# MASS FLOW MEASUREMENT OF PNEUMATICALLY CONVEYED COTTON

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## Abstract

Mass flow measurement of pneumatically conveyed cotton is important in at least two processes: yield monitoring during harvesting, and input and output determinations at various stages of ginning. In this work, two electronic devices were constructed and tested for measuring the flow of pneumatically conveyed cotton. One (device A) was used to collect data in the seed-cotton unloading duct of a gin, a cotton picker duct, and a lint-cleaner-exhaust duct. The other (device B) was used to collect data in the seed-cotton unloading duct of a gin and a lint-cleaner-exhaust duct. Tests were conducted in which known amounts of cotton were conveyed through the duct over a known time period, making it possible to calculate the average actual material flow rate. The average output of each device during the test runs was also calculated. Actual flow rate was compared to measured flow rate with linear regression. For seed cotton in the unloading duct, both devices performed well. For seed cotton in the picker chute, device A performed well, but device B was not tested. For waste in the lint-cleaner-exhaust duct, device A performed well and better than device B. In most cases, the correlation between sensor output and cotton mass flow was strong. Both devices look promising for application in appropriate locations in a cotton picker or gin.

## Background

As progress is made in the areas of "precision agriculture" and agricultural automation in general, yield monitoring and process control are increasingly important. Yield monitoring is important because of the needs to assess yield variability in (1) research plots and in (2) production fields and to relate yields to other field data by way of a geographic information system (GIS). Automatic yield monitoring in research plots is presumably less demanding in terms of economics and ease of use than in production agriculture. It is nonetheless important. Automatic process control is important because by manipulating the processing of crops, one can maximize quality and profit for each quantity of material processed. Measuring the flow rate of pneumatically conveyed cotton is required for cotton yield monitoring, and should improve gin process control. Cotton is carried by air from the picker or stripper head to the basket during harvesting, and it is carried by air between several machines in a typical ginning process.

A few attempts have been made of late to measure the velocities of flowing agricultural materials. Hofstee (1992) reported a successful method for measuring velocity and direction of fertilizer particles discharged by a fertilizer distributor. The method involved detecting the Doppler frequency shift of an ultrasonic signal. Yang and Swartzel (1991) reported a successful method of measuring the residence time of particles in continuous flow thermal processing systems. Their method employed two in-line two-dimensional arrays of photo-sensors to detect breaks in optical beams projected through water. Yang and Schrock (1993) reported a successful method for measuring velocity of falling grain kernels. Their method involved a video camera and image analysis techniques.

Howard *et al.* (1993) reported a partially successful method of measuring grain flow in a combine. Their method was mechanical, involving a triangular paddle elevator and a load cell. Calculated grain yields were within 5% of actual, and yield variations were detectable. Auernhammer *et al.* (1993) evaluated two commercial grain flow sensors, one based on measuring the level of grain over a paddle wheel, the other based on measuring the attenuation of electromagnetic energy by the grain. Both systems were reported to be capable of detecting yield variations of about 10%.

A few points should be made about the foregoing literature. The work of Hofstee, Yang and Swartzel, and Yang and Schrock, involved measuring particle velocity but not mass flow, which is of interest here. Further, these reports and those of Howard *et al.* and Auernhammer *et al.* concerned particles of relatively consistent size and shape. Seed cotton tends to be transported in clumps of varying size and shape. Additionally, none of the above reports concerned pneumatic conveyance. Therefore, measurement of cotton flow in pneumatic conveyance appears to be novel.

As far back as 1989, three authors of this manuscript (Pennington, Pringle, and Columbus) attempted to measure cotton mass flow rate, primarily from a yield monitoring perspective. Some encouraging results were obtained, but the work has remained heretofore unpublished. A report of this early work is included herein.

To the knowledge of the authors of this manuscript, the only report of measuring cotton flow in pneumatic conveyance is that of Wilkerson *et al.* (1994). Their work included a light-source array that projected light across a cotton picker

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discharge chute. On the opposite side of the chute was a photo-detector array that measured the amount of light crossing the chute. Measuring light attenuation caused by passing particles allowed calculations of the amount of cotton passing the sensor cross-section in a given time. The original field test of the device in a cotton picker was unsuccessful, primarily because of problems with stray light. However, laboratory tests resulted in a high correlation ($R^2 = 0.93$) between the mass of cotton passing the device and the device's output. Cotton feed rate was reported to affect sensor performance, and air flow rate was also a significant factor affecting sensor output. This device has been under patent application restrictions since the original report, so no other reports have been made (Wilkerson, 1995; 1996).

