RESISTANCE OF BULK LENTILS TO AIRFLOW

S. Sokhansanj, A. A. Falacinski, F. W. Sosulski, D. S. Jayas, J. Tang
MEMBER ASAE (S. Sokhansanj); MEMBER ASAE (D. S. Jayas); STUDENT MEMBER ASAE (J. Tang)

ABSTRACT

Using a laboratory unit, the resistance to airflow through bulk lentils (*Lens culinaris* M.) and the effect of seed moisture content, variety, method of fill, direction of airflow, and percent fines on the resistance to airflow was determined for an airflow range of 0.003 to 0.6 $m^3.s^{-1}.m^{-2}$. An increase in moisture content of Laird lentils from 10.4 to 19.9% resulted in a 22.5% decrease in resistance to airflow. The resistance to airflow of Eston lentils was 3 to 27% higher than the resistance of Laird lentils at airflow rates between 0.0028 to 0.0272 $m^3.s^{-1}.m^{-2}$, and was 1% to 6% lower at airflow rates between 0.0272 and 0.5926 $m^3.s^{-1}.m^{-2}$. The dense fill of Laird lentils produced a bulk density about 9% greater and a resistance to airflow about 50% higher compared with the loose fill. The resistance of Laird lentils to horizontal airflow was one-half of the resistance to vertical airflow. A linear equation was developed to relate the increase in pressure drop with an increase in percent fines.

INTRODUCTION

Lentils (*Lens culinaris* M.) are one of the oldest cultivated legumes and are important in diets because of their high protein content. Lentil seeds, on a moisture-free basis, contain about 27% protein (Abu-Shakra and Tannous, 1980). Lentils are usually consumed in soup and stews and less commonly as roasted and seasoned snack food.

Because of problems with shattering and brittleness, lentils are usually threshed at about 20% moisture content (m.c.) wet basis* and then dried artificially to about 14% m.c. for safe storage. A maximum temperature of 40° C is recommended for artificial drying (Slinkard and Drew, 1986). This low limit on drying temperature suggests that drying lentils at near-ambient air temperature would be most practical since little heat can be applied. Aeration is also commonly used to cool lentils and maintain uniform temperature and moisture in bulk stored lentils. To the knowledge of the authors, no data on the resistance to airflow through bulk lentils have been reported in the literature or compiled in the ASAE Standard Data D272.2 (ASAE, 1990) which gives resistance to airflow through 33 crop seeds.

The objectives of this study were to determine the resistance to airflow through bulk lentils and the effect of seed moisture content, variety, method of fill, direction of airflow through seeds, and percent fines on the resistance to airflow.

EXPERIMENTAL EQUIPMENT

The resistance to airflow through lentils was measured using a modification of the experimental unit developed by Jayas et al. (1987a). The schematic of the modified experimental unit is shown in figure 1. The main components of the system are: a holding tank with telescopic discharge tube, airflow sources, and instrumentation for airflow and pressure drop measurement.

The cylindrical container was constructed from several lengths of smooth PVC pipe, each 250 mm long and 320 mm i.d. Two airflow straighteners were installed between the plenum and the test chamber to ensure uniform air distribution in the grain column. The straighteners were fabricated from 12.7 mm diameter copper tubing soldered together in honeycomb structures. Two lengths of tubing, 190 and 76 mm, were used for the lower and upper airflow straighteners, respectively. The pressure taps were located at intervals of 250 mm along the column height. Each level had four taps horizontally placed 90° apart.

The lentil seeds in the container were supported by No. 24 copper wire mesh having a 44.2% open area. The mesh was placed on top of the upper 76 mm long airflow

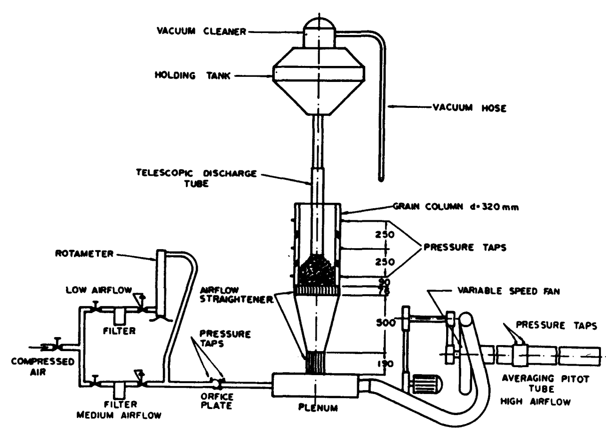

Figure 1–Schematic of the experimental apparatus for measuring the resistance of lentils to airflow. The support structure is removed for clarity. All dimensions are in mm.

