Optical Sensor for Granular Fertilizer Flow Rate Measurement

D. W. Swisher, S. C. Borgelt, K. A. Sudduth

Abstract. *An optical sensor to measure granular fertilizer flow in an airstream was designed, built, and laboratory tested. The sensor components included a laser line generator that transmitted light across a trapezoidal chamber to a 32–element photodiode array. The air–suspended granules would break the light, causing a count to be recorded. The counts were translated into a mass flow rate. Static tests of five materials and six mass flow rates were performed in a replicated block design. Dynamic tests of one material with six step changes in mass flow rate were performed. Results of the static tests showed a strong linear, repeatable relationship between sensor output and mass flow rate. For maximum accuracy, individual calibrations were required for different fertilizer products. Dynamic test results showed that the sensor followed step changes in mass flow rate well, but indicated some limitations in the data analysis algorithm. The optical sensor system showed potential as a first step to a real–time granular fertilizer flow rate sensor.*

Keywords. *Precision farming, Sensor, Fertilizer, Optical measurement, Granular flow.*

Variable–rate application of granular fertilizer material is a common practice in precision agriculture. Granular fertilizers need to be accurately delivered at the prescribed application rates to accomplish the desired outcome of correcting within–field variations in plant nutrients. With air spreader fertilizer applicators, granular fertilizer material is metered from the on–vehicle holding bin into an airstream by rotating metering wheels. The granules then travel with the airstream through a flexible tube to a location on a boom where they are dispersed by a deflection plate and drop to the ground (Solie et al., 1994). Commercially available granular fertilizer air spreaders do not directly measure the flow of material through the pneumatic tubes. Application rates are determined by measuring the rotational speed of the fertilizer metering wheels. From the monitored rotational speed and the delivery capacity of the metering wheels, granular material flow rate through the boom is estimated (Van Bergeijk et al., 1997). Although this method can be calibrated to accurately estimate application rates under ideal conditions, issues such as worn metering wheels, fertilizer application on uneven terrain, and changing fertilizer properties may reduce the accuracy of this delivery.

A sensor to directly quantify granular fertilizer material delivered through a tube could allow on–the–go measurements of granular material flow for more accurate monitoring of application rates. Accurate measurements of granular material rates could allow improved troubleshooting and provide the ability to implement closed–loop adjustments in metered flow for greater accuracy in fertilizer application. Various methodologies have been devised to measure the flow rate of granular materials delivered pneumatically. However, many of these methodologies have not been implemented commercially due to intrinsic complexities of the measurement problem, sensor designs based on over–simplification of the nature of granular material flow, and the effect of system operating conditions (Yan, 1995). Other issues, such as measurement method limitations, physical and chemical properties of the granular materials, and product distribution in delivery tubes, have also restricted development of granular material flow sensors (Yan, 1995).

Several criteria describe an ideal flow sensor for granular fertilizer materials:

- The flow sensor should not obstruct the flow of the materials and must be able to withstand the erosive nature of flowing granular materials (Yan, 1995).
- Sensors should measure the same mass flow rate over a range of particle sizes and shapes for the same velocity. Granular fertilizers come in a variety of shapes, sizes, and chemical compositions, suggesting that a flow meter may have to be calibrated for particular products.
- Sensing techniques should not be sensitive to the chemical characteristics of the granular materials. Variations in chemical composition and moisture content could change the density of the granular materials, and this could affect flow meter performance.

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- Sensor performance should not be affected by non–uniform particle distribution in the delivery tube. Distribution of particles in a delivery tube may or may not be homogenous, depending upon delivery tube orientation, measurement position, conveying air velocity, and many other factors (Yan, 1995).

Measurement techniques for granular materials conveyed pneumatically can be categorized as either direct or indirect, depending on whether or not they interact with particle flow. Direct techniques include thermal, active charging, and passive charge detecting. Indirect techniques that quantify particle volumetric concentration include dielectric, electrostatic, optical or acoustical attenuation or scattering, resonance, and tomography. Indirect techniques that quantify granular material velocity include Doppler, cross–correlation, and spatial filtering methods. A detailed description of these techniques was given by Yan (1996).

Green et al. (1995), Thomasson et al. (1999), and Wilkerson et al. (1994) used optical methods to measure the mass flow rate of pneumatically conveyed solids. Green et al. (1995) used a 16 × 16 element tomographic sensor array to measure cross–sectional variations in bulk concentrations of sand. The results obtained were good, and the relationship between sensor output and mass flow rate was approximately linear. Thomasson et al. (1999) tested two different sensor configurations that worked on the principle of optical attenuation to measure the mass flow rate of pneumatically conveyed cotton. Sensor readings could be correlated to the mass flow rate of cotton, but depended on placement of the sensor and physical properties of the cotton. Wilkerson et al. (1994) developed a cotton mass flow sensor that used the principle of optical attenuation. Rather than post–processing the data, an algorithm was developed to count the fluctuations in voltage output due to cotton moving past the sensor and display the results in real–time. Sensor counts were linearly related to cotton mass flow rate ($r^2 = 0.92$).