## Objectives

The goal of this work was to develop two prototype instruments (referred to as devices A and B) and to determine how accurately they would measure the amount of cotton flowing in a duct over a given time. The investigation was broken into four studies. Study 1 involved applying device A in a seed-cotton unloading duct; the objective was to test the reproducibility of sensor measurements of pneumatically conveyed seed cotton at constant total amounts, feed rate, and air velocity. Study 2 involved applying device A in a harvester chute during harvesting of research plots; the objective was to test the relationship between harvested seed-cotton mass and sensor output under trial conditions, and again under near-production conditions. Study 3 involved applying devices A and B in a seed-cotton unloading duct; the objective was to test the correlation between sensor output and seed-cotton mass flow at constant total amount, but varying feed rate and air velocity. Study 4 involved applying devices A and B in a lint-cleaner-exhaust duct; the objective was to test the correlation between sensor output and lint-cleaner-waste mass flow at varying total amount and feed rate, but constant air velocity.

## Materials, Methods, and Results

### Sensors

Two devices were studied as sensors for cotton flow measurement. Both worked on the principle of optical attenuation. Device A consisted of a 1-m- (39.4-in-) long light-sensing bar (LICOR LI-191SA), a light source, and data acquisition equipment. Light from the source crossed the duct, striking the light-sensing bar, which in turn produced an electrical current proportional to the incident energy. It was expected that cotton in an air stream within the duct would attenuate light, reducing the energy incident upon the light-sensing bar, and thus reduce the output current. The reduction in output was expected to be proportional to the amount of cotton between the light source and light-sensing bar.

Device B was of a more compact design that has been approved for patent application by the patent advisory committee of USDA's Agricultural Research Service. The details of device B's operation will thus be revealed later.

### Duct Configuration

A custom duct (fig.1) was built for the purposes of feeding seed cotton in one end and collecting it at the other, and holding device A in the proper arrangement with respect to cotton flow. The duct was of 178-mm (7-in.) square cross-section and 1219-mm (48-in.) length. On one side the light-sensing bar was affixed to the duct at an angle giving the light-sensing bar the longest possible exposure to a vertical plane crossing the duct; *i.e.*, on the side where the light-sensing bar was mounted, one end of the light-sensing bar touched the left edge of the side and the other end touched the right edge. Between the light-sensing bar and the duct was a rectangular aperture to ensure that any light and attendant attenuation traveled through the exposure plane of the light-sensing bar. The light source was mounted on the opposite side of the duct from and parallel to the light-sensing bar.

When included in a study, device B was affixed to either the inlet or exit end of the light-sensing-bar duct section. In certain cases, square-to-round transitions were used to adapt the light-sensing-bar section to 203-mm (8-in.) diameter round duct.

### Study 1: seed-cotton unloading duct, device A, 1989

**Data Collection.** A test apparatus (fig. 2), including a small gin fan, a length of duct including device A, and a vacuum dropper, was built for measuring seed-cotton flow as would be required in harvesting or seed-cotton unloading. The light source in this work was a row of incandescent lamps, powered by a charged 12-VDC automobile battery. The light-sensing bar's current was connected across a fixed resistor, and the resultant voltage was measured with a Campbell Scientific 21X data logger. The data logger sampled the voltage 17 times per second. A reference voltage was established with an empty duct. The voltage with cotton in the air stream was subtracted from the reference voltage to give a voltage difference representative of light attenuation caused by the flowing cotton.

A 6.8-kg (15-lb) lot and an 11.4-kg (25-lb) lot of seed cotton were fed through the test apparatus three times at constant feed rate and air velocity. For the purposes of this study, it was assumed that fluffing of the cotton each time through the apparatus would be negligible with respect to its effect on light attenuation. The air velocity was not measured but was sufficient to convey the seed cotton smoothly through the system. For each 1-s period (17 data points), the differences between measured and reference voltages were summed to provide a cumulative light-sensing-bar measurement.