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The authors are **S. Sokhansanj**, Professor, **A. A. Falacinski**, former Graduate Student, Agricultural Engineering Dept., **F. W. Sosulski**, Professor, Crop Science Dept., University of Saskatchewan, Saskatoon, Saskatchewan, Canada; **D. S. Jayas**, Associate Professor, Agricultural Engineering Dept., University of Manitoba, Manitoba, Canada; and **J. Tang**, Research Associate, Agricultural Engineering Dept., University of Saskatchewan, Saskatoon, Saskatchewan, Canada.

*Moisture contents in this article are given in wet basis.

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straightener. The pressure drops were measured across a 500 mm depth of grain column to a resolution of 0.34 Pa using a differential pressure transducer (Model DP103-26, Validyne Engineering Corporation, Northridge, CA).

The lowest airflow that could be measured was 0.0028 $m^3.s^{-1}.m^{-2}$. For airflow rates of more than 0.5926 $m^3.s^{-1}.m^{-2}$, the material in the test chamber was fluidized. To provide an accurate measurement, the total airflow range was divided into three sub-ranges: low airflow rates between 0.0028 and 0.1537 $m^3.s^{-1}.m^{-2}$; medium airflow rates between 0.1537 and 0.2930 $m^3.s^{-1}.m^{-2}$; and high airflow rates between 0.2930 and 0.5926 $m^3.s^{-1}.m^{-2}$. To cover the total airflow range, two different airflow sources were used. For low and medium rates, compressed air from a central compressor was filtered and regulated. The air then passed through the rotameter and a calibrated orifice plate installed in the line for measurement of airflow. Low airflow rates were measured by two rotameter tubes (Fisher and Porter Co., Warminster, PA). Medium airflow rates were measured using a calibrated orifice plate with a sharp-edge and a 19 mm diameter circular hole (ASME, 1972). These static pressures across the orifice were used to give airflow rates using the calibration relationship.

For high airflow rates (between 0.2930 and 0.5926 $m^3.s^{-1}.m^{-2}$), a variable speed, high pressure centrifugal fan was used as a source of air. The airflow was measured by an averaging pitot tube located at the mid-length of a 3050 mm long smooth PVC pipe on the suction side of the fan. Calibrations for low flow rotameters were provided by the manufacturer. The orifice plates were calibrated using a 20-point pitot tube traverse method (ASME, 1972; Ower and Pankhurst, 1966). Experiments were carried out in a laboratory where room temperature and relative humidity were in the range of 20 ± 2° C and 30 ± 10%, respectively.

To study the effect of the direction of airflow on pressure drop, another experimental apparatus of Jayas et al. (1987b) was used. Lentils were poured into the cubic container. Four faces of the cubic box were made of 16 mm thick plywood and the remaining two faces were made of brass screen material with 42% open area. The air plenum was attached to one of the brass screen sides. The pressure taps, spaced 250 mm apart, were placed along the centerline of one of the plywood faces.

Confirmation Tests

To check the performance of the system and to measure the accuracy of pressure drop measurements, a series of confirmation tests were performed on hard red spring wheat at 12.4% m.c. for loose and dense fills. These experimental values were compared to the ASAE Standard D272.2 (ASAE, 1989) which are used by industry for design of aeration and drying systems.

Curves for loose and dense fills were parallel to the ASAE data with a lower pressure drop for the loose fill and a higher pressure drop for the dense fill. Since the ASAE Standard D272.2 does not specify a fill procedure for "loose fill", it was concluded that the test equipment performed well and the measurements were sufficiently accurate to proceed with the lentil measurements. The difference of 1.4% m.c. between the tested wheat and the wheat whose data is given in the ASAE Standard should have no significant effect on resistance to airflow and was assumed to be negligible.

Materials and Methods

Materials

Two varieties of lentils, Laird and Eston, were used in this study. Both varieties were 1986 crop grown on the Canadian Prairies. Seeds were graded as Canada No. 1 according to the Canadian Grain Commission requirements (Anon., 1986). The moisture content at the time of purchase was 10.4% for the Laird lentils and 9.3% for the Eston lentils. Table 1 lists dimensions, densities, and porosities of the two varieties of lentil seeds used in the experiments.

