The *Journal of Cotton Science* 5:243-251 (2001)
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ENGINEERING & GINNING

Relative Velocity, Density, and Temperature Effects on Cotton Moisture Transfer Rates

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INTERPRETIVE SUMMARY

Moisture affects every aspect of cotton harvesting and processing. Excessive moisture results in grade losses, fiber deterioration, and decreased machine performance while low moisture can cause fiber breakage and results in operating difficulties. Moisture transfer rates of lint, seed, and burs were determined as a function of air velocity. All of the components were exposed to a temperature of 40°C (104°F). In addition, the burs also were exposed to a temperature of 75°C (167°F) and the lint to a temperature of 80°C (176°F). The air flow rates were varied from 104 to 944 $cm^3 s^{-1}$ (0.22 to 2.00 $ft^3 min^{-1}$) through a 6.9-cm (2.75-in)-diam. pipe. Lint density was varied from 0.005 to .03 g cm^{-3}. The goal was to look at relative air velocities in a range that is equivalent to cotton flowing in a pipe with no acceleration. Within the range tested, air velocity had no effect on cottonseed and affected only the moisture transfer rates of cotton burs under humidification at the 75°C temperature. As expected, lint density and temperature both had a very pronounced effect on lint moisture transfer rates. Increasing the lint density reduced transfer rates, while increasing the air velocity resulted in increased moisture transfer rates within the range tested. A generalized regression equation was developed for predicting the effects of air velocity, temperature, and lint density on cotton lint moisture transfer rates. This information will be used in conjunction with equilibrium moisture data to estimate the moisture content of harvested seed cotton during cotton harvesting and ginning.

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ABSTRACT

Moisture control during cotton (*Gossypium hirsutum* L.) harvesting, storage, and processing is essential for producing a quality product. The objective of this study was to quantify the effects of relative air velocity, air temperature, and lint density on moisture transfer rates for cotton burs, cottonseed, and cotton lint during the drying or moisture-restoration process. The volumetric flow rate of air, passing over, through, and around a sample, was varied from 104 to 944 cm s^{-1} (0.22 to 2.0 ft^3 min^{-1}). Air relative velocities varying from 4.45 to 50 cm s^{-1} (9 to 98 ft min^{-1}), depending on the sample holder used, were achieved in this way. The density of cotton lint was varied from .005 to .03 g cm^{-3} (0.31 to 1.87 lb ft^{-3}). A 40°C temperature was used for all samples. In addition, the burs were exposed to a 75°C temperature and the lint to an 80°C temperature. As expected, temperature had a pronounced effect on moisture transfer rates. Increasing the relative velocity for burs in humid air and for cotton lint in both humid and dry air resulted in increased moisture transfer rates. However, cottonseed and burs exposed to dry air showed no apparent change in moisture transfer rates with changes in air velocity. Increasing the density resulted in significantly reduced moisture transfer rates for cotton lint. A generalized equation consisting of temperature, relative velocity, and density was developed for predicting the coefficient D (containing diffusivity) for cotton lint exposed to the experimental conditions.

Controlling moisture during the cotton harvesting and processing phases is a major concern to cotton producers and ginners. Development of methods to control moisture during ginning has been a major priority of the U.S. Cotton Ginning Research Laboratories since their inception. Fiber deterioration (especially color), along with reduced yields, can result from excessive moisture during cotton harvesting (Barker et al., 1979; Barker, 1982). Leonard et al. (1970) showed that cleaning efficiency was improved when the cotton was dried early; however, excessively dry cotton is subject to fiber breakage and results in operating difficulties (static electricity) during the ginning process (Childers and Baker, 1978). Thus, the optimum moisture content for the ginning process is a compromise and is reported to be in the 6 to 8% range (Griffin, 1977).

Moisture, like most other vapor or liquid mixtures, is transferred from a region with high vapor pressure (or concentration) to a region of lower vapor pressure potential. The rate of transfer is dependent on the gradient and the resistance to flow between the two areas. This gradient can be enhanced by temperature increases and by removing stagnant air around the boundary layer. Decreasing the distance between two regions of interest reduces resistance to moisture movement. Increasing the relative velocity of the air around the cotton will reduce the boundary layer thickness and ensure that there is no stagnant air.

Cotton machinery manufacturers have used increased velocity to increase drying rates in their dryers. Hughs et al. (1994) listed dryer types as reel-type, tower, tower hybrid, and towerless systems and indicated that the air volume used for these dryers varies from 1.24 m^3 min^{-1} of air per kg min^{-1} of seed cotton to 3.12 m^3 min^{-1} of air per kg min^{-1} of seed cotton (20 ft^3 min^{-1} of air per pound min^{-1} of seed cotton to 50 ft^3 min^{-1} of air per pound min^{-1} of seed cotton), depending on dryer type.

