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Field evaluation of anhydrous ammonia manifold performance and variability

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Abstract. Experiments conducted between August 1999 and April 2002 evaluated anhydrous ammonia (NH_3) manifold distribution during field application at 84 kg N/ha and 168 kg N/ha application rates. Conventional, Vertical-Dam, Rotaflow™, Equa-flow™, FD-1200 prototype, and a new prototype manifold named the Impellicone were evaluated. At the 84 kg N/ha rate, all manifolds tested had significantly lower application variation than the conventional manifold. At the 168 kg N/ha rate the conventional, Vertical-Dam with a corn ring and the FD-1200 prototype had significantly higher application variation than the other manifolds tested.

Analysis of temperature and pressure data indicated that NH_3 flowing through the system very closely follows the saturation line. Predictions of NH_3 quality assuming saturated conditions would be would be acceptable. Investigation for correlation between coefficient of variation (CV) and air temperature or percent of volume in the vapor phase of NH_3 resulted in only a significant correlation between CV and percent of volume in the vapor phase of NH_3 for the conventional manifold.

Conclusions suggest that replacement of a conventional manifold with a Vertical-Dam manifold or any of the other manifolds tested could reduce application variation, and as a result reduce application rate by eliminating the need for over-application to compensate for variations.

Keywords. Anhydrous ammonia, nitrogen, fertilizer, manifold, distribution, applicators

Introduction

Over the past half century, NH_3 use has increased drastically. In 1999, 687,333 tons of NH_3 were applied to Iowa farm fields and accounts for 40% of the nitrogen (N) fertilizer applied (Sands, 2000). Applicators used in Iowa corn production use five to 19 shanks and employ up to two manifolds for distribution. While it was noted by Andrews (1947) that the uniformity of NH_3 application was better than the granular application, advancements in both non-pressure liquid and solid fertilizer application techniques have left NH_3 as an application source with wide variability of application rates from one knife on the applicator to the next.

Variations in application rates with NH_3 have resulted in concerns about possible water quality issues associated with over application of N. Jaynes et al. (2001), found that of three rates on N application ranging from 57 kg N/ha to 202 kg N/ha (51 to 180 lb N/ac), only for the lowest application rate for the years when soybeans were grown in a corn/soybean rotation did the concentrations in drainage water not exceed the U. S. EPA limit of 10 mg NO_3-N/L. For all years of the study, the mass of N lost at the high rate was significantly higher than the amount lost at the two lower rates. Karlen et al. (1998) found that during a four-year study in Iowa, over a wide range of N application rates, tillage practices, and application times, 50% of the applied N was available for leaching, denitrification, and/or NH_3 volatilization. Major factors supplying NH_3 to the groundwater baseflow were high levels of residual NO_3-N following continuous corn production and precipitation that was not taken up by the plant but percolated below the root zone. According to the research, the most successful management strategies to reduce offsite NO_3-N movement will be those that minimize residual NO_3-N remaining in the soil at the end of the growing season. Dinnes et al. (2002) suggested that strategies for reducing NO_3-N loss through subsurface drainage include the correct timing of N application at appropriate rates, and optimizing N application techniques.

Hedman and Turner (1954), after evaluation of NH_3 regulator and flow controlling devices noted that there was room for greater improvement in distributor (manifold) performance than could be achieved with improved total flow control. Morgahan (1980) concluded that evaluating NH_3 applicator performance by changes in field tank weight was not adequate for research work. He suggested that the distribution of NH_3 among outlets should be checked. Weber et al. (1995) studied the regulator/controller as the source of variation. Results found that over half of the producers used the measured weight difference of the field tank over a known area as the method of calibration.

Hanna et al. (2002) found that when comparing the Vertical-Dam manifold to the conventional manifold, port to port variability was less for the Vertical-Dam at the 56 kg N/ha (50 lb N/ha) application rate but produced similar variability at the 112 and 168 kg N/ha (100 and 150 lb N/ac) rates. NH_3 exiting individual ports on the manifold typically varied 10 to 20% from the mean application rate, with the highest port flow 150 to 250% of the lowest port flow.

Boyd et al. (2000) found improved performance with the Vertical-Dam over the conventional manifold. The new Rotaflow™ manifold performed very well, with coefficient of variation (CV) values between five and seven percent.

Schrock et al. (2001b) tested conventional and Vertical-Dam manifolds for distribution variation. Results showed a lower CV for the conventional manifold with a bottom inlet than a top inlet. The use of smaller diameter manifold hose barbs resulted in higher pressure with the conventional manifold but did not noticeably affect uniformity of distribution. Higher manifold pressure resulted in less variation due to varying outlet hose lengths. Schrock et al. (2001b) also investigated trends between CV and percent vapor, specific volume, inlet velocity, manifold pressure, and knife tube pressure. Only a correlation between inlet velocity and CV was observed when small diameter hose barbs were used with the Vertical-Dam or top inlet conventional manifold.

Krantz et al. (1994) suggested that distribution accuracy to individual knives is improved by minimizing the amount of NH_3 vapor in the manifold They recommended improving distribution by limiting the outlet orifice size at the manifold to increase pressure at the manifold. The difficult error to measure is the knife-to-knife outlet variation and suggest the only way to accurately determine distribution uniformity among knives is to do a water-can test.

The water-can type test was used by Hanna et al. (2002), Schrock et al. (2001a), Schrock et al. (2001b), and Boyd et al. (2000). This test used a container of water that was weighed before the application, NH_3 was applied through a knife or outlet into the container forming aqua ammonia, and the resulting mixture weighed to determine application rate.

Schrock et al. (2001a) defined the application system of NH_3 as follows: Because NH_3 enters the application machine from a pressurized tank, it typically enters the transfer hose as a saturated or slightly super cooled liquid. As it moves through the hose to the metering component, its pressure is reduced slightly by line friction. The pressure reduction leads to the vaporization of a portion of the NH_3, producing a two-phase mixture. At the meter inlet, the amount of NH_3 vapor produced by line pressure loss is usually small on a mass percentage, but it can be significant on a volume basis. As the NH_3 continues through the system, its pressure is reduced greatly by the NH_3 meter, resulting in over 90% of its volume commonly occupied by vapor. Therefore the challenge for the manifold is to divide the meter output as equally as possible into multiple outlets.

From previous studies, the following objectives were set for this research:

1. To determine the ability of the commonly available conventional and Vertical-Dam manifolds to uniformly distribute NH_3 during field application.
2. To determine the ability of other manifold designs available at the time of the research to uniformly distribute NH_3 during field application.
3. To test an alternative design such as a high pressure system or modifications to existing manifold cavities to improve NH_3 distribution during field application.
4. To design and evaluate a new low pressure manifold incorporating knowledge gathered in this research to further reduce variation during field application.
5. To examine any correlation between NH_3 quality, vapor partitioning, temperature effects, and application variation.
6. To disseminate project results to applicators and improve application techniques.

Materials and methods

Seven experiments were conducted between August 1999 and April 2002 to evaluate manifold distribution uniformity of NH_3 during field application. The experiments were on fields of the Iowa State University Agronomy and Agricultural Engineering Research Center near Boone, IA. Each experiment compared distribution of NH_3 manifolds by measuring the amount of NH_3 exiting each manifold outlet during a fixed application time.

Test apparatus and conditions

A detailed description of the test equipment and procedures can be found in Boyd (2002) and Hanna et al. (2002). A three-point mounted NH_3 applicator (DMI model 3250, Goodfield, IL) was configured for application by 11 knives (Figure 1).

Figure 1. NH_3 applicator used for all experiments

The NH_3 distribution system of the applicator was modified by inserting a pipe tee connection in each distribution line downstream from the distribution manifold. Each downstream side of the tee was connected to a 12.7-mm (0.5-in) ball valve. Tees and ball valves had 12.7-mm (0.5-in) pipe thread connections. Hoses directed the flow from one of the valves to the subsurface application knife and from the other valve to a collection container. The two valves at each tee connection were connected to a cable such that as the cable was pulled in one direction, the valve to the knife would close and the valve to the collection container would open. Pulling the cable in the opposite direction opened the valve to the knife and closed the valve to the collection container. The operating cable was attached to the valve assemblies of all 11 distribution hoses from the manifold outlets. A lever and pneumatic cylinder actuated by compressed air allowed an operator to simultaneously redirect flow from all 11 knives to 11 corresponding collection containers. Operating the cylinder in the opposite direction directed flow back to the 11 knives.

Application rates selected were 84 and 168 kg N/ha (75 and 150 lb N/ac). A variable orifice regulator (Continental Model 4103) was adjusted for tank pressure and ambient temperature to provide the N application rates as closely as possible. In an effort to more accurately meet experiment application rate goals, and allow for data logging equipment mounting on the regulator, a Nitropacer flow meter/regulator (CDS John Blue Co., Huntsville, AL, #A-3300-H) was used to meter NH_3 flow starting with the November 2000 experiment.

The collection container used for each outlet was a 19-L (5.0-gal) plastic container sealed on top with a lid. A Banjo-type quick-coupler fitting attached by stainless steel cam arms was used to attach the collection hose at the bunghole of the container. A 12.7-mm (0.5-in) diameter polyvinyl chloride (PVC) pipe attached at the bunghole extended down into the container to within 25.4-mm (1.0-in) of the bottom and was capped on the end. A single hole, equal in size to the outlet orifice on an application knife was drilled near the bottom of the pipe cap to allow entry of the NH_3 into the water. Two sets of 11 collection containers (A and B) were constructed and numbered 1A through 11A and 1B through 11B, respectively. A frame was constructed of steel, wood, and PVC pipe to carry the containers on the applicator. The containers were connected to the applicator one complete set at a time (A or B) and container numbers always corresponded to the same manifold distribution outlet and knife (left-to-right across the applicator). Containers were partially filled with water and later emptied of ammonia/water solution by removing a cap from the second bunghole so that container lids did not have to be removed. Outlet #1 on the manifold, located at 0° (in the direction of travel), was consistently plumbed to deliver NH_3 to container #1.

Application plots were arranged in the field as a randomized complete block with three replications of each treatment. Plots for treatments were randomly located in terrain that ranged from 0 to 5 percent slope. Most plots were 0 to 3 percent slope with the travel direction roughly perpendicular to slope contour.

A standard 3785-L (1000-gal) field tank towed behind the applicator provided the NH_3. A single axle utility trailer towed behind the field tank carried the air cylinder for the pneumatic control valve and a portable generator for the electric solenoid controlling the pressure switch, and provided space for the system operator to ride and operate the flow switch. A 9.5-mm (0.38-in) hose connected into a blank outlet on the manifold was connected to a pressure gage on the trailer and used to measure manifold pressure through March 2000. The operator riding on the trailer recorded tank pressure, manifold pressure, and operated the air cylinder to re-route flow to the collection containers for a specific time period.