Sensing particle volumetric concentration by optical attenuation, as described by Green et al. (1995), Thomasson et al. (1999), and Wilkerson et al. (1994) has several advantages for systems where particle loadings in the airstream are relatively low. Yan (1996) stated that variations in material chemical composition and moisture content would likely have little effect on optical sensor output. Optical methods are inherently suitable for dilute–phase applications because of their high sensitivity. However, contamination and/or misalignment of optical components can cause false or erroneous readings (Yan, 1996). Measurement of the dynamic components of the optical signal as illustrated by Wilkerson et al. (1994) can help to overcome the effects of misalignment and contamination (Yan, 1996). Another advantage of this approach of counting fluctuations in the optical signal as an indication of particle flow rate is its relative insensitivity to changes in the optical absorbance characteristics of the material and conveying medium.

Objectives

The overall objective of this research was to develop an optical sensor to measure granular particle flow in a fertilizer air delivery tube. Specific objectives were to:

1. Design and build a prototype sensor using a light source and light intensity detector.
2. Develop data analysis techniques for measuring granular material flow.
3. Test sensor performance in the laboratory.

Materials and Methods

Flow Rate Sensor Design

The sensor was designed to be compact and self–contained to facilitate its placement on a fertilizer applicator. It was also designed to minimize changes in the normal flow characteristics of the air delivery system. The prototype sensor was configured for installation and testing on a small fertilizer applicator with delivery tubes having a 25 mm inside diameter. The sensor consisted of an optical source and detector, electronic circuitry to process and interface the optical signals to a computer, and a sensing chamber inserted into the fertilizer delivery tube. Details of the design are found in Swisher (1999).

A line light source and a linear array photodetector reduced errors due to misalignment between the source and detector by allowing flexibility in light source positioning. To provide high optical power output, a red (670 nm) laser diode line generator (VLM3, Coherent Auburn Group Instruments Division, Auburn, Cal.) was chosen as the light source. The laser diode output was configured as a fan of light having an 85° included angle. A linear silicon photodiode array placed on the opposite side of the sensing chamber intercepted this fan of light. The 32–element array had a sensing length of 51 mm and was fabricated from two 16–element arrays (PDB–C216, Photonic Detectors Inc., Simi Valley, Cal.). Each photodiode element was 1.8 mm wide by 1.2 mm long.

Conditioning of the photodiode signals was accomplished using low–bias–current operational amplifiers (AD546JN, Analog Devices, Norwood, Mass.) connected as current–to–voltage converters. A 100 kΩ feedback resistor provided a 0 to 5 V output range. Each of the 32 photodiodes was connected to a separate amplifier. Voltage regulators were used to provide low–noise power for the amplifiers (±15 V) and laser diode (–5 V). The negative supply to the laser diode was required so that its case could be grounded to the sensor and the applicator frame.

The sensing chamber was designed to accommodate the fan–shaped beam of light emitted by the laser diode and to provide flexibility in light source positioning. The chamber, milled from an aluminum block, was trapezoidal (fig. 1), with the optical source placed at the small base of the trapezoid and the detector placed at the large base. A positioning device was provided for the laser diode to allow its alignment with respect to the photodiode array. Transitions were required from the round fertilizer delivery tube to the trapezoidal chamber and back to the round delivery tube. The inside diameter of the entrance delivery tube was physically smaller than the trapezoidal shape of the chamber; therefore, an abrupt transition into the larger sensing chamber was used. The exit transition was a trapezoidal shape that funneled into a circular shape milled into another block of aluminum attached to the sensing chamber. Sapphire optical windows were installed in the sensing chamber to protect the optical source and detector. Sapphire was chosen for its high light transmittance and resistance to abrasion. Any sensing chamber leaks were sealed using a clear silicone sealant.

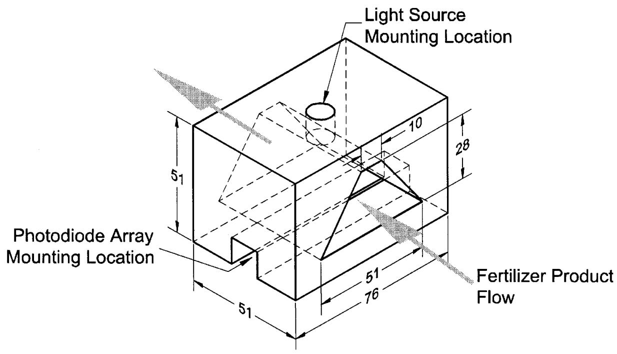

Figure 1. Sensing chamber configuration (all dimensions are mm).