**Data Analysis.** The 1-s sums, which had been recorded with the data logger, were summed to produce a cumulative light-attenuation estimate over the duration of the test. These test sums were compared to the total amount of cotton that had passed device A during the given time period.

**Results and Discussion.** Curves of cumulative 1-s voltage-difference sums are given in fig. 3. The point at which each curve levels off represents the point at which the cotton had finished flowing in the system. Each curve begins at approximately the 5-s mark. It can be seen that the curves are very similar up to about the 40-s mark. The curves of the 6.8-kg (15-lb lots) all leveled off at that point with a similar total of about 300 units. The curves of the 11.4-kg (25-lb) lots continued on the same linear path to nearly the 60-s mark, at which point they leveled off at approximately 500 units. It is noteworthy that the voltage-difference totals of the 6.8-kg (15-lb lots) and 11.4-kg (25-lb) lots were in proportion to their weights; *i.e.*, 500 / 300 = 11.4 / 6.8 (= 25 / 15).

**Study 2: picker chute, device A, 1989**

**Data Collection.** For trial harvesting conditions, device A was next attached to a chute of a one-row cotton plot harvester (fig. 4). Device A was mounted such that the light-sensing bar was on the inward side (facing the harvester) of the chute, and a plexiglass window was mounted on the outward (skyward) side. The harvester was used to harvest research plots in a field with an expected range of seed-cotton yields. The plots were harvested on consecutive cloudless days in October. Seed cotton from 9.1-m (30-ft), one-row plots was captured in bags and weighed. Light-sensing-bar data were collected at the same time plots were conventionally harvested. All harvesting was completed by driving through the plots to the south. The sun shining through the window was used as the light source. The light-sensing-bar voltage was sampled 17 times per second, and each sample was stored in the data logger. A reference voltage was established when the harvester passed through the alleys between plots. Nominal harvester velocity was calculated by dividing the known row length by the recorded time from row beginning to row end. Distance down the row was calculated by multiplying the time since the beginning of the row by the nominal velocity.

For near-production conditions, device A was mounted on the inward side of a single chute on a two-row cotton harvester. In this case, a row of incandescent lamps was mounted on the outward side to serve as a light source instead of sunlight. Again, a charged 12-VDC automobile battery powered the incandescent lamps. The harvester was operated to allow two adjacent rows to be harvested with the same picker head, the one attached to the chute equipped with device A. The difference between reference voltage and measured voltage was sampled 17 times per second, with 1-s summations recorded by the data logger. Distance down the row was calculated as it was for trial conditions.

**Data Analysis.** For trial conditions, actual sample voltages, recorded 17 times per second, were used to compare light-sensing-bar response to plot location. Then, the differences between sample and reference voltages were summed to produce one voltage difference for each plot harvested. For both fields, simple-linear regression was used to determine the correlation between summed voltages and harvested amounts of cotton.

For near-production conditions, when two adjacent rows were harvested, it was intended to compare the general yield trends through the field on the two rows. Whereas the 1-s values exhibited large variations such that trends were obscured, a 10-s moving average was used to smooth the data.

**Results and Discussion.** For trial conditions, individual sample voltages are plotted against field location in fig. 5. It can be seen that the light-sensing-bar response for plot areas, in which seed cotton passed through the chute, was clearly different from that for alley areas, in which no cotton passed through the chute. Cumulative voltage differences are plotted against mass of seed cotton harvested, for each plot harvested on two days, in figs. 6 (day 1) and 7 (day 2). The relationship between light-sensing-bar output and cotton harvested was highly linear for both days ($R^2 = 0.89$ for day 1, $R^2 = 0.98$ for day 2).

For near-production conditions, averaged voltage differences are plotted against distance down the adjacent rows in fig. 8. Some differences in light-sensing-bar response between the two rows are evident, but the yield trends compare favorably. Whereas yield variations on adjacent rows could be expected to match fairly closely, the light-sensing-bar output appeared to allow for differentiation in yield down the row, but a firm conclusion on this point cannot be drawn from this study.