Applicator travel speed was 8 km/h (5 mi/h). Plots were a minimum of 64-m (210-ft) long. Collection times were adjusted based on the application rate to collect an anticipated average of 0.3 to 0.5-kg (0.7 to 1.1-lb) of NH_3. Before each application, each manifold was operated for a short period of time to cool it to operating temperature. At the beginning of each test run, the tractor operator opened the regulator and allowed NH_3 to flow into the ground for approximately 10 sec before the system operator switched flow to the collection containers. This allowed NH_3 to flow through all lines and equilibrate to field operating conditions. Manifold temperature was checked immediately prior to testing with an infrared thermometer and throughout the run with thermocouples starting with the November 2000 experiment. This tested the manifold's ability to distribute NH_3 at temperatures near those encountered in field operations. Containers were weighed in the field before and after plot application within 10-min of application. Actual weight of NH_3 delivered from each outlet was determined gravimetrically.

Because NH_3 is a hygroscopic or water-seeking compound that can cause caustic burns, safety equipment was worn by those working anywhere in the vicinity of collection containers and applicator.

This equipment included unvented goggles, long rubber gloves, and long-sleeved clothing and long pants. Emergency water dispensers were on the application equipment and a livestock tank of water was placed near the measuring site for emergency immersion. In addition, a respirator with NH_3 cartridges was worn at all times by the valve operator and by other workers when conditions warranted. Whenever the applicator moved from a plot to the centralized weighing area, the main tank supply valve to the applicator was closed and the regulator opened to purge the system of any remaining NH_3.

Manifolds tested

To test manifolds during a limited set of temperature and field conditions, the number of manifold configurations to be tested for each experiment was limited to a maximum of six. An attempt was made to test each manifold for a minimum of three experiments. This allowed for a range of field and weather conditions affecting the temperature and pressure of NH_3.

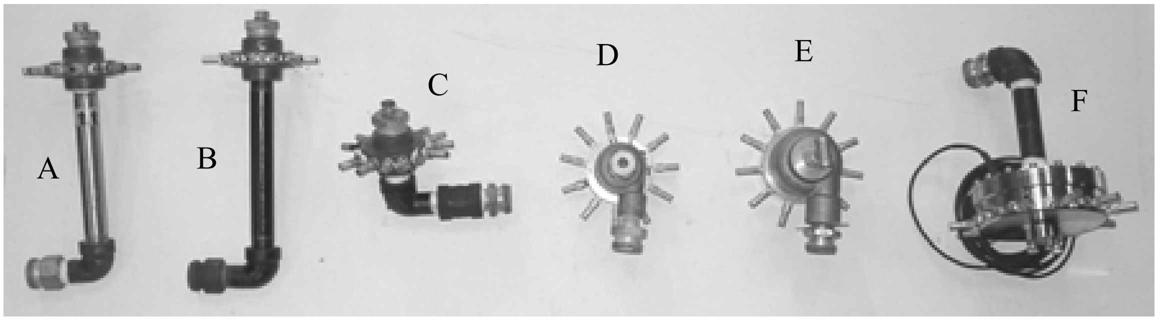
The August 1999 experiment compared conventional, Vertical-Dam, and Cold-flo® manifold designs using both 7- and 11-outlet manifold configurations. The conventional manifold (Continental NH_3 Model 3497, Dallas, TX) had spaces for 14 outlets with 9.5-mm (0.38-in) female pipe thread (FPT) connections. Hose barbs that were 9.5-mm (0.38-in) outside diameter and 7.1-mm (0.28-in) inside diameter were evenly spaced in the outlets and the remaining outlets were plugged. Flow entered the conventional manifold directly from below via a 25.4-mm (1.0-in) diameter 254-mm (10.0-in) long steel pipe nipple. The Vertical-Dam manifold (Continental NH_3 Products, Dallas, TX) used either 7- or 11-outlet distribution rings and manifold housings suggested by the manufacturer for each distribution rate. For the 84 kg N/ha (75 lb N/ac) application rate, a MVD housing was used with a SM:12”=165#N/acre ring. For the 168 kg N/ha (150 lb N/ac), application rate an SVD-01 housing with an R-152 cotton ring was used. The MVD housing and SM ring were also evaluated at the 168 kg N/ha (150 lb N/ac) application rate. Although this application method is not recommended by the manufacturer, it was investigated as a method to increase manifold pressure and the amount of NH_3 present in the manifold as liquid. The Cold-flo® system used a Cold-flo® system 16 #20340 canister and separate 16 outlet distribution manifolds for NH_3 liquid and NH_3 vapor. For the conventional and Cold-flo® manifolds, plugged (unused) outlets were spaced as evenly as possible around manifold. Outlet hoses were connected in order sequentially counterclockwise around each manifold as viewed from above. The outlet for knife one on the left end of the applicator was always at a position of 0° when viewed from above (0° was the direction of travel). In this manner, the location of distribution outlets was able to be determined relative to input flow into the manifold assembly.

In order to reduce back pressure for the Cold-flo® manifold, it is recommended to use 12.7-mm (0.5-in) hose. For this experiment, 12.7-mm (0.5-in) hose and hose barbs were used from the manifold to the valve assembly, but 9.5-mm (0.38-in) hose was used downstream from the valve assembly (12.7-mm or 0.5-in. reducer was used to connect the 9.5-mm (0.38-in) hose to the liquid inlet on each distribution knife). The smaller hose was used to avoid longer times for changeover between manifolds being tested and re-plumbing of connections into the collection containers. Pressure loss calculations from fluid mechanics indicated that most pressure drop would be at the valve assembly and that using smaller 9.5-mm (0.38-in) hose beyond that point would contribute little to pressure loss. For the Cold-flo® manifold, equal lengths of 12.7-mm (0.5-in) hose were used from the vapor distribution manifold to the vapor inlet on each knife. Because only one set of 11 valve assemblies was available to measure distribution, only the liquid phase of distribution was measured. The Cold-flo® manifold was mounted to the applicator by a mast provided by the manufacturer to maintain a fixed elevation above the outlets.

Treatments were a factorial combination of the number of manifolds tested, two application rates, and number of outlets used. (i.e. each manifold was operated three times at each of two application rates).

For the November 1999 experiment the conventional manifold was used with minor modifications. In addition to the design used in the August experiment (straight-entry), the manifold was also used with only a 25.4-mm (1.0-in) elbow (elbow-entry). The 254-mm (10.0-in) long nipple was also replaced with a 316 Stainless steel nipple of the same length with a Teflon™ coated static flow mixer (Omega Part No. FMX8413T) in the nipple (mixer-entry). In addition to the two Vertical-Dam manifolds, a Rotaflow™ (H.I. Fraser Pty Ltd, Sydney, Australia) manifold was added with the 11 outlet ports evenly spaced in the 24 outlet housing.

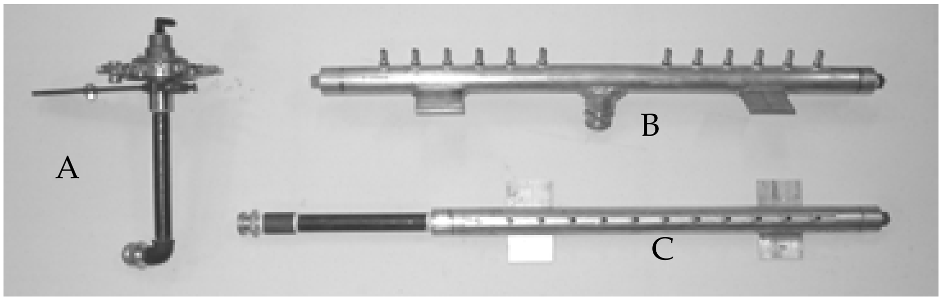
To compare distribution characteristics within the conventional manifold, a treatment was added with all three blocked ports together on the far side of the manifold across from the direction of the incoming flow (uneven plugs) using the elbow entry conventional manifold. Figure 2 shows some of the manifolds used in the November 1999 experiment. For the November experiment and all subsequent experiments, all tests were run with 11 manifold outlets and knives.



A) 3497 w/mixer B) 3497 w/nipple C) 3497 w/ elbow D) Small Vertical-Dam E) Large Vertical-Dam F) Rotaflow

Figure 2. Manifolds used in the November 1999 experiment

For the spring of 2000, the conventional (elbow-entry) was retained for its use as the “control” manifold due to its widespread use on current applicators. Because of concerns about flow metering due to small orifice size for the small housing Vertical-Dam at the 168 kg N/ha (150 lb N/ac) application rate, this treatment was dropped from subsequent experiments. As a replacement, the large housing (SVD-01) Vertical-Dam was tested using the common ‘corn’ ring, and the large housing Vertical-Dam with the ‘cotton’ ring (Continental NH_3 Products #R-152) treatment continued. The ‘cotton’ ring contained smaller outlet orifices that the ‘corn’ ring but larger ones than the small housing Vertical-Dam ring. Two manifolds were designed and tested by the research group to determine if the radial manifold designs or linear manifolds should be given continued consideration. They were the side-entry and the tee-entry manifolds. Each manifold was fabricated out of 25.4-mm (1.0-in) inside diameter aluminum pipe and had 12 outlets spaced 50.8-mm (2.0 in) on center. A 254-mm (10.0-in) straight nipple was added to the side entry linear manifold to help straighten flow before it entered the manifold. Each manifold was mounted to the tool bar so that the outlets were vertical with the outlet barbs pointing upward. The tee-entry manifold allowed NH_3 to enter the manifold between two sets of 6 outlets with the same spatial orientation as the side-entry manifold. An FD-1200 prototype (CDS John Blue Co., Huntsville, AL) was also tested. The manifold was a prototype and liquid fertilizer manifolds designated FD-1200 are different and should not be used for NH_3. The FD-1200 prototype was plumbed with a 19-mm (0.75-in) straight inlet nipple 254-mm (10.0-in) long. Manifolds used 11 outlets, and extra ports were evenly distributed around the manifold body. Figure 3 shows the manifolds added for the March 2000 experiment.



A) John Blue FD-1200 prototype B) Tee Entry Linear Manifold C) Side Entry Linear Manifold

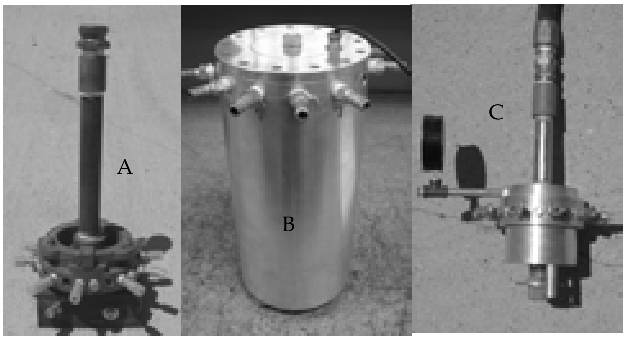
Figure 3. Manifolds added for the March 2000 experiment

In November 2000, datalogging equipment was added to measure temperature and pressure. The “control” conventional 3497, Vertical-Dam (small housing, cotton, and corn rings), FD-1200 prototype, and Rotaflow™ were included in the experiment.

