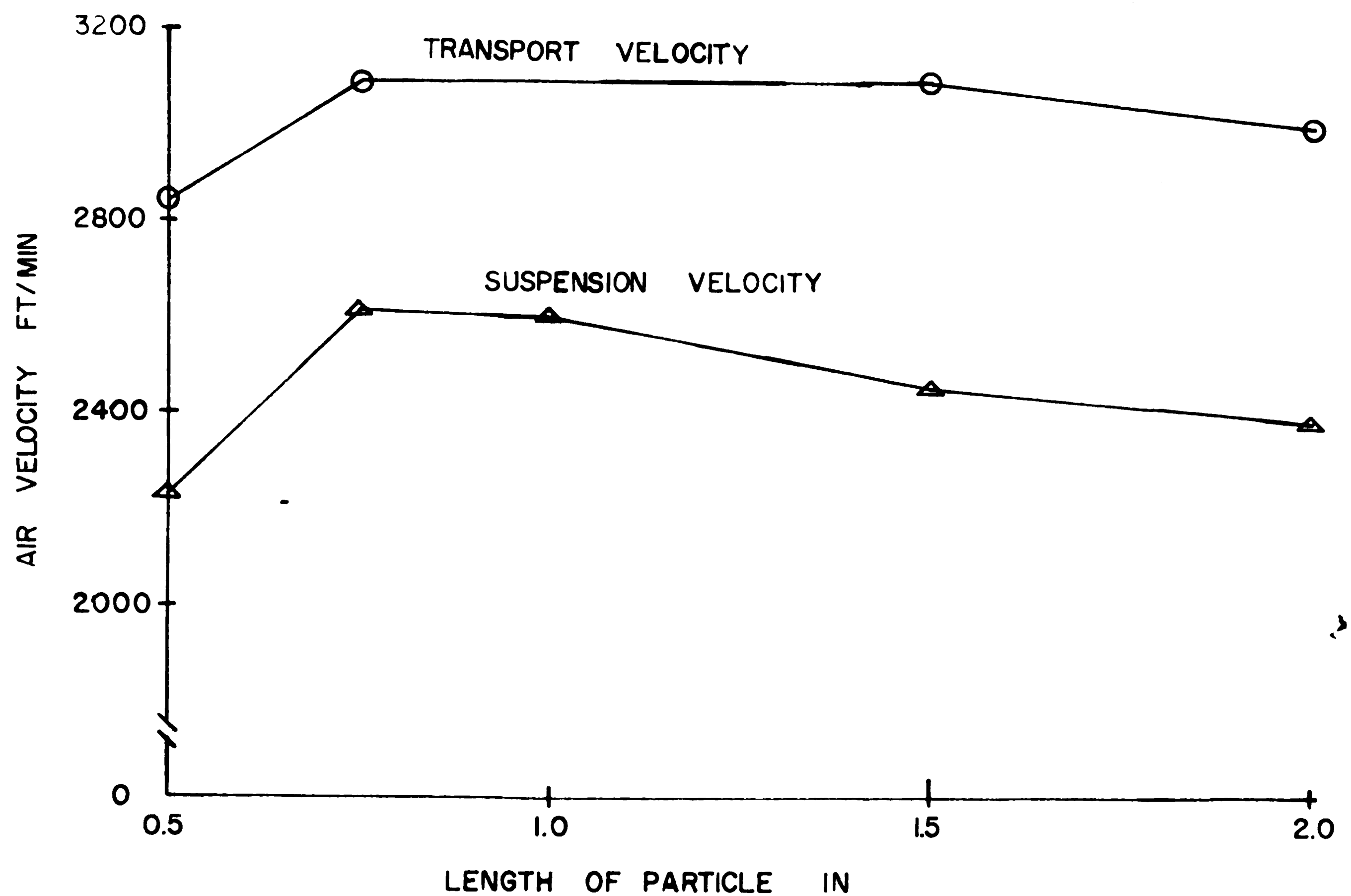


Figure 24. Comparison of transport and suspension velocities of 3/4" dia. cylinders.

obtained by using the experimentally obtained velocities in equation (11) and solving for "C". These "C" values, when available for a particular shape and size particle, can be used to determine the velocity required, however there are cases where this information is not available.