**Study 3: seed-cotton unloading duct, devices A and B, 1995**

**Data Collection.** The equipment for collecting data from device A was changed. Instead of the data logger, the new data acquisition system consisted of appropriate circuitry to provide a 0- to 5-VDC signal, an A/D board, and an INTEL 80486-based personal computer running a BASIC program for acquiring and recording light-level data. The program was written to account for variations in air velocity. In this work, a regulated 12-VDC power supply furnished power to the incandescent lamps.

Device B was installed in-line at the exit of device A in the seed-cotton unloading line of a small (0.3 bale/h maximum) research gin (fig. 9). Data from devices A and B were recorded during testing in which 11.4-kg (25-lb) quantities of seed cotton were introduced to the feed control of the gin. The same computer and software recorded data from both devices. Because an averaging scheme was used in the collection of data from device A, the computer collected a data point from device B much less frequently (5 samples per second) than that of which device B was capable (1000 samples per second).

The cotton was diverted around the rest of the ginning machinery, because the sensors were placed almost immediately after the feed control, and thus no ginning was needed. The rate of the feed control was varied by adjusting its variable-speed motor to accomplish four nominal throughput rates: 3.63, 6.27, 10.3, and 12.5 kg/min (8.0, 13.8, 22.7, and 27.6 lb/min). The velocity of the conveying air was varied by adjusting a gate valve on the gin fan to produce four nominal air velocities: 20.3, 22.7, 25.6, and 26.4 m/s (4000, 4470, 5030, and 5200 ft/min), as converted from the velocity pressures measured with a pitot tube and manometer. These velocities are reasonable for seed cotton unloading systems. The ratios of air flow to cotton flow ranged from 3.1 to 13.9 $m^3$/kg (49 to 221 $ft^3$/lb). These ratios tended to be considerably higher than the typical range for seed cotton unloading systems, 1.2 to 3.1 $m^3$/kg (20 to 50 $ft^3$/lb). This means that the cotton mass flow rates were lower than those in a typical seed cotton unloading system.

**Data Analysis.** In this test, the instantaneous data from each sensor were averaged over the duration of the individual test. The seed cotton had been weighed in advance and fed into the system by a motorized feeder. The test durations varied along with the feed control rate, from 1 min 45 s to 6 min 25 s. The actual average flow rate was compared with the average sensor output over the same time period. Simple-linear regression was used to determine the correlation between average sensor output and average actual flow rate.

**Results and Discussion.** Data recorded from device A were in some cases readily understood and analyzed, while in other cases unexplained negative values occurred. Further examination determined that improvements in the electronic circuitry and in the calibration procedure were necessary. However, device B produced data as expected. For device B, measured and actual flow rates were highly correlated, with an $R^2$ value of 0.90 and an F value of 129.3. This appears to be quite good because, although the amount of data collected from device B was much less than that of which it was capable, the correlation was strong. The regression line and actual flow data are plotted in fig. 10.

**Study 4: lint-cleaner-exhaust duct, devices A and B, 1996**

**Data Collection.** Prior to this study, device A was modified as follows: a low-pass filter was constructed and placed between the output of the light-sensing bar and the computer's A/D board, and the calibration procedure was changed to allow more time for light-source stabilization and for averaging values for the high-reference and low-reference numbers. Devices A and B were subsequently placed in the lint-cleaner-exhaust duct of another small (1.0 bale/h maximum) research gin (fig. 11). An extra 305-mm-(12-in-) long section of square duct was included at the inlet end to stabilize the air-flow regime after the transition and prior to the light-sensing-bar section. This gin was equipped with a full-scale process control system in which the number of lint cleaners could be adjusted from 0 to 3. In this configuration, device B was placed at the inlet to device A. In this test, roughly 45-kg (100-lb) lots of seed cotton were fed into the gin. The following sequence of machinery was employed before the gin stand: 1st tower-dryer, 6-cylinder cleaner, stick machine, 2nd tower-dryer, impact cleaner (the 2nd 6-cylinder cleaner was bypassed), and extractor feeder. After the gin stand, the number of lint cleaners was varied from 0 to 3 with 3 replications. The air velocity in the lint-cleaner-exhaust duct was nominally 13.2 m/s (2600 ft/min), as converted from the velocity pressure measured with a pitot tube and manometer. During each replication, the exhaust of lint-cleaner waste and gin motes proceeded through the measuring devices, was removed from the air by a drum condenser, and was collected in a sack. The contents of each sack were weighed, and the duration of ginning was measured. Devices A and B collected data during each replication.