Manifolds tested in April 2001 included the Vertical-Dam (small housing and cotton ring), conventional, FD-1200 prototype and the Equa-Flow™ manifold (PGI International, Houston, TX). The Equa-Flow™ manifold had an operator adjustable plunger to adjust back pressure in the manifold by controlling manifold volume. The manufacturer recommended adjustment so that back pressure at the manifold was 60-75 percent of the tank pressure. In addition, the Impellicone manifold, designed by the research group, was tested in two configurations.

Manifolds evaluated in the November 2001 experiment were the same as in April 2001 with the exception of a slight modification to the Impellicone manifold.

In April of 2002 the A-6600 manifold (CDS John Blue Co., Huntsville, AL) was tested. The A-6600 manifold used a rotating outer ring that allowed for the changing of the area of the outlet orifice. Testing of the conventional, Equa-Flow™, and the Impellicone continued. Only Impellicone #2 was tested, the version that had shown rotation in the November 2001 experiment. Figure 4 shows the three manifolds introduced in the 2001 and 2002 experiments.



a) CDS John Blue Co. A-6600 b) Impellicone c) PGI Equa-Flow™

Figure 4. Manifolds added to the 2001 and 2002 experiments

Impellicone manifold development

During late fall of 2000, conceptual development began of a NH_3 manifold. Requirements were developed from the preceding research with input from producers. The design goals for the manifold were as follows:

1. The design must be able to be machined from commonly available material stock.
2. The manifold must be able to simply replace an existing manifold, without the addition of new plumbing or controller systems.
3. The manifold should require no input from the operator, i.e. the operator should not have to "set" the manifold.
4. A single design unit should handle all application rates up to 224 kg N/ha (200 lb N/ac, 4000 lb NH_3/h on the test applicator), as this is a common high application rate in Midwest corn.

A 19.1-mm (0.75-in) Acme NH_3 fitting was selected as the inlet fitting. The 19-mm fitting was selected as it would allow for the maximum flow rate without the excess area of the common 25.4-mm (1.0-in) Acme fitting. The cross sectional area of the inlet on the 19.1-mm fitting was 285-mm^2 (0.430-in^2). Throughout the design, the total cross-sectional area through which the material flowed was limited to this value if possible. The sum of the groove area in the impeller, and the sum of the area of the 13 outlets were set within a range of 270 to 300-mm^2 (0.421 to 0.438-in^2) to allow for any limitations in machining capability.

Three impeller cone designs were fabricated for testing. The first two were machined from the raw stock material, and the third a modification of the first design. Impellicone #1 used a tapering cone with a 20.5 degree taper with a single 3.2-mm (0.125-in) square groove completing 3.25 revolutions before reaching the base of the cone. The taper between the housing and the cone retained a constant cross-sectional area as the material moves up the cone. Impellicone #2 used the same taper as the housing, 17.5 degrees, with three 9.53-mm (0.375-in) square grooves that make 1.25 revolutions each. In addition, #2 had a 6.4-mm (0.25-in) square groove cut into the impeller at the elevation of the outlets. Impellicone #3 was the same as Impellicone #1 with the original groove cut out to 9.53-mm (0.375-in) square. The increased groove of #3 was tried after initial tests indicated that impeller #1 was turning while NH_3 was flowing through the manifold.

The base width of each cone was cut to 9.779-cm (3.850-in), resulting in a clearance of 0.191-cm (0.075-in) between the cone and housing. The cone was not fixed to the axle, rather it was allowed float up due to the force of the incoming NH_3. When the incoming material stream forced the cone to raise off the housing, the material moving through the rifled grooves should cause the impeller to spin. The NH_3 would move up through the grooves and be distributed to the outlets near the base of the impeller.

To measure the impeller spinning speed, a magnetic pulse tachometer was installed in the lid of the manifold housing. An A103-003 Tachometer (Dynapar brand, Danaher Controls, Gurnee, IL) was coupled to a 103SR13A Hall Effect Position Sensor (Honeywell, Freeport, IL). The sealed sensor, designed for harsh conditions, was installed in the lid of the manifold and four bi-polar magnets were installed into the top of each of the impeller cones. The tachometer had a sensitivity of 15 revolutions per minute (rpm), and maximum of 450 rpm.

Statistical analysis

Four measures of variability among outlet distribution were computed from the data collected (weight of NH_3). The average outlet difference was the average absolute difference in kg (lb) NH_3 of all outlets from the mean outlet output for a particular test plot. The average percentage outlet difference was the average of absolute outlet difference from the mean outlet output expressed as a percentage of the mean outlet output. This percentage measure was used to indicate the average percentage each outlet varied from the mean application rate and to normalize variability based on the NH_3 collected during each plot run. High/low ratio was the ratio of the NH_3 weight from the outlet with the greatest output divided by the output from the outlet with the least output for a given plot. Coefficient of variation (CV) among the outlets was also included. CV was calculated as:

$$CV = (\text{Std. dev./mean})*100\%$$

and is a common indicator of variation of application across agricultural applicators.

Results and discussion

The seven experiments conducted resulted in data sets being compiled that included a wide range of field conditions and distribution data for 16 manifold configurations and types. During the latter four experiments, temperature and pressure data at points along the NH_3 flow path were recorded.

August 1999

Table 1 lists the tank and manifold pressures for all manifolds in the experiment as well as the average measured application rate, and statistical analysis of the experimental results.

As noted in the methods description, the application rate appears low for the Cold-flo® due to the measurement of NH_3 in the liquid phase only. Application rate deviations from the target rate were attributed to regulator settings in the field.

The highest pressures at the manifold were observed with the Vertical-Dam manifolds. The manufacturer (Continental NH_3 Products, Dallas, TX) did not design, nor does it recommend the use of the small housing manifold for application rates approaching the 168 kg N/ha (150 lb N/ac) rate. This application was attempted to retain as much pressure as possible at the manifold and keep the amount of NH_3 in the liquid phase high. According to Continental NH_3, pressure at the manifold in excess of 65% of the tank pressure may overly restrict and meter flow through the orifice at the manifold. This was observed because at the same regulator setting as the other manifolds tested at the 168 kg N/ha (150 lb N/ac)application rate, the Vertical-Dam (SH) resulted in an application rate nearly 20% lower than the conventional and Vertical-Dam (cotton) manifolds. The corn ring commonly used on the large housing Vertical-Dam manifold was replaced with the cotton ring with smaller orifices also in an attempt to increase back pressure and increase the percentage of NH_3 in the liquid phase at the manifold.

Comparing the two different outlet treatments (7- and 11-outlets), no differences in distribution variability were measured when comparing the two outlet configurations. Statistical analysis of the treatments for number of outlets yielded a significant difference at $\alpha=0.10$ in only one of eight instances (absolute difference in ammonia weight for the Vertical-Dam (Cotton) at the 168 kg N/ha (150 lb N/ac)

Table 1. Tank and manifold pressure, application rate, and distribution variation during treatments with various manifolds (August 1999).[a]

Treatment	Tank pressure[b]	Manifold pressure[b]	N application rate[c]	Avg. outlet difference, NH_3[d]	Avg. % outlet difference[e]	High/low ratio[f]	Coefficient of variation, %
	kPa (psi)	kPa (psi)	kg/ha (lb/ac)	kg (lb)			
84 kg N/ha (75 lb N/ac)							
Conventional	1061 (154)	165 (24)	82 (73)	0.053 (0.116)*ab*	12.4*a*	1.66*a*	16.1*a*
Vertical Dam (SH)	978 (142)	441 (64)	74 (66)	0.041 (0.091)*a*	10.9*a*	1.47*a*	13.4*a*
Cold-flo®	999 (145)	14 (2)	63 (56)[g]	0.064 (0.141)*b*	19.9*b*	5.18*b*	27.1*b*
168 kg N/ha (150 N lb/ac)							
Conventional	1082 (157)	345 (50)	173 (154)	0.038 (0.083)*b*	8.2*a*	1.39*a*	10.4*a*
Vertical Dam (Cotton)	971 (141)	496 (72)	182 (162)	0.032 (0.071)*b*	7.5*a*	1.51*a*	9.7*a*
Vertical-Dam (SH)	971 (141)	723 (105)	147 (131)	0.017 (0.037)*a*	4.2*a*	1.21*a*	5.7*a*
Cold-flo®	992 (144)	21 (3)	116 (103)[g]	0.049 (0.107)*b*	15.8*b*	17.59*b*	22.1*b*

[a] Values in each column within each rate followed by a different *italic* letter are significant at the α = 0.05 level
[b] Gage pressure
[c] Application rate as measured into collection containers
[d] Average kg (lb) NH_3 difference of an outlet from mean of outlets
[e] Average difference of outlet from mean of outlets expressed as a percentage of mean
[f] High/low ratio = maximum single outlet weight/minimum single outlet weight
[g] Measured liquid (without vapor) application rate only for Cold-flo®

application rate. These results supported the decision to run future experiments at 11 knives only. The values reported in Table 1 are the average of 7- and 11-outlet measurements.

Statistical analysis separated the manifolds into two groups. At the lower application rate, the Cold-flo® manifold had a significantly higher CV than the conventional and Vertical-Dam (SH) manifolds. The Cold-flo® also had a higher average outlet difference than the Vertical-Dam manifold. Increasing the application rate yielded similar results with CV, high/low ratio, % outlet difference, and average outlet difference. Because of the high variability of flow to the outlet ports and the inability to measure vapor application rates, the Cold-flo® was excluded from later tests. At the 168 kg N/ha (150 lb N/ac) application rate, the Vertical Dam (SH) had a much lower average outlet difference than all other manifolds. This lower difference may be attributed to the high manifold pressure or the slightly reduced application rate. The average pressure during the runs was 75% of the tank pressure. Exceeding the pressure ratio guideline may have limited application rate due to the inability of the manifold orifices to allow sufficient flow of NH_3. This metered flow could have resulted in the measured application rate lower than the goal; both the conventional and the Vertical-Dam (cotton) exceeded the application goal.

November 1999

Table 2 shows the data analysis summary and statistical results for the November 1999 experiment.

The lower measured application rate for the Vertical-Dam (SH) at the 168 kg N/ha rate was similar to the effect seen in the August 1999 experiment. For the November experiment, the ratio of manifold pressure to tank pressure was 87%. The Vertical Dam (SH) used at the 84 kg N/ha (75 lb N/ac) rate fell within the application range of the manifolds tested. The pressure ratio was 79%, still well above the recommended ratio.

The conventional manifold treatments had the greatest variability at each rate. At the 84 kg N/ha (75 lb N/ac) rate, the elbow-entry and uneven plugs had the greatest variability with the mixer-entry only slightly less. The straight-entry had less variability than the mixer-entry, indicating that any increased cross-sectional distribution with the mixer-entry may have been offset by increased pressure loss and ammonia vaporization due to flow friction.