Formulas were developed to give approximate "C" values that can be used in the theoretical formula to obtain the required velocity. Properties of the particles were used to develop the formulas. The term "K" is used to distinguish it from the drag coefficient "C". The properties considered were as follows: volume, area, maximum projected area, and dimensions.

The "C" values were plotted for a particular shaped range of particles. This information was used to develop a general formula to represent this information. The properties of the particles were inserted as variables in this general formula and constants determined.

The formula that applies to the cylindrical form is of the type:

$$K = \left(\frac{V}{X}\right)^{a} + \frac{v}{A}$$

$$(12) \quad K = \left(\frac{V}{L/D}\right)^{\frac{1}{4}} + \frac{mpa}{A}$$

Where: V = Volume in.^{3}

L = Length in.

D = Diameter in.

mpa = maximum projected area $in.^2$

A = Area $in.^2$

The formula that applies to rectangular particles is of the type:

$$K = \left(\frac{V}{W}\right)^{a} + \frac{bY}{Z} + D$$

$$(13) \quad K = \left(\frac{L}{S}\right)^{\frac{1}{2}} + \frac{2\,mpa}{A} + 0$$

Where:

L = Length in.

S = Side in.

mpa = maximum projected area in^2.

A = area in^2.

D = 0

The formula that applies to the triangular particles is of the same form as for rectangular particles.

$$(14) \quad K = \left(\frac{L}{S}\right)^{\frac{1}{2}} + \frac{2\,mpa}{A} + .3$$

Where: D = .3

These formulas checked out with maximum error of 18.2 percent on the heavy plastic 1 inch cube and less on the others. The average value obtained differed from the experimentally obtained value by less than 10 percent. There was no statistically significant difference in the two sets of values.

The suspension and minimum transport velocities do not cover a wide range of velocities and the range of "C" values is limited. The formulas obtained are valid in the range of velocities from 1000 feet per minute to 4000 feet per minute.

The formulas can be used with the theoretical formula to obtain required suspension and minimum transport velocities with a reasonable degree of accuracy.

TABLE 2

"K" VALUES FOR CYLINDERS

Particle Maple Cylinders	"K" Calculated	Drag Coefficient "C"
3/4" dia. x 2"	1.02	1.04
3/4" dia. x 1½"	1.00	1.14
3/4" dia. x 1"	.98	.97
3/4" dia. x 3/4"	.96	.97
3/4" dia. x ½"	.98	1.10
3/4" dia. x ¼"	1.07	.96

TABLE 3

"K" VALUES FOR RECTANGLES

Particle: Douglas Fir Rectangles	"K" Calculated	Drag Coefficient "C"
$\frac{1}{2}$" x $\frac{1}{2}$" x 2"	2.44	2.22
$\frac{1}{2}$" x $\frac{1}{2}$" x $1\frac{1}{2}$"	2.16	1.93
$\frac{1}{2}$" x $\frac{1}{2}$" x 1"	1.81	1.77
$\frac{1}{2}$" x $\frac{1}{2}$" x $\frac{1}{2}$"	1.33	1.54
$\frac{1}{2}$" x $\frac{1}{2}$" x $\frac{1}{4}$"	1.20	1.13

TABLE 4

"K" VALUES FOR TRIANGLES

Particles: Douglas Fir Triangular s Shaped	"K" Calculated	Drag Coefficient "C"
1 3/8" x 2"	2.03	2.30
1 3/8" x 1½"	1.90	1.98
1 3/8" x 1"	1.66	1.78
1 3/8" x 5/8"	1.43	1.44
1 3/8" x ½"	1.55	1.83

APPLICATION

The information developed in the study has definite application in the field of transport of farm and other materials. The power and air velocities required to transport material is effected by the dimensions of the particles transported.