**Data Analysis.** The mass of material conveyed was divided by the test duration to get the actual average flow rate over the test. The instantaneous data from each sensor also were averaged over the test duration. The test durations varied slightly with slight variations in seed-cotton input. The actual average flow rate was compared with the average sensor output over the same time period. Simple-linear regression was used to determine the correlation between average sensor output and actual average flow rate.

**Results and Discussion.** Modifications to the circuitry and calibration procedure of device A proved successful. Both devices produced data as expected. For device A, measured and actual flow rates were highly correlated, with an $R^2$ value of 0.92 and an F value of 108.9. The probability of non-significance (p) was less than 0.0001. The regression line and actual flow data are plotted in fig. 12. For device B, although still highly significant ($p \leq 0.0062$, F = 11.9) the correlation was much less, with an $R^2$ value of 0.54. The regression line and actual flow data are plotted in fig. 13.

## Conclusions

In Study 1, device A, the light-sensing-bar device, exhibited good measurement reproducibility for constant amounts of seed cotton in a gin unloading duct at constant feed rate and air velocity. In Study 2, device A, mounted in a picker chute, exhibited a strong linear relationship between harvested seed-cotton mass and light-sensing-bar output under trial and near-production conditions. In Study 3, device B, mounted in a gin unloading duct, exhibited a strong linear relationship between sensor output and seed-cotton mass flow at constant total amount, but varying feed rate and air velocity. In Study 4, device A, mounted in a lint-cleaner-exhaust duct, exhibited a strong linear relationship between light-sensing-bar output and lint-cleaner-waste mass flow at varying total amount and feed rate, but constant air velocity. Device B did not work as well as device A for measuring lint-cleaner-waste flow. Thus, device B appears appropriate for measuring seed-cotton flow, but not lint-cleaner-waste flow.

## Future Work

It is believed that either device could be used at other locations in a gin, or in a cotton picker. It is expected that device B, being more compact than device A, will be implemented in a cotton picker within the next year. More data will be collected with both devices in the seed-cotton line of a gin, and more data will be collected with device A in the lint-cleaner-exhaust duct.

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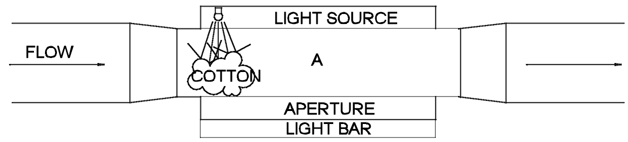


Figure 1. Diagram of cotton flow through duct and sensor location.

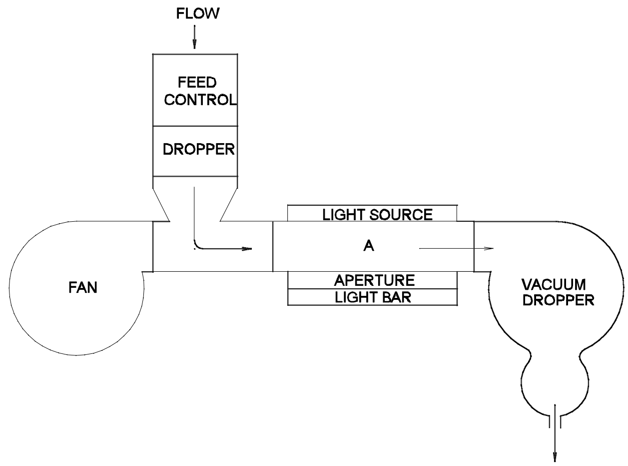


Figure 2. Diagram of custom seed-cotton unloading and measurement system, Study 1.