The objective of this study was to determine the effect of relative air velocity and cotton lint density on absorption and desorption (drying) rates for gin-run cottonseed, cotton burs, and cotton lint under controlled temperature and humidity conditions. The volumetric flow rate of the air, passing over, through, and around the sample, was varied from 104 to 944 cm^3 s^{-1} (0.22 to 2.0 ft^3 min^{-1}). Depending on the sample holder used, air relative velocities through a 6.97-cm-diam. glass tube were achieved that varied from 4.45 to 50 cm s^{-1}. The results will be useful to scientists developing models for ginning and harvesting systems and to engineers designing conditioning systems for the cotton processing industry.

EQUIPMENT AND TEST PROCEDURE

The equipment assembled by Barker and Laird (1997) was used to control temperature, humidity, and air velocity in this study. A Wilkerson[1] compact heatless dryer (Wilkerson, Englewood, CO) was used to provide a continuous source of dry air. To provide saturated air, air was bubbled through a column of water and then passed through a water mist. Three constant-temperature water baths (accuracy ±0.1°C) were used to control the temperature of the sample, the humidification tank, and the dew point temperature of the humid air. The dew point temperature of the air was measured with a General Eastern Hygro SIM-12H dew point sensor (General Easton, Woburn, MA), with a range of -40 to 85°C and an accuracy of ±0.2°C, located upstream of the sample chamber. Small thermocouples (type J, iron-constantan, accuracy ±0.8°C, Omega Engineering, Stamford, CT) and platinum resistance temperature detector (accuracy ±0.3°C, R.T.D., Cambridge, MN) sensors were inserted into the sample chamber upstream and downstream from the sample to indicate the air temperature surrounding the sample. A Cahn model 1000 recording balance (Cahn Instruments, Cerritos, CA), with an accuracy of ±10 mg and a repeatability of ±0.1 mg, was used to record the weights continuously.

Air entered the top of the sample chamber and flowed around the sample before exiting to the atmosphere (Fig. 1). The flow rate was controlled with needle valves and measured using a Brooks variable area flow meter (Brooks Instrument, Hatfield, PA) with an accuracy of 12 $cm^3 s^{-1}$ (0.025 ft^3 min^{-1}) and a range of 104 to 944 cm^3 s^{-1} (0.22 to 2.00 ft^3 min^{-1}). However, flow rates above 470 $cm^3 s^{-1}$ (1 ft^3 min^{-1}) exceeded the capacity of the equipment used to generate humid air. The temperature used for this study was 40°C (104°F) for both the hydration (exposure to humid air) and dehydration (drying) cycles of burs, seed, and lint. In addition, a temperature of 80°C (176°F) was also used for hydration and dehydration of the lint, and a temperature of 75°C (167°F) was used for burs. Since temperatures above 50°C prevent the germination of cottonseed, the cottonseed was exposed to only a 40°C temperature. The sample

[1]Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the USDA and does not imply approval of the product to the exclusion of others that may be available.

