Uniformity of Distribution of Anhydrous Ammonia into Shelled Corn in a Continuous Ammoniator

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Abstract. *Cost-effective recovery of non-fermentable, insoluble parts of the corn kernel before fermentation may increase the efficiency of fermentation and lower the overall cost of producing ethanol fuels. Treating whole corn with ammonia gas may weaken the physical structure of the kernel, and improve grinding and separations sufficiently to make fractionation of the non-fermentable components of the kernel cost-effective. The quick and even distribution of a controlled amount of ammonia into a batch of corn is problematic because the absorption of ammonia is rapid and exothermic. A device to continuously and evenly treat 2.3 kg/min (5 lb/min) of corn with ammonia gas (1000 mg N per kg corn) was designed, built, and tested. Ammonia was trapped and recycled within the treatment section of the ammoniator by feeding continuous streams of buffer solution and air flowing counter-current to the corn through the device. The kernel residence time in the treatment section was approximately 8 min. An assay for the ammonia content of individual corn kernels was developed, and the standard deviation among kernels from samples of ammoniated corn showed that ammonia was much more evenly distributed in the continuous ammoniator than in a bench-scale batch ammoniator.*

Keywords. *Ammonia, Corn, Fuel ethanol, Kernels.*

The current supply of transportation fuel in the U.S. includes more than 2% of ethanol produced from corn by fermentation. Like its alternative, methyl tertiary butyl ether (MTBE), ethanol increases the octane number and oxygen content of gasolines, so they burn more cleanly. Ethanol production is expected to double to approximately 30 billion L (8 billion gal) per year by 2012, in part because of new state and federal laws limiting the use of MTBE and requiring the use of renewable fuels. Coproducts contribute significantly to the profitability of the fuel ethanol industry. In corn wet milling, the main product, starch, is separated from coproducts such as corn germ, corn gluten meal, and corn gluten feed. Edible corn oil is obtained from the germ, while starch can be converted to glucose using enzymes and to ethanol by yeast fermentation. In the dry-grind fuel ethanol industry, coproducts such as distillers' dried grains with solubles (DDGS) and carbon dioxide are obtained after the enzymatic and fermentative conversion to ethanol of the starch in whole ground corn. Current research is directed toward recovery of more valuable coproducts in the dry-grind process. Separation of the germ containing valuable corn oil and the non-fermentable hulls (pericarp) will enable more efficient fermentation of the remaining endosperm containing the fermentable starch (Taylor et al., 2001).

In processing of other grains such as wheat and oats, the hulls can be removed, purified, and sold as bran. Alkali debranning is accomplished by immersing the grain in hot caustic solution to loosen the hulls, followed by mechanical separation (Morgan et al., 1964). Strong alkali solutions have been shown to improve the recovery of starch in corn wet milling (Du et al., 1999) and can be used to dissolve the hull away from corn kernels (Blessin et al., 1970). In the corn-to-ethanol industry, the use of anhydrous ammonia to loosen the pericarp may be preferable to the hot caustic method for a number of reasons. First, on a molar basis, ammonia is less expensive. Next, it diffuses into corn kernels much more rapidly than an aqueous solution (seconds instead of minutes). Anhydrous ammonia combines with the 15% moisture inside the kernel to form a strong base solution, and the high cost of disposing of spent caustic solution surrounding the kernels is avoided. Finally, corn is deficient in available nitrogen for yeast fermentation. Up to approximately 1000 mg available nitrogen per kg dry grain has been shown to increase the rate of ethanol production by fermentation (Thomas and Ingledew, 1990). Ammonia can supply this nitrogen requirement. Pretreatment with ammonia using only the amount needed to improve fermentation rates can improve grinding and separation of the components of the kernel (Taylor and Singh, 2003).