In the transport of forages, long or extremely short cuts would require less air velocity than particles cut in lengths approximately equivalent to the diameter of the particle, i.e. $\frac{L}{D} = 1$.

In the transport of smaller materials, the results obtained indicate that grain that has been rolled or crushed could be transported with less air velocity than the original grain.

The greater the projected area of the particle in relation to its volume, the lower the air velocity that is required for the same density. Treatment of material to obtain greater projected area would reduce the air velocity and save power.

An application of the principles involved would be the handling of materials for prepared animal feeds. They could be used in the handling of materials from the farm or at any stage in the materials handling at the feed plant.

The air velocity required to suspend a $\frac{1}{2}$" x $\frac{1}{2}$" x 2" Douglas fir particle was 1450 feet per minute, while for a $\frac{1}{2}$" x $\frac{1}{2}$" x $\frac{1}{2}$" particle the velocity was 1705 feet per minute. To this velocity 3000 feet per minute conveying air velocity must be added to obtain the total required velocities of 4450 feet per minute for ½" x ½" x 2" particle and 4705 feet per minute for the ½" x ½" x ¼" particle. According to well known fan laws the horsepower required for a unit fan varies as the cube of the revolutions per minute and cubic feet per minute. On this basis it will take 17.2 percent more horsepower to convey the ¼" lengths than the 2" lengths. Since the suspension velocity of the ¼" lengths is the same as the 2" lengths it will also require 17.2 percent more horsepower to convey the ½" lengths than the ¼" lengths.

If the susepnsion velocity for the ½" x ½" x ¼" Douglas Fir particles was not known and the Drag Coefficient "C" was not available, the approximate suspension velocity can be calculated by the method developed.

$$(13)\quad K = \left(\frac{L}{S}\right)^{\frac{1}{2}} + \frac{2\ mpa}{A} + 0$$

$$K = \left(\frac{0.25}{.5}\right)^{\frac{1}{2}} + 2\left(\frac{0.25}{1.00}\right)$$

$$= (0.5)^{\frac{1}{2}} + 0.5 + 0$$

$$= 0.705 + 0.5 = 1.205$$

$$(11)\quad C^{\frac{1}{2}}V = \sqrt{\frac{W\ \rho_p}{A\ \rho\ \rho_p}}$$

$$(1.205)^{\frac{1}{2}}V = 8.08\ \sqrt{\frac{0.001146 \times 33}{(0.00173)\ (33)\ (0.074)}}$$

$$(1.205)^{\frac{1}{2}}V = 8.08\ \sqrt{\frac{0.652}{0.074}}$$

$$(1.205)^{\frac{1}{2}}V = 8.08\ \sqrt{8.96}$$

$$(1.205)^{\frac{1}{2}}V = 24.20$$

$V = 22.1$ ft/sec

$V = 1320$ ft/min

The experimentally obtained value was 1440 ft/min. The difference between the two values, experimentally and calculated, is 80 ft/min or 5.6 percent.

The "C" value obtained from the experimental data was 1.13 compared to the "K" calculated value of 1.205.

SUMMARY

In this study, the minimum suspension and minimum transport air velocities were determined for a group of particles of different sizes, shapes and densities. The experimental design required numerous replications to determine if the differences in the required velocities were significant. The "F" test was used at the five percent level.

The results of these velocity tests were analyzed and the relationship of the particle properties were related to the air velocities required. Formulas were developed that will permit calculation of constants that are needed in the theoretical equation. The required velocity can then be calculated for a particle using its properties of size, shape and density.

CONCLUSIONS

This study was based on the following hypothesis: The air velocity required to support or transport a material is related to the physical properties of the particle. These properties include density, size, shape and surface conditions.