Moisture content of lentils was determined by drying 50 g whole seeds, placed in a heavy gauge aluminum dish, in a convection oven at 103° C for 24 h. Lentils at moisture contents higher than 9 or 10% were prepared by forcing conditioned air through a bulk sample of lentils. The air at 30° C and 95% humidity was generated by a humidifier (Aminco-Aire, Parameter Generation and Control Inc., Black Mountain, NC). Lentils were taken out of the container every 10 h and mixed thoroughly to promote a uniform moisture in the lentils.

Method

Two fill methods were used in this study. For the loose fill, lentil seeds were allowed to flow out of the telescopic discharge tube into the test chamber with a zero height of fall. For a dense fill, lentil seeds were discharged into the test chamber through a flexible hose from a height of 500 mm in a circular motion.

To study the effect of variety on resistance to airflow, experiments were conducted for Laird and Eston lentils at 12.8% and 12.1% m.c., respectively. These experiments were for loose fill only.

For the direction of flow experiment the test chamber was positioned horizontally, and the top side (plywood wall) of the chamber was removed for loading (Jayas et al., 1987b). After the box was filled with lentils, the top surface of the grain was covered with a 7-mm-thick sponge to avoid possible air leaks as the grain settled during the experiment. The pressure drop was measured across 250 mm of the grain column. The experiments were conducted for airflow rates between 0.0019 to 0.1920 $m^3.s^{-1}.m^{-2}$. For vertical airflow measurement, the apparatus was positioned vertically and the top face, which was the brass screen, was removed before the box was filled with the lentils.

For the effect of fines, about 30 kg of Laird lentils at 11.6% m.c.were crushed in a roller-type crusher and separated into eight size fractions using a set of Tyler

TABLE 1. Dimensions and bulk properties of Laird and Eston lentil seeds measured at 11.5% moisture content

		Laird		Eston	
		Mean	std. dev.	Mean	std. dev.
Major diam.	(mm)*	6.99	0.32	5.0	0. 24
Minor diam.	(mm)	6.66	0.31	4.66	0.21
Thickness	(mm)	2.77	0.15	2.48	0.16
Bulk density	(kg/m^3)†	759	2.66	762	0.59
kernel density	(kg/m^3)	1426	0.40	1395	0.82
Porosity	(%)	46.5	–	45.4	–

* Dimensions are averages of 100 seeds.
† Densities are averages of 5 samples.

sieves (Table 2). Separated fractions, of particle sizes less than 6.7 mm, were mixed with clean Laird lentils to yield mixtures of 5, 10, 15, 20, and 25% fines in the bulk on a mass basis. A concrete mixer was used for preparing the mix. A sample of 100 g was analyzed after mixing to eliminate any change in the particle size distribution. To provide a uniform distribution of fines in the test column, a dense (sprinkle) fill method was used.

Analysis of Pressure Drop Data

Airflow resistance data of agricultural crops have been analyzed using several alternative equations (Jayas, 1987a). The equations of Shedd (1953) and Hukill and Ives (1955) have been used the most in the literature. Shedd's equation is:

$$Q = a\,\Delta P^{B} \tag{1}$$

where
Q = airflow rate ($m^3.s^{-1}.m^{-2}$),
P = pressure drop per unit depth of grain ($Pa.m^{-1}$)
A and B = constants for a particular grain.

Hukill and Ives' equation is:

$$\Delta P = \frac{a\,Q^2}{\ln(1 + bQ)} \tag{2}$$

where a and b are constants for a particular grain.

Segerlind (1983) has discussed the utility of many airflow-pressure drop relationships in mathematical models for predicting airflow fields in stored grain. He recommended the use of Shedd's equation, but with A and B as piecewise constants. This recommendation was based on the fact that the experimental data on pressure drop, when plotted against airflow rate on a log-log plot, did not give a straight line for large airflow ranges as was expected from Shedd's equation. In narrow ranges, however, the data can be represented by straight lines. Hukill and Ives' equation has been used in the ASAE Standard D272.2 to represent airflow-pressure drop data. Airflow resistance data for lentils were fitted to both equations (eqs. 1 and 2) using the least squares technique.

