Airflow Resistance of Rough Rice as Affected by Moisture Content, Fines Concentration and Bulk Density

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ABSTRACT

THE effect of moisture content, fine material concentration and bulk density on the airflow resistance of long-grain rough rice was determined. Airflow resistance was measured at air velocities ranging from 0.013 to 0.387 m/s, bulk densities from 480 to 604 kg/m^3, fines concentrations from 0 to 30% and moisture contents from 12 to 24%. Airflow resistance was accurately described by an empirical equation comprised of these variables with over 99% of the variance in resistance being accounted for by the variables. Inclusion of each variable significantly improved the prediction of airflow resistance. Using an air velocity of 0.10 m/s and typical design conditions of 18% moisture content, bulk density of 577 kg/m^3 and clean rice (0% fines concentration) as a base condition, it was found that increasing fines concentration by 1% increased airflow resistance by 0.87%, increasing bulk density by 16 kg/m^3 (1 lb/ft^3) increased resistance by 3.37% and increasing moisture content by 1% decreased resistance by 3.73%.

INTRODUCTION

Estimating airflow resistance of a product is an important consideration in the design of grain drying and aeration systems. This is especially critical in rice drying and aeration systems since drying rate can influence cracking of rice kernels, which dramatically reduces market value. Although variables encountered in system design, such as packing, fines concentration and moisture content, are known to affect airflow resistance, little information is available on the relative contributions of these variables to airflow resistance in rough rice.

LITERATURE REVIEW

One of the earliest airflow resistance studies was conducted by Stirniman et al. (1931) using short-grain rough rice. Extensive curves of pressure drop versus airflow rate and rice depth were reported. Moisture content varied between 8 and 14.5%, and test weight ranged from 563 to 615 kg/m^3 (44 to 48 lb/bu). Since most rice currently produced in the United States is long-grain, this study is of limited value.

Shedd (1953) included rough rice as one of the grains in his study of airflow resistance in grains. Shedd measured the airflow resistance of rough rice at 13.4 and 20.7% moisture content (MC)* at loose fill and 'packed' fill. Relatively clean grain was used with some hulled grains (2.6% whole kernels and 1.6% broken kernels) but with no foreign material. Neither grain length nor variety was reported.

Calderwod (1973) measured the airflow resistance of rough, brown and milled long- and medium-grain rice at 12 and 16% MC. Two levels of packing were tested, loose fill at an average bulk density of 633 kg/m^3 (39.5 lb/ft^3) and packed fill at an average bulk density of 722 kg/m^3 (45.1 lb/ft^3). Calderwood found that for long-grain rough rice with chaff and light-weight kernels removed by aspirating, airflow resistance decreased with increased moisture content. The change in resistance attributed to moisture content was minor compared to the more than doubled resistance due to packing. This conclusion was supported by Husain and Ojha (1969) and Agrawal and Chand (1974), who reported that rice bed depth had an effect on per unit depth airflow resistance. Bern and Charity (1975) used an equation form proposed by Ergun (1952) to relate pressure drop per unit depth to airflow rate and bulk density in corn.

More recently, Bowrey and Intong (1983) reported the results of their study on pressure losses in two varieties of rough rice aerated at low velocities. They concluded that rice variety was the most important factor affecting porosity, which in turn dictated resistance to airflow.

No information was found that related the percentage of fines in rice to airflow resistance. However, Haque et al. (1978) investigated this relationship in shelled corn. Twelve levels of fines concentration under loose fill were used with a wide range of airflow rates. Pressure drop increased linearly with increases in fines concentration up to about 20%. The data were used in developing an equation that predicted pressure drop in corn as affected by fines. A subsequent study was conducted by Grama et al. (1984) in which the effect on airflow resistance of various percentages of various sizes of fines in shelled corn was determined. It was found that the increase in airflow resistance due to the addition of fine material became greater as the size of the fines was decreased.

