RESEARCH BULLETIN 864 JUNE, 1964

UNIVERSITY OF MISSOURI COLLEGE OF AGRICULTURE
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Resistance of Hay to Air Flow

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(Publication authorized June 23, 1964)

COLUMBIA, MISSOURI

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INTRODUCTION

The laws governing the flow of fluids through porous media are of importance in many engineering problems. They are essential in determining the movement of water, oil, and gas through beds of sand, rock, and soil. They are needed for determining soil moisture movement and seepage from lakes and ponds. Of special interest in the agricultural engineering field is the flow of air through grain and hay.

Considerable research has been done on the flow of fluids through beds of various kinds of materials. Most of the work has been with material such as lead shot, balls, shells or other material having a smooth surface and of a given size and shape. While the results of this work might be applied to flow through grain, it is not applicable to the flow through hay since hay particles do not have smooth surfaces and are not of uniform size and shape.

Since about 1943 there has been considerable interest in drying grain and hay on farms. To properly design equipment for drying, some information on the resistance of grain and hay to air flow was essential. Consequently, a number of investigators began to conduct research on air flow through grain and hay at about that time.

In 1943 Henderson (6) published the results of some tests on the resistance of shelled corn to air flow. He also reported data on the resistance of soybeans and oats to air flow (7) in 1944. In 1945 Shedd (10) published the results of tests on the resistance of ear corn to air flow. In 1951 and again in 1953 the same investigator (11, 12) reported on tests of the resistance of grains and seeds to air flow. Curves based on the work by Shedd have been published annually since 1954 in the yearbook of the American Society of Agricultural Engineers.

A number of investigators, including Shedd (13), Hendrix (8, 9), Guillou (5), Davis (3), Bruhn (2), Zerfoss (14), Davis and Baker (4), and Ball (1) published results of tests on air flow through hay during the period 1944 to 1951. These investigators agreed, in general, that the relationship between air velocity and pressure drop could be expressed by an equation of the form $v = aH^n$ where v is velocity, H is pressure drop and a and n are constants for a given set of conditions. Values of n as determined by various investigators ranged from 0.55 to 0.78.

HYPOTHESES

In general, the pressure drop in an air stream through a mass of hay depends upon the rate of flow of the air, the density and the viscosity of the air, the size of the passages through which the air must flow, the roughness of the material, the porosity of the mass, and the length of the air path.

The pressure drop can be expressed as a function of the factors listed as follows:

$$p = f(v, L, d, \rho, \mu, r, h) \qquad \text{Eq. 1}$$

where

Symbol	Definition	Dimensions
p	pressure drop	FL^{-2}
v	velocity	LT^{-1}
L	control length	L
d	diameter of air passages	L
ρ	density of fluid	FT^2L^{-4}
μ	viscosity of fluid	FTL^{-2}
r	roughness	------
h	porosity	------

Making use of dimensional analysis and the Buckingham Pi theorem, an expression involving five dimensionless groups (or pi terms) can be written as follows

$$\frac{p}{\rho v^2} = \left(\frac{\rho v d}{\mu},\ r,\ \frac{d}{L},\ h\right)$$

let

$$\pi_1 = \frac{p}{\rho v^2}$$

$$\pi_2 = \frac{\rho v d}{\mu}$$

$$\pi_3 = r$$

$$\pi_4 = d/L$$

$$\pi_5 = h$$

π_2 is an expression for the Reynolds number, π_3 is a roughness factor. π_4 is a factor which designates the air passage size, and π_5 is the porosity of the material.

If realistic numerical values could be assigned to r and d, it would then be possible to devise an experiment in which the Pi terms were independently varied over a suitable range of values and expressions for π_1 in terms of π_2, π_3, π_4, and π_5, could be obtained. With information presently available, it is not possible to assign a numerical value to roughness. It is reasonable to assume that roughness depends upon the shapes of the particles, the kind of material, the size and shapes of the air passages, and perhaps the moisture content of the material.

It is equally difficult to assign a numerical value to the sizes of the air passages. The air passage sizes depend upon the total volume of the enclosure, the number of particles, the sizes and shapes of the particles and the moisture content of the material.

It becomes evident that it is impossible to vary the air passage sizes without affecting roughness and that it is equally impossible to reproduce any given roughness or air passage size if the material under test is disturbed or replaced. The design of an experiment based on the parameters determined by the dimensional analysis above is, therefore, precluded and another approach must be used.

It is possible to determine precisely a relationship between the pressure drop and the specific air flow rate for a given batch of material under a given set of conditions. This information is not generally useful since it may be impossible to find another batch of material with exactly the same case history to which it can be applied. Of greater interest is the effect of certain variables on the pressure drop.

From this point on, the material will be limited to hay and the fluid limited to air. A examination of equation 1

$$p = f\,(v\ L,\ \rho,\ \mu,\ d,\ r,\ h)$$

reveals that the quantities, v, ρ and μ depend upon properties of the air, that d, r, and h depend upon properties of the hay, and that L is independent of both the material and the fluid.

The air flow rate can be controlled and measured, but the density and viscosity of the air cannot be independently varied by any practical means. Both are affected by changes in temperature. The variations in the density and viscosity of air over the usual range of drying temperatures when unheated air is used appear to be of little consequence. The Reynolds number, as defined above, is expressed by

$$R = \frac{\rho v d}{\mu}$$

For a given batch of hay and a given air flow rate, d and v will be constant.

$$\text{let } vd = k$$

For air at 70 F

$$\rho = 2.32 \times 10^{-3} \text{ slugs per cubic ft.}$$

$$\mu = 3.78 \times 10^{-7} \text{ slugs per ft. - sec.}$$

Then

$$R = 6140\ k$$

For air at 100 F

$$\rho = 2.20 \times 10^{-3} \text{ slugs per cubic ft.}$$

$$\mu = 3.95 \times 10^{-7} \text{ slugs per ft. -sec}$$

Then

$$R = 5580\ k$$

Thus, about a 10 percent change in Reynolds number would result from a change in temperature from 100°F to 70°F. Assuming that turbulent flow prevails, it is unlikely that a 10 percent change in Reynolds number has any appreciable effect on the pressure drop.

Since the material has been limited to hay, the principal variations which are of interest are changes in the length and conditions of the hay, the degree of packing, and the moisture content.

It would be expected that chopped hay at a given moisture content and packed to a given bulk specific weight would have a different roughness and different air passage sizes when compared with long hay. It would also be expected that conditioned hay (i.e. hay that has been crimped or crushed) would differ from the non-conditioned hay in these respects. If, then, roughness and air passage sizes are pertinent variables, a difference in the pressure drop for given air flow rates would be expected when these variables are changed.

APPARATUS

To check the effect of the variables above and others on pressure drop, a test bin was connected to a positive displacement type air pump as shown in Figure 1. The specific air flow rate can be precisely calculated since the diameter of the upper bell is known and the rate of descent can be determined from the drive shaft speed and sprocket ratios. The one foot in diameter test bin was placed horizontally on the floor to minimize the variation in density due to the weight of the hay itself. A plenum chamber was located between the pump and the test bin and pressure taps were located at one foot intervals along the bin. Hay was weighed and packed into the test bin in one foot increments using a graduated tamper (Figure 1). The specific air flow rate was changed by using different sets of sprockets on the air pump. Pressure differences were measured between position 1 (the position nearest the plenum) and each of the other taps along the bin using an inclined tube manometer as shown in Figure 2. The manometer has a range of 0-2 inches of water and a least count of 0.02 inches of water.

