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Application of air flow measurements to the determination of cotton fiber specific surface area and maturity

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To the Graduate Council:

I am submitting herewith a thesis written by William Paul Hawkins entitled "Application of air flow measurements to the determination of cotton fiber specific surface area and maturity." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biosystems Engineering.

Z. A. Henry, Major Professor

We have read this thesis and recommend its acceptance:

K. E. Duckett, Smith Worley

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

August 22, 1974

To the Graduate Council:

I am submitting herewith a thesis written by William Paul Hawkins entitled "Application of Air Flow Measurements to the Determination of Cotton Fiber Specific Surface Area and Maturity." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Agricultural Engineering.

Zachary A. Henry
Z. A. Henry, Major Professor

We have read this thesis
and recommend its acceptance:

Kermit E. Duckett

Smith Worley, Jr

Accepted for the Council:

Hilton A. Smith
Vice Chancellor
Graduate Studies and Research

APPLICATION OF AIR FLOW MEASUREMENTS TO THE DETERMINATION OF COTTON FIBER SPECIFIC SURFACE AREA AND MATURITY

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee

William Paul Hawkins
December 1974

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My wife, Paula, was very patient and supportive throughout this endeavor.

To all go my deepest gratitude.

ABSTRACT

An instrumentation system and measurement techniques were developed to determine if the relationships for specific surface area and maturity used with the Arealometer were applicable to a system using a larger specimen size and random fiber orientation. Air flow resistance was determined for various varieties with a wide range of specific surface area and maturity. Fiber orientation effects were found to be negligible and the optimum specimen plug lengths and air flow rate were determined. It was concluded that the Arealometer flow equation performed satisfactorily with the experimental system, providing compatible specific surface area values and indications of maturity.

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A = Cross-sectional area of the chamber.

A' = Cross-sectional area open to flow.

C_n = Constant of proportionality.

D = Diameter of the pipe.

$F(\ )$= Denotes a functional relationship.

K = Dimensionless constant (K_o/ζ).

K_o = Shape factor.

L = Length of the medium.

L_e = Average distance the fluid travels in the medium.

M = Mass of the medium.

Q = Volumetric flow rate.

R = Resistance to air flow $(\Delta P/Q)$.

R_{ey} = Reynolds number.

S = Chamber wall surface area per unit volume.

S_o = Surface area per unit volume (specific surface area) of the medium.

V_m = Mean fluid velocity.

a = Average grain diameter.

b_n = Coefficient of a regression equation.

d = Average porespace diameter.

d_h = Hydraulic radius, or ratio of void volume to surface area.

f = Friction factor.

g = Acceleration due to gravity.

k = Coefficient of a regression equation.

v = Fluid velocity in a pipe.

ΔP = Pressure drop across the medium.

ε = Porosity, or ratio of void volume to total volume.

ζ = Orientation factor.

θ = Wall surface correction factor.

μ = Viscosity of the fluid.

ρ = Density of the fluid.

ρ_m = Density of the medium.

ϕ = Angle between the direction of macroscopic flow and the normal to the surface in contact with the fluid.

CHAPTER I

INTRODUCTION

Background

The physical properties of cotton fibers have gained additional significance as the textile field has attempted to keep up with today's advanced technology. Two of these properties are specific surface area and maturity. The specific surface area is the external surface area per unit volume of the fibers. Fiber maturity is a term which can be measured in several ways, all of which originate from the development of the fiber cell. In the early stages, cotton fibers consist of a single cell having approximately the length and perimeter of the final fiber (Balls, 1915 and 1928). Successive layers of cellulose are deposited along the inside surface of the cell membrane. The fiber cavity is never completely filled and therefore collapses upon drying, causing the fiber to appear as a flattened tube. Maturity is defined as the degree of cell wall development (ASTM Standard D 1442, 1970).

Specific surface area is an indication of fiber fineness and has a significant effect on yarn strength. Maturity is important to the strength and workability of the fiber. More mature fibers are stronger and tend to be easier processed than less mature ones. Knowledge of both of these properties allows the calculation of other useful geometrical parameters such as average wall thickness and cross-sectional perimeter.

Many attempts have been made to evaluate the above parameters. Some procedures claim to indicate fineness and others maturity. The measurements from some procedures have been found to be dependent on both fineness and maturity. For this and other reasons the usefulness of these methods has been questioned.

The Arealometer

The Arealometer (Hertel and Craven, 1951) is one method of measuring both specific surface area and maturity. Morton *et al*. (1954) found that this laboratory instrument measures both physical properties with good precision, even when compared to very laborious methods. It operates on the principle that the resistance to air flow through a bed of porous media is a function of the specific surface area of the media in contact with the air. The measurement of specific surface area is made by determining the length to which a plug of cotton must be compressed to have a certain resistance to air flow. An indication of maturity is obtained by measuring the difference in specific areas at two levels of resistance. This increase in specific area at higher compressions is attributed to rotation of the fibers within a plane perpendicular to the direction of flow. Less mature fibers are flatter and therefore provide a greater increase in resistance when compressed to this perpendicular orientation than do the more mature fibers. A diagram of the Arealometer system is shown in Figure 1. Figure 2 shows the instrument as manufactured by Special Instruments Laboratory, Inc., Knoxville, Tennessee.

The advantage of the Arealometer over other instruments is that it provides an indication of specific surface area and maturity independent of each other. These two properties are somewhat related within a

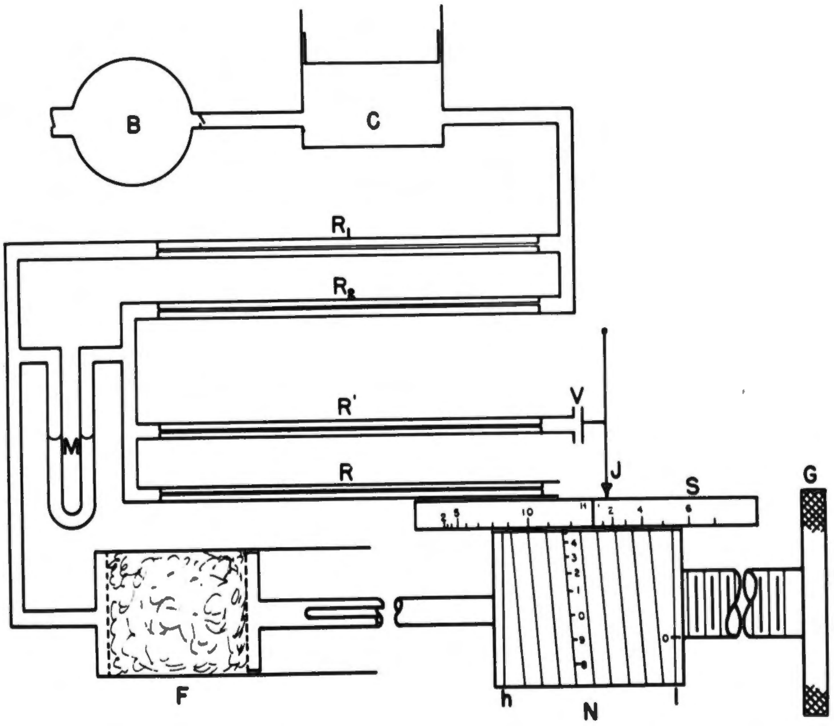

Figure 1. Diagram of the Arealometer.

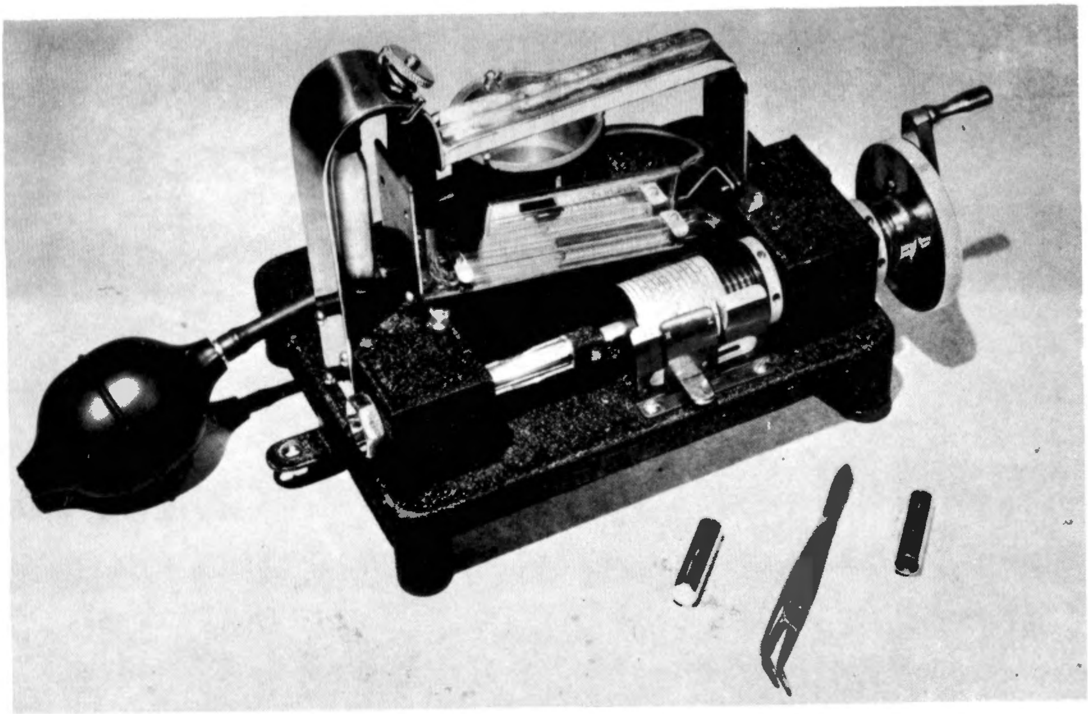

Figure 2. Photograph of the Arealometer.

species due to the geometry of the cotton fiber, but this relationship does not hold across species (Clegg, 1932 and Pierce *et al*., 1939). Instruments have been developed which produce a reasonable indication of fineness within a species, but the calibration must be changed to be used with another species. The Arealometer, however, has been found to operate very well for most conditions.

The instrument has several disadvantages, the primary one being its rate of testing. The specimen used is very small (152 ± 0.5 mg), requiring very high accuracy in weight measurements. Extensive specimen preparation is also required for reproducible results. Both of these are extremely time consuming. Because the compression is done by hand, variation in rate of compression introduces operator error in the system. The effect of the chamber wall surface on the reading is thought to be significant. Other problems, such as the delicate nature of the instrument, also add to the problems associated with its general use.

Objectives

A new instrumental design has been suggested which might eliminate some of the disadvantages of the Arealometer. It would consist of enlarging the present system to accept a much larger specimen. The operator error in the weighing step should be reduced and much of the specimen preparation could be eliminated. A larger chamber might also reduce the effect of the chamber wall on the measurement, since the chamber wall surface area would be a much lower portion of the total surface area exposed to the air. Automation of the system might include mechanisms to produce constant rates of compression and control devices to coordinate the proper events. Direct computer input could eliminate the need for the mass to be held constant. All of these modifications should result in a much faster, simpler, and more effective instrument.

The development of such an instrument from conception to final product was a task much greater than that which could be accomplished in this research effort. The objectives of this project were:

1. To establish that the relationships between the air flow parameters and the physical properties of cotton fibers were applicable for the proposed system.
2. To develop the basic elements of an instrumentation system, along with methods and techniques which might be used to reduce the disadvantages presented by the Arealometer.

CHAPTER II

REVIEW OF LITERATURE

The Importance of Specific Surface Area and Maturity

Specific surface area is directly proportional to fineness and is a good fineness index. For a particular size of yarn, finer fibers have higher interfiber friction as a result of increased surface area available for contact (Hertel and Lawson, 1970). This improves the regularity and strength of yarns as well as the smoothness of the fabrics (ATIRA, 1960). Fabric flexibility is directly dependent on the fineness of the fibers from which the fabric is made. The dyeing characteristics are also affected. Fabrics made of finer fibers tend to have a better cover and lower luster, but they also require more dye and have less resistance to abrasion (Finlayson, 1946). Leigeb *et al.* (1956) studied the effect of fineness on processing and fabric quality and concluded that the finer cottons showed definite advantages in all areas considered except the formation of neps.

Fineness also affects the fabric insulation properties. Because the thermal conductivity of cotton is approximately 24 times greater than that of air, fabrics with lower bulk density will also have lower conductivity. Maximum exposure of fiber surfaces to the air will increase the resistance to air passing through the fabric because the layer of air in immediate contact with the surface of the fiber is at rest (Cassie, 1946). Both factors are maximized with high fiber specific surface areas. The large fiber surface also insures that the moisture content of the fabric will adjust rapidly to the atmospheric conditions. This process either produces or absorbs heat, which in turn helps damp the effect of sudden heat and humidity changes on the person wearing the fabric. A fabric made from coarser fibers will react more slowly and thus the damping effect will be much smaller.

The maturity of the cotton is important because it affects yarn strength, carding and spinning characteristics, and nep formation. Mature fibers also withstand the action of heat and chemicals better than immature fibers (Pattee, 1934). It is also important in the ease of cleaning, the yarn appearance, and the dyeing behavior (ASTM Standard D 1442, 1970).