FERTILIZER APPLICATOR

A tractor–mounted Gandy 6210 Orbit–Air fertilizer applicator (Gandy Corp., Owatonna, Minn.) (Gandrud et al., 1993) with 10 delivery outlets was used to test sensor performance. In this applicator, a fan blower driven at constant speed by the tractor hydraulic system delivered air to a venturi chamber. For each delivery outlet, fertilizer was metered into the venturi by fluted plastic metering wheels, where it mixed with the airstream. The air–suspended fertilizer was then conveyed through 25 mm inside diameter plastic tubes to the point of application. The metering wheels used on this applicator delivered approximately 50 cm^3/rev of product. A Raven SCS 700 (Raven Industries, Sioux City, S.D.) system was used to control the speed of the metering wheel shaft. The SCS 700 allowed a target rate to be set either manually through the console or by computer through a serial port. The controller then automatically maintained the application rate regardless of vehicle speed. An override switch allowed the operator to manually control application rate, if desired. The Gandy Orbit–Air applicator was mounted to and powered by a 60 kW row crop tractor. The prototype sensor was attached to one of the 10 fertilizer delivery tubes, approximately 0.25 m downstream from the venturi chamber.

In low–pressure venturi feed systems such as the Gandy 6210, the flow of granular material must be metered at a low level for proper system operation. Exceeding this level will upset the venturi action, plugging the delivery tube (Stoess, 1983). For the system used in these tests, air velocity in the delivery tubes was approximately 20 m/s with no fertilizer flow. The highest fertilizer flow rate tested, 0.06 kg/s, was near the maximum capacity of the system. At this near–capacity level, fertilizer particles comprised less than 0.4% of the total volumetric flow in the delivery tubes. Fertilizer applicator blower fan speed was held constant for the sensor tests. As varying amounts of fertilizer material were metered into the system, some level of static pressure variations and changes in air velocity would result. However, due to the low concentration of solids in the system, these changes in air velocity were expected to be small and to not significantly affect system operation.

DATA ACQUISITION

The 100 kHz 12–bit, 16–channel A/D converter available in a DaqBook/100 data acquisition system (IOtech, Inc., Cleveland, Ohio) was used to collect data from the photodiode amplifiers at approximately 250 Hz, the maximum sampling rate possible. Since the photodiode array consisted of 32 elements, two DaqBook/100s were required. They were interfaced to a 486 DX–100 portable computer through two parallel ports, one for each DaqBook/100. Tests revealed a data acquisition time delay of approximately 5 ms between the two DaqBook/100s.

For dynamic tests, one DaqBook/100 counter was used to record the pulses (360/rev) from an optical shaft encoder attached to the metering wheel shaft on the fertilizer applicator. During dynamic tests, the data acquisition computer also sent rate control commands to the Raven SCS 700 through a serial port.

FERTILIZER PRODUCTS

Three granular fertilizer products were used for testing: triple super phosphate ($Ca(H_2PO_4)_2$ or TSP), ammonium nitrate (NH_4NO_3 or AN), and potash (KCl or KCL). A Sylvite Size Guide Number (SGN) scale (Hamilton, Ontario, Canada) was used to determine average particle size. This scale sifted a 210 mL fertilizer sample into five bins by means of five different screens (1.0, 1.4, 2.0, 2.8, and 4.4 mm). The point on the scale that divided the sample into two equal parts provided an estimate of the average particle size. Three samples of each product were tested to determine the average particle size (table 1).

Average particle mass was determined by counting the number of particles in a 100 g sample of each product (table 1). ASAE Standard S269.4 was used to determine product density (*ASAE Standards*, 1997). The product was poured into a container 208 mm in height by 117 mm in diameter and settled by dropping the container five times from a height of 150 mm against a hard surface. The mass of the product was measured and divided by the calculated volume of the container. The average of three replications was reported (table 1).

Particle size distribution was determined by sifting 1 L of fertilizer product through four sieves: 4 mm, 3 mm, 2 mm, and 1 mm. The volume of fertilizer passing through each sieve was measured using a graduated cylinder. The average of three replications was used to develop a particle size distribution (table 2).

Table 1. Physical characteristics of the three fertilizer materials.

Product	Color	Avg. Particle Size (mm)	Avg. Particle Mass (mg)	Density (kg/m^3)
TSP	Black	2.80	26.0	933.3
KCL	White	2.67	22.7	943.2
AN	White	3.15	23.1	774.9

Table 2. Fertilizer particle size distribution determined on a volume basis.

	Portion in Size Range (%)		
Particle Size	TSP[a]	KCL[a]	AN[a]
<1 mm	0.2	1.1	1.9
1 mm – 2 mm	3.1	16.3	3.7
2 mm – 3 mm	83.3	60.4	79.1
3 mm – 4 mm	11.0	19.2	13.2
>4 mm	1.8	2.3	1.6
Total <2 mm	3.3	17.4	5.6
Total >2 mm	96.1	81.9	93.9

[a] Totals do not add to 100% due to rounding.