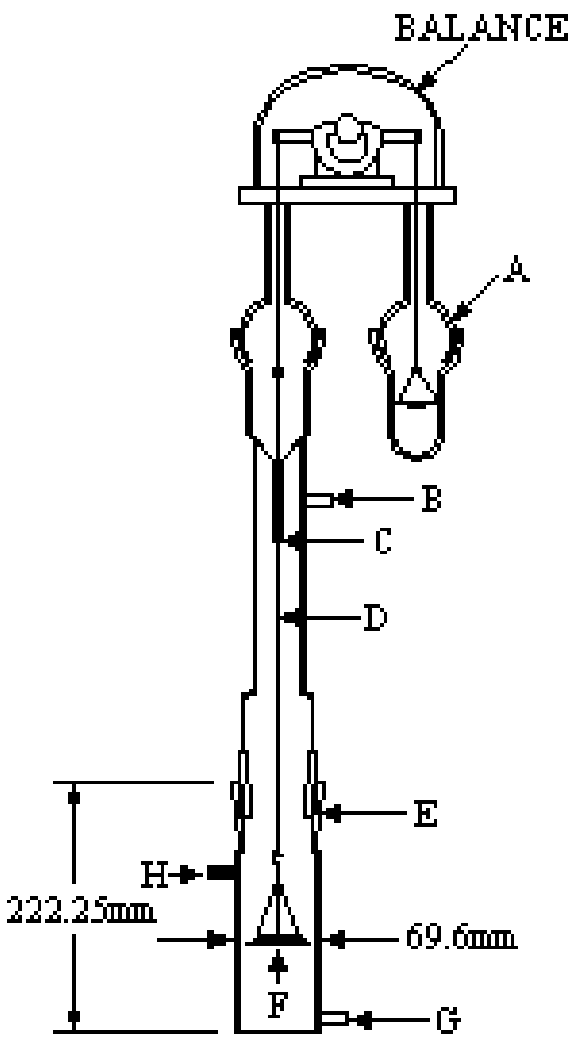

Fig. 1. Schematic of air-tight cottonseed conditioning system using Cahn C-1000 balance and including A) counter weight; B) air inlet tube; C) restriction to prevent air from reaching balance; D) hangdown wire to support samples; E) tapered joint; F) sample holder for seeds; G) air outlet and thermocouple insertion point; H) barometer and insertion point for resistance temperature detector.

size was ~3 g for seed (28-30 seeds) and burs (8-10 burs). Preliminary work (Barker et al., 1999) had shown that density of the lint had a significant effect on drying and humidification rates; therefore, a range of sample weights, 0.5 to 3.0 g (providing a density range of 0.005 to 0.028 g cm^{-3}), was used for the lint. The devices used to hold the samples in this experiment are shown in Fig. 2.

A Hewlett-Packard data logger (model 75000, with 16-bit analog-to-digital input board, Hewlett-Packard, Loveland, CO) was used to record all the test information, which included weight, temperature, dew point temperature, barometric pressure, velocity pressure, and time. Data were collected at 1-s intervals during the first 10 min of the study, at 15-s intervals for the next 8 h, and finally at 2-min intervals for the remainder of the time the sample was exposed to temperature-constant humidity conditions.

The samples were placed in position in the chamber and conditioned in dry air at the test temperature until dry (no data were taken during this period). To determine true dry weights, samples were not removed from the holder or system. They were exposed for the necessary times to: 1) conditioned humid air (90-95% RH) to reach equilibrium (hydration phase); 2) dry air to reach equilibrium (dehydration phase); 3) air at or above 100°C (212°F).

RESULTS

Plots of the normalized moisture content (percent dry basis) show an exponential decrease with time until the sample approaches equilibrium (Fig. 3 and 4). This is analogous to a falling-rate drying process. The classical three-dimensional diffusion equation can be used to describe this phenomenon (Newman, 1932):

$$\frac{\partial c}{\partial \theta} = k\,\frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2}\,\frac{\partial^2 c}{\partial z^2} \qquad [1]$$

Fig. 2. Sample holders for lint, burs, and seed. Two baskets were used for lint: the smallest was 14.67 cm^2 (2.27 in^2) and the largest was 19.97 cm^2 (3.10 in^2) in cross-sectional area. The burs occupied approximately 14.45 cm^2 (2.24 in^2) and the seed hanger occupied 22.88 cm^2 (3.55 in^2).

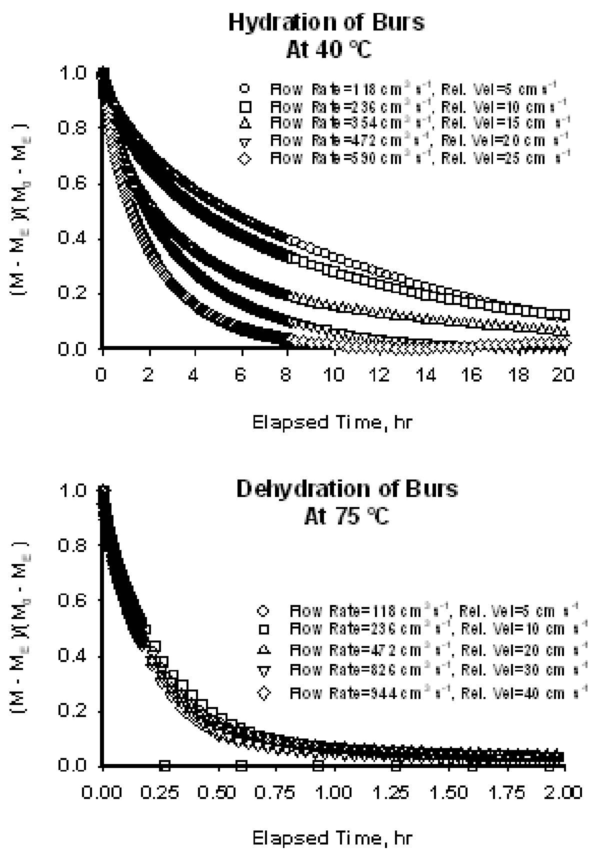

Fig. 3. Effects of air velocity and time on the hydration and dehydration of burs at 40 and 75°C, respectively. Only every 10th data point is shown for clarity.