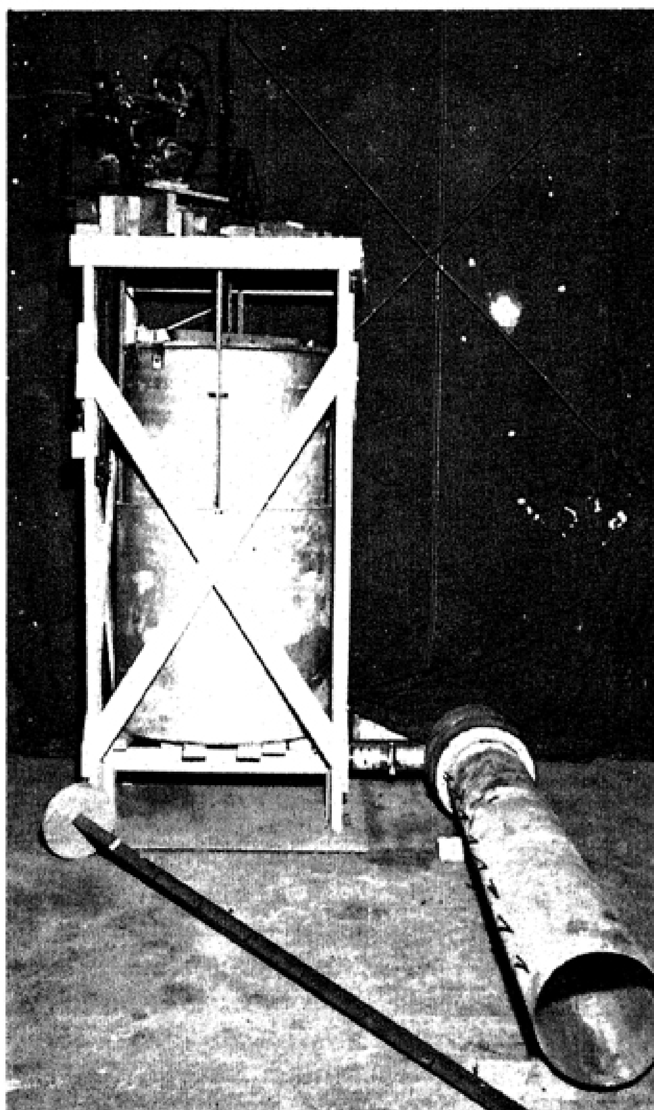

Fig. 1—Positive displacement air pump, test bin, and graduated tamper used in determining resistance of hay to air flow.

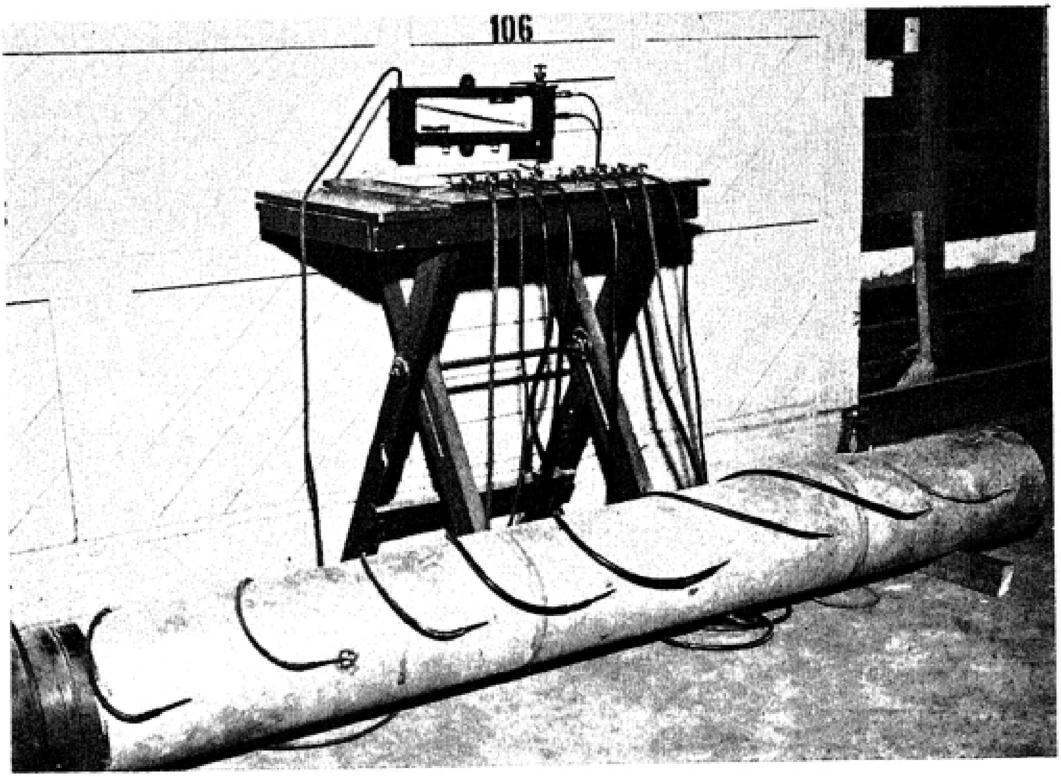

Fig. 2—Test bin showing pressure taps and inclined tube manometer.

PROCEDURES AND RESULTS

A series of tests was designed to check the effect of chopping and crushing on resistance to air flow. The procedure used was as follows: Alfalfa hay was mowed and part of it was crushed with a hay conditioner having rubber rollers. Hay was allowed to field cure to approximately 30 percent moisture and then was raked with a side delivery rake and picked up with a pitch fork. The hay was then hauled to the laboratory and allowed to dry to about 11 percent (wet basis) before loading the bin. Exactly the same amount of hay by weight was loaded in the bin for each of the tests and it was packed uniformly in the bin so that the same volume was occupied in each case. The resulting bulk specific weight was 3.82 pounds per cubic foot. Figure 3 shows typical results of a comparison of crushed and uncrushed chopped hay. Note that for a given flow rate the pressure drops were slightly higher for crushed hay than for uncrushed hay.

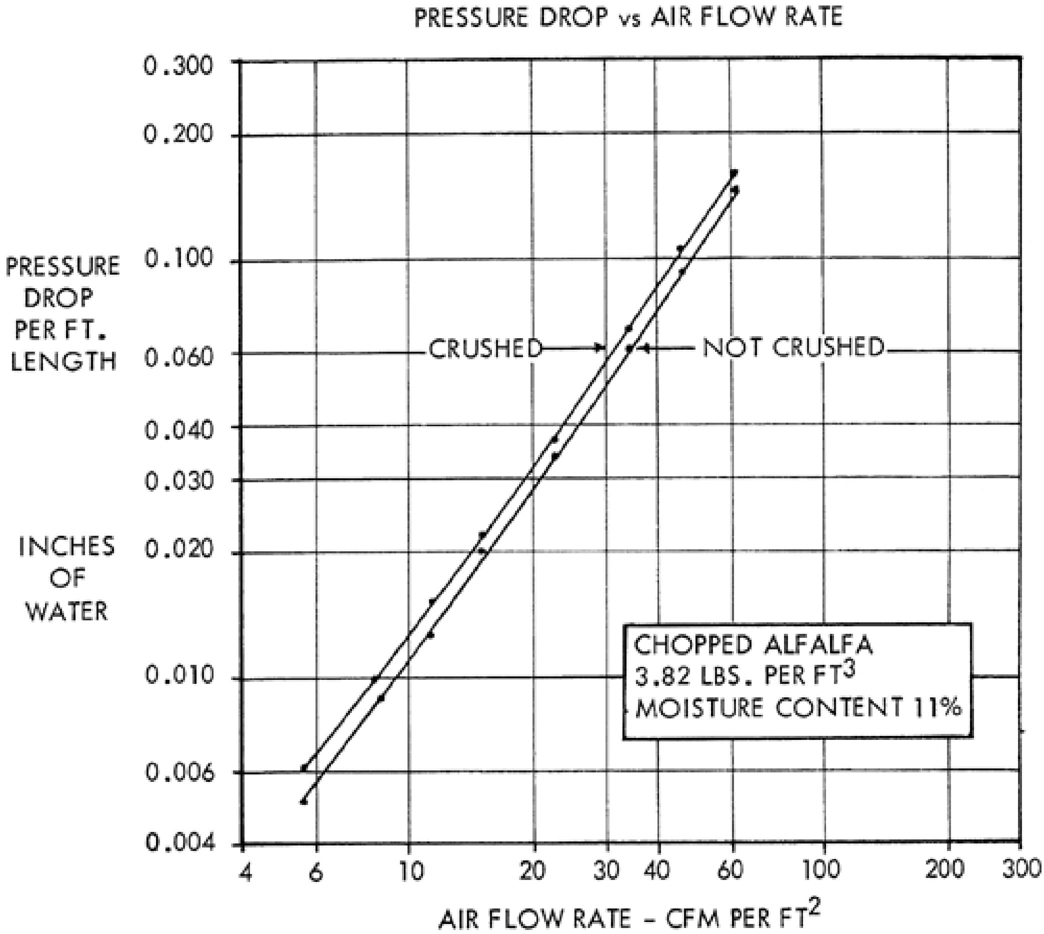

Fig. 3—Pressure drop versus air flow rate for crushed and non-crushed hay.