To relate the presence of fines to the changes in the pressure drop data for lentils, the method of Haque et al. (1978), which has been adopted in ASAE Standard D272.2, was used. The method involved applying a correcting factor to pressure drop data of clean seeds to account for the presence of fines. In equation form it is expressed as:

TABLE 2. Particle size and distribution in the fines mixture

Particle diameter range (mm)	Percentage in whole sample
4.76 - 6.70	3.8
3.36 - 4.76	28.4
2.38 - 3.36	33.2
1.68 - 2.38	17.5
1.19 - 1.68	9.0
0.84 - 1.19	4.7
0.59 - 0.84	2.4
0.00 - 0.59	1.0

$$\Delta P' = \Delta P\,[1 + (a' - b'Q)fm] \tag{3}$$

where
$\Delta P'$ = pressure drop across per unit of bed mixed with fines ($Pa.m^{-1}$),
ΔP = pressure drop across per unit depth of clean bed, calculated using Hukill and Ives' equation (eq. 2) in ASAE Standards D272.2 ($Pa.m^{-1}$),
fm = mass fraction of fines in the sample (decimal),
a′ and b′ = constants for a particular grain.

Results and Discussion

Comparative Airflow Resistance of Lentil Seeds

The American Society of Agricultural Engineers has published data on pressure drop as it relates to airflow for 33 agricultural crops excluding lentils in ASAE Standards D272.2. The experimental data on resistance to airflow (expressed as pressure drop/meter of column height) through loose fill, cleaned, Laird lentils at 11.4% m.c. were compared to the resistance data of some common crops from the ASAE Standard D272.2 and of canola from Jayas (1987a) in figure 2. The data for lentils were averages of triplicates. The variations among triplicates were less than 3% for all measurements. The resistance to airflow of Laird lentils was about 4.8 times the resistance of pea bean for airflow rates between 0.0057 and 0.0906 $m^3.s^{-1}.m^{-2}$, and 2.5 times the resistance of shelled corn for airflow rates between 0.0057 and 0.2930 $m^3.s^{-1}.m^{-2}$.

The airflow-pressure drop curve for Laird lentils was not parallel to the curve for wheat. The curve intersects with the wheat curve at an airflow rate about 0.22 $m^3.s^{-1}.m^{-2}$. It was concluded from figure 3 that a ventilation system designed to dry and aerate pea beans, shelled corn, or barley could not be satisfactory for drying and aerating an equal depth of lentils. On the other hand, systems designed for wheat, canola or alfalfa would be adequate, but over-designed for drying or aeration of lentil seeds.

The experimental data on pressure drop across Laird lentils at 11.4% m.c. were fitted to the Shedd's equation (eq. 1) for full airflow range between 0.0028 to 0.5926 $m^3.s^{-1}.m^{-2}$ and for three sub airflow ranges: between

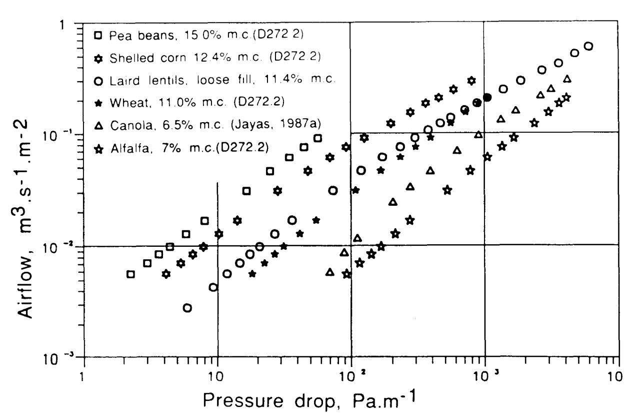

Figure 2–Comparisons of the pressure drops across loose fill Laird lentils with the pressure drops across selected seeds from ASAE Standard D272.2 and across canola from Jayas et al. (1987a).

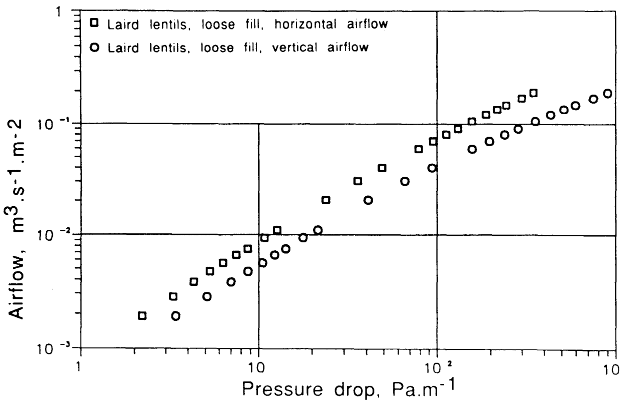

Figure 3–The effect of the direction of airflow on pressure drop across loose fill Laird lentils at 11:6% m.c.