Sometimes it is necessary to know both of these properties. It is generally accepted that the perimeter is largely a genetic factor and remains generally constant within a species (Clegg, 1932 and Pierce _et al_., 1939). If this is true any of the fiber geometrical properties, such as the linear density, the specific surface area, the wall thickness, the amount of filling (maturity), or the perimeter can be calculated geometrically by knowing any two others. Relationships were developed empirically by Hertel and Craven (1951) from which each quantity can be calculated from two of the others. In their study of light-absorption as a measure of linear density, Krowicki and Duckett (1972) have shown that the slope of the mass versus absorption curves is dependent on the average radial cross-sectional area of the fibers. This information can also be calculated from any two of these quantities.

Measurement of Specific Surface Area and Maturity

Air flow resistance is the only practical method of measuring specific surface area at the present time. It is possible that the method of gas absorption (Brunauer et al., 1938 and Emmett et al., 1941) might be used, but it has not been proven effective for use with fibers. A microscope can be used to measure specific surface area, but this requires preparing and mounting fiber cross-sections on slides, which in itself is a very tedious process.

Grimes (1942) developed an air flow instrument which measured linear density, but the laboratory device was not developed for wider distribution. Pfeiffenberger (1946) also developed an instrument to measure linear density which seemed to work relatively well. Elting and Barnes (1948) developed a fineness tester which produced a "fineness index." This index was proportional to the resistance to air flow but had no physical significance other than to be an indication of fineness.

The Micronaire (ASTM Standard D 1448, 1970) is a widely used instrument which applies the principles of air flow to obtain an indication of fiber fineness known as "Micronaire Units." The basis for the calibration of this instrument is mostly empirical and the physical significance of the units is not clear because they involve both the maturity and linear density of the fibers (Lord, 1956a). For this reason this instrument cannot be used across species without recalibration. The Port-Ar (Special Instruments Laboratory, Inc., 1962) and the Fibronaire (Motion Control, Inc., 1968) operate on the same principle as the Micronaire. The WIRA Fineness Meter (ATIRA, 1960) is basically the same type of instrument. The ATIRA Fineness Tester (ATIRA, 1960) claims to measure the maturity-linear density product very well for any species of cotton, but is unable to measure either property separately.

The Arealometer (Hertel and Craven, 1951), as previously discussed, provides a very good measurement of specific surface area (Morton _et al_., 1954). The Speedar was developed by Hertel and Craven (1955) to provide a more rapid indication of specific surface area than obtained from the Arealometer. This instrument eliminates the weighing step, does not require fiber orientation, and uses a large specimen in comparison to the Arealometer. Although it measures specific surface area relatively well, it does not indicate maturity.

Maturity is very hard to measure other than by the use of cross-sections and a microscope. Most methods which claim to be measuring maturity are actually measuring wall thickness, which is proportional to maturity only for constant perimeters. Although the average perimeter of varieties within a species is relatively constant there is considerable variation from fiber to fiber, and therefore estimations of maturity from the wall thickness of individual fibers is not entirely correct.

The Causticaire Method (Lord, 1956b and ASTM Standard D 2480, 1970) consists of running the Micronaire test before and after the sample has been treated with sodium hydroxide. From this it is possible to obtain an indication of maturity and linear density. However, the use of the Micronaire introduces the bias of this instrument into the Causticaire Method, causing it to produce biased results in general use.

The Sodium Hydroxide Swelling Method for measuring maturity (ASTM Standard D 1442, 1970) is based on the principle that cotton fibers will react differently according to their maturity when swollen in sodium hydroxide. This difference is observed through a microscope and an indication of the maturity of the fibers is obtained. This method is often used as a standard of comparison for other maturity measurements.

The Polarized Light Method for measuring maturity (Pattee, 1934 and ASTM Standard D 1442, 1970) uses the principle that the wall thickness of the fiber affects the interference colors when viewed between crossed polarizers. The maturity can therefore be estimated by the color of the fibers. This method shows finer distinctions between different stages of maturity than does the Sodium Hydroxide Method. However, the latter is more often used because only a single indication of maturity is generally needed. The polarized light method requires a more careful, subjective judgment. Dischka (1958) developed the "Cotton Grader," another instrument which uses polarized light to obtain an indication of maturity.

Chapman and Staten (1957) reported obtaining an indication of maturity from the difference in Micronaire readings at two levels of compression. Craven and Lawson (1974) found that this was probably another indication of fineness and not maturity.

The Flow Relationships

The relationships used today for fluid flow through porous media are based on the following equation developed empirically by Darcy (Muskat, 1946) for the flow of water through sand:

$$Q = C_1 A \frac{\Delta P}{L} , \qquad (1)$$

where Q = volumetric flow rate,

C_1 = constant of proportionality,

A = cross-sectional area of the chamber,

ΔP = pressure drop across the medium, and

L = length of the medium.

Most of the relationships derived since Darcy's time include this basic relationship. Slichter (1897-98) developed an equation theoretically by considering the geometry of the porespaces in a bed of spheres. The resulting flow equation was

$$Q = C_2 A \frac{\Delta P}{L} \frac{a}{\mu F(\varepsilon)} , \qquad (2)$$

where C_2 = constant of proportionality,

a = average grain diameter,

μ = viscosity of the fluid,

F()= denotes a functional relationship,

ε = porosity, or ratio of void volume to total volume, and

others as previously defined.

This relationship was the basis for the work done by Schriever (1930). Carman (1937 and 1938a) began with Darcy's law and developed an equation which had been derived theoretically by Kozeny (Wiggins _et al._, 1939). This equation was

$$Q = \frac{\Delta P}{L} \frac{g}{\mu} \frac{A}{C_3} \frac{1}{S_o^2} \frac{\varepsilon}{(1-\varepsilon)^2} , \qquad (3)$$

where g = acceleration due to gravity,

C_3 = constant of proportionality,

S_o = surface area per unit volume (specific surface area) of the medium, and

others as previously defined.

Several others have used this result as a basis for their work (Lea et al., 1939 and Wiggins et al., 1939). Fair and Hatch (1933) began with the basic equation for flow in a pipe,

$$\frac{\Delta P}{L} = \frac{C_4}{g} \frac{\mu}{\rho} \frac{v}{D^2} \quad , \qquad (4)$$

where C_4 = constant of proportionality,

ρ = density of the fluid,

v = fluid velocity in a pipe,

D = diameter of the pipe, and

others as previously defined,

and developed an equation for the flow of water through sand. Their resulting equation was

$$Q = C_5 \frac{\Delta P}{L} \frac{g\ \rho}{\mu} \frac{\varepsilon^3}{(1-\varepsilon)^2} \frac{A}{S_o^2} \quad , \qquad (5)$$

where C_5 = constant of proportionality, and

others as previously defined.

This was again the Kozeny equation. Basically the same equation was developed by Sullivan (1941 and 1942). Sullivan divided the proportionality constant (C_5) into an orientation factor (ζ) and a shape factor (K_o). This equation was

$$Q = \frac{\zeta}{K_o} \frac{\Delta P}{L} \frac{1}{\mu} \frac{\varepsilon^3}{(1-\varepsilon)^2} \frac{A}{S_o^2} \quad . \qquad (6)$$

Dimensional analysis has been used to develop a relationship for flow through porous media (Sullivan and Hertel, 1940b). The dimensionless number called a friction factor,

$$f = \frac{1}{2} \frac{d \, \Delta P}{\rho \, L \, V_m^2} \quad , \qquad (7)$$

where f = friction factor,

V_m = mean fluid velocity, and

others as previously defined,

has been found to be proportional to Reynolds number. From this relationship the following equation was derived:

$$Q = C_6 \, A' \, \frac{d^2}{\mu} \, \frac{\Delta P}{L} \quad , \qquad (8)$$

where C_6 = constant of proportionality,

A' = cross-sectional area open to flow, and

others as previously defined.

Substituting for the diameter and flow rate the relationships for hydraulic radius and microscopic flow rate developed by Fair and Hatch (1933) and others, this again becomes the Kozeny equation (Equation 6).

Many researchers have found validity in either part or all of the Kozeny equation. The first part considered was the basic structure, $Q = A \, \Delta P/L$, which is Darcy's law. Muskat (1946), in his discussion of the applications and limitations of Darcy's law, concluded that within the limitation of laminar flow it provided good results. Slichter (1897-98), Schriever (1930), and Smith (1932) developed relationships for flow through porous media which corroborated the results of Darcy. The work of Bakhmeteff _et al_. (1937) and of Lord (1955) also confirmed this relationship.

Muskat (1937) showed that Darcy's law applied when the Reynolds number was between certain minimum and maximum values. Hatfield (1939) studied this relationship over very large ranges of fluid density, viscosity, sample thickness, pore diameter, pressure drop, and flow rate, and found it to be true up to a point where inertial forces became effective, causing turbulence. His results showed the transition beginning at a Reynolds number of 4.0. Carman (1937) found that the flow began showing turbulence at a Reynolds number of about 2.0. Carman (1937) and King (1897-98) found that at very low velocities the proportionality between pressure drop and flow rate did not hold. This was attributed to the formation of stagnant rings at the points of contact between particles, or layers of fluid around the particles. Most of the work done with fluid flow through porous media has either assumed or proved Darcy's law to be acceptable.

The porosity, defined as the ratio of void volume to solid volume, has been found in the studies of several people to be a very significant parameter. Donat (Carman, 1937) found that the porosity factor $\varepsilon^3/(1-\varepsilon)^2$ was applicable over a porosity range of 0.45 to 0.54 for a flint sand. Carman (1938a and 1939) compiled data for several materials with a porosity range of 0.26 to 0.90 and concluded that the relationship is sufficiently accurate. Hatch (1940) was successful in using the porosity function in his studies of the viscous flow of water through sand beds of porosities in the range of 0.324 to 0.437. However, in his tests for the individual effect of this function, he was not able to obtain accuracy as high as that claimed by Carman (1938a and 1940). According to Lord (1955), the porosity function was good up to a porosity of 0.85 or 0.90. Bakmeteff *et al*. (1937) found

Darcy's permeability constant to be proportional to $\varepsilon^{1.25}$ rather than $\varepsilon^3/(1-\varepsilon)^2$. Craven, Fowler, Hertel, and Sullivan have used the porosity function successfully throughout their work on fluid flow through fibers (Fowler, et al., 1940; Sullivan and Hertel, 1940a, 1940b, and 1942; Sullivan, 1941 and 1942; and Hertel and Craven, 1951 and 1955).

Carman (1938a) used data from Schriever (1930) to show that the flow rate is inversely proportional to the square of specific surface area. He also stressed that assuming a constant shape factor and the inverse squared specific surface relationship the variation between observed and calculated values of specific surface was within the limits of experimental error. Sullivan and Hertel (1940a) found that for plugs of cotton fibers in the porosity range of 0.665 to 0.89 the assumption that the flow rate was inversely proportional to the square of the specific surface predicted this parameter with the same accuracy as microscopic measurements. Hertel and Craven (1951) applied this relationship in developing the Arealometer and obtained specific area measurements with a 2% coefficient of variation. Lord (1955) concluded that for plugs in the medium porosity range the relationship holds true but that this is not the case for all values of plug density. Sullivan (1941) found that as the value of porosity increased above 0.90 the exponent of S_o dropped off to a value lower than 2.0. He attributed this to the shape factor increasing in this range of porosity.

Sullivan and Hertel (1940a) indicated that theoretically the value of K (K_o/ζ in Equation 6) should approximate $3/(\sin^2\phi)_{av}$, where the denominator is the average square of $\sin\phi$, and ϕ is the angle between the direction of macroscopic flow and the normal to the surface in contact with the fluid. They concluded that the value of $(\sin^2\phi)_{av}$ should be 2/3 for a bed of spheres, 1 for flow parallel to the axis of a bed of cylinders, and 1/2 for flow perpendicular to a bed of cylinders. Therefore K should have a value of 4.5, 3.0, and 6.0, respectively. Their results showed K to be 4.5 for spheres, 3.07 for fibers parallel to flow, and 6.04 for fibers perpendicular to flow. Donat (Carman, 1937) found that for the flow of water through beds of glass spheres the value of K was 5.2. Fowler and Hertel (1940) found that for the flow of air through plugs of textile fibers the value of K was 5.55. For fibers with porosities in the range of 0.665 to 0.890 being compressed in the direction of flow Sullivan and Hertel (1940a) found the value of K to be 6.3. Lord (1955) found K to hold relatively constant up to a porosity of about 0.85 or 0.90, after which it began to increase as porosity increased. Considering it as the ratio of a shape factor and an orientation factor $(K = K_o/\zeta)$, Hertel and Craven (1951) found that the correlation between specific surface area and plug length was relatively insensitive to a shape factor variation from 2.55 to 2.90. Sullivan (1941 and 1942) found that the shape factor was constant at about 3.0 up to a porosity of about 0.87. High porosities caused the shape factor to increase. Carman (1937, 1938a, 1938b, and 1939) reviewed the work of several people and found that the value of K should be 5.0.

Lord (1955) concluded that the wall effect was negligible at low porosities, but at high values of porosity it became an appreciably higher proportion of the total surface area. Carman (1938a) determined that the wall surface friction contributed an appreciable amount to the observed value of specific surface only when the particle diameter was an appreciable fraction of the container diameter. In this case he suggested that the observed specific surface was the actual specific surface plus the function $2/(D_c(1-\varepsilon))$, where D_c is the diameter of the chamber. Sullivan and Hertel (1940b) found that the observed specific area was the actual value plus the function $\theta\ S/(1-\varepsilon)$, where θ is a wall surface correction factor and S is the surface per unit volume of the chamber. The value of θ was found to be 0.667 for the conditions of their experiment, but would be expected to vary with different conditions.