Haque et al.(1982) measured airflow resistance across beds of corn, sorghum and wheat at four moisture contents ranging from 12.4 to 25.3%. The data were fitted to a nonlinear regression model that accurately described the relationship among static pressure drop, moisture content and airflow rate for all three grains.

Given the reported importance of bulk density, fines

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*All references to moisture content are on a wet basis.

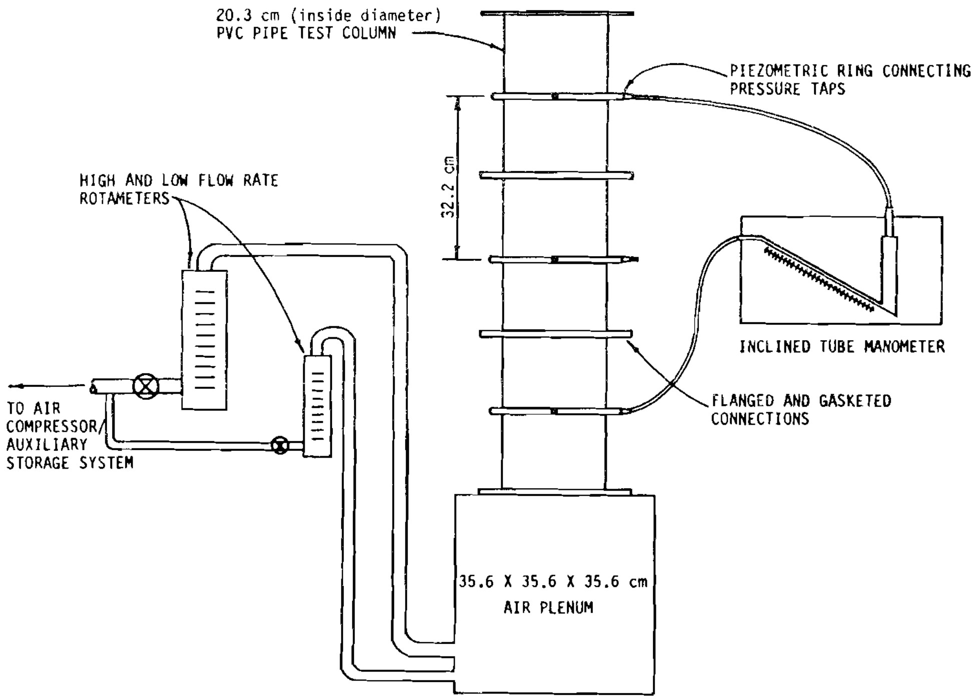

Fig. 1—Airflow resistance test apparatus.

concentration and moisture content in determining airflow resistance in grains, this study was conducted to determine the overall and relative effect of these properties in determining airflow resistance in long-grain rough rice.

OBJECTIVES

The first objective of this study was to experimentally determine the resistance to airflow in a common variety of long-grain rough rice as affected by the following variables:

1. moisture content
2. fines concentration
3. bulk density.

A second objective was to develop an empirical relationship between airflow resistance and varying levels of these experimental variables, based on the experimental data.

PROCEDURE

Airflow Resistance Apparatus

The apparatus used to measure airflow resistance is shown in Fig. 1. The test column was constructed of flanged sections of PVC pipe which were 30.5 cm (1 ft) deep and 20.3 cm (8 in.) in diameter (inside diameter). The sections were bolted together to provide a test column depth of 91.4 cm (3 ft). Piezometric rings were constructed at the vertical center of each section and connected to an inclined-tube manometer (graduated to 0.02 in w.g.) to measure pressure drop. A perforated sheet of steel with 0.206 cm (0.081 in.) diameter holes (42% open area) served as a floor for the test column. Air was supplied by a compressor with an auxiliary storage tank added to dampen the pressure/flow oscillations caused by compressor cycling. Airflow rate was measured by one of two rotameters: the first (Brooks† Model 1357) measured flow rates in the range of 0.424 to 0.911 L/s (0.898 to 1.93 ft^3/min); the second (Brooks Model 1307) measured rates from 1.42 to 12.2 L/s (3 to 25.8 ft^3/min). Each rotameter was equipped with a calibrated float supplied by the manufacturer. The airflow rate was manually adjusted by valves at each rotameter.