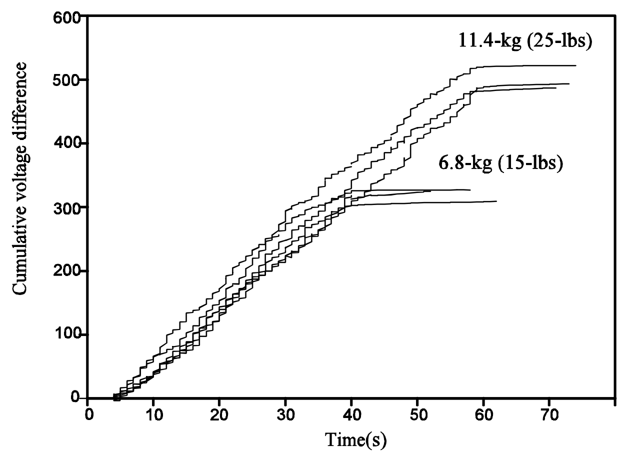


Figure 3. Cumulative voltage difference vs. time for various tests, Study 1.

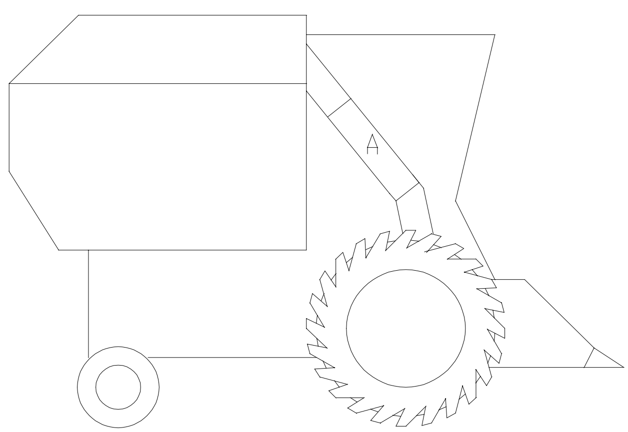


Figure 4. Location of device A on cotton picker.

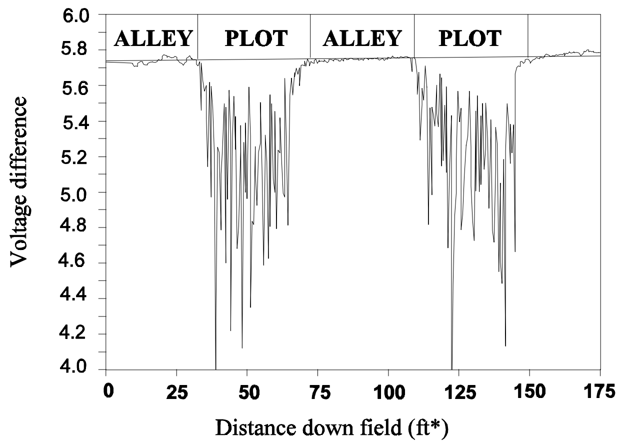


Figure 5. A sample of voltage difference vs. distance, Study 2.
*Distance in m is calculated by multiplying distance in ft by 0.305.

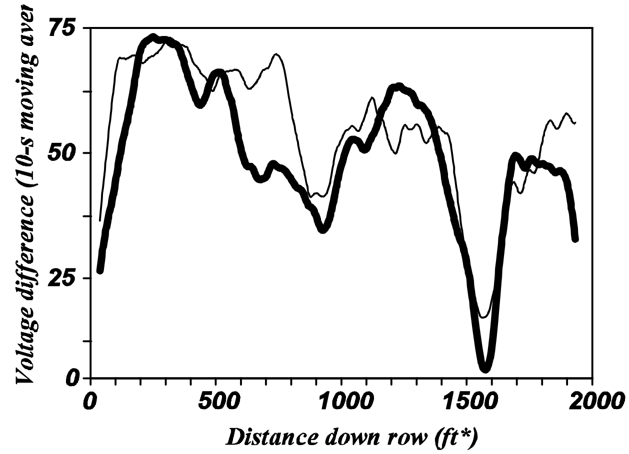


Figure 8. Voltage difference (10-s moving average) vs. distance down row for two adjacent rows in a field.
*Distance in m is calculated by multiplying distance in ft by 0.305.