Equation 6 was used by Hertel and Craven (1951) in the development of the Arealometer. By rearranging this equation into the form

$$S_o^{\ 2} = \frac{\Delta P}{Q}\ \frac{1}{L}\ \frac{\varepsilon^3}{(1-\varepsilon)^2}\ \frac{1}{K}\ \frac{A}{\mu} \quad , \qquad (9)$$

where $K = K_o/\zeta$, and

others as previously defined,

an equation was obtained for specific surface area in terms of the other parameters. The porosity was defined as

$$\varepsilon = 1 - \frac{M}{\rho_m\ A\ L} \quad , \qquad (10)$$

where M = mass of the medium,

ρ_m = density of the medium, and

others as previously defined,

and the porosity function became

$$\frac{\varepsilon^{\ 3}}{(1-\varepsilon)^2} = \frac{(\rho_m\ A\ L - M)^3}{\rho_m\ A\ L\ M} \quad . \qquad (11)$$

Substituting this into Equation 9 and replacing $\Delta P/Q$ by R, the resistance of the medium, the following equation was obtained:

$$S_o^{\,2} = \frac{R}{K} \; \frac{(\rho_m \, A \, L - M)^3}{L^2 \, \rho_m \, M \, \mu} \quad . \tag{12}$$

All of the terms in the equation (except S_o) were then either measurable or could be held constant. Therefore the Arealometer was designed to hold everything constant except the plug length. Specific surface area was calculated from the length at which the set resistance was obtained.

CHAPTER III

RESEARCH METHODS AND INSTRUMENTATION

The first objective of this study was to determine if the Arealometer relationship for specific surface area and maturity in terms of air flow parameters (Equation 12) could be used with a system using a larger specimen of cotton than that used with the Arealometer. The air flow parameters of interest were pressure drop across and flow rate through a plug of cotton, from which resistance was calculated ($R = \Delta P/Q$). Other variables considered were plug length and fiber orientation. The laboratory equipment necessary consisted of a variable plug length specimen chamber adapted to pass air evenly through the plug and appropriate pressure and flow monitoring devices. Figure 3 is a diagram of the experimental system and Figure 4 shows a picture of the laboratory set-up.

Design Considerations

The porosity range of the Arealometer (0.63 to 0.85) was maintained in order to prevent significant variation in the shape factor (Sullivan, 1941 and 1942). A flow range of 400 to 1300 cc/min was chosen in an attempt to stay within the laminar range, since previous work was based on this restriction. The ratio of plug length to diameter was kept around 1:1. This was desired because both structural and flow problems arise as the ratio is extended beyond this point. With high length to diameter ratios the chamber wall surface area becomes a large part of the total exposed area, which increases the wall effect on the

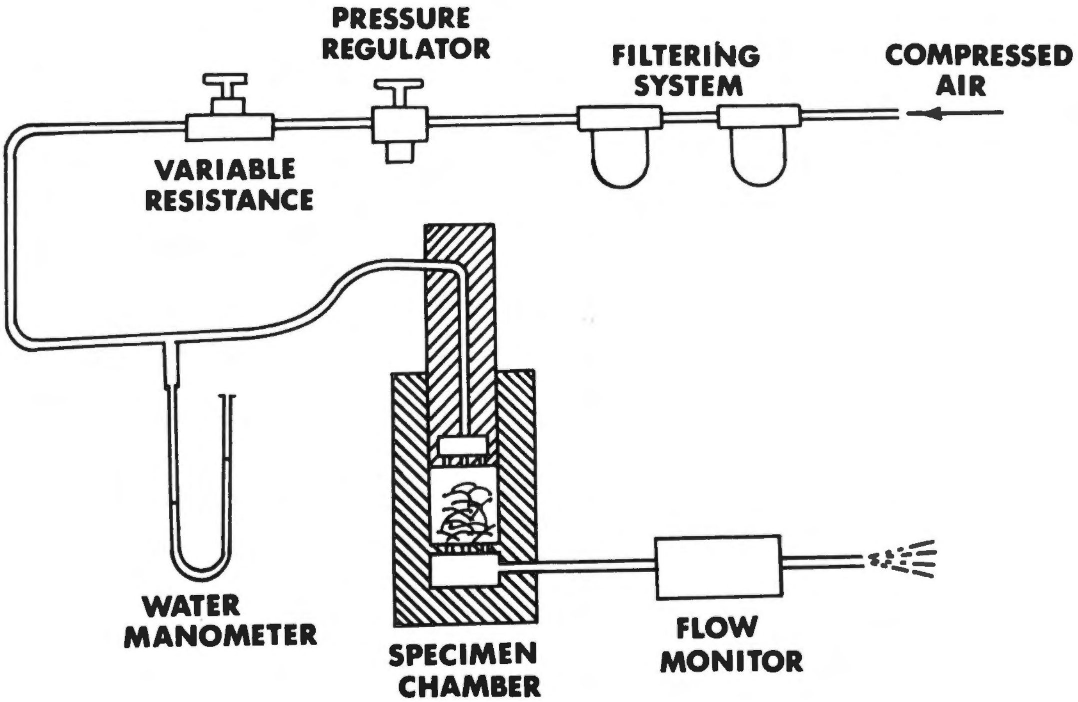

Figure 3. Diagram of the experimental system.

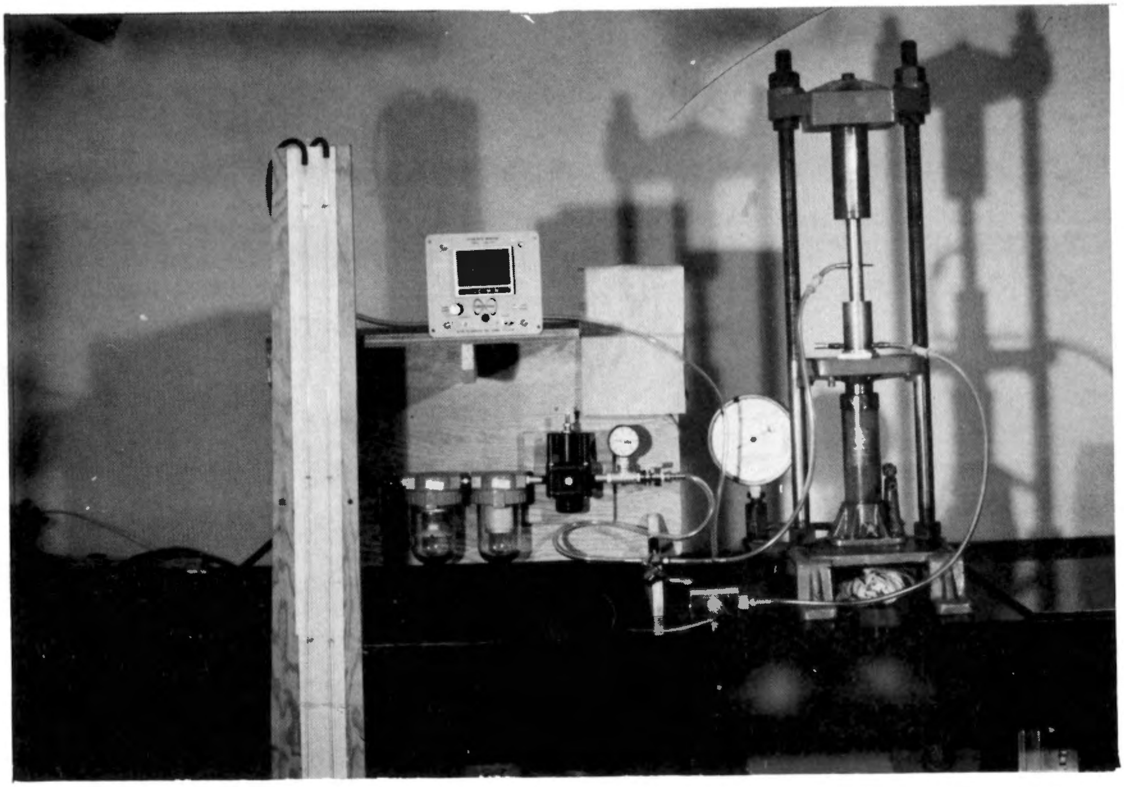

Figure 4. Photograph of the experimental system.

resistance. With low ratios the specimen becomes a disk, which increases the tendency for the air to be channeled through certain points in the specimen rather than to pass evenly throughout the cross-section. This ratio ranges from 2:1 at maximum plug length to 1:1 at minimum length for the Arealometer. A range from 1.5:1 to 0.5:1 was used in this study. A specimen chamber diameter of 25.4 mm was arbitrarily chosen.

The specimen size and compression range were calculated by combining the known porosity range, length to diameter ratios, and chamber diameter. The plug size chosen was 4.25 grams and this resulted in a plug length range from 36 to 14 mm. Therefore the porosity range was 0.61 to 0.85, roughly that of the Arealometer.

Instrumentation

Four basic components were required for the system: (1) a source of compressed air, (2) a specimen chamber with variable plug length, (3) a flow monitoring instrument, and (4) a pressure monitoring instrument (see Figures 3 and 4). An industrial air compressor which varied from 30 to 70 psi (206.8 to 482.6 kPa) was used with a pressure regulator adjustable from 0.5 to 30 psi (3.4 to 206.8 kPa). The filter system placed in the high pressure line consisted of two filtering elements which removed particles of solids as well as droplets of oil and water as small as 0.3 μm.

The specimen chamber consisted of a brass cylinder and piston designed to provide variable plug length. The cylinder was 70 mm long with a 25.4 mm diameter, and the piston was 165 mm long with a 25.4 mm diameter. It was fitted with an "o" ring to prevent air from escaping between it and the cylinder. Air was passed through holes down the center of the piston into the chamber. The ends were perforated to minimize chamber resistance and to allow air to pass through evenly across the entire specimen. Graduations on the side of the piston provided a means of measuring the plug length. The system was designed to be hydraulically compressed because of the tightness of fit of the piston and the large quantity of cotton being compressed. Figure 5 is a photograph of the specimen chamber.

The flow rate was measured using an Omniflo turbine flow transducer and monitor from Flow Technology Incorporated calibrated for a range of 300 to 1300 cc/min. The pressure was measured by a 1250 mm of water (12.3 kPa) manometer which was built in the laboratory. This was connected across the chamber and a correction factor was applied to remove from the reading the drop due to the chamber itself. The values used were therefore due only to the pressure drop across the cotton specimen.

Experimental Design

The dependent variable in this study was the resistance to air flow through a plug of cotton fibers. The independent variables were: (1) cotton variety, (2) fiber orientation, (3) flow rate, and (4) plug length.

Cottons with as wide a range of specific surface area and maturity as possible were used because these were the parameters which were to be determined from the resistance data. Samples of

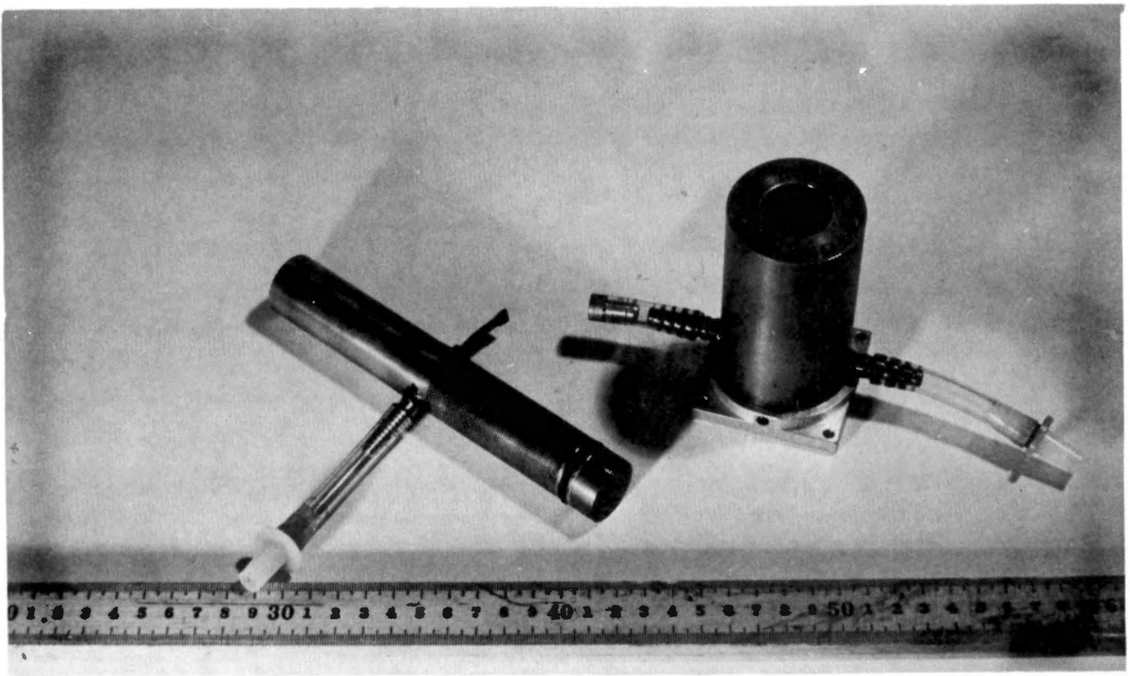

Figure 5. Photograph of the specimen chamber.

seven varieties, covering a wide range of fineness and maturity, were chosen from a set of fineness standards for which extensive Arealometer data was available. A possible disadvantage of using these samples was that a high correlation existed between specific surface area and maturity. Table 8, Appendix A, shows the Arealometer data for these cottons. These samples were carded and folded into laps of approximately 50 grams (Landstreet _et al_., 1962). These were stored in a laboratory which was maintained at 72°F and 55% relative humidity.