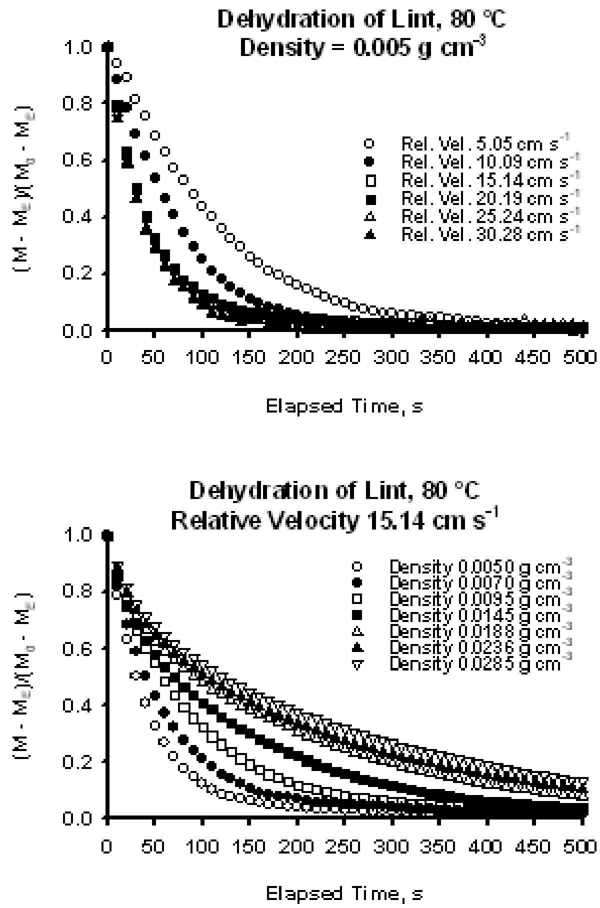

Fig. 4. Effects of relative velocity and density on lint drying (dehydration) rates at 80°C. Only every 10th data point is shown for clarity.

Where:

c = concentration of water vapor
θ = elapsed time
k = diffusivity (diffusion coefficient) ($m^2\ time^{-1}$)
x, y, and z = Cartesian coordinates

Newman (1932) presented solutions for Eq. [1] for a flat plate, a sphere, a cylinder, and combinations thereof for drying by diffusion. All of the solutions presented were infinite series. A simplified version of the solution to Eq. [1] presented by Newman is:

$$\frac{M - M_E}{M_O - M_E} = \beta\left(\frac{1}{\alpha}e^{-\alpha D\theta} + \frac{1}{\gamma}e^{-\gamma D\theta} + \frac{1}{\eta}e^{-\eta D\theta}\right) \quad [2]$$

Where:

M = moisture content, % dry basis, after a period of time, θ
M_0 = initial moisture content, % dry basis, at time zero
M_E = equilibrium moisture, % dry basis, moisture content when the air and the lint are in equilibrium (stagnant sample weight)
β = $6/\pi^2$, $8/\pi^2$, and 4 for the spherical, flat plate, and cylindrical solutions, respectively. (Actual value used should produce a value of 1 when θ = 0; therefore, we used 0.7346, 0.8687, and 4.564, respectively, for the three-term model.)
α = 1, 1, and 5.7831 for the spherical, flat plate, and cylindrical solutions, respectively.
D = coefficient containing diffusivity, $time^{-1}$
γ = 4, 9, and 30.4715 for the spherical, flat plate, and cylindrical solutions, respectively.

Table 1. Linear regression coefficients for cottonseed and burs, using the coefficient D (h^{-1}) as the dependent variable and relative velocity as the independent variable.