Experimental Design

Airflow resistance was measured at three moisture content levels of 12, 18 and 24%, at fine material concentrations of 0, 5, 10, 15, 20, 25 and 30% and at three bulk densities ranging from that attained with loose fill to the maximum packing that could be achieved. Resistance was measured at sixteen airflow velocities‡ ranging from 0.0135 to 0.387 m/s. This range includes the airflow rates commonly used in rice systems as well as the airflow rate ranges used in the airflow resistance studies previously mentioned. Each moisture content level/fine material concentration combination was replicated twice to produce 42 experimental units, each of which was tested at three bulk densities. Although moisture content and fine material concentration were held at the desired levels for each replicate, bulk density varied as determined by the amount of packing. Bulk density was thus experimentally determined by dividing the weight of rice in the test cylinder by the rice volume at each packing level. A regression analysis was used in relating the variable effects to airflow resistance in the data analysis. This method of analysis did not require that the variables be maintained at set levels. Thus, the absence of maintaining bulk density at preset levels was not statistically restrictive.

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†Mention of a commercial name does not imply endorsement by the University of Arkansas.

‡Reference to velocity implies an "apparent" velocity representing the volumetric flow rate (m^3/s) divided by the cross-sectional area (m^2).

TABLE 1. MASS PERCENTAGES OF RICE COMPONENTS AS SEPARATED BY THE A. T. FARREL MODEL 2B SEED CLEANER.

Component	Mass, kg	Mass percentage, %
Aspirated material	2.3	0.23
Large kernels*	4.1	0.42
Clean rice	950.2	96.67
Fine material†	26.3	2.68

*Material which passed over the top cleaner screen having #20 (20/64 inch) round holes.
†Material which passed through the bottom cleaner screen having 0.159 cm x 1.27 cm slots.

TABLE 2. SIEVE ANALYSIS OF CLEAN RICE AND GRINDING TESTS OF CLEAN RICE WITH A HAMMERMILL.

U.S. standard sieve no.	Percentage mass (g) retained*					
	Clean rice	Fine material from cleaner	Hammer mill output†			
			Screen #1	Screen #2	Screen #3	No screen
6	0.21	0.12	0.00	0.00	0.05	0.12
8	1.03	0.62	0.00	0.12	0.53	1.60
12	98.69	81.43	13.70	40.06	57.68	85.32
16	0.04	11.02	21.38	25.02	17.69	7.80
20	0.01	2.41	20.97	13.63	9.08	2.16
30	0.01	1.93	24.23	11.52	8.18	1.38
pan	0.01	1.94	19.23	9.03	6.49	1.04

*Average of two tests.
†Round hole screen sizes were as follows:
Screen #1; Diameter=3.175 mm (0.125 in.) with 40.5% open area
Screen #2; Diameter=4.76 mm (0.1875 in.) with 44.2% open area
Screen #3; Diameter=6.35 mm (0.25 in.) with 47.2% open area

Experimental Procedure

Rice (Tebonnet variety) was harvested at the Rice Research and Extension Center, Stuttgart, AR, at 25% MC with a Massey Ferguson 750 combine. Immediately after combining, the rice was aspirated and cleaned in an A. T. Farrel Model 2B cleaner with a #20 (20/64 in.) round hole top screen and a bottom screen with 1.59 mm × 12.7 mm (1/16 in. × 1/2 in.) slots. Material which passed over the bottom screen was considered "clean rice", and that passing through the bottom screen was considered fine material. Weight percentages of various components of rice from the combine are given in Table 1. The aspirated material and the material that passed over the top screen were assumed to be insignificant in affecting airflow resistance due to the low weight percentages and large effective particle diameters. Omitting this material in the laboratory tests enabled maintaining more uniform test conditions throughout the experiment. The rice was stored in a cooler at 1°C (34°F) for approximately two months prior to testing.