The conclusions based on properties of density, size and shape are as follows:

1. The suspension velocities and minimum transport velocities are related to the L/D ratio: i.e. the required air velocity increases as L/D approaches 1. Observations indicate that required air velocities are minimized as L/D approaches zero.
2. The suspension velocities and minimum transport velocities are related to the $\frac{\text{maximum projected area}}{\text{volume}}$ ratio: i.e. The required velocity increases as the ratio decreases and reaches a maximum as the ratio reaches a constant value.
3. The suspension velocities and minimum transport velocities are related to the maximum projected area: i.e. The required velocity increases as the maximum projected area decreases and reaches a maximum at the point where the maximum projected area reaches a constant value.
4. The suspension velocities and the minimum

transport velocities are approximately proportional to the cube of the densities of the material.

5. The fan horsepower can be reduced when handling material when particle shape can be controlled to take advantage of the above conclusions.
6. "K" values for air velocities may be calculated based on the physical properties of the material when drag coefficients are not available.

PROBLEMS RECOMMENDED FOR FUTURE STUDY

The results of this study open up several possible application possibilities. Three suggested studies on application are given.

1. The effect on horsepower requirement of blowing rolled grain as compared to whole grain.
2. The effect on horsepower requirement of blowing crushed forage as compared to normally chopped material of the same length cut.
3. Determination of the conveying rate of forages with different length of cut.

APPENDIX

EQUIPMENT USED

The plastic variable-area meter was developed so that the floating particle could be seen in a column of air of gradually decreasing velocity. Some of the particles varied widely in the suspension velocity required due to the temporary position assumed by the particles. The variable-area meter was able in most cases to furnish the required range.

The square edged orifice, made from plastic, was machined in the shop.

The manometer used was a micro-manometer which permitted reading of low pressure drops.

The blowers were used as a source of air. The blower used to determine minimum transport velocities had a variable speed drive to permit variation of air velocity. An adjustable gate to control air intake was used in the suspension velocity tests.

The pitot tube was used in making traverses of the pipe cross section and in checking the calibration of the hot wire anemometer.

The hot wire anemometer was used to check air velocities calculated using the square edged orifice, and to measure air velocities required for transport.

The vertical pipe system was developed to permit injection of material into the system, the measurement of air velocity, and to permit the return of particles. A clear plastic section was included to permit visual observation.

The velocity calculations were based on a development of Polson and Lowther (17) in their expansion of the work of Durley.

Durley's equation was:

(15) $v = (2gh)^{\frac{1}{2}}$

v = velocity feet per second.

g = acceleration of gravity feet per second.

h = total differential head feet of air.

This equation was modified to give the weight (W) of the air discharged per square foot of orifice per minute.

(16) $$W = \frac{60v}{V} = \frac{60(2g \times 5.1916\ iV)^{\frac{1}{2}}}{V}$$

$$= 60 \left(\frac{64.4 \times 5.1916\ i}{V}\right)^{\frac{1}{2}}$$

W = weight pounds per minute per square feet.

i = total differential head, inches of water.

v = specific volume, cubic feet per pound.

5.1916 = constant to convert inches of water to pounds per square foot.

The value for V is determined from the equation of a perfect gas.

(17) $$PV = RT$$
$$V = \frac{53.34T}{P}.$$

Substituting in equation 16

(18) $$W = 60\left(\frac{64.4 \times 5.1916\ iP}{53.34}\right)^{\frac{1}{2}}$$

$$= 150.21 \left(\frac{iP}{T}\right)^{\frac{1}{2}}$$

P = Pressure pounds per square foot.

R = A constant 53.34 for air.

The discharge (W) in pounds per minute for an orifice of d inches in diameter would be:

$$(19)\quad W = \frac{0.7854 d^2}{144} \times 150.21 \left(\frac{iP}{T}\right)^{\frac{1}{2}}$$

$$= 0.8193 \ d^2 \left(\frac{iP}{T}\right)^{\frac{1}{2}}$$

If standard conditions of 29.92 inches of Hg. and 60°F are used.

$$P = 2116.3 \text{ lb/ft}^2$$

$$(20)\quad W = 1.6528 \ d^2 \ (i)^{\frac{1}{2}} \text{ pounds per minute.}$$

Corrections can be made by multiplying coefficients for the orifice and by correction factor for conditions other than standard.