0.0028 to 0.0309 $m^3.s^{-1}.m^{-2}$; 0.0309 to 0.1218 $m^3.s^{-1}.m^{-2}$; and 0.1218 to 0.5926 $m^3.s^{-1}.m^{-2}$ based on the recommendations of Segerlind (1983) and Shedd (1953). The estimated coefficients A and B for all airflow ranges are given in Table 3. The measured pressure drop data and the computed pressure drop data using equation 1 and coefficients for full airflow range did not compare well at low airflow rates (less than 0.09 $m^3.s^{-1}.m^{-2}$). The measured and computed data compared very well when piecewise constants A and B were used in equation 1.

The constants a and b of Hukill and Ives' equation (eq. 2) were determined for Laird lentils for the full airflow range between 0.0028 to 0.5926 $m^3.s^{-1}.m^{-2}$ and for two sub-airflow ranges: between 0.0028 to 0.1605 $m^3.s^{-1}.m^{-2}$ and 0.1605 to 0.5926 $m^3.s^{-1}.m^{-2}$ (Table 4). Division of airflow range into only two sub-airflow ranges resulted in better fit between experimental and computed pressure drop data from equation 2 than Shedd's equation. The Hukill and Ives' equation described the airflow resistance data better than the Shedd's equation for the full airflow range between 0.0028 to 0.5926 $m^3.s^{-1}.m^{-2}$.

EFFECT OF MOISTURE CONTENT

To study the effect of moisture content on the resistance to airflow, the resistance to loose fill clean Laird lentils was determined at five m.c. (10.4, 11.4, 12.8, 14.3, and 19.9%). An increase in m.c. of Laird lentils by 9.5 percentage points caused a decrease in pressure drop by about 22.5%. Further analysis of the data showed that, for Laird lentils, a one percentage point increase in moisture content caused about 2.3% decrease in the pressure drop for airflow rates between 0.0028 and 0.2930 $m^3.s^{-1}.m^{-2}$ and about 3.0% decrease in pressure drop for high airflow rates between 0.2930 and 0.5926 $m^3.s^{-1}.m^{-2}$. For the total airflow range pressure drop decreased by an average of 2.4% as moisture content increased by 1.0 percentage point. This reduction in pressure drop was because of a decrease in bulk density and an increase in porosity with an increase in moisture content.

TABLE 3. Estimated parameters A and B of shedd's equation (eq. 1)*

Airflow range $m^3.s^{-1}.m^{-2}$	A	B	r^2†
0.0028 - 0.0309	0.536 x 10-3	0.960	0.99
0.0309 - 0.1218	1.414 x 10-3	0.727	0.99
0.1218 - 0.5926	2.961 x 10-3	0.608	0.99
0.0028 - 0.5926‡	2.914 x 10-3	0.610	0.99

* For loose fill Laird lentils at 11.4% moisture content for three narrow airflow ranges and the full airflow range.
† Correlation coefficient squared.
‡ Full range.

TABLE 4. Estimated parameters a and b of Hukill and Ives' equation (eq. 2)*

Airflow range $m^3.s^{-1}.m^{-2}$	A	B	r^2†
0.0028 - 0.1605	45502	27.32	0.99
0.1605 - 0.5926	53544	35.20	0.99
0.0028 - 0.5926‡	54312	36.79	0.99

* For loose fill Laird lentils at 11.4% moisture content for two narrow airflow ranges and full airflow range.
† Correlation coefficient squared.
‡ Full range.

The mass of lentils in the test chamber divided by the chamber volume gave *in situ* measurements of bulk density. The particle densities were measured using an air comparison pycnometer and porosities were calculated from these two densities. The recorded bulk densities and calculated porosities for loose fill Laird lentils were 815 $kg.m^{-3}$ and 763 $kg.m^{-3}$ and 43% and 45.5% at 10.4% and 19.9% m.c., respectively.

VARIETAL DIFFERENCE

The curves showing the resistance to airflow of Laird and Eston lentils, at 12.8% and 12.1% moisture content, respectively, were not parallel over the total range of airflow tested. The resistance to airflow of the smaller seeded lentil variety Eston was 3 to 27% higher than that of the large-seeded lentils variety Laird at low and medium airflow rates (between 0.0028 and 0.0272 $m^3.s^{-1}.m^{-2}$), and 1 to 6% lower at high airflow rates (between 0.0272 and 0.5926 $m^3.s^{-1}.m^{-2}$). The difference in slopes may be due to different physical seed characteristics, such as shape and size, which, in turn, determine the bulk density and porosity of the bulk. Shedd's (1953) data also showed the same behavior for large and small seeded grains.