Static Tests

A series of static tests was conducted to evaluate the performance of the sensor under constant fertilizer flow rates. The three fertilizer materials (triple super phosphate, TSP; potash, KCL; and ammonium nitrate, AN) were used to test sensor performance with a single product. Two blends of TSP and AN were mixed to test the sensor using a mixture of products: 2/3 TSP:1/3 AN and 1/3 TSP:2/3 AN. Single tube mass flow rates of 0.01, 0.02, 0.03, 0.04, 0.05, and 0.06 kg/s were chosen to cover the range of flow rates feasible with the Gandy Orbit–Air applicator. Three replications of each fertilizer or blend test were performed. At flow rates less than 0.01 kg/s, the applicator could not accurately apply the target rate because the controller could not maintain a uniform shaft speed. Flow rates greater than 0.06 kg/s approached the fertilizer delivery capacity of the applicator.

Each test replication was 60 s in duration. Fertilizer passing through the sensor and delivery tube was captured and weighed to determine the actual average mass flow rate for each replication.

Dynamic Tests

Dynamic tests were conducted with AN to test the capability of the sensor and data analysis methods to track step changes in application rate. Two sets of flow rate step changes were evaluated. The first set of flow rates included 0.01, 0.03, and 0.05 kg/s, while the second set included 0.02, 0.04, and 0.06 kg/s. Within each set, flow rate order was randomized for each of three replications. Each dynamic test run began with 5 s of zero–flow data collection. Then the application rate command was incremented every 15 s until the last rate change was completed. The rate command was then decremented every 15 s until zero flow was reached for 5 s. Timing of the rate changes was controlled by the data acquisition computer through the serial port of the Raven SCS 700. The duration of each run was approximately 85 s. The fertilizer was caught and reused after each replication.

Results and Discussion

Sensor Characterization and Data Transformation

The graph of the output voltage across the photodiode array under full–light and no–light conditions with no fertilizer flow (fig. 2) showed that the no–light voltage of the photodiodes was essentially zero. The output voltage at full light consisted of a near–normal distribution. A difference in output between elements was expected since the light traveled a different distance to each element and struck each element at a different angle due to the fan–shaped output of the light source and the sensing chamber geometry (fig. 1). This range in light intensity and resulting output voltage posed a problem for determining when the light beam was attenuated by a particle moving through the sensor. Analyzing the output voltage across all elements by simply comparing the raw data was not feasible because a value that might be a count for an interior element could be the normal background (full light) response for an exterior element. Therefore, an approach was developed to count interruptions in the optical signal due to particle flow, rather than measure the degree of light attenuation as an indicator of flow rate.

This particle–counting approach had a further benefit of making the sensing system robust to any changes in the optical absorbance characteristics of the fertilizer products (i.e., due to particle size, color, or chemical composition) and airstream (i.e., due to moisture content) at the illumination wavelength of 670 nm. Particle absorbance effects were expected to be minor, since the main mechanism affecting sensor output was the blocking of direct illumination by the passage of fertilizer particles between the illumination source and the photodiode array. In addition, the effect of moisture content variations was expected to be minor, since the optical absorption of water is low at the illumination wavelength. Any absorbance effects that were present and that changed the overall level of illumination reaching the photodiode array would be further minimized by counting light–dark transitions rather than relying on illumination level as the indicator of flow rate.

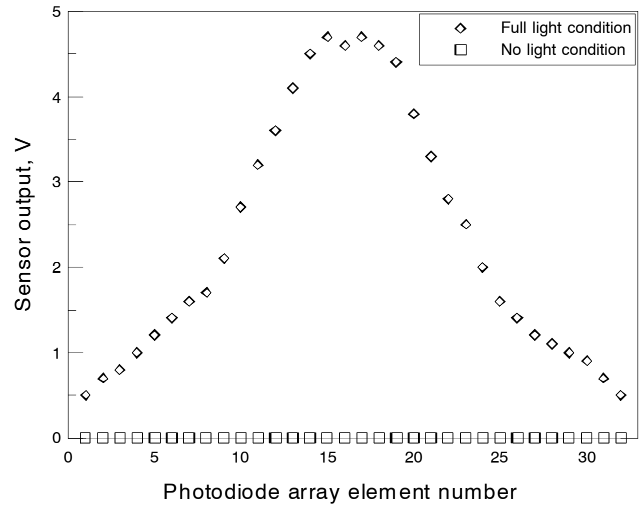

Figure 2. Sensor output for full–light and no–light conditions with no fertilizer flow.