	Treatment			Coefficient D (h^{-1})				
Item	**Temp.**	**Air type**	**DF‡**	**Intercept**	**CI‡**	**Slope**	**CI**	R^2
				Flat plate solution				
Seed	**40°C**	**Humid**	**5**	**0.049**	**±0.019**	**0.000055**	**±0.0005**	**0.01**
Seed	**40°C**	**Dry**	**6**	**0.274**	**±0.187**	**0.000979**	**±0.0050**	**0.04**
Burs	**40°C**	**Humid**	**3**	**-0.014**	**±0.124**	**0.016350**	**±0.0075**	**0.94**
Burs	**40°C**	**Dry**	**4**	**0.649**	**±0.763**	**0.007440**	**±0.0392**	**0.06**
Burs	**75°C**	**Humid**	**3**	**0.387**	**±0.221**	**0.053900**	**±0.0205**	**0.96**
Burs	**75°C**	**Dry**	**13**	**3.317**	**±0.680**	**0.020430**	**±0.0307**	**0.14**
				Spheical solution				
Seed	**40°C**	**Humid**	**5**	**0.042**	**±0.015**	**0.000072**	**±0.0004**	**0.03**
Seed	**40°C**	**Dry**	**6**	**0.240**	**±0.167**	**0.000854**	**±0.0045**	**0.03**
Burs	**40°C**	**Humid**	**3**	**-0.018**	**±0.113**	**0.014540**	**±0.0068**	**0.94**
Burs	**40°C**	**Dry**	**4**	**0.571**	**±0.675**	**0.006590**	**±0.0347**	**0.06**
Burs	**75°C**	**Humid**	**3**	**0.340**	**±0.200**	**0.048560**	**±0.0185**	**0.96**
Burs	**75°C**	**Dry**	**13**	**2.803**	**±0.554**	**0.016680**	**±0.0250**	**0.14**

‡ DF is the degrees of freedom in error for the regression analysis.

‡ CI is the 95% confidence interval for the parameter estimate immediately preceding the value.

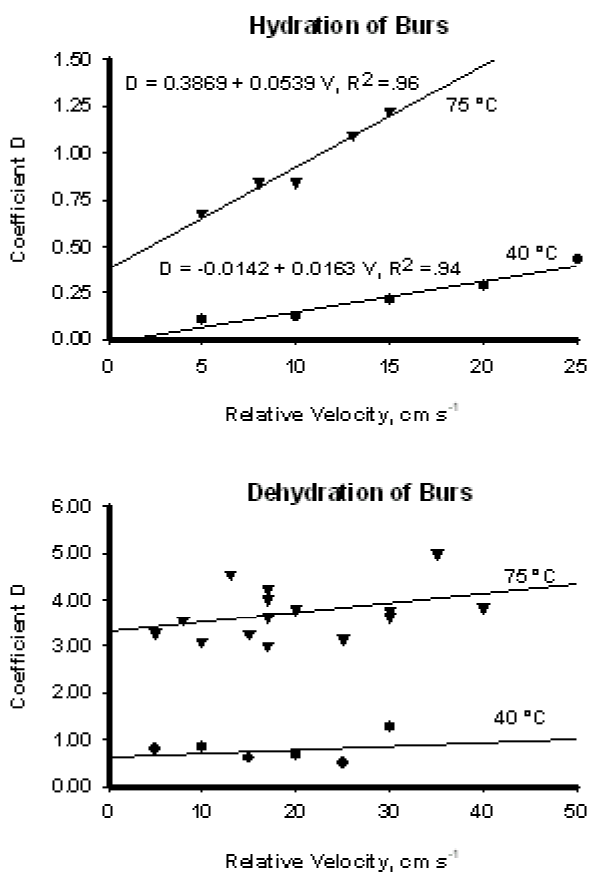

Fig. 5. Effects of relative velocity on the coefficient D (containing diffusivity) for cotton burs. The units of D are hr^{-1}.

η = 9, 25, and 74.8917 for the spherical, flat plate, and cylindrical solutions, respectively.

Henderson and Perry (1979) showed that the term, *D*, containing diffusivity in Eq. [2] is a function of temperature. They stated that it can be related to the temperature of the drying air, although technically it should be the temperature of the drying object. Barker and Laird (1993 and 1997) and Barker et al. (1995) investigated the effects of temperature on moisture transfer rates in lint, seed, and trash, respectively. They showed that the relationships proposed by Newman (1932) and Henderson and Perry (1979) adequately described their experimental data and developed values for the coefficients in the equations.

The SAS procedure, Proc SYSNLIN (Freund et al., 1986), was used to determine the value of *D* in Eq. [2], for each individual data set. Values for M_0 and M_E used in Eq. [2] were determined from the individual data sets.

Examination of Eq. [2] shows that when the data are transformed to logarithmic form, the value of coefficient D approaches the value of the slope of each individual curve and the larger its value, the faster the drying rate.

Examination of Figs. 3 and 5 shows that relative velocity has a significant effect on the moisture transfer rates for cotton burs during the hydration phase, but may have only a very small effect on the transfer rates during the drying phase. Plots of coefficients against relative velocity showed a linear trend. Linear regression of data from burs and cottonseed, shown in Table 1, indicate that under the conditions tested, relative velocity had no effect on

Table 2. Regression coefficients, with 95% confidence intervals, for Eq. [3] using coefficient D (s^{-1}) from Eq. [2] for both the flat plate and the spherical solutions for cotton lint.