Tests comparing long crushed alfalfa with long uncrushed alfalfa hay indicated that there was even less difference in resistance to air flow than was the case in the chopped hay comparison.

Several tests were run in which the resistances of chopped and long hay to air flow were compared. A typical set of data is shown in Figure 4. Note that for a given air flow rate, the resistance to flow is higher for chopped than for long hay.

A series of tests was run to determine the difference in the resistance of hay leaves and hay stems. Leaves were stripped from enough hay to load the bin to approximately 3 feet with a bulk specific weight of 4.24 pounds per cubic foot. Pressure measurements were made for air flow rate ranging from 5.6 to 60 cfm per square foot. After the leaves were removed from the test bin, the stems were placed in the bin and packed to the same bulk specific weight as the leaves, and the air flow tests were repeated.

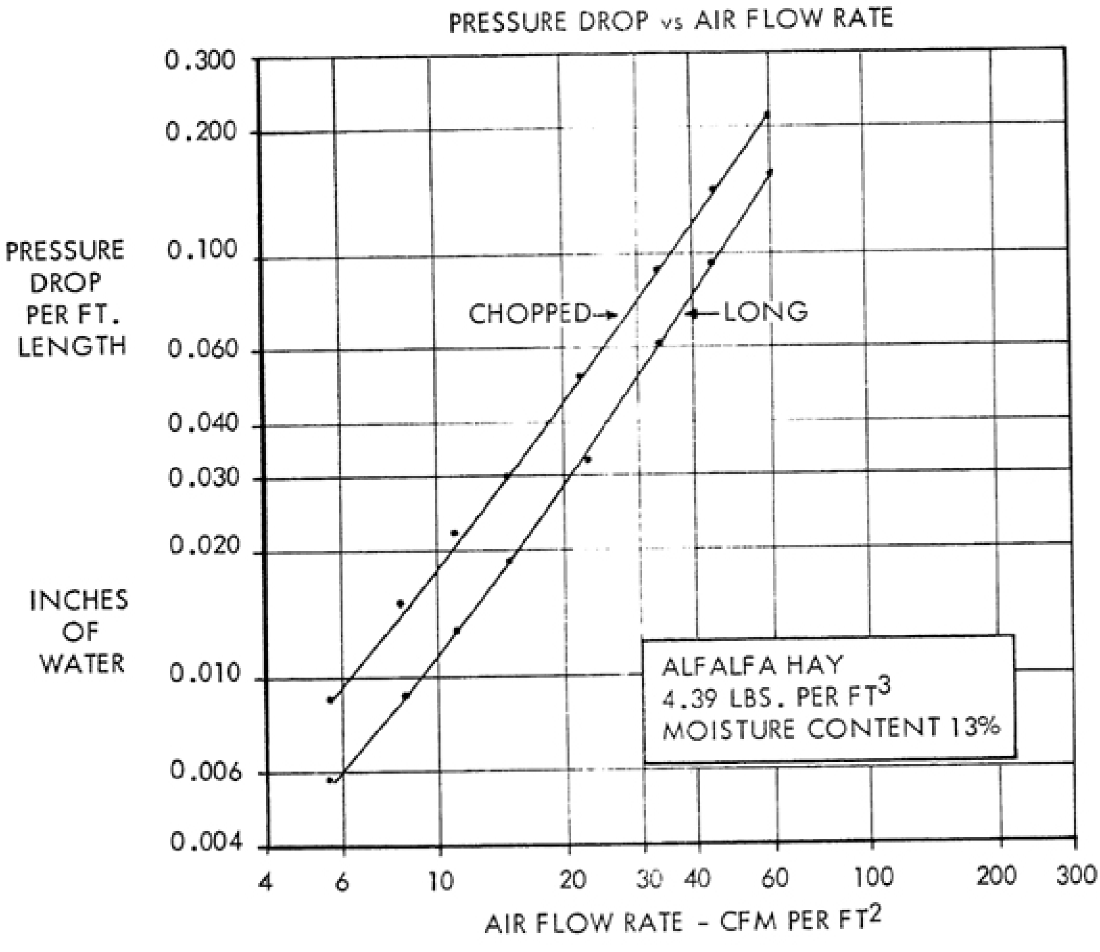

Fig. 4—Pressure drop versus air flow rate for chopped and long alfalfa hay.

For comparison, the bin was then loaded with chopped hay packed to 4.24 pounds per cubic foot. Figure 5a shows the results of these tests.

There is also evidence which indicates a considerable variation in resistance of hay cut at different times during the haying season. Figure 5b, for example, shows results of some tests on hay cut on June 19, 1962, compared with hay cut on August 7, 1962. The earlier cutting resulted in pressure drops approximately 50% higher than the later cutting even though the bulk specific weight and moisture content of the hay were the same in each case. The early growth of alfalfa in central Missouri is generally more luxuriant and consequently would be expected to have a higher percentage of leaves than that cut later in the season when soil moisture conditions are less favorable for growth. The ratio of leaves to stems is also affected by the stage of maturity of the plants.