Physical properties of the Tebonnet rice were determined using hand-counted, 1000-kernel samples of the clean rice at an average moisture content of 18.6%. The true volume of the samples was determined using an air comparison pycnometer (Beckman Model 930, accuracy of ± 0.1 cc). The average volume of two 1000-kernel samples was 17.0 cc; the average mass was 23.4 g. The average kernel density was thus 1.38 g/cc (86.1 lb/ft^3). The average of four test weight determinations at this moisture content was 550 kg/m^3 (34.3 lb/ft^3).

A large amount of fine material was needed for this study due to the volume of the test chamber and the number of moisture content/fines concentration test combinations of the experimental design. The particle size distribution of the fine material was required to be uniform throughout the tests. Further, the fine material was to be representative of that removed by the seed cleaner both in terms of particle size distribution and moisture content. To facilitate obtaining enough fine material which met these requirements, a laboratory method of creating fine material was developed. This method also provided a procedure for reproducing fine material for future research.

A sieve analysis of fine material removed from the field rice was first conducted in order to characterize its mass/size distribution (Table 2). This analysis was used as a basis in producing fine material that was subsequently mixed with clean rice to attain the desired fine material concentration. Fine material was produced by grinding rice in a 0.746 kW (1 hp) hammer mill using different screens to vary particle size. Sieve analysis results for 24% MC rice ground with each screen and with no screen are listed in Table 2. Grinding rice with no screen produced fine material similar to that obtained from the seed cleaner. Thus, enough clean rice at 24% MC was ground with no screen to produce the desired fine material concentrations for all test combinations. The fine material was placed in a cooler at 1°C (34°F) for approximately one month prior to testing.

Rice and fine material were air-dried to the desired moisture content by spreading on a floor. For each moisture content/fines concentration combination, clean rice and fine material were mixed in a portable cement mixer to insure a uniform distribution of fines. The mixture was then placed in the test column using a conical hopper attached to a 10.2 cm (4 in.) PVC pipe. The PVC pipe was placed in the test column and was filled with the mixture. The end of the PVC pipe was held just above the rice surface and was slowly raised allowing the rice to flow out of the pipe to produce a loose fill and to minimize separation of fine material and clean rice. To insure statistical independence, mixtures for each test were made with clean rice and fine material that had not been used in previous tests.

For each airflow setting, the pressure drop from the bottom to the top piezometric ring was measured, representing the pressure drop across a 61-cm (2 ft) section of rice. For a given moisture content/fines concentration replication, pressure drop data were first recorded for the range of airflow settings at loose fill. A subsequent data set was obtained using the same airflow settings but at a higher bulk density, which was produced by vibrating the test column with a pneumatic vibrator attached to the test apparatus. Finally, a third data set was obtained at a maximum bulk density obtained by vibrating the test column until the surface level would not drop further.

RESULTS AND DISCUSSION

Bulk densities attained with each moisture content/fines concentration replication are listed in Table 3. In general, as fines concentration was increased, bulk density decreased. This is explained by the lower test weight of the fine material compared to that of the clean rice. The test weight of clean rice and fine material at 24% MC was 571 kg/m^3 (35.7 lb/ft^3) and 392 kg/m^3 (24.5 lb/ft^3), respectively. As moisture

TABLE 3. BULK DENSITY (kg/m^3) IN EACH MOISTURE CONTENT/FINES CONCENTRATION/PACKING LEVEL COMBINATION AS MEASURED DURING THE AIRFLOW RESISTANCE TESTS.