Temp	Air type	DF‡	Γ	δ	ζ	λ	R^2	Error‡
				Flat plate solution of Eq. [2]				
40°C	Humid	63	1.043135 ± 0.484§	3537716 ± 752000	0.0000004 ±---¶	176.9451 ± 40.85	0.83	0.97
40°C	Dry	65	4.51052 ± 0.530	43.9923 ± 4.295	0.241777 ± 0.044	189.0564 ± 19.500	0.97	0.91
80°C	Humid	51	2.839248 ± 1.217	42.21598 ± 27.998	0.082612 ± 0.0634	129.4197 ± 44.868	0.87	1.70
80°C	Dry	51	11.45106 ± 2.839	159.5308 ± 32.65	0.068292 ± 0.0224	148.3924 ± 25.70	0.94	16.51
				Spherical solution of Eq. [2]				
40°C	Humid	63	0.946107 ± 0.407	2954387 ± 622737	0.0000004 ±----¶	175.865 ± 40.40	0.83	0.68
40°C	Dry	65	3.776083 ± 0.458	39.07314 ± 3.814	0.239562 ± 0.0436	190.8453 ± 19.450	0.97	0.63
80°C	Humid	51	2.488425 ± 1.013	41.46565 ± 31.357	0.073104 ± 0.0622	136.0027 ± 46.283	0.87	1.34
80°C	Dry	51	9.828617 ± 2.537	138.4788 ± 30.95	0.068396 ± 0.0225	146.2664 ± 25.60	0.94	12.86

‡ DF is the degrees of freedom in error.
‡ Error is the mean square error from regression.
§ The 95% confidence interval for each parameter estimate is shown below the estimated value of the parameter.
¶ This value could not be determined.

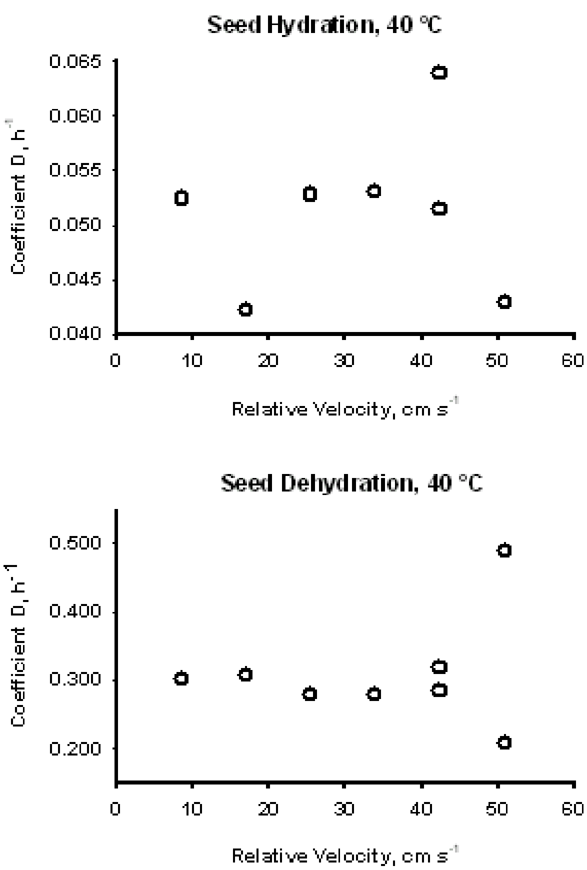

Fig. 6. Effects of relative velocity on the drying rate (coefficient D) for cottonseed.

burs when subjected to dry air. However, the burs subjected to humid air were significantly affected by relative velocity. For both humid and dry air, however, cottonseed showed no apparent changes in moisture transfer rates as a result of changing the relative velocity at 40°C (Fig. 6).

Relative velocity was shown to have some effect on lint moisture transfer rates; however, density had a more pronounced effect than relative velocity (Fig. 4). Plots of values of coefficient D against air relative velocity and lint density showed definite nonlinear trends (Fig. 7). Nonlinear regression analysis was used to develop an empirical relationship for coefficient D (from Eq. [2]), as a function of relative velocity of air and lint density at a given temperature and air condition (Eq. [3]).

$$D = \Gamma + \delta(1-e^{-\zeta V})(e^{-\lambda\rho}) \qquad [3]$$

Where:

Γ, δ, ζ and λ = regression coefficients
V = relative velocity, cms^{-1}
ρ = density, g cm^{-3}

Values of regression coefficients and other statistical information are shown in Table 2. The combination effect of both density and relative velocity on transfer rates in cotton lint can be seen in Fig. 7. The surfaces shown in Fig. 7 were created using a 3-D negative exponential smoothing function on the raw data.