Equation 1 was developed to allow comparisons across elements and determine when granular fertilizer particles attenuated the light:

$$X_F = \frac{X_O - X_B}{2048 - X_B} \quad (1)$$

where

X_F = count ratio
X_0 = measured real–time A/D output
X_B = average background A/D output per photodiode
2048 = reading at the zero–light condition (0 V = 2048 A/D counts)

The output range of the photodiode was –5 V to 0 V, representing full light to no light. With the gain setting used for the DaqBook/100s, –5 V registered 1 count, while 0 V (no light) registered 2048 counts. The test data transformed by equation 1 had an X_F range from slightly less than zero to one. Values of X_F were concentrated around zero and one with a majority having a value close to zero. The desired result of equation 1 would be to separate all data into values of either zero or one. However, due to light reflection or scattering, particles smaller than the sensing elements of the photodiode, reduced resolution of the exterior elements of the photodiode, and/or noise, the range of X_F included values between zero and one as well as some small negative values.

STATIC TESTS

The data obtained from tests with the three products and two blends were processed using equation 1. The average background A/D output (X_B) for each element was obtained by averaging all of the A/D output readings (X_0) for each photodiode element. This number provided a good representation of the background conditions during operation since, for the vast majority of the data intervals, the light incident on any one photodiode was not attenuated. This method of calculating X_B was able to account for changing conditions in the sensing chamber, such as fine particles creating a dusty environment or the optical window becoming contaminated.

The next step in algorithm development was determining where to threshold the count ratio (X_F) to indicate a particle passing between the light source and the photodiode element. Histograms of test data showed that values of X_F generally ranged between –0.4 and 1.1 (e.g., figs. 3 and 4). Negative X_F values could occur because changing conditions in the sensing chamber caused X_0 to be less than the A/D background output, but were most likely from noise in the circuit. The values of X_F >1 were due to noise in the circuit causing X_0 readings greater than the assumed value for zero light (the constant 2048 in eq. 1). After observing histograms for all static tests, a value of $X_F > 0.3$ was selected to represent a particle breaking the beam of light. This value approximated the point of transition between the near–zero peak and the relatively flat area in the center of the histograms where relatively few counts occurred. Since we wished to err on the side of counting all particles, the value of 0.3 was chosen instead of a value such as 0.5, which might have produced an equal number of missed and false particle counts. The histograms showed that the background data distribution was not centered exactly around zero, but rather around a negative number close to zero. It was thought that a value of $X_F > 0.3$ would catch all particles breaking the light beam, but not result in an excessive number of false counts.

The total number of counts for each static test run was plotted versus the mean measured mass flow rate (fig 5). There was a consistent, linear relationship between sensor counts and measured mass flow, with the exception of several

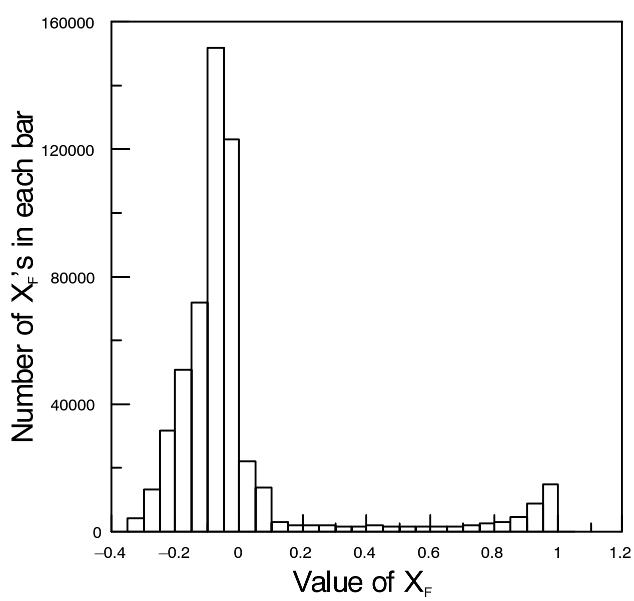

Figure 3. Histogram of TSP counts for a test run at 0.06 kg/s.

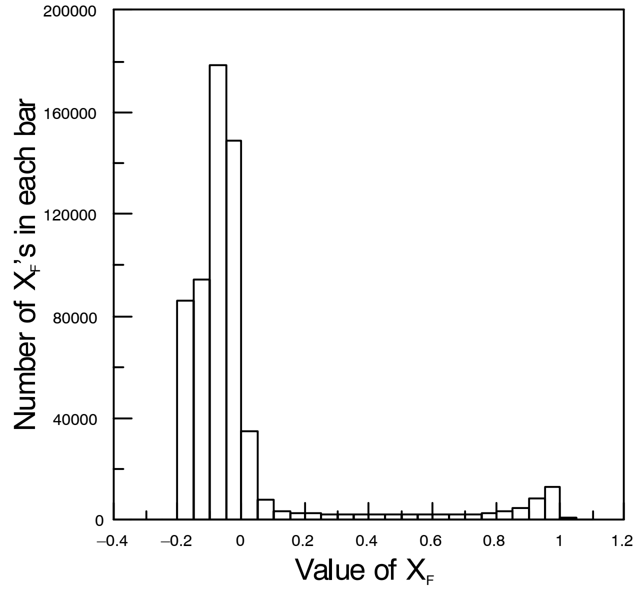

Figure 4. Histogram of AN counts for a test run at 0.05 kg/s.