Fiber orientation relative to the direction of air flow was considered because it was known to affect Arealometer values. If it were determined in the present work that orientation of the fibers was not necessary for reproducible results a much simpler and faster system could be developed. Two fiber orientations were considered. The samples had been partially oriented due to the carding process. The oriented specimens were obtained by tearing from the lap a strip perpendicular to the direction of carding and rolling it up so that the fibers would be partially oriented parallel to the direction of flow. The random specimens were obtained by simply pulling plugs from the lap and placing them in the chamber in a random fashion.

Flow rate was considered for two reasons. The first was to determine that the range of flows used was in the laminar range. The second was to determine if variation in flow rate would affect the resistance, and, if so, which level would be most suitable. The following four flow rates were chosen: 400, 700, 1000, and 1300 cc/min.

Plug length was known to have a large effect on the resistance because for a given size specimen porosity is a function of plug length.

It was therefore desirable to observe the resistance at a large number of plug lengths within the range chosen. Twelve plug lengths were chosen at 2 mm increments from 36 to 14 mm.

The specimens were prepared and placed in the chamber as discussed above, and compressed to a plug length of 36 mm. The flow rate was varied by use of the variable resistance in the air line (see Figure 3, page 20), and the pressure drop was read at each of the four chosen flow rates. The specimen was then compressed to the next plug length, and the pressures again read. This procedure was followed through the 14 mm plug length. Two specimens were used at each orientation. The 2 replications, 2 orientations, 4 flow rates, 12 plug lengths, and 7 varieties resulted in a possible 1344 data points. A few of these were not obtained, however, because the pressure was too high for the manometer being used.

When equations had been developed to predict specific surface area and maturity, and conclusions had been drawn concerning operating levels of the independent variables, resistance data was taken on a new set of cotton samples in order to verify the conclusions made from the first set. Arealometer data for this second set of cottons is shown in Table 8, Appendix A.

Statistical Analysis

The analysis for this study consisted of several parts. The first was to determine that the flow rates were in the laminar range. This was done by the method of dimensional analysis, as developed by Hatfield (1939) and Sullivan and Hertel (1942). This method consisted of a logarithmic plot of the dimensionless friction factor,

$$f = \frac{2\ d\ \Delta P}{\rho\ L_e\ V_m^{\ 2}} \quad , \qquad (13)$$

where f = friction factor,

d = average porespace diameter,

ρ = density of the fluid,

L_e = average distance the fluid travels,

V_m = mean fluid velocity, and

others as previously defined,

agains Reynolds number, R_{ey}, defined as

$$R_{ey} = \frac{\rho\ d\ V_m}{\mu} \quad . \qquad (14)$$

For laminar flow this plot has been shown to be a straight line of slope -1. Due to the difficulties in calculation of the average porespace diameter, d, this quantity was replaced by the hydraulic radius, which was defined by Fair and Hatch (1933) as

$$d_h = \frac{1}{S_o}\ \frac{\varepsilon}{1-\varepsilon} \quad . \qquad (15)$$

The average distance of fluid travel (L_e) was defined as $L_e = \sqrt{2}\ L$, and the mean fluid velocity as

$$V_m = \frac{Q}{A}\ \frac{1}{\varepsilon}\ \frac{L_e}{L} \quad , \qquad (16)$$

as suggested by Carman (1937).

The next step in the analysis was to determine the effects of the independent variables on the dependent variable. Due to the large volume of data, it was suggested by Sanders (1974) that if a regression equation could be developed to fit a large number of data points the analysis could be simplified. This procedure was used by Wishart (1938) and Box (1950) to reduce the amount of data without sacrificing the precision given by the larger number of points available. The idea was to use the coefficients of the regression equations rather than individual data points in the analysis. Such an equation was desired between the dependent variable, resistance, and an independent variable which was known to have a significant effect on resistance. An equation for resistance as a function of plug length was sought because this would eliminate one variable (plug length) from the analysis, and would reduce 12 sets of data points to the number of coefficients in the equation. These coefficients were then used in analyses of variance to test for the significance of the independent variables.

The specific surface area was determined by using the Arealometer flow equation (Equation 12, page 18). It was not known if the shape factor and orientation factor used with the Arealometer would be applicable for this situation. Therefore, it was necessary to use the specific surface values from the Arealometer along with the resistance and plug length data in order to calculate the ratio of these two constant factors.

The Arealometer measures maturity by the change in plug length between two fixed resistances. It was not possible to use this procedure with this experiment because the data did not include any constant resistances for comparison purposes. It was decided, therefore, to attempt to predict the maturity from the change in resistance between two fixed plug lengths.

CHAPTER IV

DISCUSSION OF RESULTS

Test for Laminar Flow

Values of friction factor and Reynolds number were calculated from the data taken on the first set of cottons (Table 9, Appendix B). A logarithmic plot of these values is shown in Figure 6. It was noticed that the data had a slope of -1 over most of the graph, although the friction factor tended to be a little higher than expected at the lower values of Reynolds number. This deviation was found to be mostly at the lowest flow rate used, 400 cc/min. This could be caused by the formation of stagnant rings or layers of air, as suggested by Carman (1937) and King (1897-98). Deviation at flow rates above 400 cc/min was not considered significant, and laminar flow was assumed to exist over this portion of the flow range.

Regression Equations for Resistance

Regression equations were developed for air flow resistance as a function of plug length in an attempt to reduce the volume of data being studied. Equations of the form

$$R = b_1 + b_2 e^{-kL} \tag{17}$$

were found to fit the data relatively well, with r square values of 99.7 ± 0.2. These results are found in Table 11, Appendix C. Figure 7 is an example of the plot of resistance versus plug length for both predicted regression and actual data values. A consistent pattern of

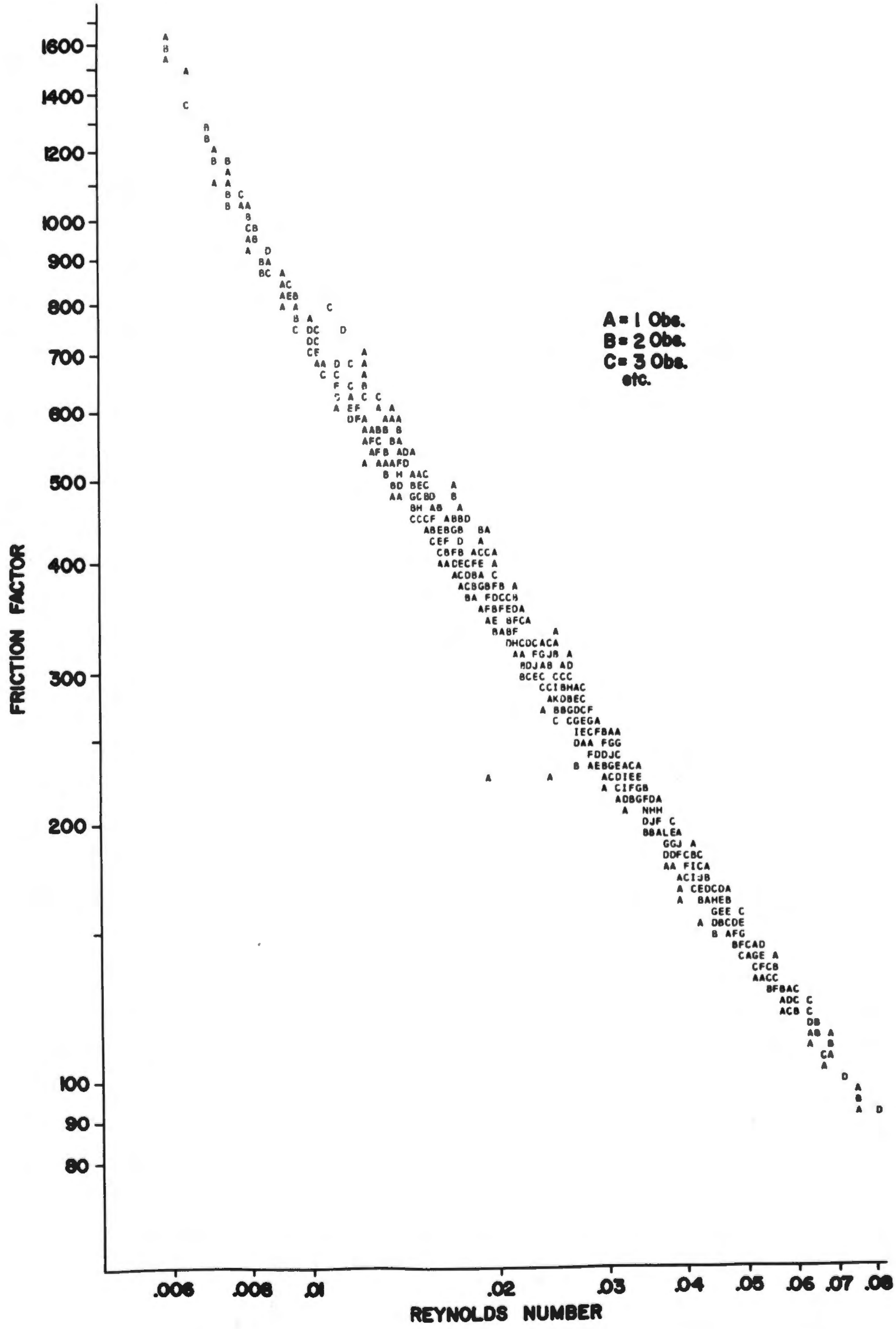

Figure 6. Friction factor versus Reynolds number calculated from experimental resistance data.

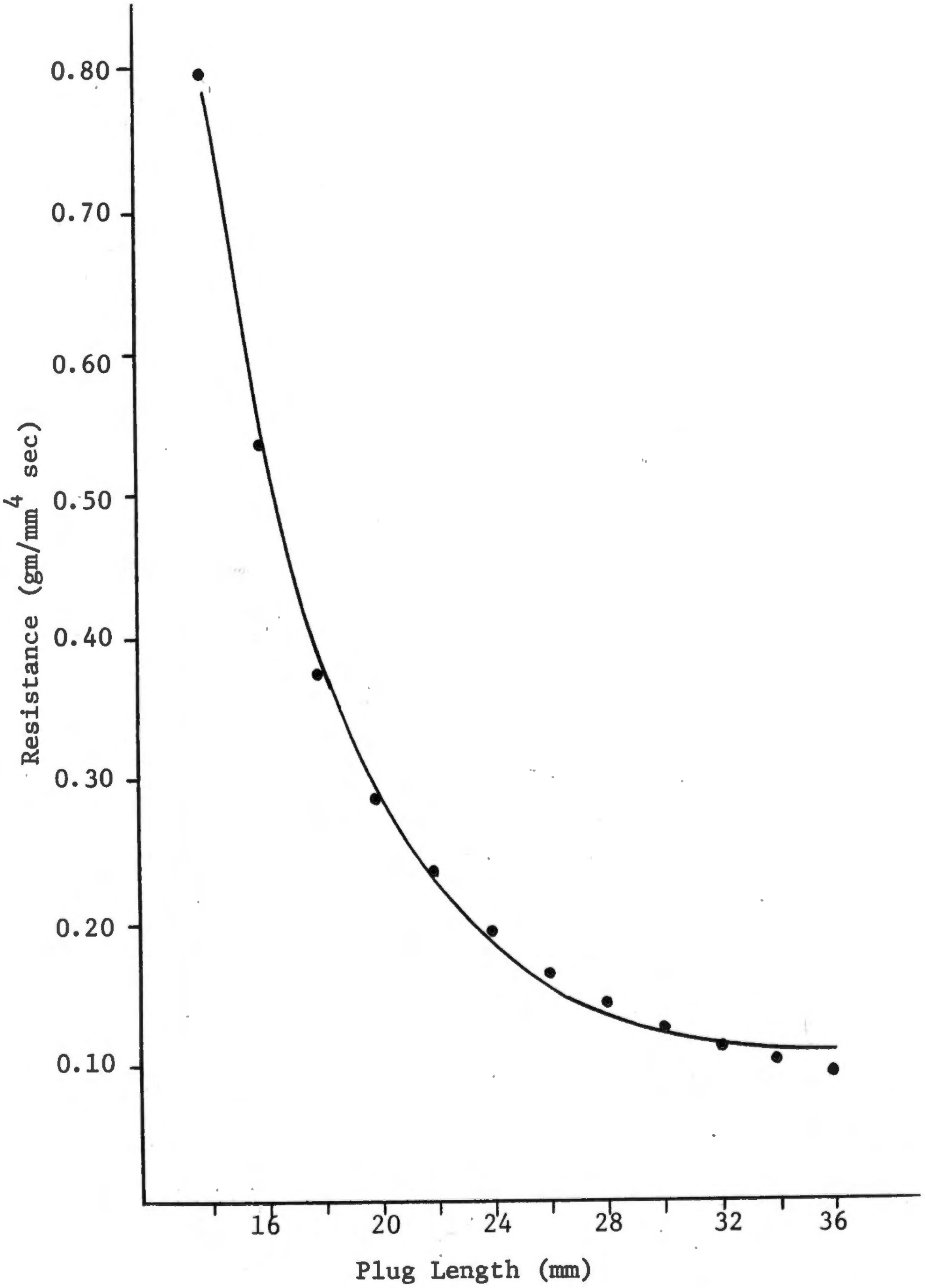

Figure 7. Typical resistance versus plug length data with the curve predicted by the regression equation.

deviation was observed. These equations were considered adequate over the entire range, however, since all regression curves systematically and uniformly deviated from the distribution of data.