At the lower application rate, the Vertical-Dam (SH) and the Rotaflow™ manifolds performed similarly statistically, both having lower variability in each category than the other manifolds in the test. Similar trends were seen at the 168 kg N/ha (150 lb N/ac) application rate. The CV dropped by

Table 2. Tank and manifold pressure, application rate, and distribution variation during treatments with various manifolds (November 1999).[a]

Treatment	Tank pressure[b]	Manifold pressure[b]	N application rate[c]	Avg. outlet difference, NH_3[d]	Avg. % outlet difference[e]	High/low ratio[f]	Coefficient of variation, %
	kPa (psi)	kPa (psi)	kg/ha (lb/ac)	kg (lb)			
84 kg N/ha (75 lb N/ac)							
Conv. elbow-entry	572 (83)	138 (20)	89 (79)	0.096 (0.212)*c*	21.1*c*	2.57*c*	29.6*d*
Conv. mixer-entry	489 (71)	145 (21)	101 (90)	0.102 (0.225)*c*	19.6*c*	2.19*b*	24.7*c*
Conv. straight-entry	482 (70)	138 (20)	103 (92)	0.052 (0.114)*b*	9.7*b*	1.42*a*	11.8*b*
Rotaflow™	448 (65)	131 (19)	106 (94)	0.021 (0.046)*a*	3.8*a*	1.18*a*	4.9*a*
Vertical Dam (SH)	517 (75)	407 (59)	98 (87)	0.022 (0.048)*a*	4.3*a*	1.20*a*	5.7*a*
Conv. uneven plugs	606 (88)	138 (20)	90 (80)	0.102 (0.225)*c*	22.1*c*	2.25*b*	28.5*d*
168 kg N/ha (150 lb N/ac)							
Conv. elbow-entry	558 (81)	241 (35)	162 (144)	0.062 (0.137)*c*	14.3*d*	1.75*b*	17.6*c*
Conv. mixer-entry	482 (70)	241 (35)	184 (164)	0.059 (0.129)*c*	11.9*cd*	1.61*b*	14.8*bc*
Conv. straight-entry	537 (78)	234 (34)	163 (145)	0.053 (0.116)*c*	11.2*cd*	1.70*b*	15.6*bc*
Rotaflow™	448 (65)	241 (35)	177 (158)	0.013 (0.028)*a*	4.1*a*	1.23*a*	5.7*a*
Vertical Dam (Cotton)	613 (89)	393 (57)	168 (150)	0.037 (0.082)*b*	9.7*bc*	1.47*ab*	11.7*b*
Vertical Dam (SH)	586 (85)	510 (74)	118 (105)	0.020 (0.044)*a*	6.4*ab*	1.32*a*	8.3*ab*
Conv. uneven plugs	467 (68)	255 (37)	191 (170)	0.059 (0.130)*c*	11.5*cd*	1.59*b*	14.1*bc*

[a] Values in each column within each rate followed by a different *italic* letter are significant at the $\alpha = 0.05$ level

[b] Gage Pressure

[c] Application rate as measured into collection containers

[d] Average kg (lb) NH_3 difference of an outlet from mean of outlets

[e] Average difference of outlet from mean of outlets expressed as a percentage of mean

[f] High/low ratio = maximum outlet weight/minimum outlet weight

approximately 10 percentage points for most conventional manifold treatments. This trend, also seen in the first experiment suggests that with increased application rate and the resultant higher flow rate of NH_3 through the manifold, variation among outlets may be reduced.

At the higher application rate, variability among some of the treatments was diminished. The range of values between manifolds was smaller than at the lower application rate. The mixer-entry manifold performed better at the higher rate, grouping it with Vertical-Dam (SH and Cotton) and the straight-entry manifold for CV. Variability for the Rotaflow™ and Vertical-Dam (SH) were similar and both lower than the Vertical-Dam (Cotton).

March 2000

Because the elbow-entry conventional manifold is the most widely used manifold configuration, this manifold was selected as the “control” manifold, and used in all subsequent tests. Good uniformity was again observed with the Rotaflow™ and Vertical-Dam (SH) manifold. Table 3 lists the summarized results for the March 2000 experiment.

The Vertical-Dam (Cotton) had significantly lower values than the Vertical-Dam (Corn) in all statistical comparisons except the high/low ratio. The Vertical-Dam (Cotton), with its smaller orifices may meter flow with rates at or above the 168 kg N/ha (150 lb N/ac) rate. The corn ring did produce a higher application rate, but with higher tank pressure.

The corn ring was below this critical value (59%) and the cotton ring was above this range (75%). The FD-1200 prototype had low variation at the high application rate but moderate variation at the low application rate. It was statistically no different than the Rotaflow™ at the high rate, but was grouped with the conventional manifold at the low rate.

The average application rate for each of the outlets on each commercial manifold for the 168 kg N/ha (150 lb N/ac) is shown in Figure 5. This graph provides an easy way to visualize the difference in application rates across the applicator.

Table 3. Tank and manifold pressure, application rate, and distribution variation during treatments with various manifolds (March 2000).[a]

Treatment	Tank pressure[b]	Manifold pressure[b]	N application rate[c]	Avg. outlet difference, NH_3[d]	Avg. % outlet difference[e]	High/low ratio[f]	Coefficient of variation, %
	kPa (psi)	kPa (psi)	kg/ha (lb/ac)	kg (lb)			
84 kg N/ha (75 lb N/ac)							
Side Entry	400 (58)	117 (17)	106 (94)	0.395 (0.869)*c*	66.0*c*	7.34*b*	74.5*c*
Tee Entry	407 (59)	110 (16)	107 (95)	0.392 (0.862)*c*	70.8*c*	8.64*b*	80.5*c*
Conventional	317 (46)	145 (21)	116 (103)	0.095 (0.210)*b*	16.3*b*	1.99*a*	22.3*b*
Vertical Dam (SH)	345 (50)	282 (41)	94 (84)	0.025 (0.054)*a*	5.1*a*	1.20*a*	6.0*a*
FD-1200	400 (58)	158 (23)	108 (96)	0.071 (0.156)*b*	12.4*b*	1.96*a*	19.1*b*
Rotaflow™	420 (61)	138 (20)	104 (93)	0.028 (0.061)*a*	5.2*a*	1.24*a*	6.7*a*
168 kg N/ha (150 lb N/ac)							
Side Entry	386 (56)	200 (29)	199 (177)	0.312 (0.686)*d*	58.4*f*	7.05*b*	65.7*e*
Tee Entry	413 (60)	220 (32)	203 (181)	0.276 (0.608)*c*	50.5*e*	5.70*b*	59.2*e*
Conventional	551 (80)	282 (41)	191 (170)	0.068 (0.149)*b*	13.2*cd*	1.66*a*	16.0*c*
Vertical Dam (Corn)	441 (64)	262 (38)	179 (159)	0.085 (0.188)*b*	16.0*d*	2.74*a*	27.5*d*
Vertical Dam (Cotton)	351 (51)	262 (38)	158 (141)	0.041 (0.090)*a*	9.8*bc*	2.55*a*	15.0*bc*
FD-1200	400 (58)	248 (36)	174 (155)	0.025 (0.056)*a*	5.5*ab*	1.24*a*	6.7*ab*
Rotaflow™	420 (61)	248 (36)	197 (175)	0.022 (0.048)*a*	4.2*a*	1.21*a*	5.4*a*

[a] Values in each column within each rate followed by a different *italic* letter are significant at the $\alpha = 0.05$ level

[b] Gage pressure

[c] Application rate as measured into collection containers

[d] Average lbs NH_3 difference of an outlet from mean of outlets

[e] Average difference of outlet from mean of outlets expressed as a percentage of mean

[f] High/low ratio = maximum outlet weight/minimum outlet weight

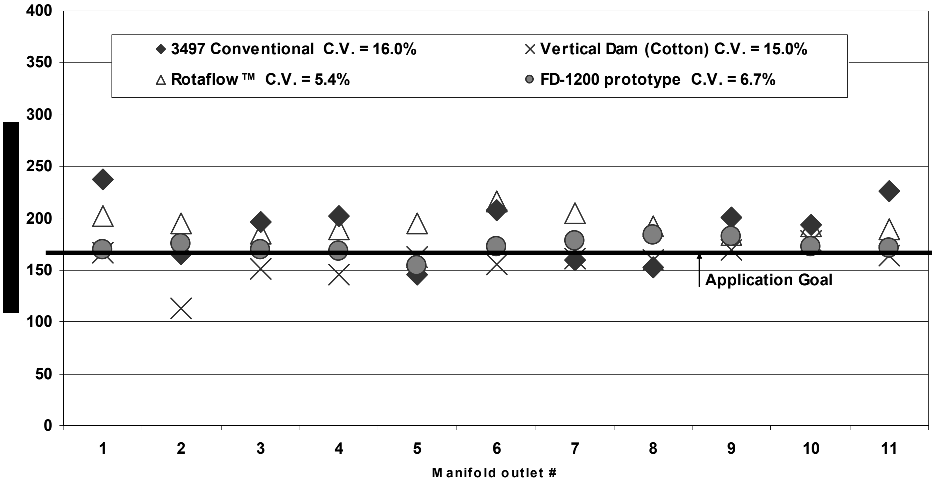


Figure 5. Distribution of radial manifolds for the March 2000 experiment

Application with the Side Entry and Tee Entry linear manifolds resulted in greater variation between outlets. Liquid flow moved to the farthest outlet away from the inlet point.

Distribution of linear manifolds yielded high/low ratios that exceeded 5.7, the equivalent of application rates between 60 and 350 kg N/ha (54 to 313 lb N/ac. Figure 6 shows the outlet distribution for the linear manifolds. The comparison between the radial manifolds in figure 5 and the linear manifolds in figure 6 indicated that distribution variation was less with all radial manifolds.

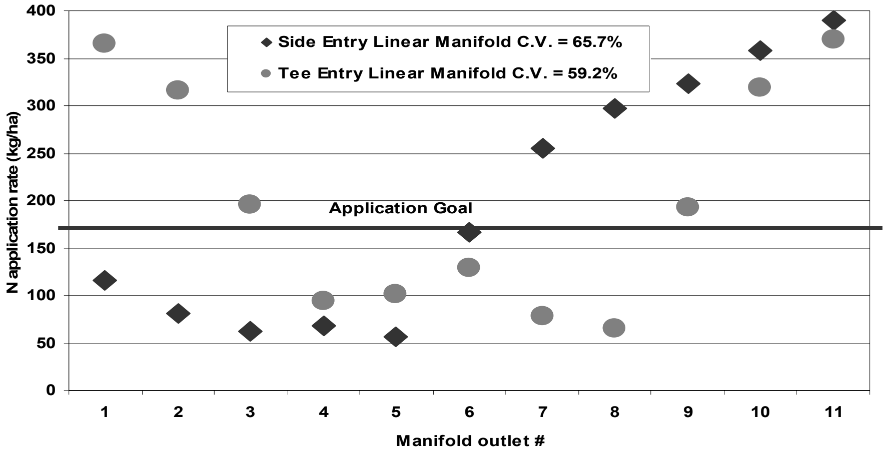


Figure 6. Distribution of linear manifolds for the March 2000 experiment

November 2000

The statistical ranking of manifolds changed only slightly during the November 2000 experiment. Both the cotton and corn ring Vertical-Dam manifolds performed better than in March 2000 with similar manifold pressures and slightly lower application rates (Table 4). The FD-1200 prototype did not perform as well, nor did the Rotaflow™ at the high flow rate.