tests at the two highest flow rates of KCL. This inconsistency could be due to the greater fraction of KCL particles <2 mm (table 2), causing more particles to be sensed even though the fine particles did not comprise much of the mass delivered. This larger percentage of small particles in the KCL, as compared to the TSP and AN, could have caused greater contamination on the windows and reduced resolution of the sensor system. Reduced resolution along with many more particles in the airstream could have caused more false counts of particles to occur only at the higher rates. Examination of raw data histograms showed that the chosen cutoff value of $X_F = 0.3$ was more likely to produce false counts in the high–flow KCL test runs, as opposed to the other tests.

Simple linear regression models were developed with the number of counts as the independent variable and measured mass flow rate as the dependent variable in the analysis. Strong linear relationships were found for all cases (table 3). Regressions for a single product or blend yielded better fits and lower standard errors than did a regression over all products and blends. This finding is consistent with Yan (1995), who suggested that a granular mass flow meter might need to be calibrated for individual products. When calibra–

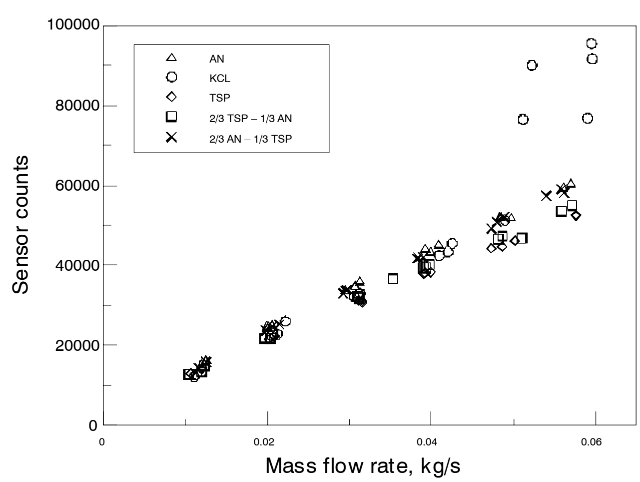

Figure 5. Static test results for all products.

tion equations were developed for single products or blends, standard errors were less than 10% of the minimum flow rate tested in all cases. With a single calibration, the standard error increased to approximately 25% of the minimum flow rate tested (table 3).

A covariance analysis for heterogeneity of slopes showed that the regression slopes for AN, KCL, and the 2/3 AN:1/3 TSP products were not significantly different. The regression slopes for TSP and the 1/3 AN:2/3 TSP products were significantly different from each other and from the three products above. To provide graphical confirmation of these results, 95% confidence intervals (CI) were calculated for each regression model. For example, figure 6 shows the overlapping CI bands for AN, KCL, and the 2/3 AN:1/3 TSP products. The similarity of calibrations between AN and KCL might be explained by their physical similarity in terms of color and average particle mass (table 1).

The 95% CI widths for the highest and lowest flow rates were calculated for each product and blend (table 4). The CI widths were smaller at the lower mass flow rates and increased as the mass flow rates increased. However, on a percentage basis, the CI width was greater at the lowest mass flow rate (in the 20% to 30% range), while the CI width at the highest mass flow rate was in the 5% to 10% range. These static test data showed that it was possible to obtain accurate mass flow data with the prototype sensor and data analysis method, when calibrated for a given product or mixture.

The ratio of regression slope to fertilizer product physical characteristics (table 1) was calculated. It was apparent that average particle mass had an effect on the slope of the regression (table 5). When the average particle mass changed, the slope of the sensor calibration also changed, producing roughly the same mass/slope ratio over all products. The density/slope and particle size/slope ratios were different among products, and thus particle density and size probably did not have a strong influence on sensor calibration.

Table 3. Regression analysis of static test data.

Product	r^2	Regression Slope	Regression Offset	Standard Error (kg/s)
TSP	0.998	1.194×10^{-6}	–0.0053	0.00062
KCL	0.894	5.680×10^{-7}	0.0101	0.00570
KCL (outliers removed)	0.996	9.852×10^{-7}	–0.0015	0.00075
AN	0.998	1.017×10^{-6}	–0.0047	0.00067
2/3 TSP – 1/3 AN	0.998	1.122×10^{-6}	–0.0040	0.00064
1/3 TSP – 2/3 AN	0.996	1.017×10^{-6}	–0.0044	0.00095
All data[a]	0.974	1.050×10^{-6}	–0.0034	0.00249

[a] With outliers removed from KCL data.