After the weight of air flow through the orifice per minute was determined, the velocity in feet per minute was determined from the equation:

$$(21)\quad V = \frac{Q}{A}$$

$$(22)\quad V = \frac{Q}{A} = \frac{W \times SP.Vol.}{.7854 \frac{d}{12}}$$

V = Velocity feet per minute.

Q = CFM

A = Area square feet.

S. P. Vol. = cubic feet per pound.

d = diameter of the rotometer at the point of suspension inches.

Equation was cleared to the following form when used with a 2 inch orifice.

$$(23)\ W = 6.6 \times (i)^{\frac{1}{2}}$$

SAMPLE DATA

Particle 1 Maple cylinder 5/8" dia. x 2"

Particle 2 Maple cylinder 5/8" dia. x 1 1/4"

Particle	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
1	35	35	35	35	35	35	35	35	35	35	35	35	35	35	34	35	34	35	34	35	69.7
2	34	35	34	34	35	34	35	34	35	34	34	34	35	34	34	35	34	35	34	34	68.7
	69	70	69	69	70	69	70	69	70	69	69	69	70	69	68	70	68	70	68	69	138.40

$$C.\ F. = \frac{19154.56}{40} = 478.864$$

$$S.\ S. = 478.96 - C.\ F. = .096$$

$$P.\ S.\ S. = \frac{9577.78}{20} - C.\ F. = 478.89 - C.\ F. = .026$$

$$Rep.\ S.\ S. = \frac{957.82}{2} - C.\ F. = 478.91 - C.\ F. = .046$$

Error = .024

ANOVA

	DF	S.S.	M.S.	F
Total	39	.096	.002461	
Particle	1	.026	.026	20.5859 **
Reps.	19	.046	.002421	1.91686
Error	19	.024	.001263	

$F_{1,\ 19}$ 5% - 4.38, 1% - 8.18

SAMPLE DATA

Suspension Velocity

Barometric pressure 29.[illegible] in hg

Air Temperature 6[illegible]°F

Orifice 2"   Date Nov. 2, 1954

No.	19		20		21	
Material	Maple		Maple		Maple	
Size	5/8" dia x 2"		5/8" dia x 1 1/2"		5/8" dia x 1 1/4"	

Manometer Reading	Rotameter Reading	Manometer Reading	Rotameter Reading	Manometer Reading	Rotameter Reading
3.5	3.5	3.5	3.5	3.5	3.4
3.5	3.5	3.5	3.5	3.5	3.5
3.5	3.5	3.5	3.5	3.5	3.4
3.5	3.5	3.5	3.4	3.5	3.4
3.5	3.5	3.5	3.4	3.5	3.5
3.5	3.5	3.5	3.5	3.5	3.4
3.5	3.5	3.5	3.4	3.5	3.5
3.5	3.5	3.5	3.4	3.5	3.4
3.5	3.5	3.5	3.4	3.5	3.5
3.5	3.5	3.5	3.4	3.5	3.4
3.5	3.5	3.5	3.5	3.5	3.4
3.5	3.5	3.5	3.4	3.5	3.4
3.5	3.5	3.5	3.5	3.5	3.5
3.5	3.5	3.5	3.4	3.5	3.4
3.5	3.4	3.5	3.4	3.5	3.4
3.5	3.5	3.5	3.5	3.5	3.5
3.5	3.4	3.5	3.5	3.5	3.4
3.5	3.5	3.5	3.4	3.5	3.5
3.5	3.4	3.5	3.4	3.5	3.4
3.5	3.5	3.5	3.4	3.5	3.4
3.5	3.4	3.5	3.4	3.5	3.4
3.5	3.5			3.5	3.4
Average	3.5		3.4[illegible]		3.45