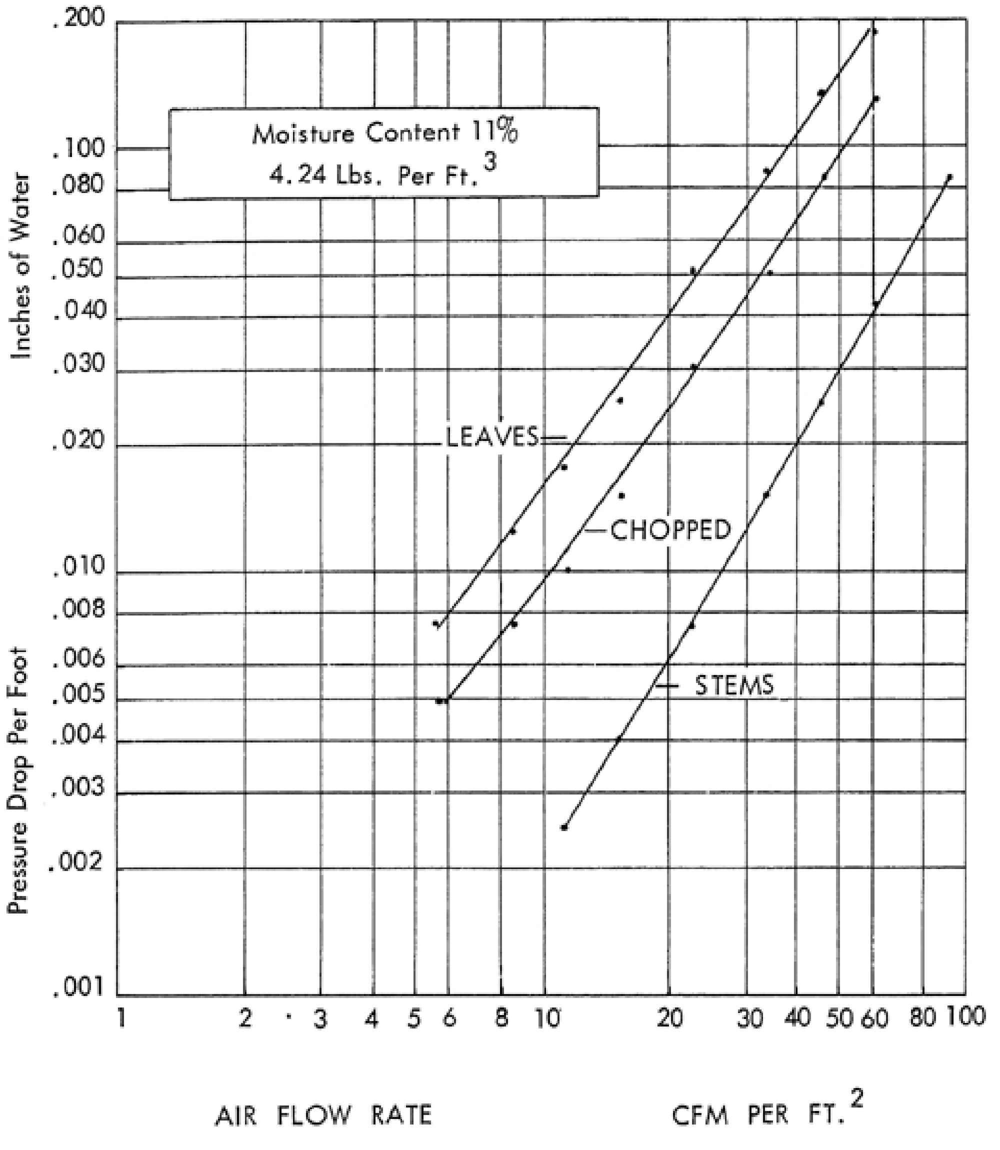

Fig. 5a—Pressure drop vs. air flow rate for alfalfa leaves, alfalfa stems, and chopped alfalfa hay.

Of far greater importance than the size and shape of the particles is the bulk specific weight of the material in the bin (i.e.) how much material is packed into a given volume. It is obvious that tighter packing results in smaller air passage sizes, lower porosity and, consequently, higher resistance to air flow.

A series of tests was run in August, 1959, with chopped alfalfa hay packed to specific weights of 3.00, 4.00, 5.00, and 6.00 pounds per cubic foot. The hay was at about 11 percent moisture in each case. Results of these tests are shown in Figure 6. Additional

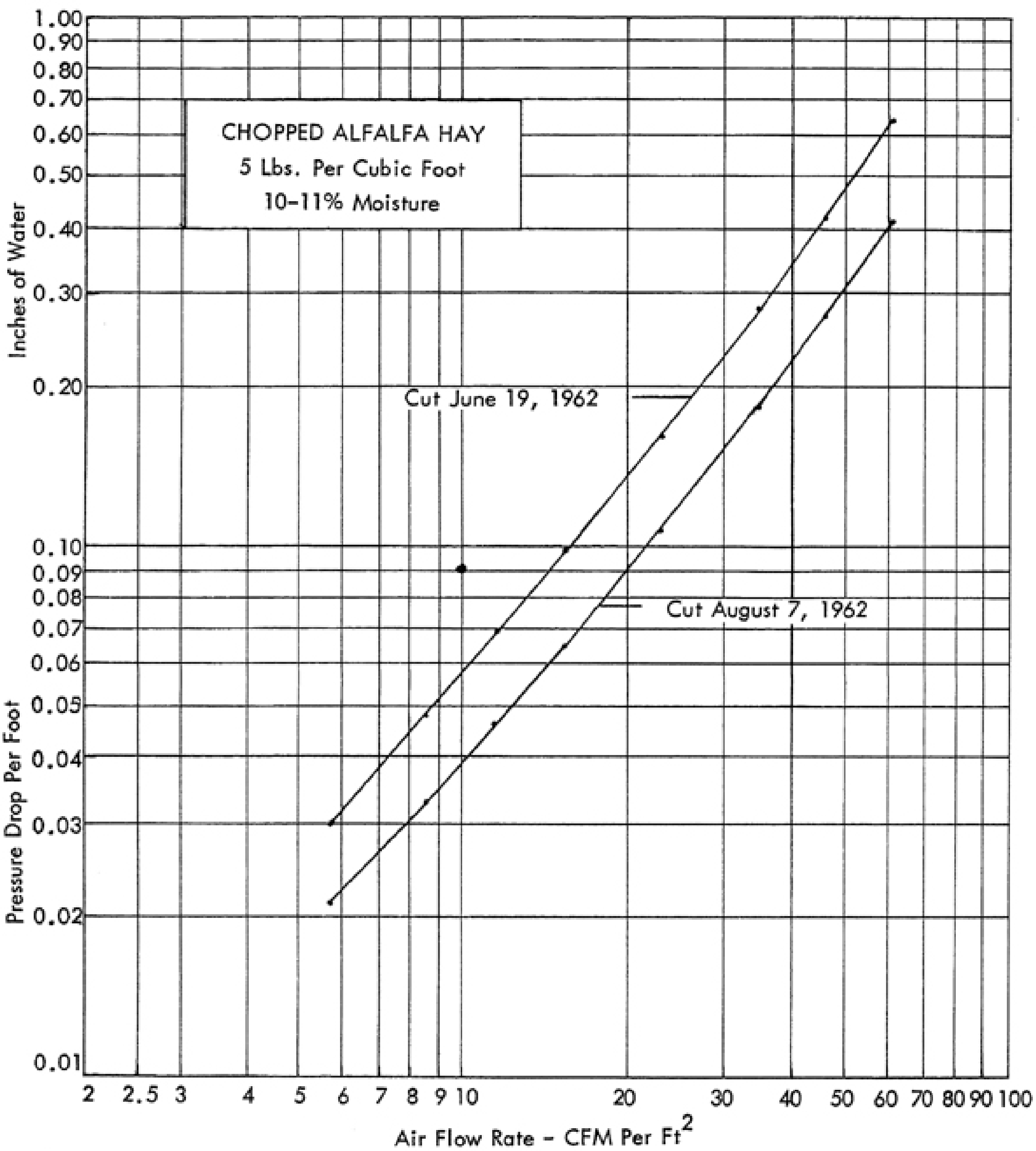

Fig. 5b—Pressure drop vs. air flow rate for chopped alfalfa hay cut on two different dates in 1962.