These early experiments indicated that in general, an increase in application rate with a resulting increase in manifold pressure, lowered the CV. The Rotaflow™ did not follow this trend in two of the three experiments, but the variation from low rate to high rate never exceeded +3.2%.

Table 4. Tank and manifold pressure, application rate, and distribution variation during treatments with various manifolds (November 2000).[a]

Treatment	Tank pressure[b]	Manifold pressure[b]	N application rate[c]	Avg. outlet difference, NH_3[d]	Avg. % outlet difference[e]	High/low ratio[f]	Coefficient of variation, %
	kPa (psi)	kPa (psi)	kg/ha (lb/ac)	kg (lb)			
84 kg N/ha (75 lb N/ac)							
Vertical Dam (SH)	358 (52)	200 (29)	81 (71)	0.020 (0.044)*a*	4.9a	1.19*a*	5.9*a*
Conventional	400 (58)	117 (17)	91 (81)	0.079 (0.173)*b*	14.6*b*	2.17*c*	22.8*b*
FD-1200	351 (51)	145 (21)	85 (76)	0.061 (0.134)*b*	14.5*b*	1.81*b*	19.0*b*
Rotaflow™	338 (49)	110 (16)	93 (83)	0.019 (0.042)*a*	4.0*a*	1.17*a*	5.0*a*
168 kg N/ha (150 lb N/ac)							
Vertical Dam (Cotton)	386 (56)	227 (33)	148 (132)	0.016 (0.036)*a*	4.1*a*	1.12*a*	5.4*a*
Vertical Dam (Corn)	386 (56)	179 (26)	147 (131)	0.033 (0.073)*b*	8.4*ab*	1.37*ab*	10.3*ab*
Conventional	400 (58)	193 (28)	157 (140)	0.060 (0.113)*c*	12.0*b*	1.71*c*	17.0*c*
FD-1200	351 (51)	200 (29)	143 (127)	0.040 (0.089)*bc*	10.5*b*	1.52*bc*	13.8*bc*
Rotaflow™	331 (48)	152 (22)	133 (118)	0.021 (0.046)*a*	6.0*a*	1.36*ab*	8.2*ab*

[a] Values in each column within each rate followed by a different *italic* letter are significant at the $\alpha = 0.05$ level

[b] Gage Pressure

[c] Application rate as measured into collection containers

[d] Average kg (lb) NH_3 difference of an outlet from mean of outlets

[e] Average difference of outlet from mean of outlets expressed as a percentage of mean

[f] High/low ratio = maximum outlet weight/minimum outlet weight

April 2001

The initial version of the Impellicone was tested during the April 2001 experiment, but failed to rotate as designed. This resulted in very poor distribution, and the results for the Impellicone were omitted in the statistical analysis. Results for the Vertical-Dam, conventional, and FD-1200 prototype manifolds were consistent with earlier experiments (table 5). The Equa-flow™ manifold had an average CV across both application rates of 6.0%.

Table 5. Tank and manifold pressure, application rate, and distribution variation during treatments with various manifolds (April 2001).[a]

Treatment	Tank pressure[b]	Manifold pressure[b]	N application rate[c]	Avg. outlet difference, NH$_3$[d]	Avg. % outlet difference[e]	High/low ratio[f]	Coefficient of variation, %
	kPa (psi)	kPa (psi)	kg/ha (lb/ac)	kg (lb)			
84 kg N/ha (75 lb N/ac)							
Vertical Dam (SH)	730 (106)	338 (49)	85 (76)	0.041 (0.091)*b*	9.5*b*	1.54*b*	12.6*c*
Conventional	827 (120)	145 (21)	77 (69)	0.080 (0.176)*c*	20.1*c*	2.26*c*	25.9*d*
FD-1200	661 (96)	172 (25)	91 (81)	0.039 (0.086)*b*	8.3*b*	1.14*a*	9.8*b*
Equa-Flow™	675 (98)	469 (68)	92 (82)	0.020 (0.045)*a*	4.3*a*	1.26*a*	6.1*a*
168 kg N/ha (150 lb N/ac)							
Vertical Dam (Cotton)	689 (100)	400 (58)	171 (152)	0.038 (0.084)*b*	8.3*b*	1.38*a*	10.5*b*
Conventional	834 (121)	331 (48)	170 (151)	0.059 (0.130)*c*	13.0*c*	1.95*b*	19.1*c*
FD-1200	675 (98)	331 (48)	177 (158)	0.033 (0.072)*b*	6.9*b*	1.44*a*	9.9*b*
Equa-Flow™	675 (98)	462 (67)	177 (158)	0.019 (0.041)*a*	3.9*a*	1.22*a*	5.8*a*

[a] Values in each column within each rate followed by a different *italic* letter are significant at the $\alpha = 0.05$ level

[b] Gage Pressure

[c] Application rate as measured into collection containers

[d] Average kg (lb) NH$_3$ difference of an outlet from mean of outlets

[e] Average difference of outlet from mean of outlets expressed as a percentage of mean

[f] High/low ratio = maximum outlet weight/minimum outlet weight

November 2001

A third experiment for the FD-1200 prototype manifold produced similar results to earlier experiments (Table 6). Distribution variation increased at both application rates for the Equa-flow™ manifold. Due to a calibration error, the Equa-flow™ was tested with a manifold to tank pressure ratio of 17% for the lower application rate, and 36% for the higher rate. With the pressure ratio well below the recommended level, the Equa-flow™ placed in the second statistical grouping.

An attempt was made during this experiment to set the pressure ratio with the Equa-flow™ as close to the manufacturers recommendation as possible. Gage error may have been responsible for pressure ratios below the specified range.

Testing of the Impellicone resumed after modifications during the summer of 2001 confirmed that the impeller was spinning in the manifold housing. Two impellers styles were tested. Impellicone 2 placed in the top statistical category at both application rates (Table 6). The tachometer measured fairly constant rotation of the impeller. Impellicone 3 operated well at the lower application rate but was the worst performer of all the manifolds tested at the higher application rate. The tachometer measured only occasional pulses of rotation within the manifold for Impellicone 3.

Table 6. Tank and manifold pressure, application rate, and distribution variation during treatments with various manifolds (November 2001).[a]

Treatment	Tank pressure[b]	Manifold pressure[b]	N application rate[c]	Avg. outlet difference, NH$_3$[d]	Avg. % outlet difference[e]	High/low ratio[f]	Coefficient of variation, %
	kPa (psi)	kPa (psi)	kg/ha (lb/ac)	kg (lb)			
84 kg N/ha (75 lb N/ac)							
Vertical Dam (SH)	758 (110)	345 (50)	99 (88)	0.032 (0.071)*a*	6.4*ab*	1.33*a*	8.5*ab*
Conventional	744 (108)	172 (25)	101 (90)	0.070 (0.153)*c*	13.3*c*	1.91*c*	18.9*d*
FD-1200	758 (110)	193 (28)	99 (88)	0.047 (0.103)*b*	9.2*b*	1.48*b*	12.1*c*
Equa-Flow™	758 (110)	131 (19)	69 (61)	0.028 (0.062)*a*	7.9*b*	1.44*b*	10.6*bc*
Impellicone 2	688 (97)	172 (25)	102 (91)	0.024 (0.053)*a*	4.6*a*	1.18*a*	5.5*a*
Impellicone 3	688 (97)	179 (26)	100 (89)	0.035 (0.077)*ab*	6.7*a*	1.33*a*	8.6*ab*
168 kg N/ha (150 lb N/ac)							
Vertical Dam (Cotton)	688 (97)	338 (49)	192 (171)	0.020 (0.044)*a*	3.9*a*	1.20*a*	5.3*a*
Conventional	723 (105)	282 (41)	169 (151)	0.051 (0.112)*b*	11.2*c*	1.96*c*	17.2*c*
FD-1200	758 (110)	331 (48)	185 (165)	0.030 (0.067)*a*	6.1*ab*	1.26*a*	7.5*ab*
Equa-Flow™	758 (110)	276 (40)	143 (127)	0.030 (0.065)*a*	7.7*b*	1.30*a*	9.1*b*
Impellicone 2	688 (97)	269 (39)	180 (160)	0.021 (0.046)*a*	4.3*a*	1.27*a*	6.2*ab*
Impellicone 3	655 (95)	324 (47)	198 (176)	0.090 (0.198)*c*	15.9*d*	1.74*b*	19.0*c*

[a] Values in each column within each rate followed by a different *italic* letter are significant at the $\alpha = 0.05$ level

[b] Gage Pressure

[c] Application rate as measured into collection containers

[d] Average kg (lb) NH$_3$ difference of an outlet from mean of outlets

[e] Average difference of outlet from mean of outlets expressed as a percentage of mean

[f] High/low ratio = maximum outlet weight/minimum outlet weight

April 2002

The experiment in April 2002 was conducted in cold air temperatures (-2 to 4° C (28 to 39° F)). The experiment generally had the lowest values of distribution variation (table 7) of any experiment. The Equa-flow™, while only tested with manifold pressure 43% of tank pressure at the lower application rate, produced a relatively low CV of 4.0%. At the high application rate and 65% of tank pressure, the manifold had a CV of 3.2%; the lowest value recorded in all experiments.

Table 7. Tank and manifold pressure, application rate, and distribution variation during treatments with various manifolds (April 2002).[a]

Treatment	Tank pressure[b]	Manifold pressure[b]	N application rate[c]	Avg. outlet difference, NH_3[d]	Avg. % outlet difference[e]	High/low ratio[f]	Coefficient of variation, %
	kPa (psi)	kPa (psi)	kg/ha (lb/ac)	kg (lb)			
84 kg N/ha (75 lb N/ac)							
Vertical Dam (SH)	282 (41)	234 (34)	91 (81)	0.029 (0.063)*b*	6.2*b*	1.37*c*	5.7*ab*
Conventional	269 (39)	124 (18)	99 (88)	0.060 (0.133)*c*	11.8*c*	1.96*e*	18.7*c*
A-6600	269 (39)	179 (26)	99 (88)	0.078 (0.171)*d*	15.3*d*	1.56*d*	17.4*c*
Equa-Flow™	317 (46)	138 (20)	98 (87)	0.016 (0.035)*a*	3.2*a*	1.14*a*	4.0*a*
Impellicone 2	338 (49)	138 (20)	97 (86)	0.029 (0.064)*b*	5.8*b*	1.26*b*	7.3*b*
168 kg N/ha (150 lb N/ac)							
Vertical Dam (Cotton)	282 (41)	241 (35)	159 (142)	0.012 (0.027)*ab*	2.8*a*	1.14*ab*	4.0*ab*
Vertical Dam (Corn)	303 (44)	220 (32)	168 (150)	0.030 (0.065)*c*	6.6*c*	1.27*c*	7.9*c*
Conventional	269 (39)	186 (27)	163 (145)	0.050 (0.110)*e*	11.5*e*	1.91*d*	16.2*e*
A-6600	276 (40)	241 (35)	163 (145)	0.040 (0.088)*d*	8.7*d*	1.33*c*	10.1*d*
Equa-Flow™	317 (46)	207 (30)	157 (140)	0.011 (0.024)*a*	2.5*a*	1.12*a*	3.2*a*
Impellicone 2	324 (47)	207 (30)	157 (140)	0.020 (0.043)*b*	4.7*b*	1.24*bc*	6.2*bc*

[a] Values in each column within each rate followed by a different *italic* letter are significant at the $\alpha = 0.05$ level

[b] Gage Pressure

[c] Application rate as measured into collection containers

[d] Average kg (lb) NH_3 difference of an outlet from mean of outlets

[e] Average difference of outlet from mean of outlets expressed as a percentage of mean

[f] High/low ratio = maximum outlet weight/minimum outlet weight

The Impellicone manifold produced a slightly higher CV for the lower application rate and the identical CV at the higher application rate as it had in the November 2001 experiment. The A-6600 had orifice settings were set using manufacturer (CDS John Blue Co.) recommendations. Performance was similar to the conventional at the lower application rate and between the conventional and the group including all other manifolds at the higher application rate.