Analyses of variance were applied to determine the effects of cotton variety, orientation, and flow rate on the coefficients b_1, b_2, and k. Table 1 shows the results of these analyses. Variety, flow rate, and the variety x flow rate interaction were found to be highly significant. This indicated that a constant flow rate was necessary in order to eliminate both the flow rate effect and the variety x flow rate interaction. An important observation made from these analyses was that fiber orientation was not a significant factor. This indicated that the specimens in which the fibers were oriented parallel to the direction of flow did not produce significantly different results from those which were oriented at random.

Analysis of the Arealometer Flow Equation

The determination of an appropriate flow rate was needed in order to make further conclusions concerning the use of Equation 12 (page 18) to predict specific surface area. Ideally, the lower flow rates were more desirable because they assured laminar flow and they reduced the pressure and volume of air required. This tended to indicate that the rate of 400 cc/min was the most desirable. However, there were some mechanical difficulties in setting and holding this flow rate. It was also noted that the deviation in the test for laminar flow was primarily due to the data at the 400 cc/min flow rate. Therefore the next lowest rate available, 700 cc/min, was chosen and the data for this flow rate used in the further analyses.

TABLE 1. Analyses of variance for regression coefficients b_1, b_2, and k.

Source	Degrees of Freedom	b_1 Mean Square x 10^4	b_2 Mean Square	k Mean Square x 10^4
Variety (V)	6	69.93**	76.46**	16.35**
Orientation (OR)	1	0.32	5.33	4.81
V x OR	6	0.28	3.08	2.39
Observation within Variety and Orientation	14	0.32	2.86	2.75
Flow Rate (Q)	3	4.56**	139.74**	68.23**
OR x Q	3	0.14	4.36	2.24
V x Q	18	1.63**	26.75**	10.80**
V x OR x Q	18	0.13	2.91	1.60
Experimental Error	42	0.13	2.69	1.88
Total	111			

** Denotes significance at the 99% level of probability.

The ratio of shape factor to orientation factor ($K = K_o/\zeta$) was calculated from the flow equation (Equation 12, page 18) using the known Arealometer data and the resistance data. Table 2 shows the average of the four observations (2 observations at each orientation) for the flow rate of 700 cc/min. These values were higher than expected theoretically (Sullivan and Hertel, 1940a), but no explanation for this difference was found. It was noted from the means for each plug length that this value was relatively constant between 36 and 24 mm. After this point it tended to increase. The variation between cottons was not considered significant because these values were calculated from the known Arealometer data. Therefore any error in this data was compounded with the experimental error in the resistance data, causing the variation of K to appear significant. A value of 6.7 was chosen for use in the calculation of specific surface area.

Values of specific surface area were calculated from Equation 12 using the chosen value of K and the resistance data for the chosen flow rate (Table 9, Appendix B). Table 3 shows the average of four observations at each plug length along with the Arealometer data. A comparison of the calculated values and the Arealometer data showed that there was no significant difference between the calculated and Arealometer values for plug lengths from 36 to 24 mm. As the plug length decreased from this point the calculated values tended to increase. This was expected, since this occurrence in the development of the Arealometer resulted in the Arealometer measurement of maturity.

Table 4 shows the difference in calculated specific surface area between upper plug lengths from 36 to 28 mm and lower lengths of 16

TABLE 2. Calculated values of K*, the ratio of shape factor to orientation factor.

Cotton	Plug Length (mm)											
#	36	34	32	30	28	26	24	22	20	18	16	14
1	6.63	6.70	6.58	6.65	6.70	6.70	6.70	6.78	6.85	6.90	7.05	7.25
3	6.70	6.55	6.58	6.58	6.45	6.60	6.68	6.73	6.75	7.00	7.15	7.38
4	6.58	6.80	6.73	6.68	6.55	6.50	6.58	6.60	6.60	6.75	6.83	6.93
6	6.98	6.93	6.93	6.78	6.78	6.78	6.75	6.80	6.73	7.00	7.10	7.25
7	6.60	6.73	6.80	6.80	6.90	7.00	7.10	7.23	7.40	7.68	8.08	
9	6.75	6.78	6.83	6.83	6.88	6.90	7.00	7.18	7.33	7.60	7.85	8.00
10	6.40	6.60	6.48	6.55	6.48	6.43	6.35	6.30	6.35	6.40	6.45	6.70
Average	6.66	6.73	6.70	6.70	6.68	6.70	6.74	6.80	6.86	7.05	7.21	7.25

*Averages of four observations.

TABLE 3. Specific surface area calculated for resistance data and obtained from the Arealometer.

Cotton #	Plug Length (mm)												Area-lometer
	36	34	32	30	28	26	24	22	20	18	16	14	
1	455.1	458.3	454.8	457.4	458.8	459.1	459.7	461.4	463.6	466.1	471.4	476.9	458.7
3	483.6	480.2	480.1	480.2	476.4	481.1	483.6	486.0	487.6	495.3	501.3	508.7	485.0
4	387.0	394.1	392.4	390.4	387.3	385.6	388.0	388.2	388.3	391.7	395.5	399.4	391.3
6	427.6	428.1	427.7	422.5	423.1	423.7	423.1	424.0	422.0	430.2	433.2	437.7	421.0
7	561.8	567.3	569.5	569.4	573.4	577.9	583.2	587.6	594.0	605.2	620.8		565.6
9	527.0	528.8	530.8	531.3	533.4	533.8	537.4	543.6	549.5	559.9	569.5	575.6	525.9
10	322.1	326.9	324.4	326.1	325.1	323.0	320.8	320.2	320.8	322.5	323.6	329.4	329.6

TABLE 4. Maturity values from the resistance data and from the Arealometer.

Cotton #	Lower Plug Length = 14 mm Upper Plug Length (mm) 36	34	32	30	28	Lower Plug Length = 16 mm Upper Plug Length (mm) 36	34	32	30	28	Area-lometer
1	21.8	18.6	22.1	19.5	18.1	16.3	13.1	16.6	14.0	12.6	23.4
3	25.1	28.5	28.6	28.5	32.3	17.7	21.1	21.2	21.1	24.9	33.0
4	12.4	5.3	7.0	9.0	12.1	8.5	1.4	3.1	5.1	8.2	20.2
6	10.1	9.6	10.0	15.2	14.6	5.6	5.1	5.5	10.7	10.1	21.0
7						59.0	53.5	51.3	51.4	47.4	54.1
9	48.6	46.8	44.8	44.3	42.2	42.5	40.7	38.7	38.2	36.1	43.3
10	7.3	2.5	5.0	3.3	4.3	1.5	-3.3	-0.8	-2.5	-1.5	20.1

and 14 mm. Arealometer maturity values are listed in the last column. It was noticed that the lower length of 14 mm produced much better values relative to the Arealometer data than did the 16 mm length. No significant difference was noted between the values for the different upper lengths.

Test of Conclusions Using a New Set of Cottons

A final question to be answered was how well the values of the parameters which were chosen from the results of this set of data would work with data from a different set of cottons. The second set of data previously discussed was used for this purpose. The specimens were placed in the chamber at random, since no effect of specimen orientation had been found. An upper plug length of 30 mm was arbitrarily chosen because no significant difference had been found between lengths from 36 to 24 mm. The lower plug length which had been chosen, 14 mm, was used in this procedure.

It was noticed from Table 5 that the mean specific surface areas for flow rates of 400 and 700 cc/min were very similar, as were the means for 1000 and 1300 cc/min. The difference between 700 and 1000 cc/min was considerably larger, although this difference was still only 2%. Therefore any flow rate between 400 and 700 cc/min should provide the same value of specific surface area. Due to mechanical difficulties in setting and holding a specific flow rate the flow rate was not held fixed, but was allowed to settle between 400 and 700 cc/min, at which both pressure drop and flow rate were recorded. This provided a much simpler and faster experimental technique. A second observation was

TABLE 5. Specific surface area values calculated from resistance data, averaged for each flow rate.

Plug Length mm	Flow Rate (cc/min) 400	700	1000	1300
36	450.3	452.0	461.7	462.0
34	456.1	454.8	462.0	461.9
32	455.1	454.2	460.9	462.5
30	454.9	453.9	461.1	461.6
28	455.5	453.9	461.0	462.0
26	456.6	454.9	460.7	462.5
24	457.9	456.9	462.8	463.4
22	460.6	458.7	464.9	465.3
20	465.3	460.7	468.7	468.1
18	470.7	467.3	471.5	
16	478.7	473.6		
14	489.8			

then made by allowing the flow rate to settle at another value and pressure and flow were again recorded.

Three specimens were used for each of the eleven cottons. Two observations were made at each plug length for each specimen. The resistance data is found in Table 10, Appendix B.

The calculated values of specific surface area are shown in Table 6. The variation between observations for a particular specimen was due primarily to the experimental error associated with the flow and pressure monitoring instruments. This variation was small relative to the variation observed between specimens. The variation between specimens was thought to be due to such factors as inaccuracies in mass measurement, undesirable particles in the specimen, and variations in uniformity of packing density.

A summary of the results of this step are shown in Table 7. No estimates of variation were made because of the quantity and experimental nature of the data. Figure 8 shows the comparison of the Arealometer data with the calculated values of specific surface area. Most calculated values were very close to the Arealometer data, with the exception of the two points at the upper end of the graph. The Arealometer data was predicted well by the calculated values.

Figure 9 shows the comparison of the Arealometer indication of maturity with the difference between values of specific surface area calculated at 30 mm and 14 mm plug lengths. Although the calculated values were different in numerical value from the Arealometer data, very high correlation was noticed between the two. The difference in

TABLE 6. Calculated values of specific surface area for SR cottons.

		30 mm Plug Length		14 mm Plug Length	
Cotton #	Specimen	Observation #1	Observation #2	Observation #1	Observation #2
SR-1	1	447.9	447.1	497.9	491.3
	2	455.8	457.4	508.4	506.3
	3	454.2	452.4	508.7	504.9
SR-2	1	446.0	444.5	486.1	482.2
	2	452.6	453.4	487.1	481.5
	3	444.5	443.3	484.4	482.7
SR-3	1	522.4	519.8	600.6	595.7
	2	525.1	520.4	601.9	596.8
	3	521.5	520.9	535.5	531.0
SR-4	1	479.9	478.9	551.0	546.4
	2	495.3	492.7	557.1	551.6
	3	490.9	490.6	556.0	549.6
SR-5	1	473.4	477.9	551.0	546.4
	2	571.0	569.2	659.7	653.4
	3	571.4	568.1	677.4	670.1
SR-6	1	592.8	591.2	719.8	713.2
	2	603.3	601.2	730.2	722.6
	3	599.0	599.3	716.1	707.3
SR-7	1	436.5	434.4	463.7	461.5
	2	441.8	440.7	462.3	460.1
	3	439.8	438.9	462.0	460.4
SR-8	1	515.7	517.1	583.5	577.7
	2	510.7	509.5	574.6	568.8
	3	516.9	515.0	590.4	585.7
SR-9	1	432.4	430.1	453.5	450.4
	2	431.9	430.6	457.3	455.7
	3	441.0	438.0	472.8	469.7
SR-12	1	479.5	478.9	503.7	500.5
	2	477.5	474.9	509.7	506.3
	3	473.0	473.2	508.5	505.3
SR-13	1	497.6	497.6	535.0	531.6
	2	504.4	502.8	548.6	545.4
	3	504.0	503.0	540.8	536.7

TABLE 7. Summary of the results from the SR cottons.

Cotton #	Specimen	Specific Surface Area (Average Over 2 Obs.)		Difference Between 30 and 14	Arealometer Data	
		30 mm	14 mm		A	D
SR-1	1	447.50	494.60	47.10	463.0	44.0
	2	456.60	507.35	50.75		
	3	453.30	506.80	53.50		
	Average	452.46	502.91	50.45		
SR-2	1	445.25	484.15	38.90	458.0	35.0
	2	453.00	484.30	31.30		
	3	443.90	483.55	39.65		
	Average	447.38	484.00	36.61		
SR-3	1	521.10	598.15	77.05	512.0	50.0
	2	522.75	599.35	76.60		
	3	521.20*	533.25*	12.05*		
	Average	521.93	598.75	76.83		
SR-4	1	479.40	548.70	69.30	488.0	46.0
	2	494.00	554.35	60.35		
	3	490.75	552.80	62.05		
	Average	488.05	551.95	63.90		
SR-5	1	475.65*	548.70*	73.05*	543.0	58.0
	2	570.10	656.55	86.45		
	3	569.75	673.75	104.00		
	Average	569.93	665.15	95.23		
SR-6	1	592.00	716.50	124.50	552.0	64.0
	2	602.25	726.40	125.15		
	3	599.15	711.70	112.15		
	Average	597.80	718.20	120.26		
SR-7	1	435.45	462.60	27.15	446.0	28.0
	2	441.25	461.20	19.95		
	3	439.35	461.20	21.85		
	Average	438.68	461.66	22.98		
SR-8	1	516.40	580.60	64.20	516.0	48.0
	2	510.10	571.70	61.60		
	3	515.95	588.05	72.10		
	Average	514.15	580.11	72.10		
SR-9	1	431.25	451.95	20.70	418.0	31.0
	2	431.25	456.50	25.25		
	3	439.50	471.25	31.75		
	Average	434.00	459.90	25.90		

TABLE 7. (continued).