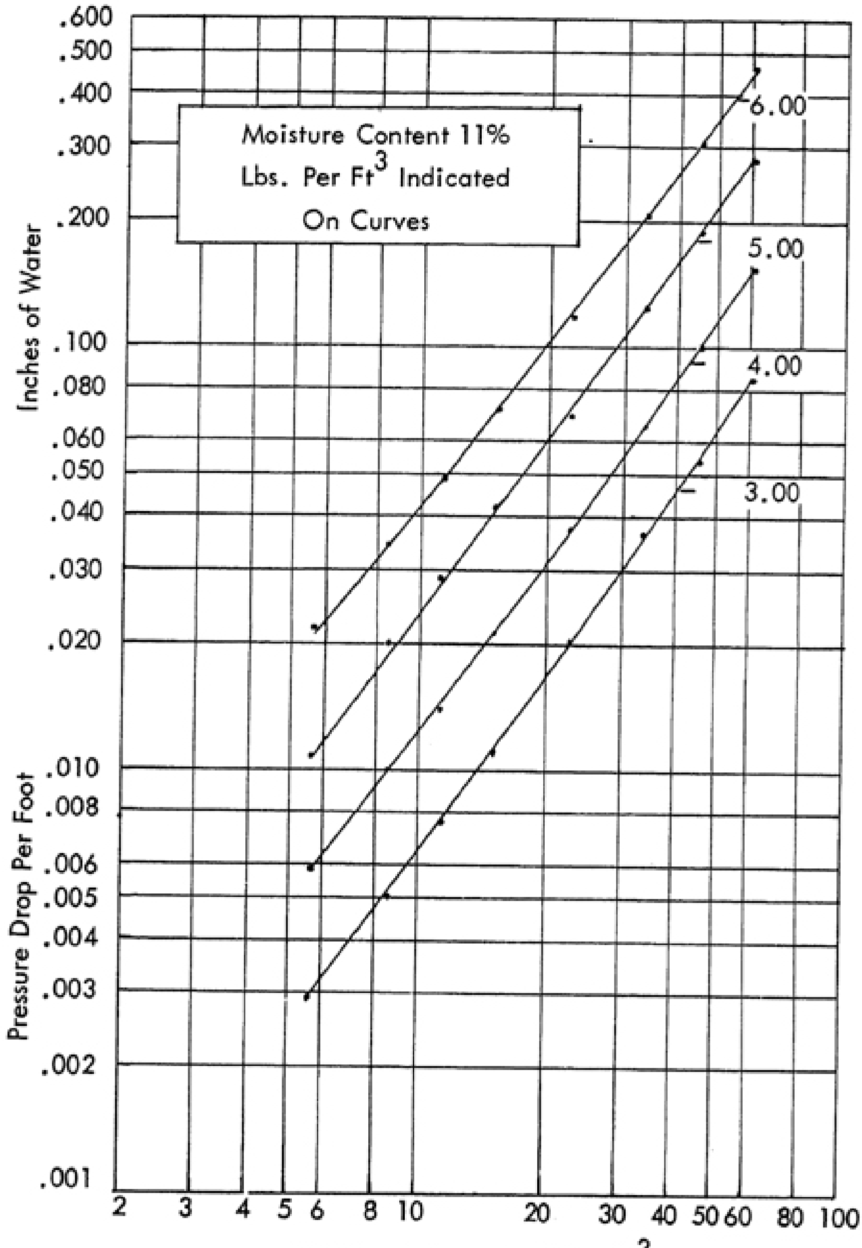

Fig. 6—Pressure drop vs. air flow rate for chopped alfalfa hay cut August, 1959.

tests were run in June, 1960, with bulk specific weights ranging from 3.18 to 5.73 pounds per cubic foot. Again the moisture content was about 11 percent. Results of the 1960 tests are shown in Figure 7. The results shown in Figures 6 and 7 show a consistent pattern, but are not entirely compatible. The differences are believed to result from differences in material. As previously mentioned, the cutting date has an effect upon the leafiness of the material which in turn affects its resistance to air flow.

It is of interest to determine the relationship between air pressure drop and bulk specific weight for a given air flow rate. From Figures 6 and 7, points were slected at the various bulk specific weights for constant air flow rates of 10, 20, and 40 cfm per square foot of bin cross section and were plotted in Figure 8 along with data from additional tests with chopped hay with moisture ranging from 11 to 13 percent. For chopped alfalfa hay the pressure drop varies approximately as the third power of the bulk specific weight of the material.

Although sufficient data are not available for high moisture material to definitely establish curves similar to those in Figure 8, enough data are available to indicate that the relationship between pressure drop and bulk specific weight is similar regardless of the moisture content. Figure 9 again shows the relationship between pressure drop and bulk specific weight for chopped alfalfa hay with 11 to 13 percent moisture and an air flow rate of 20 cfm per square foot of bin cross section. In addition, data for chopped alfalfa hay with moisture ranging from 37 to 40 percent and with moisture ranging from 64 to 67 percent are plotted in separate curves. These curves indicate that the pressure drop increases approximately as the third power of the bulk specific weight regardless of the moisture content. They indicate also that hay with a high moisture content offers less resistance to air flow than hay with a low moisture content if the bulk specific weight is the same in each case.

To determine the effect of moisture on resistance to air flow, a series of test was run on hay samples ranging from 12 to 63 percent in moisture content, but with the bulk specific weight of the material constant at five pounds per cubic foot. Figure 10 shows the results of this series of tests. From this family of curves, a relationship between pressure drop and moisture content was obtained by selecting points at air flow rates of 10, 20, and 40 cfm per square foot of bin cross section. The results are shown in Figure 11. Note that if the curve were extrapolated, a zero pressure would be indicated for hay with moisture between about 60 and 65 percent. This simply means that five pounds of hay with more moisture than this would not occuupy a full cubic foot. (Five lbs. of water with no hay would occupy about 0.08 cubic foot.) If such high moisture material were uniformly placed in a horizontal bin, such as the one shown in Figures 1 and 2, an air space would remain at the top of

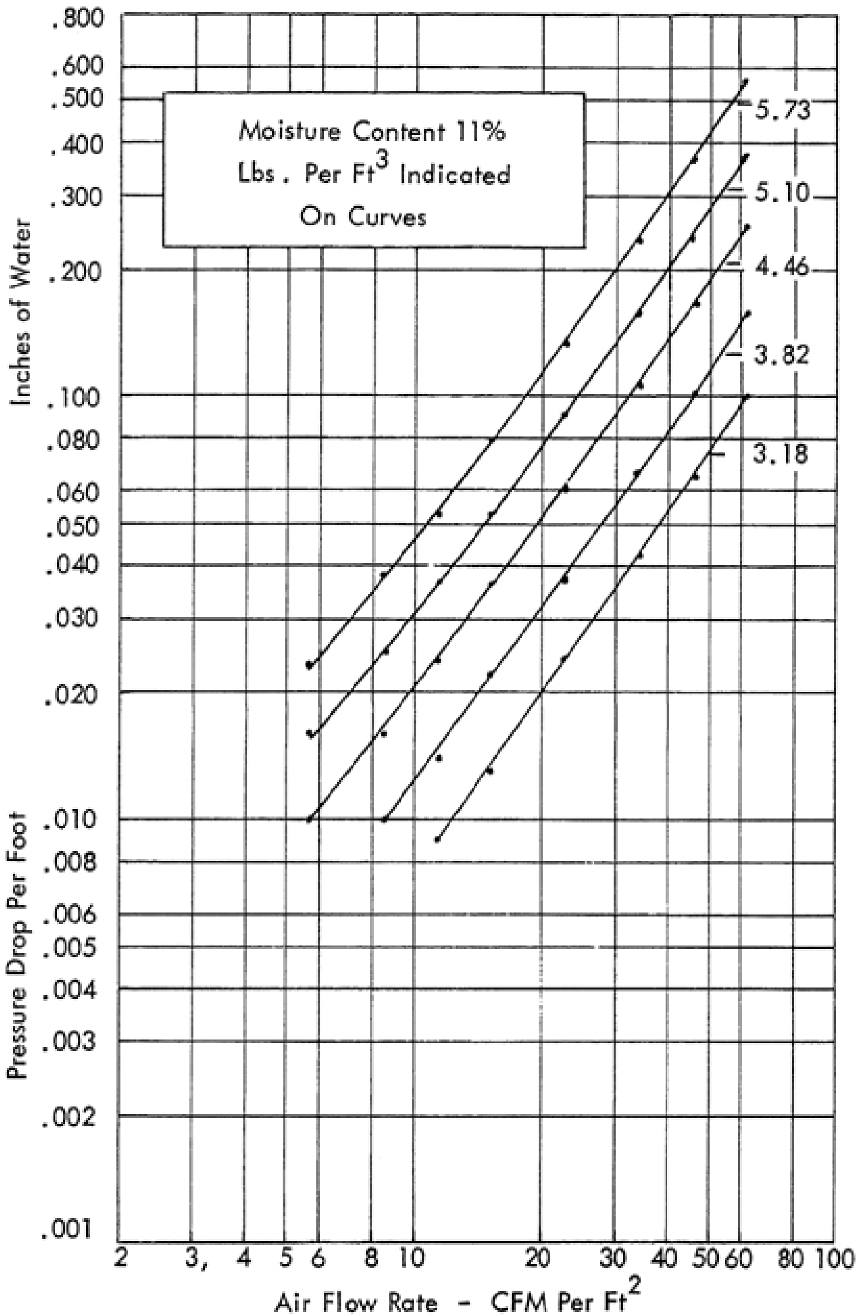

Fig. 7—Pressure drop vs. air flow rate for chopped alfalfa hay cut June, 1960.