Treatment of corn with a limited dose of ammonia is difficult, because the absorption of anhydrous ammonia by corn is extremely rapid and exothermic (Taylor et al., 2003; Taylor and Singh, 2003). When attempting to evenly distribute small amounts of anhydrous ammonia into corn in

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a bin or silo, hot spots can form and move about (Lancaster et al., 1974). Described here are the design, construction, and testing of an atmospheric-pressure continuous corn ammoniator that can evenly distribute ammonia into a stream of corn.

The primary objective of the work described here was to compare the uniformity of distribution of ammonia in a bench-scale batch reactor with that in a continuous pilot-scale ammoniator. Measurement of the ammonia nitrogen in individual kernels from a sample of ammoniated corn could provide a way to evaluate both the amount of ammonia delivered to the kernels (average) and the uniformity of the treatment (standard deviation). Nitrogen in corn is usually measured by Kjeldahl or other total nitrogen methods, and expressed as protein (6.25 × Kjeldahl N), but the amount of ammonia nitrogen added here is small compared with the amount of protein nitrogen already present in the corn. For fermentation mashes, the free amino nitrogen (FAN) method measures the amount of organic nitrogen available for yeast nutrition (ASBC, 1992). Although sensitive to ammonium ions, the FAN method is subject to interference by soluble organic amino compounds in corn. In the present work, a new method to measure ammonium nitrogen in individual corn kernels was developed. The ammonia content of individual kernels from samples of untreated and treated corn was measured. The standard deviation among individual kernels from a sample of treated corn was taken as a measure of the uniformity of distribution of ammonia into corn.

Materials and Methods

Yellow dent corn was obtained from a local feed mill. Moisture was determined, and 800 g were loaded into a bench-scale batch ammoniator. As previously described (Taylor et al., 2003), the reactor was evacuated, filled with anhydrous ammonia, and flushed with air. The treated corn, containing approximately 1 g of ammonia nitrogen per kg of corn, was emptied into 800 mL of phosphate buffer solution (19 g of monobasic potassium phosphate in 800 mL) to neutralize the ammonia and quench the reaction. In one experiment, to show that corn near the ammonia inlet absorbed more ammonia, a screen was inserted into the reactor to separate the lower 200 g of corn (near the ammonia inlet) from the upper 600 g. The upper portion was emptied into 600 mL of the same solution, and the lower portion was emptied into 200 mL. In this way, the effect of proximity to the gas inlet of the reactor could be determined. Ten minutes after quenching, 15 individual kernels were dried with tissue paper. Each was weighed, placed in a tared screw-cap vial with 25 mL of deionized water, and analyzed for ammonia nitrogen as described below.

The continuous ammoniation device (figs. 1 and 2) was approximately 3.7 m (12 ft) tall. The upper section was a stainless-steel cylinder 46 cm (18 in.) in diameter and 91 cm (36 in.) long with a converging conical section 51 cm (20 in.) long terminating in a 7.6 cm (3 in.) tri-clamp fitting. Below this was a standard 7.6 cm (3 in.) tri-clamp cross. Inserts in the horizontal legs of the cross (fig. 2) were closed off with