Cotton #	Specimen	Specific Surface Area (Average Over 2 Obs.) 30 mm	14 mm	Difference Between 30 and 14	Arealometer Data A	D
SR-12	1	479.20	502.10	22.90	474.0	31.0
	2	476.20	508.00	31.80		
	3	473.10	506.90	33.80		
	Average	476.16	505.66	29.50		
SR-13	1	497.60	533.30	35.70	495.0	34.0
	2	503.60	547.00	43.40		
	3	503.50	538.75	35.25		
	Average	501.56	539.68	38.11		

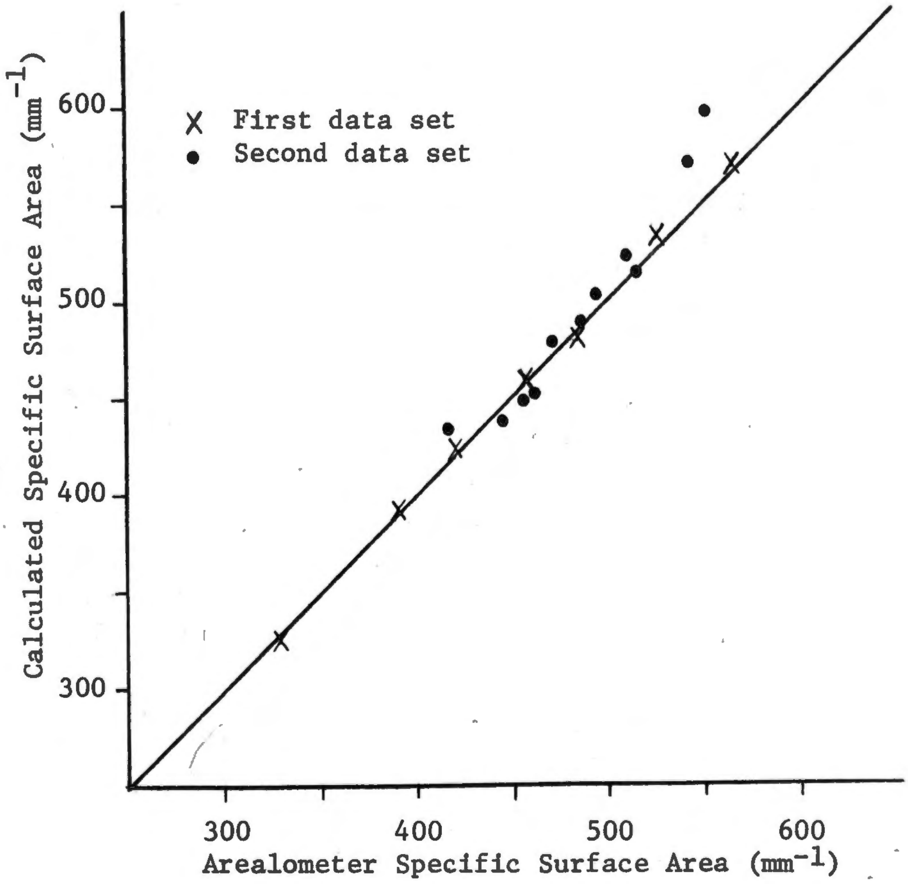

Figure 8. Calculated specific surface area versus Arealometer specific surface area.

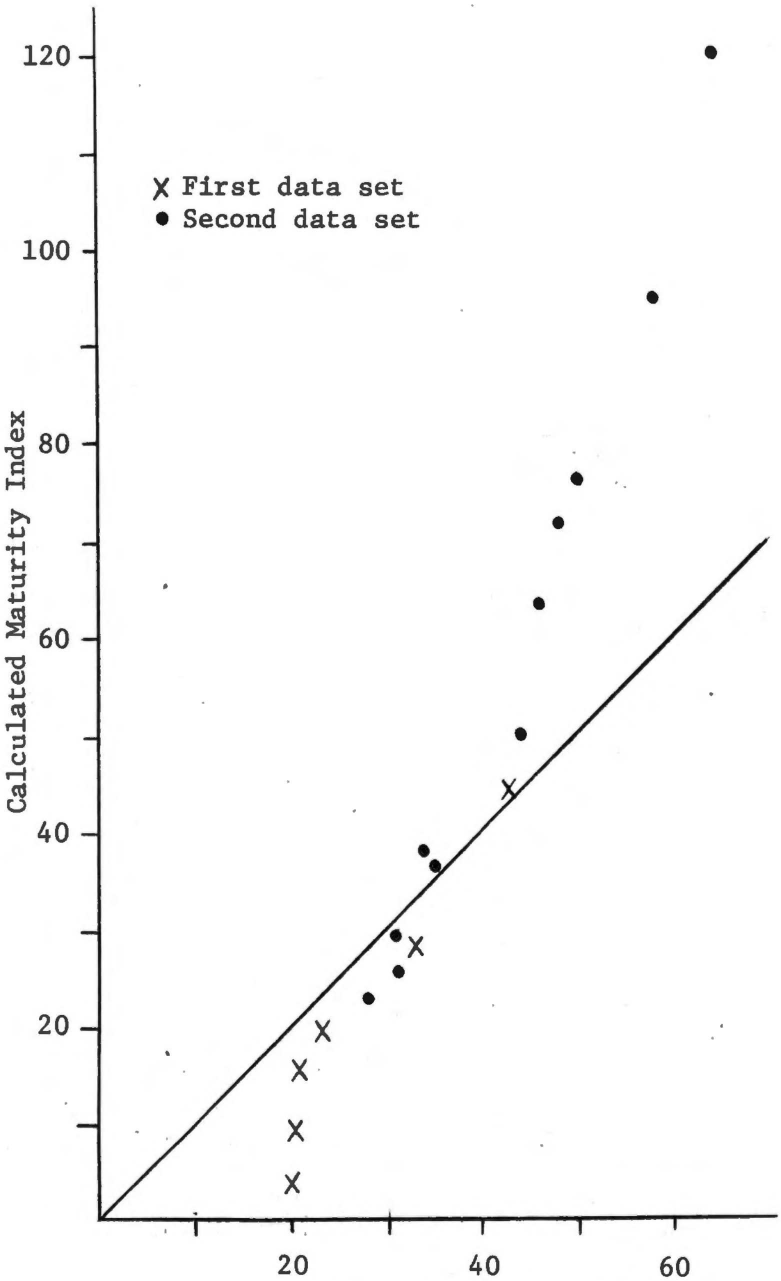

Figure 9. Calculated maturity index versus Arealometer maturity index.

numerical value was considered of little consequence because neither value has any numerical significance, but are merely relative indications of maturity.

CHAPTER V

SUMMARY AND CONCLUSIONS

This project was the first step in a much broader research effort aimed at the development of a new instrument to measure specific surface area and maturity of cotton fibers by air flow resistance methods. The purpose of this project was to determine if the air flow relationships on which the Arealometer is based could be used with a system using a much larger specimen. The effects of fiber orientation, flow rate, plug length, and cotton variety on the resistance to air flow, and thus to the indication of specific surface area, were considered. One set of data was analysed, after which another set of data was taken to test the conclusions drawn from the first data.

The primary conclusion to be made was that the air flow relationship (Equation 12, page 18) was indeed applicable to the proposed system. Calculated specific surface area values were very close to Arealometer values. Relative indications of maturity were also close. The greater spread in the numerical values of maturity by the experimental method was considered desirable because this allowed for more precision in obtaining an indication of maturity. No problem was foreseen with a new range for maturity since there was no physical meaning associated with the numerical value of maturity obtained from the Arealometer.

Specific statistical comparisons were not made in the comparison of the two instruments. Such analyses are based on the comparison of an experimental value with an actual value. The accuracy of the Arealometer data was not known. Therefore the variation between the Arealometer values and the experimental determinations was due to the error in both systems. Estimates of variability were not made because the amount of data taken was not considered sufficient for this purpose.

Suggested Instrumental Technique

The instrumental technique used in the collection of data for this experiment was found to produce good results. The following is a summary of the technique suggested for future use.

The cotton sample should be carded and conditioned at the same atmospheric conditions as the instrument. A specimen of 4.25 gm should be weighted. No standard procedure is needed for placing the specimen in the chanber.

A cylinder and piston of 25.4 mm diameter should be used. The cylinder should be at least 70 mm deep to allow for placing the fluffy specimen in the chamber without difficulty. The piston should be sufficiently long to allow for its removal from the compressed position. It should be made such that air can be passed through it into the specimen through a perforated plate to allow for the even distribution of air across the cotton. The cylinder end should also be perforated for the same reason. Markings should be made on the piston to allow for setting the plug length at 30 mm and 14 mm. Due to the force required for the compaction of the specimen some mechanical means is needed for the compression stroke.

The flow rate should be held constant at 700 cc/min. A good flow regulator can be obtained for this purpose. The pressure can be

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APPENDICES

APPENDIX A

EXPERIMENTAL COTTONS

The first set of cottons (7 samples) was obtained from a set of 10 cottons developed as fineness standards. The second set (11 samples) was obtained from a set of cottons used by the University of Tennessee Fiber Research Laboratory under Contract No. 12-14-100-7176(72) with the Southern Utilization Research and Development Division, ARS, USDA.

TABLE 8. Arealometer data for the cottons used.

Cotton #	Specific Surface Area, A	Immaturity D
1	458.7	23.4
3	485.0	33.0
4	391.3	20.2
6	421.0	21.0
7	565.6	54.1
9	525.9	43.3
10	329.6	20.1
SR-1	463.0	44.0
SR-2	458.0	35.0
SR-3	512.0	50.0
SR-4	488.0	46.0
SR-5	543.0	58.0
SR-6	552.0	64.0
SR-7	446.0	28.0
SR-8	516.0	48.0
SR-9	418.0	31.0
SR-12	474.0	31.0
SR-13	495.0	34.0

APPENDIX B

RESISTANCE DATA

TABLE 9. Resistance data for the first set of cottons.

Cotton #	Orientation[a]	Observation	Plug Length (mm)	Flow Rate (cc/min)			
				400	700	1000	1300
1	O	1	14	0.5301	0.5236	0.5305	
			16	0.3540	0.3541	0.3579	0.3528
			18	0.2576	0.2573	0.2627	0.2612
			20	0.2012	0.2027	0.2077	0.2051
			22	0.1613	0.1655	0.1687	0.1660
			24	0.1366	0.1399	0.1409	0.1402
			26	0.1187	0.1200	0.1214	0.1195
			28	0.1022	0.1051	0.1072	0.1062
			30	0.0912	0.0919	0.0953	0.0942
			32	0.0815	0.0828	0.0841	0.0859
			34	0.0733	0.0762	0.0776	0.0795
			36	0.0664	0.0704	0.0711	0.0707
1	O	2	14	0.5438	0.5369	0.5359	
			16	0.3636	0.3640	0.3697	0.3680
			18	0.2659	0.2681	0.2721	0.2718
			20	0.2067	0.2110	0.2112	0.2115
			22	0.1668	0.1696	0.1722	0.1733
			24	0.1393	0.1415	0.1450	0.1448
			26	0.1214	0.1241	0.1243	0.1255
			28	0.1077	0.1076	0.1095	0.1094
			30	0.0953	0.0960	0.0977	0.0979
			32	0.0843	0.0836	0.0882	0.0882
			34	0.0788	0.0762	0.0800	0.0790
			36	0.0692	0.0687	0.0723	0.0726
1	R	1	14	0.5356	0.5178	0.5175	
			16	0.3622	0.3541	0.3549	0.3546
			18	0.2604	0.2606	0.2603	0.2617
			20	0.2026	0.2011	0.2024	0.2042
			22	0.1668	0.1663	0.1675	0.1687
			24	0.1366	0.1390	0.1409	0.1425
			26	0.1159	0.1175	0.1196	0.1218
			28	0.1022	0.1043	0.1048	0.1057
			30	0.0925	0.0911	0.0953	0.0947
			32	0.0788	0.0820	0.0841	0.0850
			34	0.0733	0.0753	0.0752	0.0753
			36	0.0650	0.0662	0.0681	0.0689

TABLE 9. (continued).