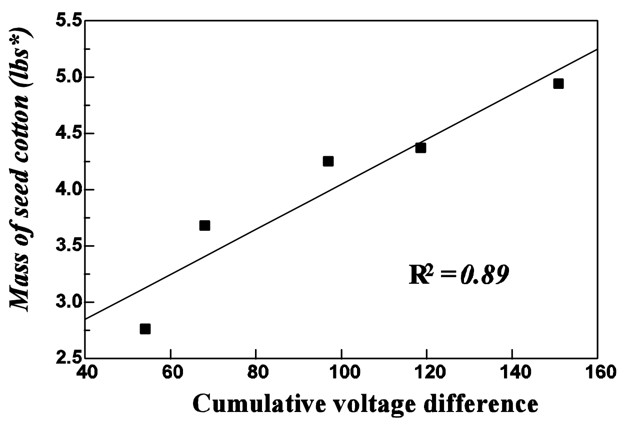


Figure 6. Mass of seed cotton (straight line is the regression line) vs. cumulative voltage difference for day 1, Study 2.
*Mass in kg is calculated by multiplying mass in lbs by 0.454.

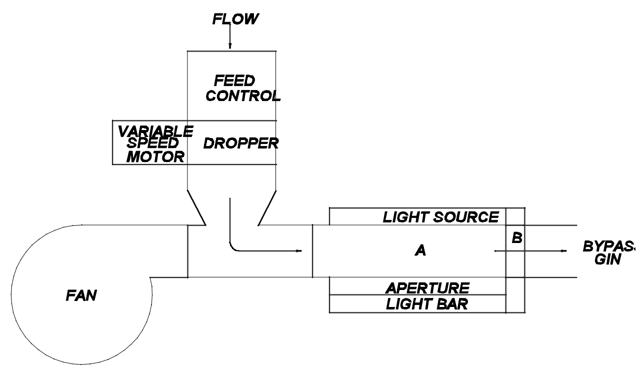


Figure 9. Diagram of mounting location for devices A and B in seed-cotton unloading duct of small gin, Study 3.

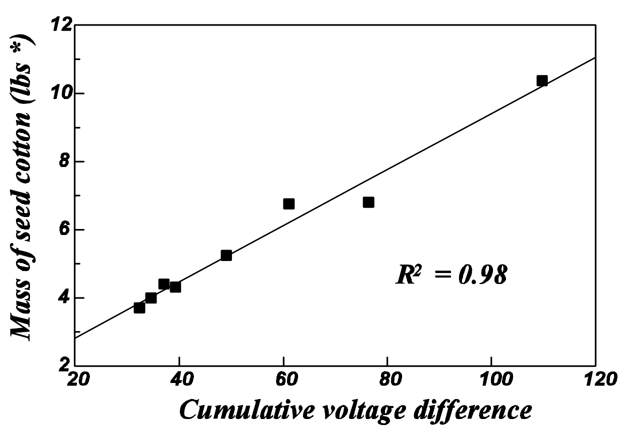


Figure 7. Mass of seed cotton (straight line is the regression line) vs. cumulative voltage difference for day 2, Study 2.
*Mass in kg is calculated by multiplying mass in lbs by 0.454.

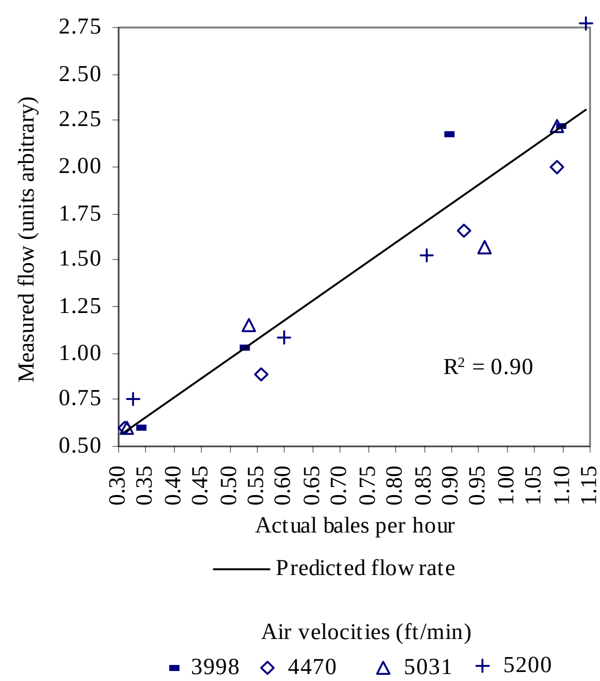


Figure 10. Measured flow rate vs. actual flow rate on device B, Study 3.