Overall manifold performance

The March 2000 experiment showed that manifolds with radial outlets outperformed linear manifolds. This may be attributed to the length of flow path and/or the velocity of NH_3 in the liquid phase within the manifold. Outlets on each of the radial outlet manifolds had similar flow length to each outlet. The linear manifolds had varying lengths of flow to each outlet and results indicated liquid NH_3 flowed to the farthest outlet and then partially filled the manifold cavity from the farthest outlet.

Variations of the standard conventional manifold with an elbow for incoming flow mounted adjacent to the manifold housing resulted in slight reduction of distribution variation. The reduction in variation was highest when a 30.5-cm (10.0-in) straight nipple was inserted between the elbow and the manifold body. For users of the conventional manifold, addition of the pipe nipple from below may decrease application variation.

The statistical results for each experiment with each of the manifolds was combined for each manifold that was tested in more than one experiment. This was done to examine if overall differences could be observed. One comparison tested for differences between application rates within each manifold (Table 8).

Only the conventional manifold showed a statistical difference between application rates when comparing within the manifold. The conventional and Vertical-Dam (SH vs Cotton) comparisons used data from seven experiments. The FD-1200 prototype comparison used four experiments of data, while the Equa-Flow™, Rotaflow™, and Vertical-Dam (SH vs Corn) used data from three experiments.

A comparison across manifolds at each application rate indicated that the conventional manifold was significantly different than all the other manifolds at the lower application rate, and grouped with the Vertical-Dam (Corn) and the FD-1200 prototype at the higher application rate. Overall manifold

Table 8. NH_3 distribution variation at two application rates within manifold types[a]

Manifold	N Application rate goal	Avg outlet diff. of NH3b	Avg. % outlet difference[c]	High/low ratio[d]	Coefficent of variation
	kg/ha (lb/ac)	kg (lb)			%
Conventional	84	0.076(0.168)*a*	15.6*a*	2.07*a*	22.0*a*
Conventional	168	0.054(0.119)*b*	11.9*b*	1.76*b*	16.2*b*
Equa-Flow™	84	0.021(0.047)	5.1	1.28	6.9
Equa-flow™	168	0.020(0.043)	4.7	1.23	6.0
Rotaflow™	84	0.019(0.041)	4.3	1.20	5.5
Rotaflow™	168	0.023(0.050)	4.8	1.27	6.3
FD-1200 prototype	84	0.057(0.125)	11.7	1.60	15.2
FD-1200 prototype	168	0.033(0.072)	7.3	1.37	9.5
Vertical-Dam (SH)	84	0.030(0.066)	6.7	1.33	8.3
Vertical-Dam (Corn)	168	0.050(0.109)	10.3	1.79	15.2
Vertical-Dam (SH)	84	0.030(0.066)	6.7	1.33	8.3
Vertical-Dam (Cotton)	168	0.028(0.062)	6.6	1.48	8.8

[a] Values in each column within each manifold followed by a different *italic* letter are significant at the α = 0.05 level
[b] Average kg (lb) NH_3 difference of an outlet from mean of outlets
[c] Average difference of outlet from mean of outlets expressed as a percentage of mean
[d] High/low ratio = maximum single outlet weight/minimum single outlet weight

performance could be separated into three groups, based on statistical results. The manifolds distribution performance could be categorized as poor, moderate, and good, using the conventional manifold as a benchmark. The results of the CV calculation were used as an indicator of the manifolds performance, as the grouping of manifolds based on CV was usually identical to the grouping dictated by other factors. At the 168 kg N/ha (150 lb N/ac) rate, performance of the manifolds tested are ranked in Table 9.

Table 9. Overall manifold performance at 168 kg N/ha (150 lb N/ac)[a]

Manifold	Average CV, %	Performance Group	Max. ΔCV among experiments, %
Conventional	16.2*a*	Poor	8.7
Vertical Dam (Corn)	15.2*ab*	Poor	19.6
FD-1200 prototype	9.5*abc*	Moderate	7.1
Vertical-Dam (Cotton)	8.8*c*	Moderate	11.0
Rotaflow™	6.3*c*	Good	2.8
Impellicone	6.2*c*	Good	0.0
Equa-flow™	6.0*c*	Good	5.9

[a] Values followed by a different *italic* letter are significant at the α = 0.05 level

The average CV was calculated for each manifold as the composite of all replications from all experiments during which the manifold was used. The conventional manifold had a consistently poor CV of 16.2%, and variation of the CV value between experiments never exceeded 8.7 percentage points. The conventional manifold performs poorly, and performs poorly fairly consistently. The Vertical-Dam (Corn) produced a CV of 7.9% during the April 2002 experiment, but the average CV was affected by greater variation in other experiments and the maximum ΔCV was 19.6%.

The manifolds grouped into the moderate range produced lower distribution variation than the poor group. The FD-1200 prototype performed at a level in the middle of the group of manifolds tested. The Vertical-Dam (Cotton) manifold produced CV values between 4.0% and 15%. The lack of consistency with the Vertical-Dam (Cotton) manifold prevented its inclusion in the group of top performers.

Between the three manifolds in the good category, it is difficult to find differences in performance among them. The Equa-flow™ had the highest ΔCV, but manifold pressures were not always in the optimum range during operation. The Impellicone produced a ΔCV of 0.0%, but it was only tested in two experiments; all the other manifolds were tested in a minimum of three experiments. The Vertical-Dam (SH) was not included in the results in table 9 because while it had low distribution variation, its inability to meet the application rate goal does not make it a viable solution for application at this rate. A similar evaluation of results at the 84 kg N/ha (75 lb N/ac) rate are shown in table 10.

Table 10. Overall manifold performance at 84 kg N/ha (75 lb N/ac)[a]

Manifold	Average CV, %	Performance Group	Max. ΔCV among experiments, %
Conventional	22.0*a*	Poor	13.5
FD-1200 prototype	15.0*b*	Moderate	9.3
Vertical-Dam (SH)	8.3*c*	Good	7.7
Equa-flow™	6.9*c*	Good	6.6
Impellicone	6.4*c*	Good	1.8
Rotaflow™	5.5*c*	Good	1.8

[a] Values followed by a different *italic* letter are significant at the $\alpha = 0.05$ level

Rankings of manifolds were similar to those at the higher application rate. The performance of the Vertical-Dam (SH), however, placed it in the top group.

Comparing these results to the summary in table 8, while only the conventional manifold had a statistically lower CV at the high rate than at the lower application rate, manifold CV dropped with the increase in application rate for most manifolds tested. Exceptions to this were the Rotaflow™ manifold which produced a CV of 5.5% at 84 kg N/ha (75 lb N/ac) and 6.3% at 168 kg N/ha (150 lb N/ac), and the Vertical-Dam which produced a CV of 8.3% for the Vertical-Dam (SH), and 15.2% and 8.8% for the Vertical-Dam (Corn) and Vertical-Dam (Cotton) respectively.

Any of the manifolds producing CV values below 10% would increase uniformity beyond use of a conventional type manifold. The Vertical-Dam manifolds (Cotton and SH) would be the least expensive solutions but may not provide the best available distribution. For producers currently using a large housing Vertical-Dam with the corn ring, a change to the cotton ring may reduce application variation if application rates do not exceed the 168 kg N/ha (150 lb N/ac) range and manifold pressure is monitored.

As occurred during the experiments, manifolds that need to be adjusted by the operator introduce the possibility of error due to adjustment. This error is also possible with the Vertical-Dam manifolds with the improper selection of ring for the desired application rate. Manifolds that did not require operator adjustment were the easiest to configure.

Test results of the Impellicone manifold

During the November 2001 experiment, tachometer output indicated spotty rotation with Impellicone 3 rate and Impellicone 2 consistently measured the impeller accelerating to a maximum speed of 210-285 rpm when the regulator valve was first opened and NH_3 began to flow through the manifold. During application, the impeller speed varied between 0 and 90 rpm. At 168 kg N/ha (150 lb N/ac), the impeller appeared to spin continuously. At the 84 kg N/ha (75 lb N/ac) rate, the impeller speed appeared to drop to zero every 2-3 seconds and then accelerate to the 60-75 rpm range. The low application rate may not have had sufficient flow to keep the impeller spinning continuously, and it only spun when a volume of NH_3 built up under the impeller to create enough force to push it up against the bearing surface and cause temporary rotation. Scaling down the manifold for lower flow rates or reducing the rotational inertia of the impeller may be solutions to this problem.

Temperature and pressure of NH_3 within the applicator

Measurements of temperature and pressure at points both upstream and downstream of the regulator and at the manifold were made as described in the materials and methods. As the NH_3 flowed through the system, flow restrictions due to the regulator and line friction caused pressure drops, which resulted in temperature drops as the NH_3 stayed at or near saturation. The data, collected at one second intervals was used to evaluate whether NH_3 acted as a saturated mixture as it moved through the distribution system, from the tank to the regulator, and then to the manifold. A saturated mixture is defined as a mixture of material in liquid and vapor phases coexisting in equilibrium (Cengel and Boles, 1994). The average temperature and pressure values during application were used in analysis. These data points were grouped by manifold in an attempt to detect any trends and anomalies in the results. Figure 7 shows temperature and pressure data compiled for the FD-1200 prototype, tested in the November 2000, April 2001, and November 2001 experiments. Each symbol represents three data points for the replications of each treatment.

The saturation line (Sonntag and Van Wylen, 1982) separating liquid and vapor phases, identifies the conditions at which NH_3 changes phase. NH_3 will be a liquid above and to the left of the line, and a vapor below and to the right of the line. A change in enthalpy, the internal energy of NH_3, is required to move NH_3 away from the saturation line.