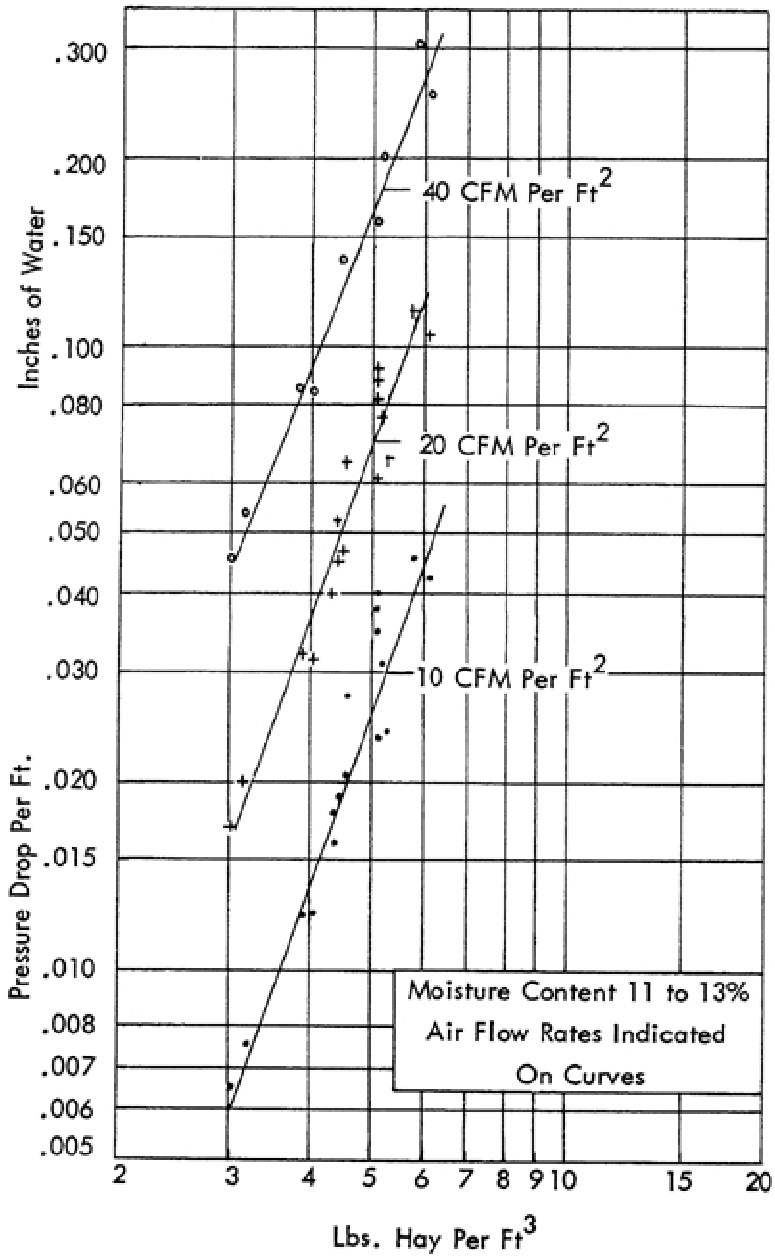

Fig. 8—Pressure drop vs. bulk specific weight for chopped hay with moisture content of 11 to 13 percent.

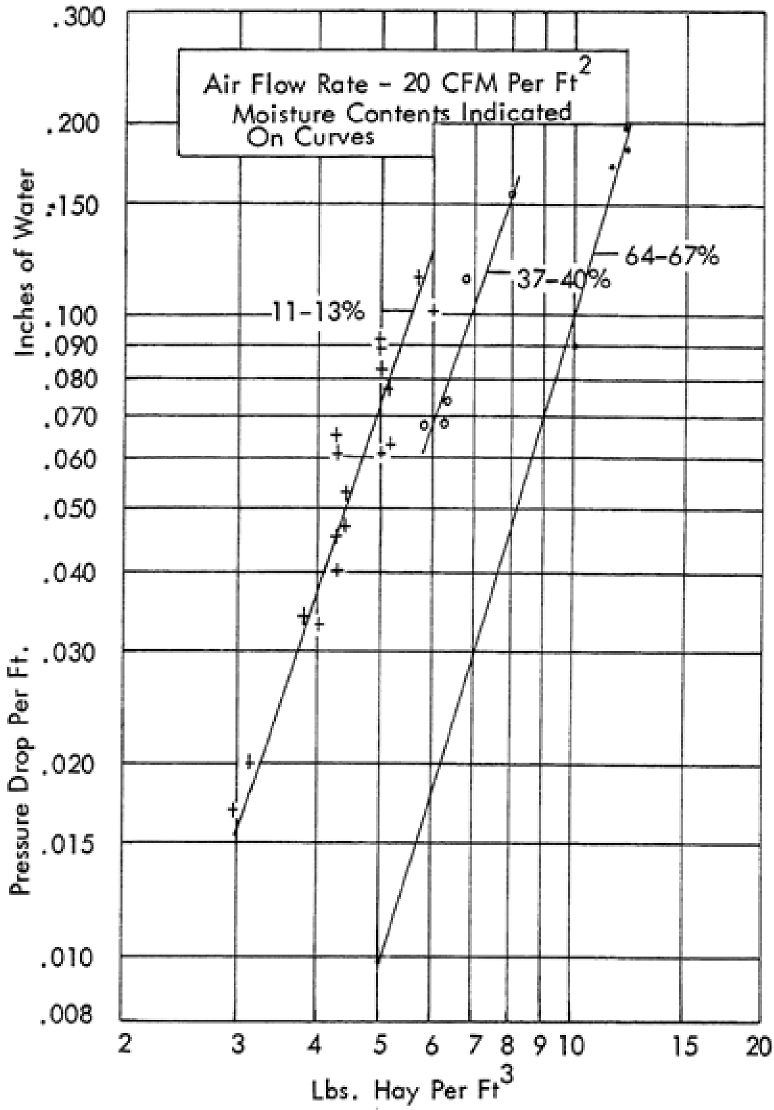

Fig. 9—Pressure drop versus bulk specific weight for chopped hay at three moisture levels.

the bin which would offer essentially no resistance to the flow of air at the velocites used in these experiments.

Since moisture is expressed as percent on a wet basis, hay at 25 percent moisture is one-fourth water and three-fourths dry matter, hay at 50 percent moisture is half water and half dry weight etc. It is not surprising that for a given bulk specific weight (water plus dry matter) the drier hay offers more resistance to air flow. The spaces occupied by the water are believed to be the minute pores in the material and, consequently, the sizes of the passages through which most of the air passes are not greatly affected.

As hay dries in the mow, the total weight per unit volume is actually reduced because of moisture removal. This is true even though some settling usually occurs which tends to increase the