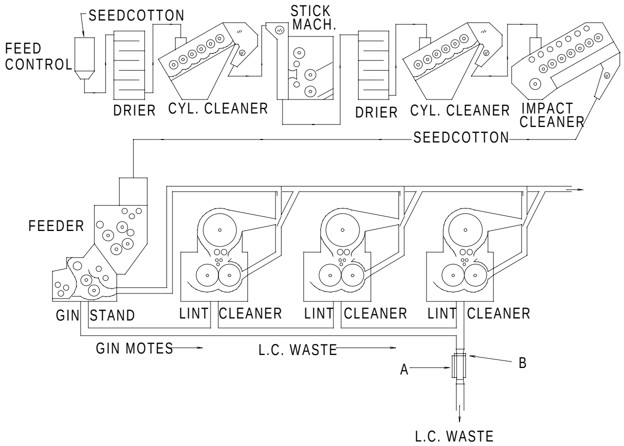


Figure 11. Diagram of mounting location for devices A and B in lint-cleaner-exhaust duct of small gin, Study 4.

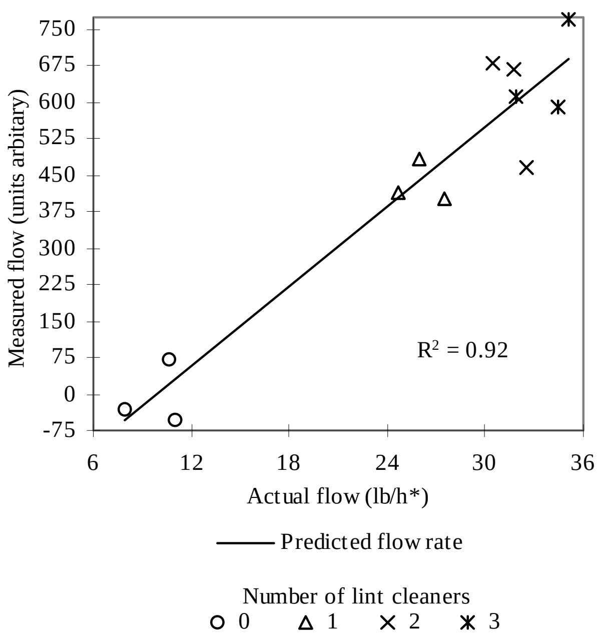


Figure 12. Measured flow rate vs. actual flow rate on device A, Study 4.
*Flow in kg/h is calculated by multiplying flow in lb/h by 0.454.

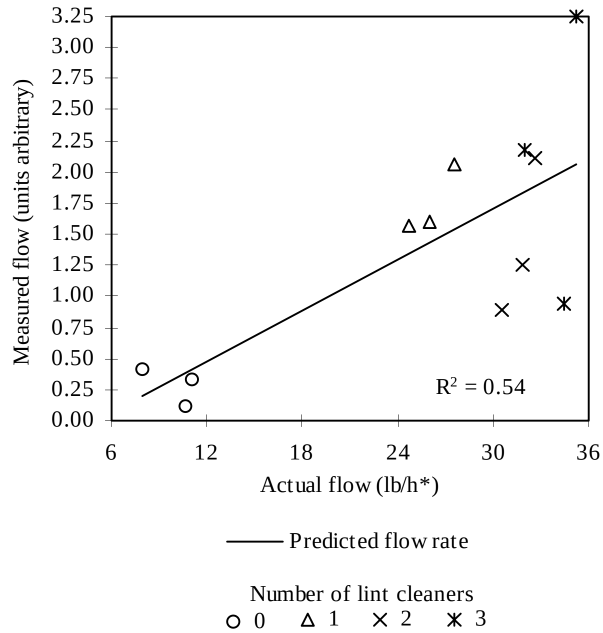


Figure 13. Measured flow rate vs. actual flow rate on device B, Study 4.
*Flow in kg/h is calculated by multiplying flow in lb/h by 0.454.