Barker and Laird (1993) showed a relationship between moisture transfer rates for cotton lint and temperature of the conditioning air. Their work indicated that the relationship presented by Henderson and Perry (1979) could be used to describe the effect of temperature on moisture transfer rates. Thus, additional analysis was performed to develop a single relationship, including

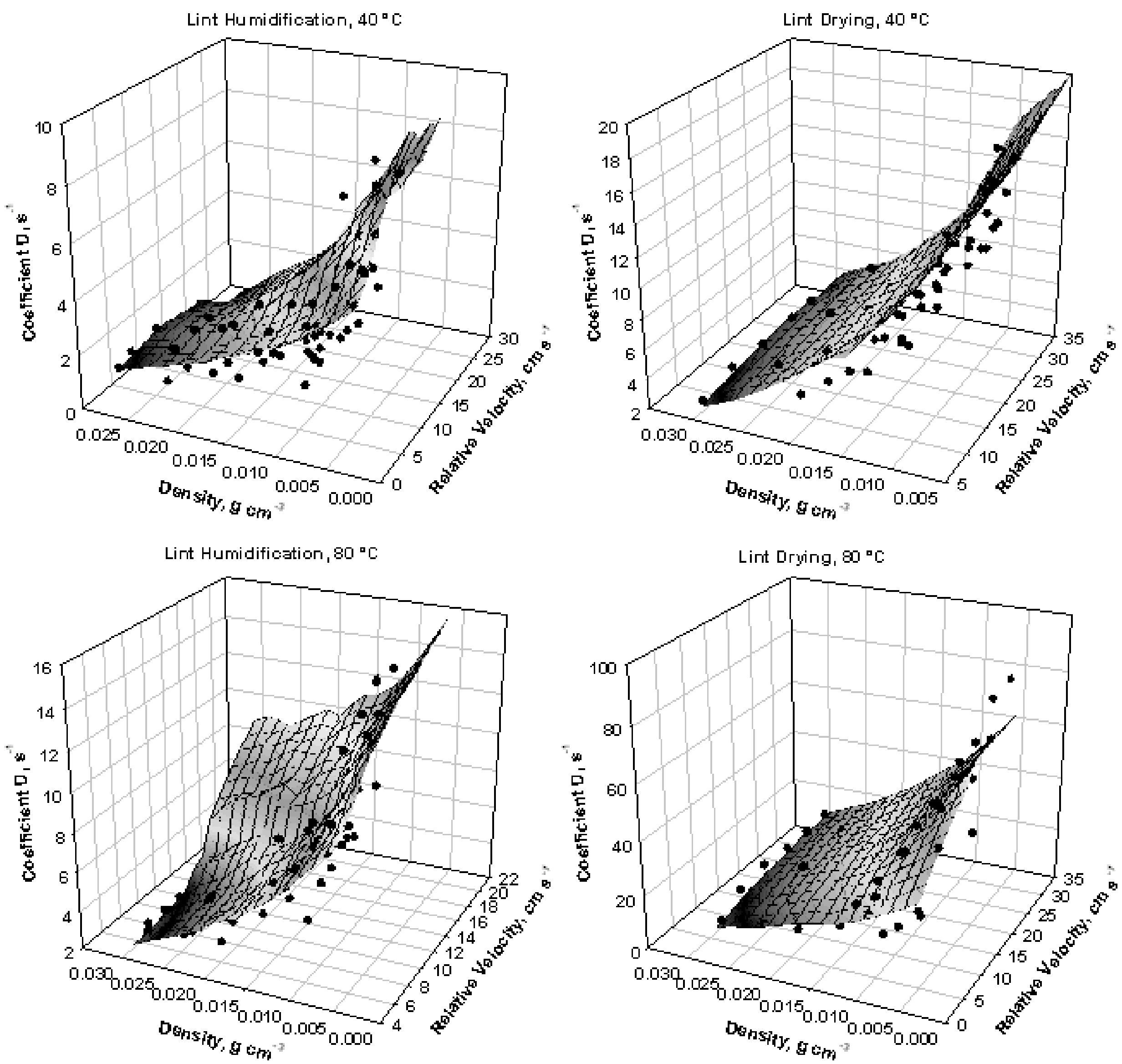

Fig. 7. Effects of lint density and the relative velocity of the air on the coefficient D (Eq. [2]) for cotton lint at 40 and 80°C. Larger values of D indicate higher transfer rates. The plots were made using a 3-D (negative-exponential) smoothing function on the original data. The symbols show the actual data points.