Fines %	12% MC			18% MC			24% MC		
	BD1	BD2	BD3*	BD1	BD2	BD3	BD1	BD2	BD3
0	548	561	571†	558	568	579	581	588	599
	547	562	573	550	560	573	584	591	604
5	550	560	571	550	568	581	581	593	596
	532	545	558	549	565	580	574	585	596
10	552	565	577	544	562	568	575	585	593
	541	554	566	535	550	560	573	584	593
15	537	549	562	542	554	568	572	581	594
	540	550	563	543	556	570	570	581	590
20	535	545	556	531	542	555	562	572	579
	535	546	559	531	542	554	558	568	575
25	518	530	542	535	546	561	522	531	543
	513	522	533	545	555	567	521	533	547
30	514	525	536	530	540	552	507	522	531
	513	524	534	531	542	555	480	494	505

*BD1=bulk density achieved at loose fill, BD2=bulk density after short period of vibration, BD3=maximum bulk density attained with extended vibration.
†Each set of three values for a moisture content/fines concentration combination represents one replication in the test apparatus.

TABLE 4. ROUGH RICE AIRFLOW RESISTANCE DATA (Pa/m) FOR SELECTED MOISTURE CONTENT/FINE MATERIAL/BULK DENSITY COMBINATIONS.*

Airflow rate, m/s	Moisture content (wet basis): 12%			18%			24%		
	Bulk density (BD),† kg/m^3								
	BD1 548	BD2 562	BD3 572	BD1 554	BD2 564	BD3 576	BD1 583	BD2 590	BD3 602
	Fine material concentration = 0%								
0.014	17	19	23	17	19	19	15	15	15
0.023	39	43	48	37	37	43	31	31	31
0.029	58	60	72	54	60	64	46	46	46
0.045	83	87	104	75	89	89	62	66	66
0.060	122	137	153	112	118	128	85	93	108
0.075	158	184	201	153	158	174	124	131	143
0.090	205	232	259	209	213	228	170	178	186
0.105	257	290	323	255	263	280	216	216	236
0.120	311	354	385	309	323	336	259	263	281
0.135	373	421	460	369	385	404	309	309	332
0.150	431	483	539	425	444	483	359	367	390
0.180	566	632	657	555	578	614	479	487	510
0.210	713	806	984	711	740	800	607	607	655
0.270	1067	1188	1312	1036	1076	1159	897	900	955
0.330	1463	1644	1834	1465	1509	1637	1227	1264	1333
0.387	1899	2118	2166	1886	1938	2091	1604	1635	1724
	BD1 514	BD2 525	BD3 535	BD1 531	BD2 541	BD3 554	BD1 494	BD2 508	BD3 518
	Fine material concentration = 30%								
0.013	23	23	25	21	21	23	17	17	19
0.023	48	48	54	46	50	54	35	35	41
0.029	72	72	81	70	72	79	54	54	60
0.045	106	114	122	95	100	114	85	87	87
0.060	151	160	176	137	147	162	118	122	129
0.075	201	214	234	189	203	224	157	162	176
0.090	255	271	298	245	263	290	203	203	234
0.105	319	342	367	313	328	369	249	265	284
0.120	381	408	446	377	396	448	303	313	348
0.135	454	479	528	448	468	528	357	371	406
0.150	522	553	611	518	533	614	425	434	477
0.180	684	717	802	674	707	866	549	560	618
0.210	866	914	999	858	881	1005	669	684	790
0.270	1241	1283	1443	1233	1277	1441	1013	1034	1154
0.330	1747	1822	2019	1720	1770	2013	1409	1434	1612
0.387	2199	2207	2274	2201	2222	2288	1811	1861	2068

*Values represent an average of the two replications of a moisture content/fines concentration combination.
†Bulk density values represent an average of the two bulk density values listed in Table 3 for each moisture content/fines concentration combination.

content increased, bulk density increased. This trend is consistent with the rice bulk density data presented by Mohsenin (1986) and is accounted for by the fact that porosity of bulk rice decreases with increasing moisture content (Mohsenin, 1986). The maximum bulk density was 604 kg/m^3 (37.8 lb/ft^3) attained at 24% MC and 0% fines concentration.