Transport Velocity

Minimum

Transport Velocities

Temp. 85
B.P. 74.4
Date 9-15-56

Run No	Particle Size & Shape	Velocity Nearside ft/min	Velocity Center ft/min	Velocity Farside ft/min	Cylinder
225	VV	3000	3050	3000	3/4" dia.
226	ZZ	2250	2300	2300	symbol.
227	XX	3000	3050	3000	VV-2"
228	VV	3050	3100	3000	WW-1½"
229	YY	2700	2850	2700	XX-3/4"
230	ZZ	2300	2350	2300	YY-½"
231	XX	3100	3100	3050	ZZ-¼"
232	WW	3100	3150	3100	
233	YY	2900	3000	2900	
234	XX	2950	3000	2950	
235	ZZ	2200	2250	2200	
236	VV	3000	3100	3050	
237	WW	3000	3000	3050	

TABLE 5

DATA

MAPLE CYLINDERS

43 lb/ft^3

Particle Size	Area	Volume	Suspension Velocity	Transport Velocity
in.	in^2	in^3	ft/min	ft/min
1 dia. x 2	7.85	1.57	2580	3100
1 dia. x 1½	6.29	1.18	2720	3116
1 dia. x 1	4.71	0.78	2700	2975
1 dia. x 3/4	3.93	0.59	2500	2683
1 dia. x ½	3.14	0.39	2170	2250
1 dia. x ¼	2.36	0.20	1600	1933
7/8 dia. x 2	6.70	1.20	2490	3183
7/8 dia. x 1½	5.32	0.90	2610	3116
7/8 dia. x 1	3.95	0.60	2710	3150
7/8 dia. x 3/4	3.26	0.45	2480	3133
7/8 dia. x ½	2.58	0.30	2270	2633
7/8 dia. x ¼	1.89	0.15	1700	2566
3/4 dia. x 2	5.60	0.88	2390	3083
3/4 dia. x 1½	4.42	0.66	2450	3083
3/4 dia. x 1	3.24	0.44	2605	--
3/4 dia. x 3/4	2.65	0.33	2615	3050
3/4 dia. x ½	2.06	0.22	2250	2883
3/4 dia. x ¼	1.47	0.11	1740	2300

TABLE 6

DATA

MAPLE CYLINDERS

43 lb/ft^3

Particle Size	Area	Volume	Suspension Velocity	Transport Velocity
in.	in^2	in^3	ft/min	ft/min
5/8 dia. x 2	4.54	0.61	2420	2983
5/8 dia. x 1½	3.55	0.46	2460	
5/8 dia. x 1	2.58	0.31	2500	2750
5/8 dia. x 3/4	2.08	0.23	2580	2900
5/8 dia. x ½	1.59	0.15	2500	2833
5/8 dia. x ¼	1.10	0.08	1725	2116
½ dia. x 2	3.53	0.39	2110	2700
½ dia. x 1½	2.74	0.30	2130	2716
½ dia. x 1	1.96	0.20	2240	2666
½ dia. x 3/4	1.57	0.15	2300	2850
½ dia. x 5/8	1.37	0.12	2300	2816
½ dia. x ½	1.16	0.10	2240	2750
½ dia. x ¼	0.79	0.05	1785	2600

TABLE 7

DATA

MAPLE CYLINDERS

43 lb/ft^3

Particle Size	Area	Volume	Suspension Velocity
in.	in^2	in^3	ft/min
3/8 dia. x 2	2.56	0.22	1855
3/8 dia. x 1½	1.99	0.17	1950
3/8 dia. x 1	1.40	0.11	2000
3/8 dia. x 3/4	1.10	0.08	2060
3/8 dia. x 5/8	0.96	0.07	2060
3/8 dia. x ½	0.81	0.06	2060
3/8 dia. x ¼	0.52	0.03	1300

TABLE 7

DATA

MAPLE CYLINDERS

43 lb/ft^3

Particle Size	Area	Volume	Suspension Velocity
in.	in^2	in^3	ft/min
3/8 dia. x 2	2.56	0.22	1855
3/8 dia. x 1½	1.99	0.17	1950
3/8 dia. x 1	1.40	0.11	2000
3/8 dia. x 3/4	1.10	0.08	2060
3/8 dia. x 5/8	0.96	0.07	2060
3/8 dia. x ½	0.81	0.06	2060
3/8 dia. x ¼	0.52	0.03	1300