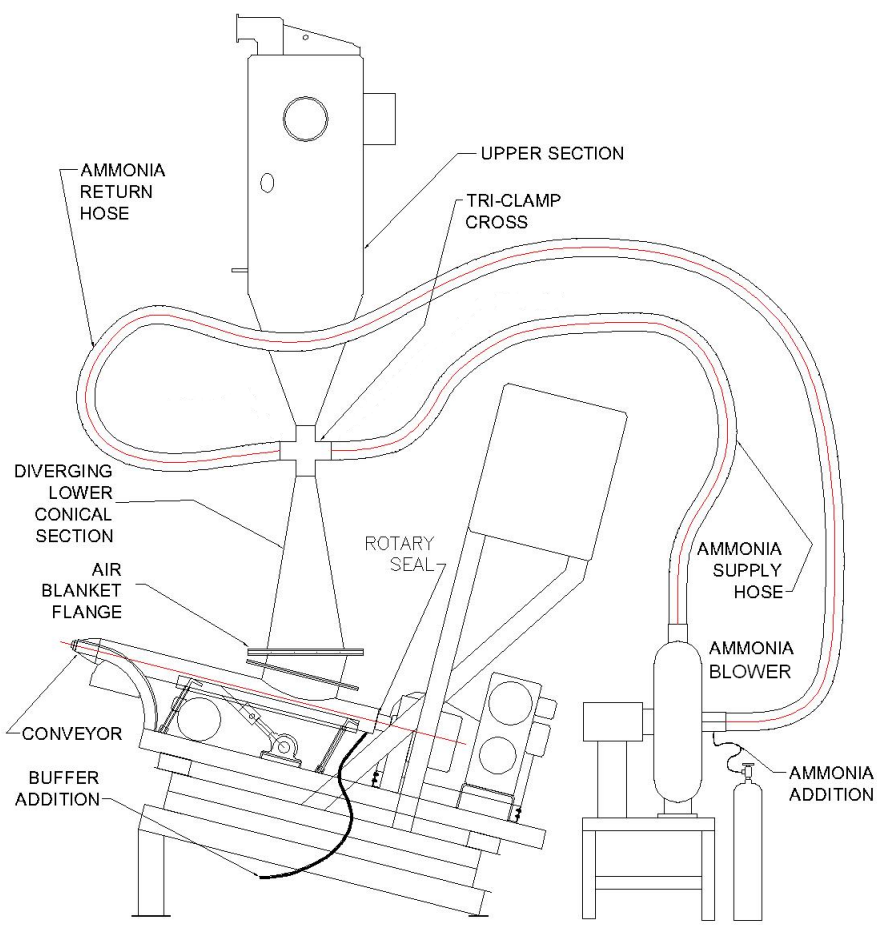

Figure 1. Drawing of continuous corn ammoniator.

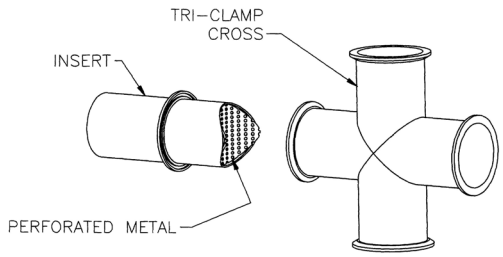

Figure 2. Detail of tri-clamp cross.

perforated metal, confining the descending kernels to a vertical cylindrical space.

The ammonia treating gas was circulated through the horizontal legs of the cross with a blower (model CMHP-4, Ceilcote, Cleveland, Ohio). The gas flow rate in the hose was measured using a hot-wire anemometer (model 9880, Alnor, Skokie, Ill.) inserted through and sealed to the hose wall. Ammonia was admitted at the suction side of the blower through a stainless-steel rotameter calibrated for ammonia and adjusted to 3.6 L/min, or approximately 1000 mg N per kg corn at a corn flow of 2.3 kg/min (5 lb/min). For safety purposes, a solenoid valve at the ammonia supply tank was set to automatically close if ammonia was detected in the room by an ammonia meter (model OWLC100ST2, International Sensor Technology, Irvine, Cal.).

Below the tri-clamp cross was a 71 cm (28 in.) long diverging conical section that terminated in a flange having 30 cm (12 in.) inside diameter. The circumference of this flange was drilled and tapped in 12 evenly spaced locations. Half of these penetrations were fitted to a manifold through which air was metered at 3.6 L/min. Denser than ammonia, air formed a stagnant layer or blanket just above the water level so that ammonia gas would not flow directly into the water. The counter-current flow of air and corn through the device recycled ammonia from treated corn to untreated corn above. The flow of air carried ammonia up above the tri-clamp cross, where untreated corn absorbed any remaining ammonia from the air before it exited the top of the ammoniator.