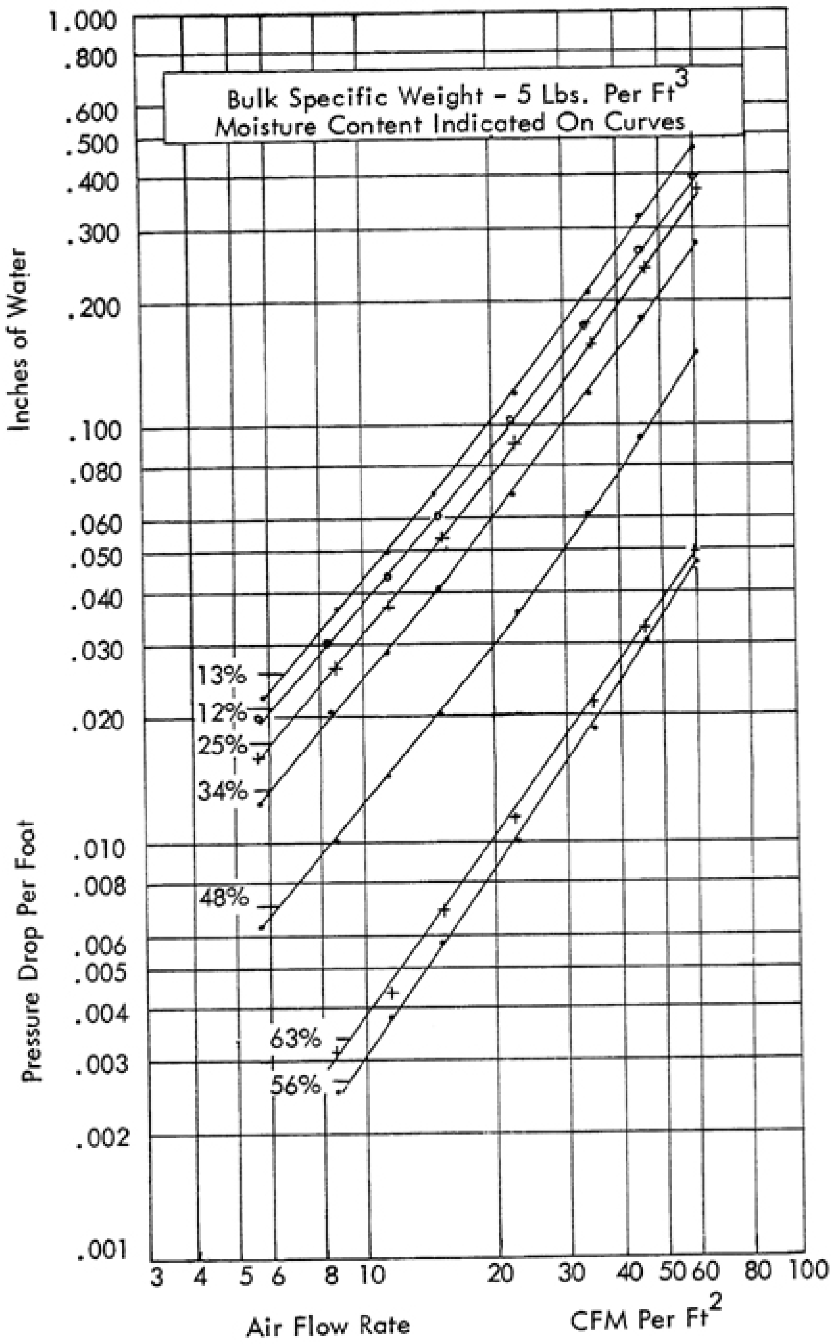

Fig. 10—Pressure drop vs. air flow rate for chopped alfalfa hay with moisture contents from 12 to 63 percent and bulk specific weight constant at five pounds per cubic foot.

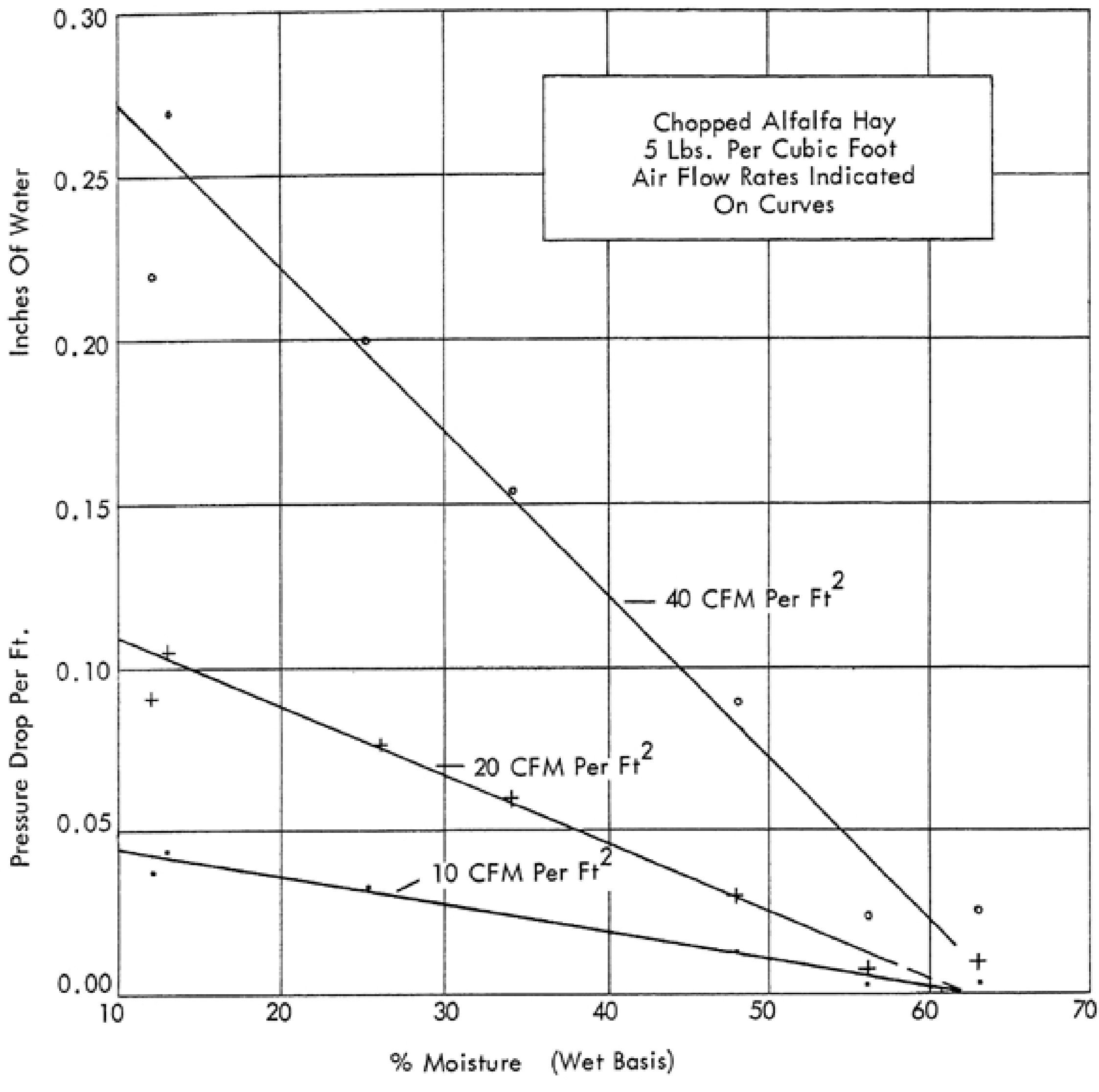

Fig. 11—Pressure drop vs. moisture content for chopped alfalfa hay with bulk specific weight constant at five pounds per cubic foot.

weight per unit volume. The amount of dry matter per unit volume probably increases slightly as the hay dries and settles.

A series of tests was run with the amount of dry matter per cubic foot volume constant. A value of four pounds dry matter per cubic foot was selected and hay samples ranging in moisture content from 10 to 67 percent were used. Figure 12 shows the results of these tests and Figure 13 shows a relationship between pressure drop