TABLE 8

DATA

DOUGLAS FIR RECTANGLES

33 lb/ft^3

Particle Size	Area	Volume	Suspension Velocity	Transport Velocity
in.	in^2	in^3	ft/min	ft/min
$1\frac{1}{2} \times 1\frac{1}{2} \times 2$	16.50	4.50	1840	1917
$1\frac{1}{2} \times 1\frac{1}{2} \times 1\frac{1}{2}$	14.50	3.38	1830	2358
$1\frac{1}{2} \times 1\frac{1}{2} \times 1\frac{1}{4}$	12.00	2.82	1630	2566
$1\frac{1}{2} \times 1\frac{1}{2} \times 1$	10.50	2.25	1730	2233
$1\frac{1}{2} \times 1\frac{1}{2} \times 3/4$	9.00	1.68	1710	2383
$1\frac{1}{2} \times 1\frac{1}{2} \times \frac{1}{2}$	7.50	1.13	1590	2000
$1\frac{1}{2} \times 1\frac{1}{2} \times \frac{1}{4}$	6.00	0.56	1160	1616
$1\frac{1}{4} \times 1\frac{1}{4} \times 2$	13.12	3.14	1530	2550
$1\frac{1}{4} \times 1\frac{1}{4} \times 1\frac{1}{2}$	10.62	2.34	1790	2566
$1\frac{1}{4} \times 1\frac{1}{4} \times 1\frac{1}{4}$	9.37	1.90	1820	--
$1\frac{1}{4} \times 1\frac{1}{4} \times 1$	8.12	1.56	1720	2650
$1\frac{1}{4} \times 1\frac{1}{4} \times 3/4$	6.87	1.17	1530	2650
$1\frac{1}{4} \times 1\frac{1}{4} \times \frac{1}{2}$	5.62	0.78	1360	2200
$1\frac{1}{4} \times 1\frac{1}{4} \times \frac{1}{4}$	4.55	0.39	1300	--

TABLE 9

DATA

DOUGLAS FIR RECTANGLES

33 lb/ft^3

Particle Size	Area	Volume	Suspension Velocity	Transport Velocity
in.	in^2	in^3	ft/min	ft/min
1 x 1 x 2	10.00	2.00	1740	2633
1 x 1 x 1½	8.00	1.50	[illegible]	2560
1 x 1 x 1¼	7.00	1.25	[illegible]	2500
1 x 1 x 1	6.00	1.00	1900	2650
1 x 1 x 3/4	5.00	0.75	1850	2410
1 x 1 x ½	4.00	0.50	1740	2000
1 x 1 x ¼	3.00	0.25	1450	
3/4 x 3/4 x 2	7.12	1.12	1550	
3/4 x 3/4 x 1½	5.62	0.84	1730	
3/4 x 3/4 x 1¼	4.88	0.70	1840	
3/4 x 3/4 x 1	4.12	0.56	1900	
3/4 x 3/4 x 3/4	3.37	0.42	2020	
3/4 x 3/4 x ½	2.62	0.28	1730	
3/4 x 3/4 x ¼	1.87	0.14	1400	

TABLE 10

DATA

DOUGLAS FIR RECTANGLES

33 lb/ft^3

Particle Size	Area	Volume	Suspension Velocity
in.	in^2	in^3	ft/min
$\frac{1}{2}$ x $\frac{1}{2}$ x 2	4.50	0.50	1450
$\frac{1}{2}$ x $\frac{1}{2}$ x $1\frac{1}{2}$	3.50	0.38	1540
$\frac{1}{2}$ x $\frac{1}{2}$ x $1\frac{1}{4}$	3.00	0.31	1570
$\frac{1}{2}$ x $\frac{1}{2}$ x 1	2.50	0.25	1620
$\frac{1}{2}$ x $\frac{1}{2}$ x 3/4	2.00	0.19	1680
$\frac{1}{2}$ x $\frac{1}{2}$ x $\frac{1}{2}$	1.50	0.13	1730
$\frac{1}{2}$ x $\frac{1}{2}$ x $\frac{1}{4}$	1.00	0.06	1450