Airflow resistance data from test runs at 0 and 30% fines concentrations are presented in Table 4. The values listed in Table 4 represent the average of the two values measured at the various airflow rates for each replication of a given moisture content/fines concentration/packing level combination. The bulk density values listed are the average of the two bulk density values listed in Table 3 for each moisture content/fines concentration combination.

A least squares regression analysis was used to describe the relationship between pressure drop and velocity, bulk density, moisture content and fines concentration. Values of pressure drop were regressed against each and all combinations of these variables in a step-wise approach. This technique allowed testing the statistical validity of including each of the variables as a component of a model predicting airflow resistance. The model that was used to describe airflow resistance is as follows:

$$PD = V*(b_1*F + b_2*MC + b_3*BD + b_4*V) \quad \ldots\ldots [1]$$

where:

b_1, b_2, b_3, b_4 = regression coefficients
PD = pressure drop, Pa/m
V = velocity, m/s
F = fines percentage, %
MC = moisture content, % wet basis
BD = bulk density, kg/m^3.

This equation form allowed relative comparison of each of the variable effects. Velocity was included as an overall multiplier to insure that the model would not predict a pressure drop at zero velocity. Further, since drag is a function of velocity squared, the addition of velocity as an overall multiplier in the empirical model better approximates airflow resistance theory.

The pertinent results of the regression analysis are shown in Table 5 with the model variables listed in the order in which they were tested for inclusion in the model. This test, described by Neter and Wasserman (1974), uses the F statistic defined in Table 5. It was found that all of the model variables of equation [1] sufficiently improved the model to warrant inclusion in the model at a level of significance of 5%. The regression coefficients and standard error of estimates for the coefficients were:

b_1 = 25.859 Pa·s/(m^2·%) $s(b_1)$ = 0.711 Pa·s/(m^2·%)
b_2 = -90.056 Pa·s/(m^2·%) $s(b_2)$ = 1.570 Pa·s/(m^2·%)
b_3 = 5.587 Pa·s·m/kg $s(b_3)$ = 0.066 Pa·s·m/kg
b_4 = 9133.696 Pa·s^2/m^3 $s(b_4)$ = 74.423 Pa·s^2/m^3

The regression coefficients indicate that airflow resistance is increased when all variable levels except moisture content are increased, which is consistent with the findings of other airflow resistance studies (Calderwood, 1973, and Shedd, 1953).

TABLE 5. STEPWISE REGRESSION ANALYSIS RESULTS OF AIRFLOW RESISTANCE DATA.

Variables in model†	r^2	SSE	DF‡	Test-statistic§
V	0.944	6.94E07	2005	-
(V)*V	0.966	4.34E07	2005	infinity
(MC,V)*V	0.968	4.02E07	2004	156
(BD,MC,V)*V	0.991	1.11E07	2003	5246
(F,BD,MC,V)*V	0.995	6.69E06	2002	1323

† V = velocity, MC = moisture content, BD = bulk density and F= fines concentration.

‡ Degrees of freedom associated with the error sum of squares.

§ Test-Statistic listed by Neter and Wasserman (1974) as:

$$\text{Test-Statistic} = \frac{[SSE(R) - SSE(F)]/[DF(R) - DF(F)]}{SSE(F)/DF(F)}$$

where; 'R' refers to the reduced model.
'F' refers to the full model with additional variables included in the model.

If Test-Statistic > F(1-a;DF(R)-DF(F),DF(F)), full model is valid.