The other half of the air blanket flange penetrations were used for six thermistors that protruded just beyond the inside diameter of the flange. During ammoniation runs, the temperature at each of the six evenly spaced thermistor locations was recorded every 10 s with a datalogger (Analog, J-Kem Scientific, St. Louis, Mo.). Dissolution of ammonia in water is exothermic. Treatment of dry corn containing 15% moisture with 1000 ppm ammonia nitrogen raises the temperature of corn by approximately 2°C (Taylor et al., 2003). Recording the temperature rise around the circumference of the air blanket flange during ammoniation revealed whether corn was moving uniformly down all sides of the lower conical section.

The ammoniator was built on a Vibra-Portioner (Jeffersonville, Ind.) screw conveyor with a 76 cm (30 in.) long, 10 cm (4 in.) diameter barrel, which delivered approximately 2.3 kg/min (5 lb/min) of corn at the lowest speed setting. A stainless-steel flange, 30 cm (12 in.) inside diameter, was fitted and welded to the inlet of the screw conveyor. The screw conveyor was inclined with the discharge above the inlet end to allow the creation of a water trap in the barrel. The screw conveyor was fitted with a liquid-tight rotary seal at the driven end to keep the water out of the driving mechanism. Between the air blanket flange above and the screw conveyor inlet flange below, an elbow fabricated of 304 stainless steel compensated for the incline of the screw conveyor and allowed the upper sections to remain vertical.

When filled, the device held approximately 140 kg (300 lb) of corn. Of this, approximately 27 kg (60 lb) was below the tri-clamp cross. Of this, approximately 18 kg (40 lb) was above the water level. During runs 1 and 2, a buffer solution consisting of 1% monobasic potassium phosphate in water was delivered to the screw conveyor (fig. 1) with a peristaltic pump at approximately 2 L/min in run 1 and 1 L/min in run 2. During runs 3 and 4, the buffer concentration was increased to 4% monobasic potassium phosphate and the flow rate of buffer was decreased to approximately 190 mL/min. The buffer solution created a water seal, as described above. During runs 1 and 2, buffer solution overflowed with the corn and was collected with the corn at the screw conveyor discharge. During runs 3 and 4, the level of the water seal was below the screw conveyor discharge so that buffer solution did not overflow with the corn. The buffer solution feed was approximately 8% by weight of the corn feed, increasing its moisture from 12% to approximately 20%.

The ammoniator was loaded with either 90 kg (200 lb) (run 1) or 140 kg (300 lb) (runs 2, 3 and 4) of corn. During runs 3 and 4, an additional 45 kg (100 lb) was added after the start of the run. The moisture of the corn was 12% for all runs. Immediately before each of the four runs, the datalogger was started, and the buffer solution pump was turned on to create the water seal. A few minutes later, at time zero in figures 4 and 5, the screw conveyor, blower, and air and ammonia supplies were started. For runs 3 and 4, the ammonia gas feed was initially adjusted to a higher flow, approximately 10 L/min for approximately 1 min, and then decreased to 3.6 L/min. This helped to bring the ammoniator to steady-state operating conditions sooner in these two runs. Throughout each of the four runs, the airflow was maintained at 3.6 L/min. Feed of ammonia gas was continued for 20 min (run 1), 32 min (run 2), or 60 min (runs 3 and 4), and then stopped. Air was also stopped when the ammonia was stopped, while the screw conveyor continued to run until all the corn was removed from the ammoniator. At the time that the air and ammonia feeds were stopped, non-ammoniated corn remained in the upper section, preventing escape of ammonia gas from the top. All test methods are summarized in table 1.

During each run, the total flow rate (corn plus buffer solution) was measured, and the flow rate of corn was obtained by subtracting the previously measured buffer solution flow rate. During runs 1 and 2, samples of both corn and buffer solution were taken every 5 min (run 1) or 6 min (run 2). During runs 3 and 4, samples of corn were taken at 5 min and then at every 5 min from approximately 25 to 65 min. From each corn sample, nine individual kernels were selected and dried with tissue paper. Each kernel was placed in a tared screw-cap vial with 25 mL of either phosphate buffer solution (1% monobasic potassium phosphate) for runs 1 and 2 or borate buffer solution (1% boric acid) for runs 3 and 4.