EFFECT OF METHOD OF FILL

Dense fill resulted in an increase in pressure drop. The increase in pressure drop was greater at low airflow rates (69%) than at high airflow rates (34%). Dense fill resulted in an increase in bulk density from 814 $kg.m^{-3}$ to 887 $kg.m^{-3}$ and a decrease in porosity by about 5%. Dense packing and decreased porosity contributed to an increased pressure drop, but the increase in pressure drop cannot be explained solely by changes in bulk density and porosity. Since lentil seeds are convex lens shaped, orientation of the seeds for each type of fill may play a significant role.

EFFECT OF DIRECTION OF AIRFLOW

For horizontal and vertical directions of airflow through lentils, the pressure drops for loose-filled Laird lentils at 11.6% m.c. are given in figure 3. For Laird lentils, the resistance to airflow for horizontal direction was about 0.52 times the resistance to airflow for the vertical direction for airflow rates between 0.0019 and 0.1920 $m^3.s^{-1}.m^{-2}$. Similar lower resistances to airflow in horizontal direction than to airflow in vertical direction have been reported for wheat and barley (Kumar and Muir, 1986), for canola (Jayas et al., 1987b), and for shelled corn (Kay et al., 1989).

Effect of Fines Concentration

Figure 4 shows that the resistance to airflow increased as the fraction of fines in the sample increased. An increase in pressure drop was greater at low airflow rates (0.0028 to 0.1537 $m^3.s^{-1}.m^{-2}$). For the entire range of airflow rates, fines of 5, 10, 15, 20, and 25% in Laird lentils caused 14, 41, 77, 137, and 149% increase, respectively, in pressure drop. It was noted that the resistance to airflow increased linearly with increased fraction of fines. A similar linear relationship for a mixture of fines and shell corn has been reported (Grama et al., 1984) and the constants of equation 3 were estimated as a′ = 6.3435 and b′ = 5.7218.

Conclusions

From the results of this study on the resistance to airflow through bulk lentils, the following specific conclusions can be drawn:

1. The resistance of clean loose fill Laird lentils to airflow was 2.5 times the resistance of shelled corn and 0.7 times the resistance of wheat at comparable airflow rates and moisture content.
2. An increase of 1 percentage point in the moisture content resulted in a decrease (2.4%) in the resistance to airflow of loose fill Laird lentils.
3. The resistance to airflow of the smaller seeded lentil variety, Eston, was 3 to 27% higher than that of the large-seeded lentils variety, Laird, at low and medium airflow rates (between 0.0028 and 0.0272 $m^3.s^{-1}.m^{-2}$), and 1 to 6% lower at high airflow rates (between 0.0272 and 0.5926 $m^3.s^{-1}.m^{-2}$).
4. The dense fill increased the bulk density by about 9% which resulted in an increase in the resistance of Laird lentils to airflow by 34 to 69% over these values for loose fill.
5. The resistance to airflow of the Laird lentils for flow of air in the horizontal direction was about half the resistance to airflow for flow of air in the vertical direction at equal airflow rates.
6. An increase in the fraction of fines resulted in a linear increase in the resistance to airflow for Laird lentils.

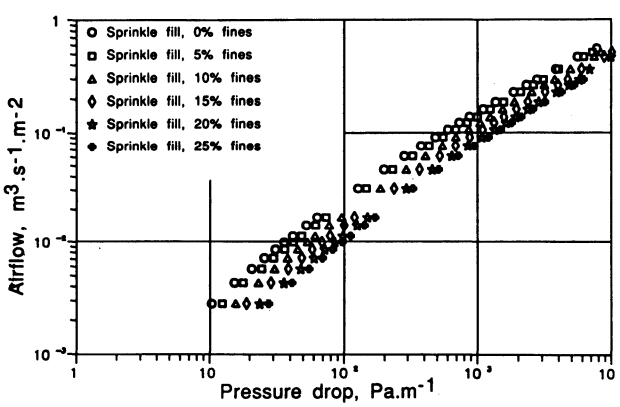

Figure 4–The effect of percent fines on the resistance to airflow through sprinkle fill (dense fill) Laird lentils at 10.8% m.c.

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