Relative Effects of Test Variables

To illustrate the relative effects of the variables, equation [1] was used to generate the values of Table 6. Using a base condition of clean rice (0% fines), a standard bulk density of 577 kg/m^3 (36 lb/ft^3), a typical harvest moisture content of 18% and velocities ranging from 0.05 to 0.15 m/s (9.84 to 29.5 ft/min), the predicted change in airflow resistance for indicated changes in the test variables was computed. For the incremental changes of the test variables listed in Table 6, moisture content produced the greatest change in airflow resistance from the base condition with a decrease of 3.73% at a velocity of 0.10 m/s. Fines concentration had a less dramatic effect with a 0.87% increase in resistance corresponding to a 1% increase in fines concentrations at a 0.10 m/s velocity. On this basis and considering that the rice used in this experiment originally contained 2.68% fines (Table 1), an error of only 2.33% would be expected in predicting airflow resistance if clean rice were assumed from the field. It is to be noted, however, that fines concentrations can increase dramatically in certain areas of bins due to particle separation during filling, both by 'spout' filling and with many mechanical grain spreaders.

High Bulk Density Effects

The test apparatus did not permit tests with high bulk densities. The highest bulk density obtained by prolonged vibration of the test column was 604 kg/m^3 (37.7 lb/ft^3). Thus, for predicting airflow resistance in conditions of high bulk densities or "packing", the equation would be accurate only if the effects of packing

TABLE 6. RELATIVE EFFECTS OF TEST VARIABLES BASED ON EQUATION [1]

Test variable	Incremental change	% Change from base condition* velocity		
		0.05 m/s	0.10 m/s	0.15 m/s
Moisture content	+1%	-4.37	-3.73	-3.14
Fines concentration	+1%	1.26	0.87	0.90
Bulk Density	+16 kg/m^3 (1 lb/ft^3)	4.27	3.37	2.91

*Base condition: Bulk density = 577 kg/m^3, Moisture content = 18%, Fines = 0%, Velocity = respective values given in column headings.

on airflow resistance are linear.

Addressing this concern, equation [1] was used to predict the airflow resistance for the conditions reported by Calderwood (1973), which included some tests with bulk densities higher than those used in this study. Calderwood states that foreign material in the rough rice used in his study was removed by aspirating, but does not mention the level of fine material. Fines concentration level was assumed to be 0.0 as an input to equation [1], recognizing that this could be a source of error in comparison. Further, the rice variety used in Calderwood's study was different from that used in this study. Bowrey and Intong (1983) state that variety was very significant in determining airflow resistance.

At low bulk density levels reported by Calderwood (639 and 626 kg/m^3 at 16 and 12% MC, respectively), the resistance values predicted by equation [1] for the conditions of Calderwood's study were lower than values reported by Calderwood for the range of airflows used. All predicted values were within 15% of the values reported by Calderwood, with the average percentage difference between predicted and actual data being 6.92%. However, at the high bulk density conditions (728 and 714 kg/m^3 at 16 and 12% MC, respectively), equation [1] underpredicted the resistance values reported by Calderwood, with an average error of 52.9%. This indicates that the effects of bulk density on airflow resistance are not linear over the entire range of bulk densities that can be achieved. Thus, the equation is not valid in highly packed conditions but is accurate at least to the "low-packing" bulk density level (639 kg/m^3) attained in Calderwood's study. Futher research is needed to determine the effect of high bulk density on airflow resistance of rough rice.

CONCLUSIONS

The following conclusions can be made from this study concerning the resistance of long-grain rough rice to airflow in the velocity range from 0.013 to 0.387 m/s with bulk densities ranging from 480 to 604 kg/m^3, fines concentrations from 0 to 30% and moisture contents from 12 to 24%:

1. Airflow resistance was accurately described by the equation used in this analysis. Using this equation, 99.5% of the variance in resistance was accounted for by the test variables.

2. Each of the test variables significantly improved the prediction of airflow resistance.

3. Using an air velocity of 0.10 m/s and typical design conditions of 18% MC, a bulk density of 577 kg/m^3 and clean rice (0% fines concentration) as a base condition, increasing fines concentration by 1% increased resistance by 0.87%, increasing bulk density by 16 kg/m^3 (1 lb/ft^3) increased airflow resistance by 3.37%, and increasing moisture content by 1% decreased resistance by 3.73%.

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