The vials containing individual kernels from batch ammoniation, continuous ammoniation, or untreated corn were capped and placed in an oven at 80°C for 22 h. In the

Table 1. Summary of methods for ammoniation runs, where methods differed among runs.

	Run 1	Run 2	Run 3	Run 4
Purpose of test	To determine the uniformity of distribution of anhydrous ammonia into corn			
	To check operation and safety of process		To produce 100 lb batches of ammoniated corn	
Amount of corn (kg)	90	140	180	180
Run buffer				
Type	1% KH_2PO_4	1% KH_2PO_4	4% KH_2PO_4	4% KH_2PO_4
Flow (L/min)	2	1	0.19	0.19
Anhydrous ammonia flow (L/min)				
During first minute	3.6	3.6	10	10
After first minute	3.6	3.6	3.6	3.6
Duration of ammonia flow (min)	20	32	60	60
Sampling of corn	Every 5 min from 0:07 to 0:38	Every 6 min from 0:02 to 0:51	Every 5 min from 0:30 to 1:05	Every 5 min from 0:25 to 1:00
Assay				
Method[a]	Phenolhypochlorite	Phenolhypochlorite	Timberline	Timberline
Buffer	1% KH_2PO_4	1% KH_2PO_4	1% borate	1% borate

[a] Method changed because assay of samples took more than one week with phenolhypochlorite but less than two days with Timberline.

oven, the kernels swelled and split open, releasing absorbed ammonia and any water-soluble components of the endosperm and germ. Ammonium ion content in the buffer solution in each vial was then determined by one of two methods. Both methods were specific for ammonium ions and were not subject to interference by any known constituent of corn kernels. When the same corn kernels were analyzed by both methods, there was good agreement (fig. 3).

For samples from bench-scale batch ammoniation and from continuous ammoniation runs 1 and 2, an adaptation of the phenolhypochlorite method (Solorzano, 1969) was used. A 0.5 mL quantity of sample, water blank, or 2 mg/L nitrogen standard solution (ammonium chloride in water) was placed in a test tube, and 4.5 mL water was added. In a fume hood, 0.2 mL phenol solution (10 g phenol in 100 mL 95% ethanol) and 0.2 mL of 0.5% sodium nitroprusside solution in water were added with mixing. Oxidizing solution was made by mixing four parts sodium citrate solution (200 g/L in 1% sodium hydroxide) with one part hypochlorite solution (commercial bleach, at least 1.5 N hypochlorite). A 0.5 mL quantity of oxidizing solution was added to each tube and mixed. After 1 h, the absorbance at 640 nm was measured with a spectrophotometer. Standards and water blanks were run both at the start and at the end of each assay, and their averages were used to calculate the sample concentrations. Ammonia in each sample was expressed as mg N per kg dry corn. Standard error when measuring standard solutions of ammonium chloride was 1.3%. The standard error when measuring ammonium in individual corn kernels, estimated from the data in figure 3, was 34 mg NH_4 N per kg corn, or 6.1%.

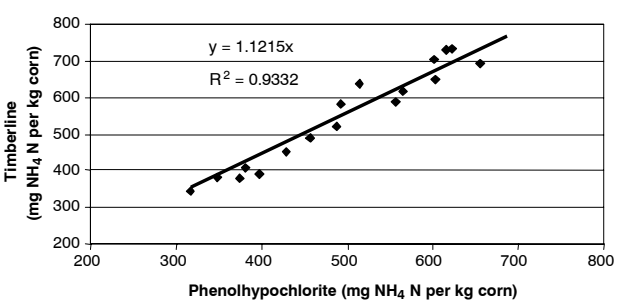

Figure 3. Comparison of two methods for measuring ammonia content of individual kernels. The same set of ammoniated corn kernels was measured by both methods.