functions of temperature, relative velocity, and density, for lint exposure to humid and dry air. Several different models, including linear and exponential (Henderson and Perry,1979), were examined in an effort to provide a single relationship for each air type. The function selected, Eq. [4] (a modified version of Eq. [3]), provides an excellent fit for the dry air and a good fit for the humid air. Table 3 shows the values of regression coefficients and the statistical information for Eq. [4].

$$D = T^{A}[\Gamma + \delta(1-e^{-\zeta V})(e^{-\lambda \rho})] \qquad [4]$$

Where:

T = temperature, °C
A = regression coefficient

DISCUSSION

Increasing the relative velocity of air around an object reduces its boundary layer thickness, removes

Table 3. Regression coefficients, with 95% confidence intervals, for Eq. [4] using coefficient D (s^{-1}) from Eq. [2] for both the flat plate and the spherical solutions for cotton lint.

Air type	DF‡	A	Γ	δ	ζ	λ	R^2	Error‡
				Flat plate solution of Eq. [2]				
Humid	117	1.31419 ± 0.128§	0.010376 ± 0.0058	0.402224 ± 0.515	0.02666 ± 0.037	166.3958 ± 33.3	0.90	1.41
Dry	119	1.72778 ± 0.0997	0.006225 ± 0.0028	0.078257 ± 0.0344	0.079966 ± 0.0172	150.5391 ± 18.55	0.96	9.45
				Spherical solution of Eq. [2]				
Humid	117	1.327424 ± 0.128	0.008380 ± 0.0047	0.359981 ± 0.498	0.024216 ± 0.0366	167.2370 ± 32.95	0.90	1.03
Dry	119	1.749824 ± 0.102	0.004853 ± 0.0023	0.062126 ± 0.0278	0.079775 ± 0.0172	149.0450 ± 18.45	0.96	7.33

‡ DF is the degrees of freedom in error.

‡ Error term is the mean square error from regression.

§ The 95% confidence interval for each parameter estimate is shown below the estimated value of the parameter.

diffusion products more rapidly, and increases local gradients around the object(s) being conditioned. The increased gradient results in faster moisture transfer rates. Since the boundary layer thickness of transitional air can never reach zero, the expected effect of relative velocity should decrease exponentially as the velocity increases above a certain point. This can be visualized by examining Figs. 3 and 4, which show that increasing the relative velocity has a diminishing effect above some value.

Burs subjected to humid air responded to the test conditions in the manner expected. However, burs subjected to dry air showed little or no response to increasing velocity. The original data sets suggested that the predicted value of D was influenced by initial moisture content. Normalization of moisture content, as per Eq. [2], is designed to eliminate this problem, but may not always do so, especially at high moisture contents.

Lint responded as expected. Changes in relative velocity dramatically affected moisture transfer rates of low-density lint, but had minimal affect on high-density lint, indicating that diffusion within the mass is limiting. There was probably some movement of air within samples with low density, but little or none within samples with high density. The lowest densities (0.005 g cm^{-3}) approximate the density of loose-blown cotton in very thin layers and/or that on the lint slide. Single locked seed cotton and lint in bats can be expected to have a density in the neighborhood of 0.009 g cm^{-3}.

SUMMARY

The objective of this study was to determine the effects of relative velocity on moisture transfer rates of cotton burs, seed, and lint. Effects of density and temperature on moisture transfer rates of cotton lint were included as variables. Cotton burs were exposed to temperatures of 40 and 75°C. Cottonseed was exposed only to a temperature of 40°C, to prevent damage from higher temperatures. Lint was exposed to temperatures of 40 and 80°C. All sample types were exposed to a range of air flow rates ranging from 104 to 944 cm^3s^{-1} (relative velocity, 5 to 50 cms^{-1}) using dry and humid air. Lint was also prepared in a way to provide a density range of 0.005 to 0.028 g cm^{-3}. Results indicate that for this limited range of air velocities, the burs exposed to humid air showed a significant response to relative velocity. Burs exposed to dry air did not respond to changes in relative velocity. Cottonseed did not respond to changes in relative velocity, regardless of air type, implying that the diffusion of moisture within the seed itself is limiting. Lint responded to changes in density, temperature, and air velocity in the expected manner. Lint moisture transfer rates increased with increasing temperature and relative velocity and decreasing density. Mathematical relationships were developed that can be used in modeling and control algorithms to indicate the changes in moisture transfer rates that occur during processing phases.

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