Figure 7 shows that as the NH_3 material moves through the system, the temperature and pressure both decrease. For after regulator and manifold data points, the grouping of three data points lower on the line were collected at the 84 kg N/ha (75 lb N/ac) application rate, and the higher three points at the 168 kg N/ha (150 lb N/ac) rate. These changes in pressure can be seen when looking at the pressure data in the experiment summary tables one through seven.

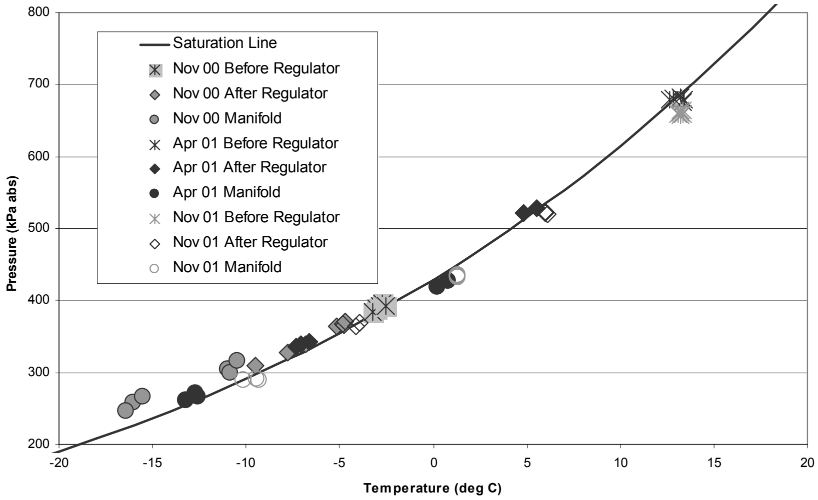


Figure 7. Temperature and pressure data for the FD-1200 manifold

To correlate the measured data to the saturation line, a linear correlation was evaluated.. The measured pressure at each recorded temperature was plotted against the theoretical pressure calculated from the saturation line. Figure 8 plots the theoretical pressure against the measured pressure for the FD-1200 prototype manifold.

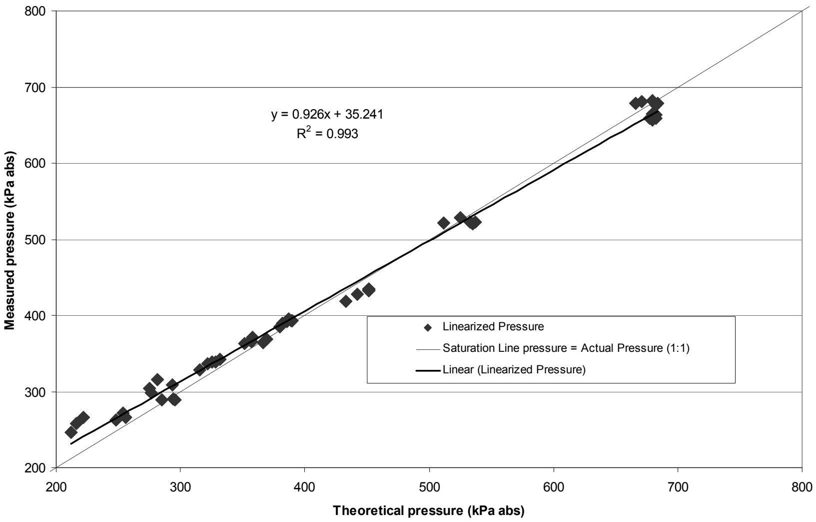


Figure 8. Measured vs theoretical pressure for the FD-1200 prototype manifold

The best fit line through the data plot resulted in a correlation of $R^2 = 0.993$, and a slope of 0.9260. The PROC GLM function of SAS was used to determine the best-fit line to the data and check the residuals for abnormalities; none were found. To compare the slope of the best fit line through the data set to a line with a slope = 1 (measured pressure = theoretical pressure), the correlation coefficient was used. In reference to the FD-1200 prototype, 99.3% of the variation in the measured pressure reading could be explained by the theoretical pressure (i.e. assumption of saturated conditions) at any given temperature.

Table 11 lists the statistical results for each manifold tested between November 2000 and April 2002 and evaluated for correlation between actual data and the theoretical saturation line. Datalogger malfunctions caused an insufficient data set and prevented evaluation of any of the Vertical-Dam manifolds for saturation line correlation.

Table 11. Statistical analysis of temperature and pressure data for correlation with the theoretical saturation line for NH_3

Manifold	Slope of best fit linear line	Degrees of freedom	R^2	Std. Error of Pred. (SEP)
Conventional	0.9405	61	0.996	+/- 16.1
FD-1200 prototype	0.9260	49	0.993	+/- 16.6
Equa-flow™	0.9837	40	0.991	+/- 15.8
Rotaflow™	0.8082	16	0.984	+/- 17.3
A-6600	0.6123	16	0.893	+/- 30.6
Impellicone	0.8837	16	0.997	+/- 12.1

In addition to the calculation of the correlation coefficient, the standard error of prediction (SEP) was calculated. The SEP was calculated as the standard deviation of the residuals between the theoretical pressure and the measured pressure. In terms of the conventional manifold, the SEP states that the actual pressure would be within +/- 16.1 kPa (2.3 psi) of the theoretical pressure during 68% (one standard deviation) of the measurements.

The slope of each correlation was less than one. This was caused by values recorded at the manifold that were slightly above the saturation line. The measured higher pressure or lower temperature pushed the data points into the liquid area of the saturation plot. Any noticeable deviation from the saturation line occurred at the manifold and was always to the liquid side of the line.

NH_3 conditions in the liquid phase of the saturation diagram would require compression of NH_3 or a loss in temperature due to a thermal sink. As differential pressure moves NH_3 through the applicator no external source of compression was evident. During all of the experiments, the air temperature was higher than the temperature of the manifold. Energy transfer from the surroundings through the manifold body would have been an energy input, which would increase the temperature and move NH_3 quality toward the vapor side of the saturation line. Without thermal energy sinks or external pressure sources available to drive NH_3 to a fully saturated liquid, the data points for the manifolds showing NH_3 as a supercooled liquid are unexpected. A possible bias error in datalogging at low temperatures and pressure may have affected data collection, but there is no obvious explanation for sampling error. The A-6600 correlation was the poorest, with the theoretical pressure value accounting for 89.3% of the variation in the measured value. The SEP value was also very high for the A-6600. Because the A-6600 was only used in the April 2002 experiment, only 18 data points were fit to the saturation line. Without additional data, no conclusion could be drawn from the results. The three manifolds with the largest data sets resulted in very good correlations, slopes near 1.0, and SEP values less than +/- 16.6 kPa (2.3 psi).

Based on these data sets, it is observed that NH_3 in a fertilizer application system including a tank, hoses, a regulator, and a manifold, does act as a saturated mixture as the pressure drops through the system. In addition, prediction of material quality and vapor production can be predicted using the established saturation data using actual temperature and pressure of NH_3.

It was hypothesized that the percentage of volume in the vapor in the manifold may be related to distribution. Possible comparisons include comparisons between CV, temperature, and quality, or vapor partitioning. Manifold CV was compared to the ambient air temperature to examine any correlation between these two factors for those manifolds with complete data sets from at least two experiments. The manifolds were separated into two groups: those with fixed volume cavities, including the conventional, Vertical-Dam, and the Impellicone, and those with variable volume cavities, including the FD-1200 prototype and the Equa-flow™ manifold.

Based on graphical comparisons of manifold CV against air temperature the hypothesis was suggested that air temperature at the time of application has an effect on distribution variation. The fixed volume cavity manifold showed a broad but weak trend towards increasing CV with increasing air temperature (figure 9). The opposite trend, that of decreasing CV with increasing air temperature, could be suggested for the FD-1200 prototype manifold.

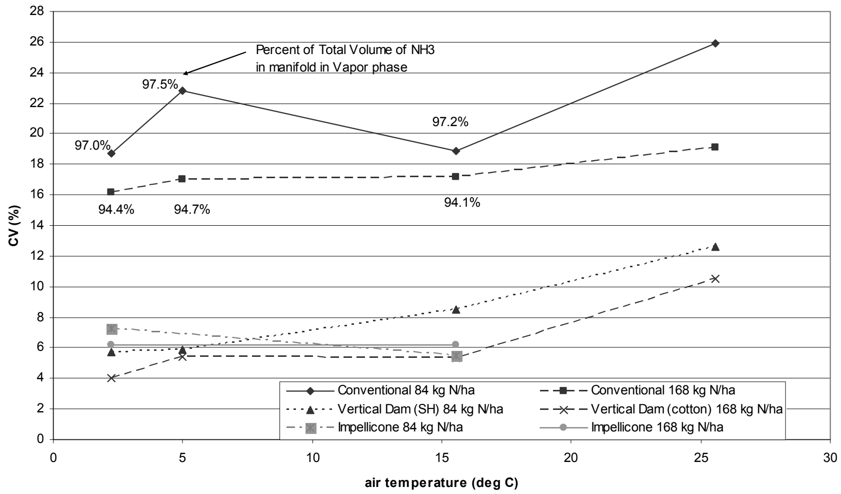


Figure 9. CV vs air temperature for fixed volume cavity manifolds

The Vertical-Dam (SH and Cotton) manifolds display this trend, as does the conventional manifold at the 168 kg N/ha (150 lb N/ac) rate. The conventional manifold at the 84 kg N/ha (75 lb N/ac) rate does not support this trend as at the 5° C (41° F) temperature the CV is 22.9%. The Impellicone manifold had very nearly the same CV at both temperatures tested and did not show any trend.

For the variable volume cavity manifolds the FD-1200 prototype had decreasing CV with increasing air temperature for the two lower air temperatures for both application rates (figure 10). CV continued to decrease with increasing air temperature at the 84 kg N/ha rate (75 lb N/ac), but increased at the 168 kg N/ha (150 lb N/ac) rate. The highest CV values for the Equa-flow™ manifold were produced at the intermediate temperature, and as such, no trend was observed.