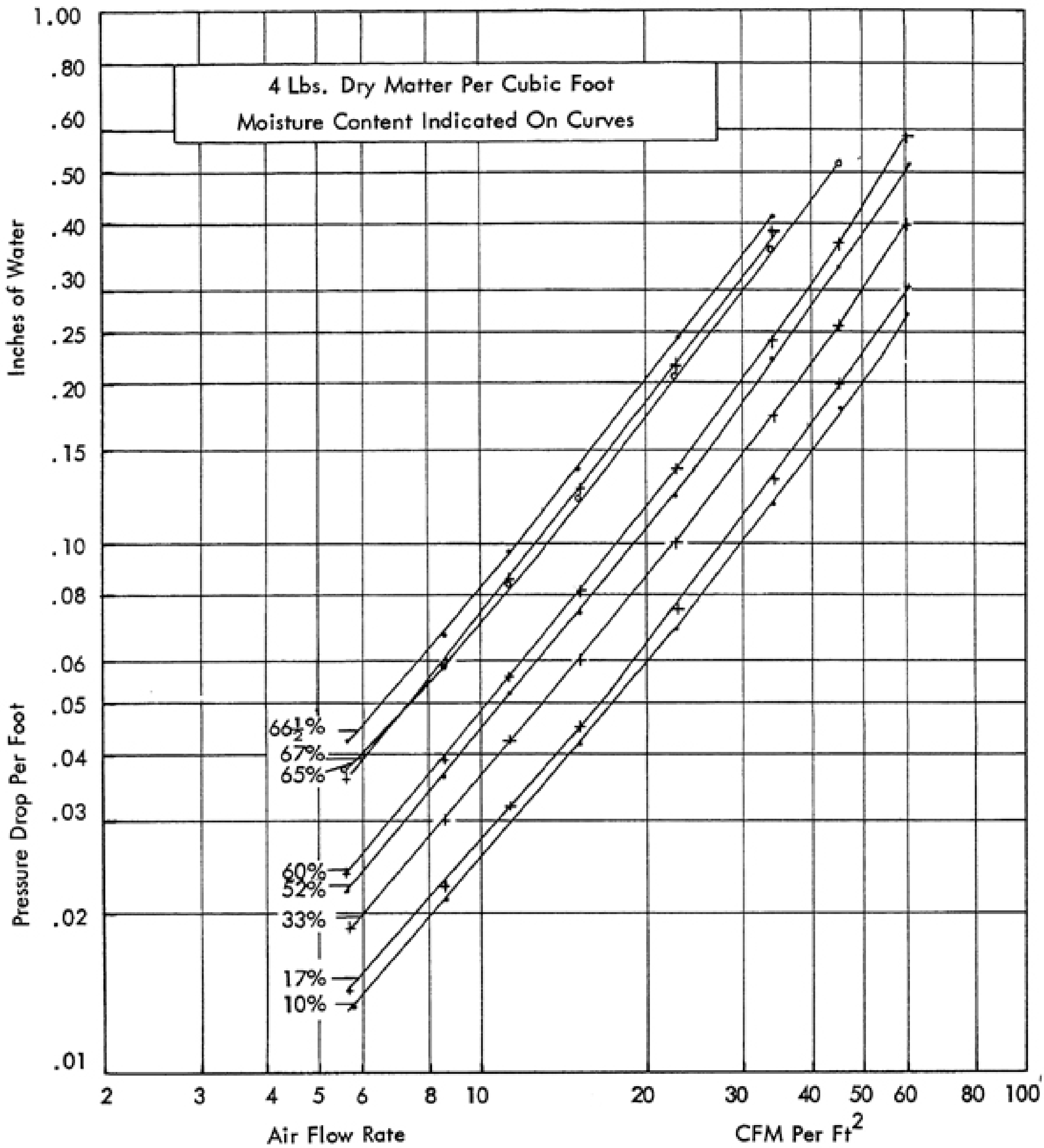

Fig. 12—Pressure drop vs. air flow rate for chopped alfalfa hay with moisture contents from 10 to 67 percent and dry matter per cubic foot held constant.

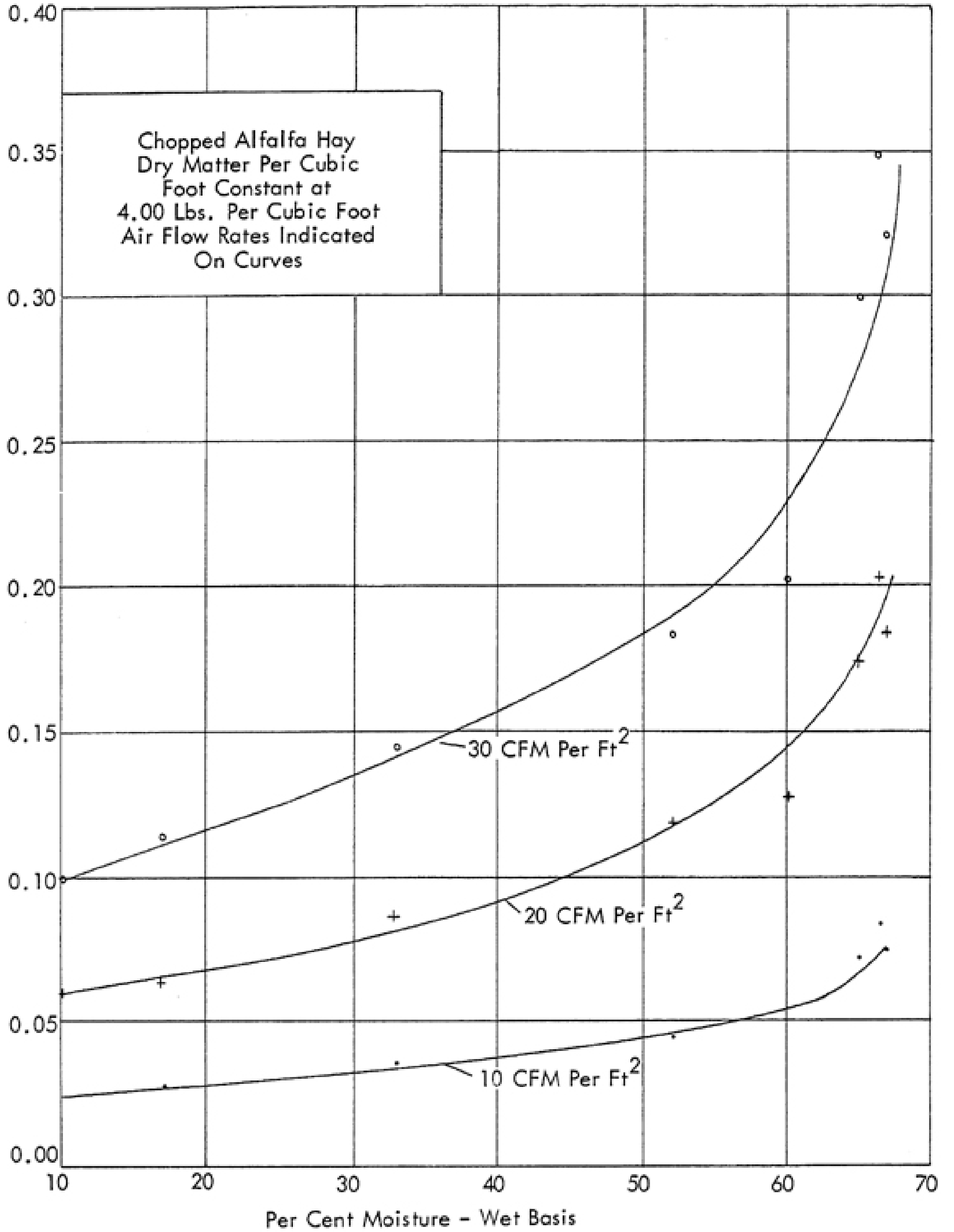

Fig. 13—Pressure drop vs. moisture content for chopped alfalfa hay with dry matter per cubic foot constant.

and moisture content for air flow rates of 10, 20, and 30 cfm per square foot of bin cross section. As the moisture content approaches 100 percent (all water and no hay), the resistance approaches the resistance of water; i.e., 12 inches of water per foot of bin length. For a constant amount of dry matter per unit volume, the resistance is lowest when the moisture content in zero (all hay and no water).

SUMMARY AND CONCLUSIONS

A considerable difference in the resistance of hay to air flow may result from the differences in leafiness, maturity, or kind of hay. Figure 5 shows the resistance of leaves to be approximately seven times that of stems. Thus, hay with a high percentage of leaves would be expected to offer more resistance to flow than hay with a high percentage of stems.

The resistance of hay to air flow was increased by chopping, crimping, or crushing, but the increases due to these operations were minor in comparison with those resulting from an increase in the amount of material per unit volume. Resistance to air flow increased approximately as the third power of the bulk specific weight with moisture content and air flow rate constant. This indicates that the resistance to air flow varies with the depth of the hay. If, for example, the bulk specific weight of the hay is twice as high at the bottom of the mow as at the top, the resistance to air flow is approximately eight times as high.

Hay with a high percentage of moisture offered less resistance to air flow than drier hay with the same bulk density. If considered on the basis of <u>dry matter</u> per unit volume, however, dry hay had a lower resistance to air flow than wet hay with the same amount of <u>dry matter</u> per unit volume.

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