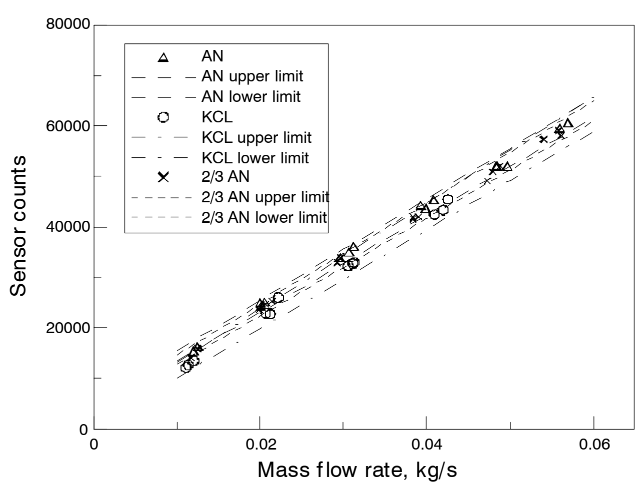

Figure 6. Confidence intervals (95%) for KCL, AN, and 2/3 AN:1/3 TSP blend.

Table 4. Width of 95% CI bands for individual products and blends.

Product	95% CI at 0.01 kg/s		95% CI at 0.06 kg/s	
	kg/s	%	kg/s	%
TSP	0.0019	18.5	0.0038	6.4
KCL (outliers removed)	0.0030	30.1	0.0061	10.2
AN	0.0021	20.5	0.0042	7.0
2/3 TSP – 1/3 AN	0.0029	29.2	0.0059	9.9
1/3 TSP – 2/3 AN	0.0020	19.8	0.0041	6.8

The number of particles that theoretically would have passed through the sensor in each static test was calculated from the average particle mass and compared to the average number of particles counted by the sensor over all replications (table 6). The number of counts determined by the sensor was lower than the calculated theoretical counts. As the mass flow rate increased, the difference between the actual and theoretical counts increased. Every particle moving through the sensing chamber did not break the beam of light because the particles closer to the light source would break the light beam first. Particles hidden by these closer particles would move past without being sensed. Therefore, when more particles passed through the sensing chamber, the proportion of uncounted particles would increase. Another cause of this difference in counts could be that the data analysis method did not differentiate between noise and particles breaking the beam of light.

Dynamic Tests

Dynamic test results for AN are shown in figures 7 and 8. The average background output (X_B) was calculated over the entire test run for each photodiode element. However, instead of summing the sensor counts representing the whole time period over which data was collected, the counts for the dynamic laboratory tests were calculated over two different time intervals, 0.1 s and 1 s. These shorter time intervals allowed the sensor to follow the changes in application rate rather than merely measure an average rate. Metering wheel shaft speed was also calculated over the same time intervals. The count data analyzed over the 0.1 s interval (e.g., fig. 7)

Table 5. Ratios of fertilizer physical characteristics to regression slopes.

Ratio	TSP	KCL	AN
Mass/slope	21.84	22.93	22.65
Density/slope	784.29	952.73	758.82
Particle size/slope	2.35	2.70	3.09

Table 6. Observed counts as a percentage of theoretical counts.

Rate (kg/s)	TSP (%)	KCL (%)	AN (%)
0.01	55.8	44.4	55.9
0.02	46.0	41.4	52.7
0.03	42.8	40.4	43.9
0.04	41.1	39.1	42.4
0.05	40.1	39.6	41.5
0.06	39.5	39.4	40.9

followed the general trend of the shaft speed data, but included excessive noise.

The 1 s time interval removed additional noise from the data (fig. 8). At this time interval, the data followed the transients in shaft speed and tracked step changes in the application rate command. Additional fluctuations were seen in the sensor count data as compared to the shaft speed sensor data (fig. 8). These could have been spurious fluctuations resulting from insufficient averaging of the dynamic test data. However, these fluctuations could really exist in the mass flow rate, but not in shaft speed. Fluctuations in mass flow not attributed to shaft speed could be due to worn metering wheels or fertilizer caking, resulting in the metering wheels not delivering the full amount per revolution. An independent dynamic measurement of mass flow would be required for definitive evaluation of sensor dynamic performance.

The present methods of data analysis and sensor configuration were adequate to track changes in flow rate and had potential for measurement of changing mass flow rates. Of the two time intervals used in this analysis, a 1 s time interval was better at smoothing fluctuations in the optical sensor data and producing useful information. Additional longer–duration dynamic tests are needed to better quantify dynamic performance of the sensor.