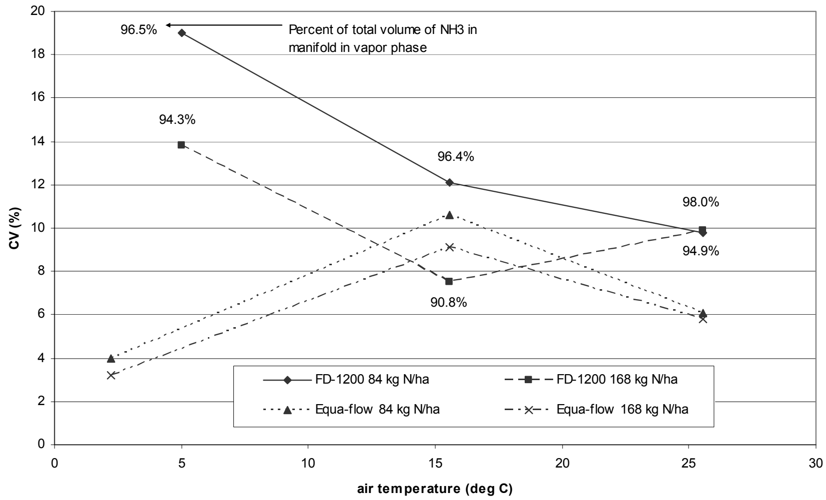


Figure 10. CV vs air temperature for variable volume cavity manifolds

NH_3 Quality and Distribution

If it is accepted that the data above supports the assumption that NH_3 does follow the saturation line in the form of a saturated mixture as it moves through the distribution system, comparisons between distribution and material quality can be made. Quality is defined as:

$$x = m_{vapor} / m_{total}$$

where: $m_{total} = m_{liquid} + m_{vapor} = m_f + m_g$

m = mass

Quality has significance for saturated mixtures only (Cengel and Boles, 1994). If NH_3 follows the saturation line, an adiabatic system with constant enthalpy ($h_1 = h_2 = h_n$) is implied. Constant enthalpy requires that all the energy exchange required for phase change within the NH_3 is provided by the NH_3 itself. To define the points along the flow path in this system, the following designations were assigned:

h_1 = enthalpy of NH_3 at the supply tank
$h_1 = h_{f1} + xh_{fg1}$
$xh_{fg1} = 0$ (NH_3 is 100% liquid at tank)

h_2 = enthalpy of NH_3 before the regulator
$h_2 = h_1 = h_{f2} + x_2h_{fg2}$

h_3 = enthalpy of NH_3 after the regulator
$h_3 = h_1 = h_{f3} + x_3h_{fg3}$

h_4 = enthalpy of NH_3 at the manifold
$h_4 = h_1 = h_{f4} + x_4h_{fg4}$

where: h_n = total enthalpy (kJ/kg)
h_{fn} = enthalpy of the liquid (kJ/kg)
h_{fgn} = latent heat of vaporization (kJ/kg)
$= h_g - h_f$
$x_n = (h_1 - h_{fn}) / h_{fng}$ = quality

These equations allowed for the calculation of quality (x) at each point along the flow path. Quality defines the partitioning between the liquid and vapor phases on a mass basis. In addition, using published data for the specific volume of the saturated vapor or liquid, the partitioning on a volume basis was calculated with the following equations:

x_n = quality = kg NH_3 in vapor if a 1 kg total mass is assumed

$1 - x_n$ = kg NH_3 in liquid

$x_n * sv_g$ = volume of NH_3 in vapor phase
sv_g = specific volume of vapor (m^3/kg)

$(1 - x_n) * sv_f$ = volume of NH_3 in liquid phase
sv_f = specific volume of liquid (m^3/kg)

$(x_n * sv_g) / ((x_n * sv_g) + ((1 - x_n) * sv_f)) * 100\%$ = % volume in vapor phase

Using these equations, the quality and volume partitioning of NH_3 through the distribution system was calculated for the manifolds used in the November 2000 through April 2002 tests.

Based on concerns in past research that the production and distribution of vapor within the manifold body are factors that may affect manifold distribution, the volume of vapor as a percent of total volume in the manifold was calculated using the equations listed above. Figures 9 and 10 have the percentage of NH_3 in the vapor phase by volume shown by each data point for the conventional and FD-1200 prototypes, as these two manifolds responses were closest to the hypotheses above. Datalogger failure prevented the collection of a data set for the Vertical-Dam manifold.

Only the conventional manifold at the 84 kg N/ha (75 lb N/ac) rate showed any correlation between CV and NH_3 volume in vapor, that of increasing CV with increasing NH_3 volume in vapor. Neither of the manifolds showed any correlation between air temperature and NH_3 volume in vapor. Based on the available data, no trends between CV, air temperature, and NH_3 volume in vapor could be defined.

Conclusions and recommendations

The seven experiments performed allowed a comprehensive look at the NH_3 distribution performance of 16 different manifold configurations. Based on the data collected, conclusions related to the design of a manifold effecting distribution were made. The number of evenly spaced outlets around a radial manifold did not have a significant effect on distribution (August 1999). The testing of the side-entry and tee-entry manifolds in March 2000 indicated distribution variation with the linear manifolds was greater than any of the radial manifolds by a factor of two. Results testing the conventional and Vertical-Dam manifolds indicate:

1. The conventional manifold consistently had the poorest uniformity. Distribution uniformity was statistically better at the 168 kg N/ha (150 lb N/ac) rate than at the 84 kg N/ha (75 lb N/ac) rate for the conventional manifold, and it had statistically worse variation than all Vertical-Dam manifolds except the Vertical-Dam (Corn) at the 168 kg N/ha (150 lb N/ac) rate.
2. Both the Vertical-Dam (Corn) and Vertical-Dam (Cotton) met the application rate goal. The Vertical-Dam (Cotton) had more uniform NH_3 distribution than the conventional manifold and the Vertical-Dam (Corn) manifold at the 168 kg N/ha (150 lb N/ac) rate.
3. The Vertical-Dam (SH) had good uniformity at the 168 kg N/ha (150 lb N/ac) application rate but did not meet the application goal because of metered flow in the manifold.

Other commercial and prototype manifolds available were tested in conjunction with the conventional and Vertical-Dam manifolds. These manifolds included the Rotaflow™, Equa-flow™, and FD-1200 prototype. Conclusions from this group were:

1. The Rotaflow™, Equa-flow™, and FD-1200 prototype manifolds had significantly lower variation in distribution than the conventional manifold at the 84 kg N/ha (75 lb N/ac) application rate, but only the Rotaflow™ and Equa-flow™ were lower than the conventional manifold at the 168 kg N/ha (150 lb N/ac) application rate.
2. The Rotaflow™ and Equa-flow™ manifolds had similar uniformity to the Vertical-Dam (SH and Cotton) and better uniformity than the Vertical-Dam (Corn).

Regarding modifications of the conventional manifold as compared to the standard conventional manifold with an elbow adjacent to the manifold to direct incoming flow, the addition of a 30.5-cm (10.0-in) pipe nipple below the manifold reduced variation by18% at the 84 kg N/ha rate and by 2% at the 168 kg N/ha rate. The addition of a similar nipple with a mixer helix inside the pipe did not improve performance. Current users of the conventional manifold may consider the addition of a pipe nipple below the manifold to straighten incoming flow.

Examining all the manifolds as a group across all experiments, only the conventional manifold had statistically higher distribution variation at the 84 kg N/ha (75 lb N/ac) application rate than at the 168 kg N/ha (150 lb N/ac) rate.

The measurement of temperature and pressure along the flow path indicated that NH_3 remains saturated as it moves through the system. Linear analysis of the theoretical pressure as predicted by the saturated condition against the measured pressure resulted in slopes very near one for most manifolds. The exception was the A-6600 manifold, where values recorded at the manifold were well within the liquid area of the pressure versus temperature plot. This resulted in a more shallow slope than the other manifolds. The A-6600 manifold was only tested during one experiment.

The standard error of prediction (SEP) was within +/- 17.3 kPa (2.5 psi) for all manifolds but the A-6600. These results support the assumption that NH_3 follows the saturation line as it moves through the application system, and predictions of quality and vapor partitioning based on theoretical saturation would give a reasonable representation of the actual temperature and pressure.

Calculations of quality and vapor partitioning were made using the assumption that NH_3 followed saturated mixture properties. The conventional manifold at the 84 kg N/ha rate showed a positive trend between NH_3 percent vapor by volume and CV, with CV increasing with increasing NH_3 percent vapor by volume. Other manifolds did not show any such trend.

The evolution of new manifolds has decreased the variability in application by nearly four times (CV of 22% for conventional at 84 kg N/ha vs new designs at approximately 6% CV). The adoption of manifolds with CV's of less than 10% could allow reduced application rates of NH_3 by excluding the "insurance" application.

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Literature Cited

Andrews, W. B. 1947. The use of anhydrous ammonia as a source of nitrogen. *American Fertilizer*. Vol. 107, pg. 9.

Boyd, P. M. 2002. Evaluation and design of anhydrous ammonia manifolds and application variation effects on corn yields. Ph.D. dissertation, Iowa State University.

Boyd, P. M., H. M. Hanna, J. L. Baker, M. White, and T. S. Colvin. 2000. Field evaluations of anhydrous ammonia distribution manifolds. ASAE Paper 00-1140. ASAE, St. Joseph, MI.

Cengel, Y. A., and M. A. Boles. 1994*. Thermodynamics: An engineering approach*. 2nd Ed. McGraw-Hill, Inc. New York.

Dinnes, D. L., D. L. Karlen, D. B. Jaynes, T. C. Kaspar, J. L. Hatfield, T. S. Colvin, and C. A. Cambardella. 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. *Agronomy Journal* 94:153-171.

Hanna, H. M., M. L. White, T. S. Colvin, and J. L. Baker. 2002. Anhydrous ammonia distribution during field application. *Applied Engineering in Agriculture* 18(4): 56-64.

Hedman, C. L., and J. R. Turner. 1954. Application of anhydrous ammonia fertilizer. *Agricultural Engineering* 35:801-803, 807

Jaynes, D. B., T. S. Colvin, D. L. Karlen, C. A. Cambardella, and D. W. Meek.2001. Nitrate loss in subsurface drainage as affected by nitrogen fertilizer rate. *J. Environ. Qual.* Vol 30: 1305-1314.

Karlen, D. L., L. A. Kramer, and S. D. Logsdon. 1998. Field-scale nitrogen balances associated with long-term continuous corn production. *Agronomy Journal* 90: 644-650.

Kocher, M. F., R. D. Grisso, and L. B. Bashford. 2001. Mass flow rate measurement of anhydrous ammonia to a single knife on an applicator using a simple thermodynamic model. Paper No. 01-1125. ASAE, St. Joseph, MI.

Kranz, W. L., C. A. Shapiro, and R. D. Grisso. 1994. Calibrating anhydrous ammonia applicators. Nebraska Cooperative Extension publication # EC 94-737-D.

Morgahan, J. T. 1980. Precautions on the use of anhydrous ammonia applicators in research plots. *Agronomy Journal* 72: 157-160.

Sands, J. K. 2000. *2000 Iowa Agricultural Statistics*. National Agricultural Statistics Sevice and Iowa Farm Bureau.

Schrock, M. D., J. J. Grimm, D. L. Oard, R. K. Taylor, T. C. Kolb, and J. D. Anderson. 2001a. Performance of a multipoint pulse-width modulation metering system for ammonia. *Transactions of the ASAE* 44(2): 211-216.

Schrock, M. D., R. K. Taylor, D. L. Oard, and J. D. Anderson. 2001b. Lateral distribution of NH_3 as affected by manifold configuration. *Applied Engineering in Agriculture* Vol. 17(6): 743-748.

Sonntag, R. E., and G. J. Van Wylen. 1982. *Introduction to Thermodynamics: Classical and statistical.* 2nd Ed. John Wiley & Sons. New York.

Weber, R. W., R. D. Grisso, C. A. Shapiro, W. L. Kranz, and J. L. Schinstock. 1995. Anhydrous ammonia application rate errors*. Applied Engineering in Agriculture* 11(2): 211-217.