TABLE 11

DATA

DOUGLAS FIR TRIANGLES

33 lb/ft^3

Particle Size	Area	Volume	Suspension Velocity	Transport Velocity
in.	in	in	ft/min	ft/min
1 3/4 x 2	12.16	2.66	1460	
1 3/4 x 1½	10.51	2.00	1540	
1 3/4 x 1¼	9.22	1.66	1635	
1 3/4 x 1	7.91	1.33	1840	
1 3/4 x 7/8	7.20	1.14	2020	
1 3/4 x 3/4	6.54	0.98	2020	
1 3/4 x 5/8	5.88	0.82	1690	
1 3/4 x ½	5.22	0.65	1590	
1 1/2 x 2	10.95	1.95	1500	2633
1 1/2 x 1½	8.70	1.46	1590	2500
1 1/2 x 1¼	7.57	1.22	1620	2350
1 1/2 x 1	6.45	0.98	1730	2600
1 1/2 x 7/8	5.85	0.84	1900	2583
1 1/2 x 3/4	5.29	0.72	1900	2333
1 1/2 x 5/8	4.72	0.60	1690	2400
1 1/2 x ½	4.16	0.48	1690	

TABLE 12

DATA

DOUGLAS FIR TRIANGLES

33 lb/ft^3

Particle Size	Area	Volume	Suspension Velocity	Transport Velocity
in	in^2	in^3	ft/min	ft/min
1 3/8 x 2	[illegible].39	1.60	1390	2650
1 3/8 x 1½	7.[illegible]4	1.20	1530	2500
1 3/8 x 1¼	6.[illegible]0	1.00	1565	2616
1 3/8 x 1	5.7[illegible]	0.[illegible]0	1640	25[illegible]3
1 3/8 x 7/8	[illegible].21	0.70	1690	2266
1 3/8 x 3/4	4.70	0.60	1730	2450
1 3/8 x 5/8	4.13	0.50	1790	2566
1 3/8 x ½	3.66	0.40	1590	2100
1 1/4 x 2	[illegible].85	1.35	1465	2616
1 1/4 x 1½	6.99	1.01	1590	24[illegible]3
1 1/4 x 1¼	6.04	0.85	1610	2466
1 1/4 x 1	5.10	0.68	1690	2666
1 1/4 x 7/8	4.60	0.57	1790	2633
1 1/4 x 3/4	4.14	0.49	1790	2550
1 1/4 x 5/8	3.66	0.41	1[illegible]50	2316
1 1/4 x 1/2	3.20	0.33	1690	

TABLE 13

DATA

DOUGLAS FIR TRIANGLES

33 lb/ft

Particle Size	Area	Volume	Suspension Velocity
in.	in^2	in^3	ft/min
1 1/8 x 2	7.[illegible]5	1.10	1390
1 1/8 x 1½	6.16	0.82	1463
1 1/8 x 1¼	5.32	0.69	1515
1 1/8 x 1	4.47	0.55	1640
1 1/8 x 7/8	4.01	0.47	1730
1 1/8 x 3/4	3.60	0.40	1730
1 1/8 x 5/8	3.18	0.33	1790
1 1/8 x ½	2.76	0.27	1790
1 x 2	6.[illegible]7	0.[illegible]7	1385
1 x 1½	5.37	0.65	1475
1 x 1¼	4.62	0.54	1590
1 x 1	3.[illegible]7	0.43	1590
1 x 7/8	3.47	0.37	1670
1 x 3/4	3.10	0.32	1690
1 x 5/8	2.[illegible]2	0.27	1640
1 x ½	2.35	0.21	1730

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