For samples from runs 3 and 4, a flow-through ammonia analyzer (Timberline Instruments, LLC, Boulder, Colo.) was used to measure the ammonium ion in the boric acid assay buffer following 22 h incubation at 80°C. This method was chosen because a set of samples that required more than one week to analyze using the phenolhypochlorite method could be finished in two days with this instrument. The instrument is based on the diffusion-conductivity method (Carlson, 1978). This is similar to the ion-selective electrode method for ammonium (Love et al., 1992; Bremner and Tabatabai, 1972). In both methods, mixing the sample with a strong base solution causes ammonia to pass through a gas-permeable membrane. In the diffusion-conductivity method, ammonia passing through the membrane is dissolved in a buffer solution, and the increase in conductivity is measured in a temperature-controlled conductivity cell. Ammonia in each sample was calculated and expressed as mg N per kg dry corn. The standard error when measuring standard solutions of ammonium chloride was 1.6%. The standard error when measuring ammonium in individual corn kernels, estimated from the data in figure 3, was 38 mg NH_4 N per kg corn, or 6.8%.

Results and Discussion

Quenching had no effect on the ammonia content of untreated kernels (data not shown). As shown in table 2, treatment in the bench-scale batch ammoniator increased the ammonia nitrogen content of individual corn kernels from 87 mg per kg corn (untreated) to 375 mg per kg corn (treated). This does not include the ammonia that dissolved in the quench water. Ammonia in the quench water was also measured and amounted to approximately 750 mg N per kg corn (data not shown). The standard deviation of untreated kernels was much larger than the standard error of the assay and indicated the variation among individual corn kernels. The much larger standard deviation of treated kernels was due to very large values (over 1000 mg N per kg corn) for one or two out of 15 kernels. Those kernels most likely absorbed much more ammonia because they were close to the

Table 2. Ammonia nitrogen (mg per kg corn) in individual corn kernels, untreated and treated in bench-scale batch ammoniator. The high standard deviation for untreated samples is primarily due to natural variability of kernels. The high standard deviation for treated samples is primarily due to uneven distribution of anhydrous ammonia in the bench-scale batch ammoniator.

Sample	Average of 15 Kernels	Standard Deviation	
Untreated	68	9	13%
Untreated	76	14	18%
Untreated	118	34	29%
Average	87	19	22%
Ammonia treated	346	472	136%
Ammonia treated	358	327	91%
Ammonia treated	368	157	43%
Ammonia treated	426	395	93%
Average	375	338	90%

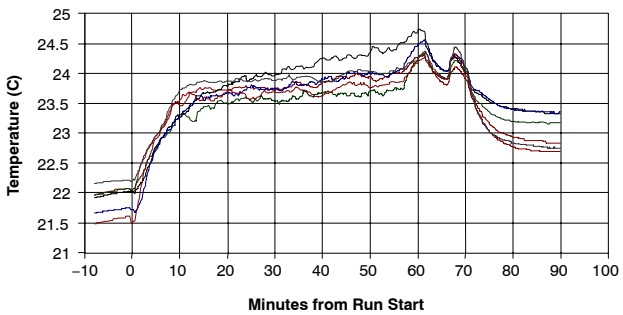

Figure 4. Temperature traces for six evenly spaced thermistors around the circumference of the air blanket flange.

ammonia inlet. In one experiment where a screen separated the lower 200 g portion of corn from the rest of the reactor, the average ammonia content for 15 kernels sampled from the bottom of the reactor was 674 mg per kg (772 mg per kg standard deviation) and 248 mg per kg (90 mg per kg standard deviation) for kernels sampled from the top. These data clearly show that kernels near the ammonia inlet absorbed much more ammonia than those far from the inlet, so that ammonia was not evenly distributed in a vertical direction, and consequently corn was not evenly treated in the bench-scale batch reactor.