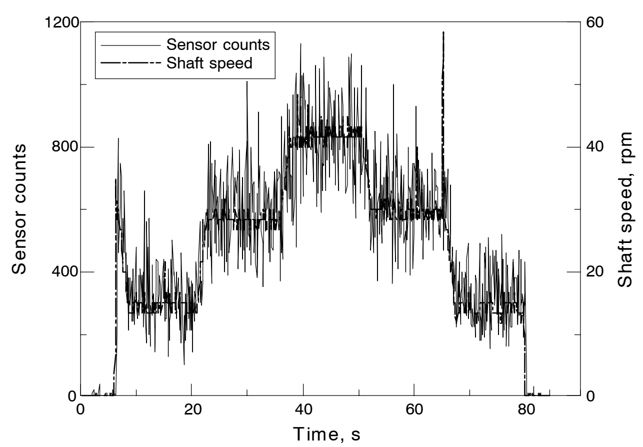

Figure 7. Dynamic test results for AN with counts summed over a 0.1 s interval.

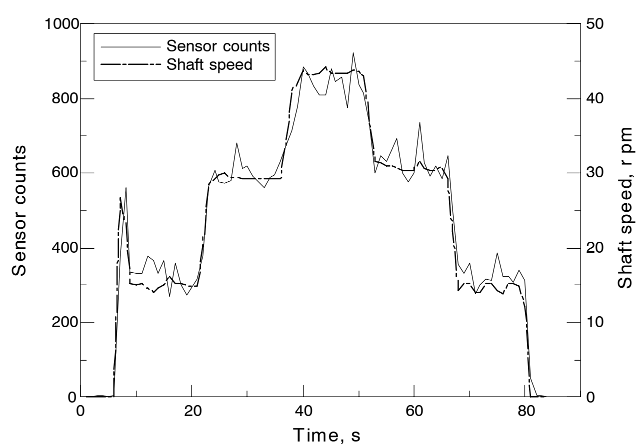

Figure 8. Dynamic test results for AN with counts summed over a 1 s interval.

The reuse of fertilizer material during the dynamic tests may have been the source of some variation, with mechanical damage due to repeated metering creating more fine particles. Such variation did not significantly affect the qualitative dynamic tests reported here, and fertilizer was not reused in the quantitative static tests. However, in a more quantitative dynamic analysis, it would be important that new fertilizer material be used for each test, minimizing any differences in particle size distribution and reducing the potential for resulting changes in sensor output.

SUMMARY AND CONCLUSIONS

A prototype optical sensor to measure the mass flow rate of granular materials was designed and built in the laboratory. A laser line generator and a 32–element photodiode array were used as the primary components. The sensor was installed on one delivery tube of a Gandy–Orbit Air fertilizer applicator for static and dynamic laboratory tests. Five products, consisting of three fertilizers and two fertilizer blends, were tested. Triple super phosphate (TSP), potash (KCL), and ammonium nitrate (AN) were chosen because of differences in shape, color, average particle size and mass, and because they are widely used in production agriculture. The mixtures tested were 2/3 TSP:1/3 AN and 1/3 TSP:2/3 AN. Each product was tested in a randomized block design with three replications of six treatments (mass flow rates) comprising the block. The data were processed and sorted based upon a ratio threshold value to determine when the light beam was attenuated by a fertilizer particle traversing the sensing chamber. The sorted data was then correlated to the measured average mass flow rate.

The trapezoidal shape of the sensing chamber was a concern before testing began. When dealing with pneumatic delivery systems, any pressure drops in the system could cause the delivery of the product to be erratic and/or inaccurate. However, in the laboratory tests, fertilizers flowed though the sensing chamber consistently.

In static laboratory tests, sensor output was linearly related to mass flow rate. The linear relationship was very strong (r^2 = 0.98 to 0.99) for all individual fertilizer products and mixtures, except KCL. Outliers in the KCL data at high mass flow rates suggested that a different choice of threshold value in the processing algorithm might be needed for KCL.

In dynamic tests, the sensor output tracked step changes in fertilizer application rate. Fluctuations were seen in the sensor output that were not seen in the metering wheel shaft speed. This may have been due to actual variability in the application rate or to problems with the data analysis techniques.

Overall, the sensor performed well in experiments and was able to non–intrusively measure the mass flow rate of granular fertilizers. Individual calibration will be needed for each fertilizer to obtain the greatest accuracy. A comparison of average particle mass and regression slope indicated that average particle mass affected the calibration more than the product type, density, or average particle size.

Improvements in the current prototype and methodology would be needed to develop a commercially usable real–time granular fertilizer mass flow rate sensor. A revised method of data acquisition and processing is needed to reduce file size, which is currently about 4 Mb/min. In addition, sensor hardware design alternatives should be considered to reduce complexity and cost. More testing of the sensor under varying fertilizer product flows and in field conditions is needed. With such improvements, the sensor system has the potential to aid researchers and producers alike in managing and applying fertilizer inputs using variable–rate technology.

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