Cotton #	Orientation[a]	Observation	Plug Length (mm)	Flow Rate (cc/min)			
				400	700	1000	1300
1	R	2	14	0.5218	0.5195	0.5199	
			16	0.3553	0.3499	0.3520	0.3560
			18	0.2590	0.2581	0.2603	0.2640
			20	0.2012	0.2027	0.2065	0.2065
			22	0.1655	0.1638	0.1675	0.1678
			24	0.1393	0.1374	0.1415	0.1411
			26	0.1173	0.1183	0.1219	0.1223
			28	0.1022	0.1035	0.1066	0.1066
			30	0.0912	0.0927	0.0953	0.0960
			32	0.0829	0.0820	0.0853	0.0864
			34	0.0774	0.0770	0.0782	0.0786
			36	0.0692	0.0695	0.0729	0.0717
3	O	1	14	0.6278	0.5989		
			16	0.4159	0.4004	0.4117	0.4057
			18	0.3003	0.2987	0.3041	0.3031
			20	0.2301	0.2275	0.2367	0.2332
			22	0.1861	0.1862	0.1905	0.1894
			24	0.1558	0.1556	0.1604	0.1605
			26	0.1324	0.1341	0.1373	0.1375
			28	0.1187	0.1159	0.1208	0.1204
			30	0.1022	0.1026	0.1060	0.1080
			32	0.0925	0.0935	0.0953	0.0960
			34	0.0843	0.0844	0.0877	0.0878
			36	0.0774	0.0786	0.0806	0.0818
3	O	2	14	0.6291	0.6072		
			16	0.4145	0.4062	0.4176	0.4167
			18	0.3044	0.2978	0.3064	0.3063
			20	0.2343	0.2284	0.2378	0.2396
			22	0.1916	0.1870	0.1923	0.1927
			24	0.1600	0.1564	0.1627	0.1632
			26	0.1338	0.1324	0.1367	0.1402
			28	0.1146	0.1076	0.1202	0.1204
			30	0.1036	0.1043	0.1078	0.1080
			32	0.0939	0.0927	0.0977	0.0974
			34	0.0857	0.0836	0.0877	0.0882
			36	0.0774	0.0786	0.0806	0.0809
3	R	1	14	0.6429	0.6063		
			16	0.4255	0.4145	0.4129	0.4163
			18	0.3141	0.2995	0.3088	0.3082
			20	0.2370	0.2284	0.2378	0.2373
			22	0.1930	0.1853	0.1923	0.1922
			24	0.1558	0.1572	0.1580	0.1591

TABLE 9. (continued).

Cotton #	Orientation[a]	Observation	Plug Length (mm)	Flow Rate (cc/min)			
				400	700	1000	1300
3	R	1	26	0.1352	0.1332	0.1361	0.1388
			28	0.1201	0.1175	0.1219	0.1218
			30	0.1063	0.1043	0.1060	0.1075
			32	0.0953	0.0927	0.0983	0.0979
			34	0.0870	0.0844	0.0888	0.0887
			36	0.0747	0.0786	0.0823	0.0813
3	R	2	14	0.5961	0.5749		
			16	0.3966	0.3872	0.4004	0.4048
			18	0.2865	0.2829	0.2958	0.2948
			20	0.2301	0.2201	0.2313	0.2309
			22	0.1820	0.1796	0.1876	0.1894
			24	0.1545	0.1481	0.1568	0.1582
			26	0.1283	0.1274	0.1302	0.1347
			28	0.1132	0.1126	0.1184	0.1181
			30	0.1022	0.0985	0.1043	0.1043
			32	0.0912	0.0894	0.0942	0.0942
			34	0.0829	0.0820	0.0253	0.0859
			36	0.0760	0.0745	0.0788	0.0772
4	O	1	14	0.3760	0.3623	0.3679	0.3694
			16	0.2480	0.2416	0.2461	0.2474
			18	0.1806	0.1829	0.1852	0.1858
			20	0.1366	0.1407	0.1450	0.1448
			22	0.1132	0.1150	0.1202	0.1200
			24	0.0980	0.0993	0.1007	0.1006
			26	0.0815	0.0836	0.0865	0.0873
			28	0.0719	0.0745	0.0782	0.0781
			30	0.0637	0.0679	0.0699	0.0698
			32	0.0581	0.0613	0.0622	0.0634
			34	0.0540	0.0563	0.0569	0.0583
			36	0.0485	0.0505	0.0522	0.0537
4	O	2	14	0.3732	0.3251	0.3715	0.3744
			16	0.2549	0.2490	0.2556	0.2566
			18	0.1902	0.1837	0.1864	0.1871
			20	0.1476	0.1415	0.1468	0.1485
			22	0.1159	0.1175	0.1214	0.1227
			24	0.0967	0.0993	0.1024	0.1034
			26	0.0843	0.0844	0.0888	0.0896
			28	0.0747	0.0745	0.0782	0.0790
			30	0.0678	0.0671	0.0705	0.0717
			32	0.0609	0.0613	0.0640	0.0643
			34	0.0554	0.0563	0.0575	0.0588
			36	0.0499	0.0497	0.0528	0.0533

TABLE 9. (continued).

Cotton #	Orien-tation[a]	Obser-vation	Plug Length (mm)	Flow Rate (cc/min)			
				400	700	1000	1300
4	R	1	14	0.3911	0.3814	0.3768	0.3804
			16	0.2645	0.2573	0.2562	0.2585
			18	0.1889	0.1853	0.1882	0.1913
			20	0.1517	0.1448	0.1533	0.1522
			22	0.1228	0.1208	0.1237	0.1241
			24	0.1036	0.1001	0.1048	0.1057
			26	0.0884	0.0861	0.0906	0.0901
			28	0.0747	0.0762	0.0788	0.0795
			30	0.0678	0.0671	0.0705	0.0712
			32	0.0595	0.0613	0.0634	0.0648
			34	0.0554	0.0555	0.0581	0.0588
			36	0.0499	0.0505	0.0539	0.0542
4	R	2	14	0.3705	0.3549	0.3656	0.3661
			16	0.2576	0.2532	0.2544	0.2552
			18	0.1880	0.1853	0.1870	0.1885
			20	0.1462	0.1465	0.1468	0.1503
			22	0.1159	0.1175	0.1202	0.1209
			24	0.0980	0.0985	0.1018	0.1011
			26	0.0843	0.0844	0.0882	0.0882
			28	0.0747	0.0745	0.0776	0.0776
			30	0.0678	0.0687	0.0693	0.0694
			32	0.0609	0.0621	0.0622	0.0629
			34	0.0568	0.0571	0.0581	0.0569
			36	0.0485	0.0480	0.0516	0.0519
6	O	1	14	0.4448	0.4260	0.4306	
			16	0.3017	0.2929	0.2928	0.2967
			18	0.2219	0.2126	0.2207	0.2217
			20	0.1723	0.1663	0.1722	0.1724
			22	0.1407	0.1365	0.1403	0.1416
			24	0.1132	0.1134	0.1196	0.1191
			26	0.1022	0.0985	0.1018	0.1039
			28	0.0884	0.0877	0.0900	0.0924
			30	0.0788	0.0762	0.0811	0.0813
			32	0.0719	0.0704	0.0735	0.0740
			34	0.0664	0.0646	0.0675	0.0675
			36	0.0595	0.0596	0.0615	0.0125
6	O	2	14	0.4461	0.4302	0.4472	
			16	0.3003	0.2912	0.3052	0.3068
			18	0.2191	0.2242	0.2278	0.2267

TABLE 9. (continued).

Cotton #	Orientation[a]	Observation	Plug Length (mm)	Flow Rate (cc/min)			
				400	700	1000	1300
6	O	2	20	0.1723	0.1680	0.1834	0.1775
			22	0.1379	0.1365	0.1456	0.1457
			24	0.1173	0.1159	0.1231	0.1237
			26	0.1022	0.1001	0.1066	0.1066
			28	0.0898	0.0869	0.0930	0.0937
			30	0.0815	0.0770	0.0835	0.0841
			32	0.0747	0.0720	0.0752	0.0763
			34	0.0692	0.0662	0.0693	0.0698
			36	0.0609	0.0613	0.0634	0.0643
6	R	1	14	0.4750	0.4599	0.4661	
			16	0.3141	0.3086	0.3123	0.3169
			18	0.2246	0.2259	0.2307	0.2318
			20	0.1778	0.1738	0.1823	0.1821
			22	0.1421	0.1448	0.1474	0.1485
			24	0.1201	0.1225	0.1237	0.1255
			26	0.1049	0.1043	0.1072	0.1075
			28	0.0939	0.0911	0.0953	0.0947
			30	0.0829	0.0820	0.0835	0.0845
			32	0.0747	0.0737	0.0758	0.0763
			34	0.0692	0.0671	0.0693	0.0694
			36	0.0609	0.0604	0.0628	0.0643
6	R	2	14	0.4723	0.4517	0.4631	
			16	0.3072	0.3086	0.3106	0.3146
			18	0.2315	0.2267	0.2313	0.2327
			20	0.1820		0.1840	0.1844
			22	0.1462	0.1440	0.1486	0.1508
			24	0.1228	0.1208	0.1243	0.1269
			26	0.1091	0.1059	0.1072	0.1089
			28	0.0953	0.0919	0.0953	0.0974
			30	0.0829	0.0820	0.0859	0.0855
			32	0.0747	0.0762	0.0770	0.0790
			34	0.0678	0.0679	0.0717	0.0689
			36	0.0609	0.0613	0.0634	0.0648
7	O	1	14	1.0020			
			16	0.6443	0.6262		
			18	0.4599	0.4475	0.4472	
			20	0.3498	0.3408	0.3608	0.3477
			22	0.2797	0.2730	0.2775	0.2736
			24	0.2329	0.2275	0.2296	0.2318
			26	0.1944	0.1920	0.1947	0.1945

TABLE 9. (continued).

Cotton #	Orientation^a	Observation	Plug Length (mm)	Flow Rate (cc/min)			
				400	700	1000	1300
7	O	1	28	0.1682	0.1638	0.1675	0.1701
			30	0.1462	0.1432	0.1474	0.1485
			32	0.1311	0.1308	0.1326	0.1329
			34	0.1187	0.1175	0.1190	0.1195
			36	0.1063	0.1043	0.1095	0.1089
7	O	2	14	0.9648			
			16	0.6140	0.6105		
			18	0.4393	0.4277	0.4424	
			20	0.3347	0.3268	0.3395	0.3417
			22	0.2659	0.2681	0.2727	0.2750
			24	0.2191	0.2241	0.2278	0.2263
			26	0.1875	0.1895	0.1947	0.1940
			28	0.1627	0.1630	0.1669	0.1674
			30	0.1421	0.1432	0.1474	0.1471
			32	0.1269	0.1283	0.1308	0.1287
			34	0.1159	0.1159	0.1196	0.1186
			36	0.1049	0.1051	0.1083	0.1075
7	R	1	14	0.9690			
			16	0.6222	0.6138		
			18	0.4516	0.4434	0.4454	
			20	0.3457	0.3400	0.3431	0.3440
			22	0.2728	0.2689	0.2739	0.2727
			24	0.2260	0.2209	0.2272	0.2240
			26	0.1902	0.1887	0.1911	0.1904
			28	0.1641	0.1638	0.1651	0.1651
			30	0.1407	0.1423	0.1456	0.1453
			32	0.1269	0.1283	0.1290	0.1301
			34	0.1159	0.1150	0.1172	0.1181
			36	0.1036	0.1018	0.1054	0.1048
7	R	2	14	0.917			
			16	0.6346	0.6163		
			18	0.4530	0.4417	0.442	
			20	0.3430	0.3342	0.3413	0.3385
			22	0.2769	0.2689	0.2751	0.2741
			24	0.2301	0.2250	0.2272	0.2290
			26	0.1957	0.1903	0.1929	0.1936
			28	0.1696	0.1663	0.1687	0.1678
			30	0.1503	0.1473	0.1509	0.1485
			32	0.1332	0.1308	0.1344	0.1352
			34	0.1173	0.1183	0.1219	0.1218
			36	0.1049	0.1076	0.1119	0.1112

TABLE 9. (continued).

Cotton #	Orientation[a]	Observation	Plug Length (mm)	Flow Rate (cc/min)			
				400	700	1000	1300
9	O	1	14	0.7970	0.7726		
			16	0.5383	0.5228	0.5223	
			18	0.3760	0.3772	0.3786	0.3781
			20	0.2879	0.2863	0.2905	0.2879
			22	0.2356	0.2317	0.2337	0.2355
			24	0.1944	0.1911	0.1953	0.1950
			26	0.1641	0.1638	0.1669	0.1669
			28	0.1435	0.1440	0.1450	0.1462
			30	0.1256	0.1258	0.1285	0.1292
			32	0.1132	0.1134	0.1149	0.1158
			34	0.1022	0.1026	0.1048	0.1057
			36	0.0912	0.0927	0.0953	0.0947
9	O	2	14	0.8548			
			16	0.5466	0.5393		
			18	0.3911	0.3905	0.3999	0.3965
			20	0.2962	0.2953	0.3047	0.3040
			22	0.2356	0.2350	0.2420	0.2442
			24	0.1944	0.1953	0.2000	0.1982
			26	0.1655	0.1647	0.1687	0.1710
			28	0.1462	0.1448	0.1486	0.1494
			30	0.1269	0.1291	0.1302	0.1306
			32	0.1118	0.1134	0.1154	0.1177
			34	0.1008	0.1010	0.1042	0.1034
			36	0.0912	0.0927	0.0953	0.0951
9	R	1	14	0.7818	0.7652		
			16	0.5149	0.5112	0.5146	
			18	0.3718	0.3690	0.3721	0.3707
			20	0.2838	0.2821	0.2869	0.2852
			22	0.2274	0.2275	0.2290	0.2281
			24	0.1847	0.1870	0.1899	0.1894
			26	0.1600	0.1597	0.1622	0.1618
			28	0.1393	0.1390	0.1426	0.1416
			30	0.1214	0.1217	0.1255	0.1246
			32	0.1104	0.1092	0.1125	0.1126
			34	0.0967	0.0993	0.1018	0.0997
			36	0.0857	0.0911	0.0924	0.0919
9	R	2	14	0.7915	0.7544		
			16	0.5259	0.5030	0.5134	
			18	0.3828	0.2698	0.3727	0.3740
			20	0.2934	0.2846	0.2857	0.2893
			22	0.2288	0.2292	0.2331	0.2327

TABLE 9. (continued).