For the continuous, pilot-scale reactor, the measured feed rate of buffer solution was 2.0 kg/min (4.4 lb/min) for run 1, 1.0 kg/min (2.3 lb/min) for run 2, and 0.19 kg/min (0.42 lb/min) for runs 3 and 4. The calculated corn flow rate was 2.1 kg/min (4.7 lb/min) for run 1, 2.3 kg/min (5.2 lb/min) for run 2, 2.3 kg/min (5.1 lb/min) for run 3, and 2.8 kg/min (6.1 lb/min) for run 4. The treating gas velocity at the center of the 7.6 cm (3 in.) circulating hose was approximately 76 m/min (250 ft/min) in all runs. The recirculating treating gas moved across the 7.6 cm (3 in.) moving column of corn in the tri-clamp cross in less than 0.1 s. In previous experiments (Taylor et al., 2003), it took more than 6 s for a similar amount of ammonia to be absorbed by corn in a batch reactor similar in volume to the cross. In these experiments, although the concentration of ammonia in air was not measured, the flow of gas through the corn was sufficiently rapid that the concentration did not change significantly from one side of the cross to the other. This was an important feature of the design, necessary to provide even distribution of ammonia into corn.

As shown in figure 4, the temperature profiles for the six thermistors stayed generally within 0.5°C of each other and indicated a temperature rise of approximately 2°C during the first approximately 10 min of each ammoniation run. This was the expected temperature increase from heat produced by the exothermic solution of ammonia in the moisture in the corn (Taylor et al., 2003). The thermistors then showed almost constant, though slightly rising, temperature profiles until the ammonia and air feeds were stopped. The temperature data show that the flow of corn was evenly distributed down all sides of the ammoniator.

Table 3. Ammonia nitrogen (mg per kg corn, dry basis) in individual kernels treated in continuous ammoniator, average and standard deviation of nine kernels at each sampling point. The average percent standard deviation for each run was consistent among the runs. The standard deviations were greater than for untreated kernels (table 2), but less than for ammoniated kernels treated in the bench-scale batch ammoniator (table 2), indicating that distribution of ammonia was more uniform in the continuous ammoniator.

	Time (hour:min)	Average of Nine Kernels	Standard Deviation	
Run 1	0:07	49	16	32%
	0:12	69	14	20%
	0:17	148	68	46%
	0:22	220	74	33%
	0:27	224	92	41%
	0:33	209	102	49%
	0:38	125	22	18%
	Average	−−	−−	34%
Run 2	0:02	67	20	30%
	0:15	86	26	31%
	0:21	157	75	48%
	0:27	255	62	24%
	0:33	350	99	28%
	0:39	395	77	19%
	0:45	297	39	13%
	0:51	129	38	29%
	Average	−−	−−	28%
Run 3	0:30	610	337	55%
	0:35	489	103	21%
	0:40	437	154	35%
	0:45	474	147	31%
	0:50	504	170	34%
	0:55	455	134	30%
	1:00	489	153	31%
	1:05	516	179	35%
	Average	497	172	35%
Run 4	0:25	307	58	19%
	0:30	476	306	64%
	0:35	530	302	57%
	0:40	325	25	8%
	0:45	507	289	57%
	0:50	534	167	31%
	0:55	401	103	26%
	1:00	390	129	33%
	Average	434	173	37%
Average of runs 3 and 4[a]		465	172	37%

[a] Averages were not computed for runs 1 and 2 because they were not steady-state data.

The ammonia contents of individual corn kernels (average and standard deviation of nine individual kernels at each sampling time) are shown in table 3. As shown in figure 5, during runs 1 and 2, the average ammonia content decreased in the last two samples in each run, because the ammonia and air supply were shut off while untreated corn remained in the upper section to prevent escape of ammonia to the room. Untreated corn (nine individual kernels sampled at 7 min in

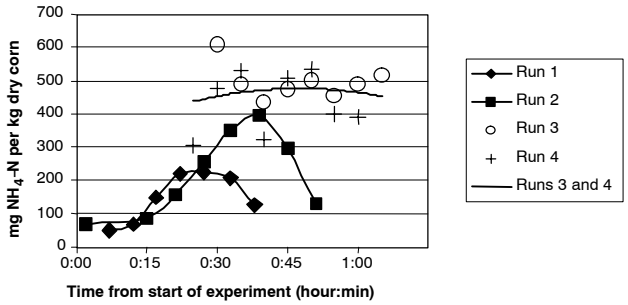

Figure 5. Ammonia data for individual kernels, average of nine kernels at each sampling point, all ammoniation runs.

run 1, at 2 min in run 2, and at 5 min in runs 3 and 4) had average ammonia contents of 49 mg N per kg corn with 32% standard deviation (run 1), 67 mg N per kg corn with 30% standard deviation (run 2), 88 mg N per kg corn with 9% standard deviation (run 3), and 57 mg N per kg corn with 9% standard deviation (run 4).

In run 1, the highest level of ammonia (sample at 27 min) was 224 mg N per kg corn (41% standard deviation). In run 2, the highest level of ammonia (sample at 39 min) was 395 mg N per kg corn (19% standard deviation). From runs 1 and 2, it could be concluded that more than 300 lb of corn should be processed in order to obtain at least 50 lb of evenly ammoniated corn. In run 3, the average of all samples from 30 to 65 min inclusive was 497 mg N per kg corn, and the average percent standard deviation among kernels, a measure of the uniformity of treatment, was 35% (table 3). In run 4, the average of all samples from 25 to 60 min inclusive was 434 mg N per kg, and the average percent standard deviation among kernels, a measure of the uniformity of treatment, was 37% (table 3).

The standard deviations in these experiments should not be interpreted as standard errors. Standard deviation here is primarily due to actual variation among individual kernels. For example, for non-ammoniated corn kernels, the standard error of the assay estimated from the data in figure 3 was only 6.1%, while the kernels had a significantly higher average standard deviation of 22% (table 2), indicating the natural variability among individual kernels. In addition, from table 2, the average percent standard deviation in ammoniated corn from the bench-scale batch ammoniator was 91%, compared with 35% and 37% in runs 3 and 4 (table 3). Because these standard deviations are much larger than the estimated standard error of the assay (6.1% for data in table 2 and 6.8% for data in table 3), the average percent standard deviations in these experiments can be taken as indicators of the relative uniformity of distribution of ammonia in the continuous ammoniator, as opposed to the relatively uneven distribution in the bench-scale batch reactor.

It can be concluded that the continuous ammoniator gave much more uniform distribution of ammonia and much more even treatment of corn than the bench-scale batch ammoniator. In the batch reactor, kernels at or near the bottom (ammonia inlet) absorbed much more ammonia than kernels at other locations. On the other hand, in the continuous ammoniator, the time for the blower to circulate the treatment gas across the tri-clamp cross (approx. 0.1 s) was much less than the time (greater than 6 s) for a similar amount of ammonia to enter into and be absorbed in the bench-scale batch reactor (Taylor et al., 2003). Further improvement in the uniformity of treatment may be possible through better control of the flow pattern of corn to achieve a narrow distribution of residence times of individual kernels.

Conclusions

A continuous ammoniator designed to safely, evenly, and reproducibly treat 2.3 kg/min (5 lb/min) of corn with approximately 0.1% (1000 mg N per kg corn) of anhydrous ammonia was successfully tested. Treated corn containing absorbed ammonia (approx. 400 mg N per kg corn) was reliably produced while anhydrous ammonia amounting to approximately 1000 mg N per kg corn was supplied to the device. The remainder of the supplied ammonia was contained in buffer solution that either overflowed from the ammoniator outlet along with the treated corn or was contained within the ammoniator. Ammonia was much more evenly distributed into corn in the continuous ammoniator than in a bench-scale batch reactor, as indicated by the standard deviation of the ammonia content of individual treated kernels.

Approximately 70 kg (150 lb) of uniformly treated corn was produced within 1 h using this device. Application of the continuous ammoniator to facilitate fractionation of corn before fermentation in a dry-grind ethanol plant has the potential to lower the production cost of fuel ethanol.

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