Cotton #	Orientation[a]	Observation	Plug Length (mm)	Flow Rate (cc/min)			
				400	700	1000	1300
9	R	2	24	0.1930	0.1887	0.1929	0.1936
			26	0.1627	0.1605	0.1645	0.1655
			28	0.1407	0.1407	0.1438	0.1439
			30	0.1269	0.1250	0.1273	0.1273
			32	0.1146	0.1142	0.1143	0.1144
			34	0.1022	0.1026	0.1042	0.1048
			36	0.0898	0.0919	0.0947	0.0951
10	O	1	14	0.2549	0.2457	0.1905	0.2516
			16	0.1682	0.1614	0.1687	0.1687
			18	0.1256	0.1217	0.1237	0.1264
			20	0.0980	0.0952	0.1007	0.1002
			22	0.0815	0.0778	0.0823	0.0827
			24	0.0692	0.0662	0.0693	0.0703
			26	0.0595	0.0680	0.0593	0.0602
			28	0.0513	0.0513	0.0522	0.0533
			30	0.0458	0.0464	0.0474	0.0477
			32	0.0420	0.0398	0.0433	0.0441
			34	0.0389	0.0365	0.0403	0.0394
			36	0.0334	0.0340	0.0380	0.0371
10	O	2	14	0.2508	0.2457	0.2556	0.2566
			16	0.1682	0.1638	0.1722	0.1720
			18	0.1242	0.1225	0.1279	0.1287
			20	0.0994	0.0968	0.1024	0.1020
			22	0.0788	0.0778	0.0847	0.0841
			24	0.0678	0.0671	0.0711	0.0717
			26	0.0595	0.0588	0.0616	0.0620
			28	0.0526	0.0522	0.0539	0.0551
			30	0.0471	0.0464	0.0486	0.0491
			32	0.0444	0.0414	0.0443	0.0441
			34	0.0416	0.0398	0.0409	0.0399
			36	0.0361	0.0348	0.0374	0.0371
10	R	1	14	0.2590	0.2499	0.2615	0.2626
			16	0.1737	0.1680	0.1781	0.1784
			18	0.1297	0.1266	0.1338	0.1338
			20	0.1008	0.0993	0.1048	0.1043
			22	0.0829	0.0828	0.0853	0.0859
			24	0.0705	0.0696	0.0717	0.0721
			26	0.0623	0.0604	0.0610	0.0634
			28	0.0513	0.0530	0.0545	0.0546
			30	0.0471	0.0472	0.0486	0.0487
			32	0.0430	0.0423	0.0439	0.0441
			34	0.0389	0.0381	0.0409	0.0404
			36	0.0361	0.0340	0.0380	0.0376

TABLE 9. (continued).

Cotton #	Orientation[a]	Observation	Plug Length (mm)	Flow Rate (cc/min)			
				400	700	1000	1300
10	R	2	14	0.2700	0.2598	0.2650	0.2649
			16	0.1806	0.1771	0.1793	0.1807
			18	0.1324	0.1291	0.1314	0.1319
			20	0.1036	0.1001	0.1036	0.1039
			22	0.0843	0.0820	0.0853	0.0855
			24	0.0705	0.0687	0.0717	0.0721
			26	0.0637	0.0604	0.0628	0.0638
			28	0.0568	0.0547	0.0545	0.0551
			30	0.0499	0.0489	0.0492	0.0492
			32	0.0458	0.0447	0.0445	0.0450
			34	0.0416	0.0406	0.0403	0.0413
			36	0.0361	0.0348	0.0368	0.0376

[a] O = Oriented specimen
R = Random specimen

Units of resistance are gm/mm^4 sec.

TABLE 10. Resistance data for the second set of cottons.

Cotton #	Specimen #	30 mm Plug Length Observation #1	30 mm Plug Length Observation #2	14 mm Plug Length Observation #1	14 mm Plug Length Observation #2
SR-1	1	0.0891	0.0888	0.5716	0.5568
	2	0.0923	0.0929	0.5960	0.5911
	3	0.0916	0.0909	0.5969	0.5880
SR-2	1	0.0884	0.0878	0.5450	0.5362
	2	0.0910	0.0913	0.5471	0.5347
	3	0.0878	0.0873	0.5412	0.5374
SR-3	1	0.1212	0.1200	0.8319	0.8184
	2	0.1225	0.1203	0.8354	0.8215
	3	0.1208	0.1205	0.6612	0.6502
SR-4	1	0.1023	0.1019	0.7001	0.6886
	2	0.1090	0.1078	0.7158	0.7017
	3	0.1071	0.1069	0.7129	0.6967
SR-5	1	0.995	0.1014	0.7001	0.6886
	2	0.1448	0.1439	1.0038	0.9846
	3	0.1450	0.1434	1.0582	1.0356
SR-6	1	0.1561	0.1552	1.1949	1.1730
	2	0.1616	0.1606	1.2297	1.2043
	3	0.1594	0.1595	1.1827	1.1538
SR-7	1	0.0846	0.0838	0.4958	0.4911
	2	0.0867	0.0862	0.4930	0.4881
	3	0.0859	0.0856	0.4923	0.4889
SR-8	1	0.1181	0.1188	0.7851	0.7697
	2	0.1158	0.1153	0.7614	0.7461
	3	0.1187	0.1178	0.8039	0.7912
SR-9	1	0.0830	0.0822	0.4744	0.4678
	2	0.0829	0.0823	0.4823	0.4789
	3	0.0864	0.0852	0.5156	0.5088
SR-12	1	0.1021	0.1019	0.5851	0.5777
	2	0.1013	0.1002	0.5992	0.5911
	3	0.0994	0.0995	0.5962	0.5889
SR-13	1	0.1100	0.1100	0.6601	0.6518
	2	0.1130	0.1123	0.6941	0.6861
	3	0.1128	0.1124	0.6746	0.6642

APPENDIX C

RESULTS OF THE REGRESSION EQUATIONS

TABLE 11. Coefficients of a regression equation of the form $R = b_1 + b_2 e^{-kL}$.

Cotton #	Flow Rate (cc/min)	Orientation[a]	Observation	b_1	b_2	k
1	400	O	1	0.0738	8.7211	0.2121
			2	0.0776	9.0535	0.2132
		R	1	0.0718	8.4224	0.2083
			2	0.0743	7.9820	0.2070
	700	O	1	0.0757	8.1496	0.2085
			2	0.0749	7.7704	0.2030
		R	1	0.0722	7.3854	0.2018
			2	0.0749	7.9879	0.2077
	1000	O	1	0.0767	8.0654	0.2069
			2	0.0773	7.6224	0.2018
		R	1	0.0741	7.3731	0.2020
			2	0.0773	7.6833	0.2053
	1300	O	1	0.0680	4.6043	0.1747
			2	0.0690	4.7380	0.1736
		R	1	0.0648	4.2441	0.1689
			2	0.0682	4.5812	0.1738
3	400	O	1	0.0852	11.3147	0.2182
			2	0.0848	10.6155	0.2136
		R	1	0.0850	10.9262	0.2137
			2	0.0828	9.8361	0.2123
	700	O	1	0.0838	9.4223	0.2089
			2	0.0828	9.8822	0.2110
		R	1	0.0835	9.1037	0.2094
			2	0.0804	9.1037	0.2093
	1000	O	1	0.0756	5.4866	0.1753
			2	0.0768	5.7698	0.1777
		R	1	0.0772	5.6974	0.1774
			2	0.0737	5.2732	0.1746
	1300	O	1	0.0766	5.3389	0.1748
			2	0.0763	5.4964	0.1748
		R	1	0.0725	4.3298	0.1623
			2	0.0739	5.3135	0.1746

TABLE 11. (continued).

Cotton #	Flow Rate (cc/min)	Orientation[a]	Observation	b_1	b_2	k
4	400	O	1	0.0542	7.0150	0.2214
			2	0.0532	5.5321	0.2046
		R	1	0.0543	6.0496	0.2077
			2	0.0529	5.3813	0.2029
	700	O	1	0.0556	5.7358	0.2107
			2	0.0480	3.1625	0.1737
		R	1	0.0556	6.2943	0.2128
			2	0.0519	4.4843	0.1932
	1000	O	1	0.0570	5.6056	0.2082
			2	0.0572	5.5336	0.2060
		R	1	0.0573	5.3644	0.2030
			2	0.0553	5.0557	0.2004
	1300	O	1	0.0581	5.8391	0.2109
			2	0.0581	5.6239	0.2068
		R	1	0.0681	5.5564	0.2048
			2	0.0545	4.8297	0.1969
6	400	O	1	0.0643	6.9643	0.2088
			2	0.0678	7.6129	0.2156
		R	1	0.0699	9.0350	0.2230
			2	0.0689	7.7972	0.2134
	700	O	1	0.0631	6.5184	0.2073
			2	0.0634	6.2838	0.2041
		R	1	0.0671	7.5082	0.2121
			2	0.0734	12.6409	0.2504
	1000	O	1	0.0655	6.1474	0.2031
			2	0.0667	6.1375	0.2000
		R	1	0.0687	7.2934	0.2093
			2	0.0697	7.0712	0.2079
	1300	O	1	0.0593	3.7952	0.1740
			2	0.0615	4.0241	0.1758
		R	1	0.0613	4.2674	0.1770
			2	0.0607	3.8072	0.1703
7	400	O	1	0.1215	20.0899	0.2248
			2	0.1199	20.7371	0.2300
		R	1	0.1166	18.3000	0.2205
			2	0.1215	18.5664	0.2215
	700	O	1	0.1022	9.9133	0.1847
			2	0.1048	10.1393	0.1888
		R	1	0.0987	9.2695	0.1814

TABLE 11. (continued).

Cotton #	Flow Rate (cc/min)	Orientation[a]	Observation	b_1	b_2	k
7	1000	O	1	0.0890	5.7732	0.1541
			2	0.0923	5.8728	0.1573
		R	1	0.0891	6.0061	0.1574
			2	0.1123	15.9776	0.2070
	1300	O	1	0.0855	4.6088	0.1440
			2	0.0822	4.3406	0.1412
		R	1	0.0855	5.0780	0.1493
			2	0.0875	4.2994	0.1423
9	400	O	1	0.1016	14.0488	0.2156
			2	0.1051	17.9551	0.2282
		R	1	0.0975	13.8073	0.2159
			2	0.1004	13.4528	0.2132
	700	O	1	0.1007	12.6655	0.2107
			2	0.0901	8.6067	0.1853
		R	1	0.0983	12.9323	0.2129
			2	0.1006	12.2408	0.2105
	1000	O	1	0.0922	7.8812	0.1826
			2	0.0835	6.0891	0.1649
		R	1	0.0896	7.8419	0.1831
			2	0.0821	5.5815	0.1604
	1300	O	1	0.0834	5.1087	0.1593
			2	0.0821	5.5815	0.1604
		R	1	0.0798	5.1565	0.1603
			2	0.0824	5.0652	0.1591
10	400	O	1	0.0385	4.1303	0.2124
			2	0.0404	4.2517	0.2160
		R	1	0.0388	3.9688	0.2080
			2	0.0418	4.6560	0.2167
	700	O	1	0.0377	4.0105	0.2131
			2	0.0389	3.9959	0.2130
		R	1	0.0378	3.5238	0.2024
			2	0.0399	4.2671	0.2129
	1000	O	1	0.0284	1.1568	0.1377
			2	0.0404	3.8517	0.2076
		R	1	0.0395	3.7461	0.2031
			2	0.0403	4.1388	0.2095
	1300	O	1	0.0398	3.8283	0.2084
			2	0.0404	3.8780	0.2079
		R	1	0.0397	3.7656	0.2033
			2	0.0668	14.4184	0.3056

[a] O = Oriented specimen, R = Random specimen.

VITA

William Paul Hawkins was born in Fort Worth, Texas, on December 24, 1950. At the age of four he accompanied his parents to Brazil, where they served as Baptist missionaires. He graduated from the Ginasio Industrial in Tupa, Sao Paulo, in 1967. In September of 1968 he entered the University of Tennessee at Martin and transferred to Knoxville in 1971. He received the degree of Bachelor of Science in Agricultural Engineering in December of 1972.

He entered the Graduate School at the University of Tennessee in January, 1973, and received a Master of Science degree with a major in Agricultural Engineering in December of 1974. He is a member of the American Society of Agricultural Engineers, Gamma Sigma Delta, Tau Beta Pi, and Phi Kappa Phi.

He is married to the former Paula Ann Covington of Martin, Tennessee.