# Performance of a Stacked Valve Multipoint Pulse Width Modulation (PWM) Manifold for Variable Rate Anhydrous Ammonia Application

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**ABSTRACT**

A pulse-width modulation metering system for anhydrous ammonia ($NH_3$) with a stacked manifold and one valve per knife was developed and tested for lateral distribution and flow characteristics. The manifold ensured that liquid ammonia was fed to the valves for correct metering. The distribution test was simulated on a trailer and flow rate from each shank was determined by a dynamic water absorption system. The flow was tested for valve duty cycle from 10% to 90% and recorded an average of 15.3 kg/hr (34 lb/hr) per knife at 10% to 106 kg/hr (235 lb/hr) per knife at 90% duty cycle. The lateral coefficient of variation was between 5.5 and 9.3%. The valve was modified with larger orifice and back-drilled increasing the flow rate to an average of 215 kg/hr (473 lb/hr) per knife at 90% duty cycle. Ammonia flow was a function of valve duty cycle and pressure drop across the valve.

**Keywords.** Pulse Width Modulation (PWM), Anhydrous Ammonia ($NH_3$), Variable Rate Fertilizer Application, Precision Agriculture.

## 1. INTRODUCTION

### 1.1 Background

Anhydrous Ammonia is the most popular source of nitrogen fertilizer in North America. Though there is increase in price in recent days, the low cost of ammonia relative to other forms of nitrogen fertilizer has encouraged its use, particularly for crops that require high amounts of nitrogen. The intensive use of chemical fertilizers has negative impact on the environment. In some cases farmers have over applied nitrogen fertilizer. The increased cost for over application and the crop response curve for nitrogen are such that the lower yield penalty for under applying is greater than the cost penalty for modest over-application. Farmers are also aware of the difficulties of applying ammonia uniformly, so they tend to compensate the non-uniformity by increasing the rate of application (Schrock et al., 2001). Over-application causes not only increased production cost, but also has been implicated in ground water contamination.

Variable –rate fertilizer application has shown promise to reduce the excess application of fertilizer. The variability can be gauged by the variability of crop yield and has become much more obvious with advent of precision farming technologies (Dinnes, 1998). Precision farming is a system concept that involves the development and adoption of knowledge based technical management systems with main goal of optimizing profit. An important aspect of this technology is the ability to vary the rate of all inputs including fertilizer (Clark, 1996). Variable-rate nitrogen application during the growing season has shown potential to increase crop yields and reduce nitrogen inputs.

Pulse width modulation (PWM) can be used to control flow by varying the valve duty cycle at a fixed frequency. By controlling the duration of the valve actuation pulse, one can vary the average amount of flow. Duty cycle (DC), expressed in percentage of time the valve is open, controls the flow in the system with higher duty cycle corresponding to higher flow. This concept has been widely used in the automotive industry (Bauer, et al., 1995) and its use has been spread to other areas including agricultural chemical application (Giles et al., 1996).

Use of PWM to control the flow of ammonia in precision application has the potential to improve lateral uniformity. It also can improve $NH_3$ application accuracy and control. Single point pulse width modulation (SP-PWM) system and multi point pulse width modulation (MP-PWM) system were tested earlier (Schrock et al., 1999) and showed encouraging results. Since application accuracy is the primary concern for variable-rate $NH_3$ application, PWM flow control is preferred to the direct injection due to its faster flow rate response. Performance of a multipoint metering system tested by Schrock et al., (2001) achieved single valve flow of over 100 kg/hr (220 lb/hr).

### 1.2 Objective

The objective of the research project was to evaluate the performance of stacked multi-point PWM manifold. The specific objectives were to measure the lateral distribution, to define flow vs DC relationship, and to investigate means of increasing flow.

## 2. METHODOLOGY

### 2.1 Manifold

A multipoint manifold was tested earlier by Schrock et al. (2001) to prove the concept of PWM technique in $NH_3$ application. That manifold was machined from a solid block of aluminum. The present manifold is a major redesign of the earlier version to enhance the heat transfer ability as well as to reduce manufacturing cost. It is multi-plate stacked valve system with built in heat transfer capabilities. Each aluminum (713 aluminum alloy) plate houses two valves, so the number of plates can be varied to produce desired number of outlets. As shown in Figure 1, $NH_3$ liquid and vapor enter from tank at ambient temperature and pass through a mesh screen into the inlet chamber. Gravity helps to separate vapor from liquid. $NH_3$ passes between cooling tubes to condense vapor into liquid. Cooled $NH_3$ Liquid enters the rail passage ready for metering. The PWM valve meters the correct amount of $NH_3$ into the outlet passage at much lower pressure. Some $NH_3$ liquid vaporizes in the outlet passage, reducing the temperature of the cooling tubes. $NH_3$ leaves the outlet tube and is routed to the knife for application to field. Two valve segments without end plates are shown in Figure 2.

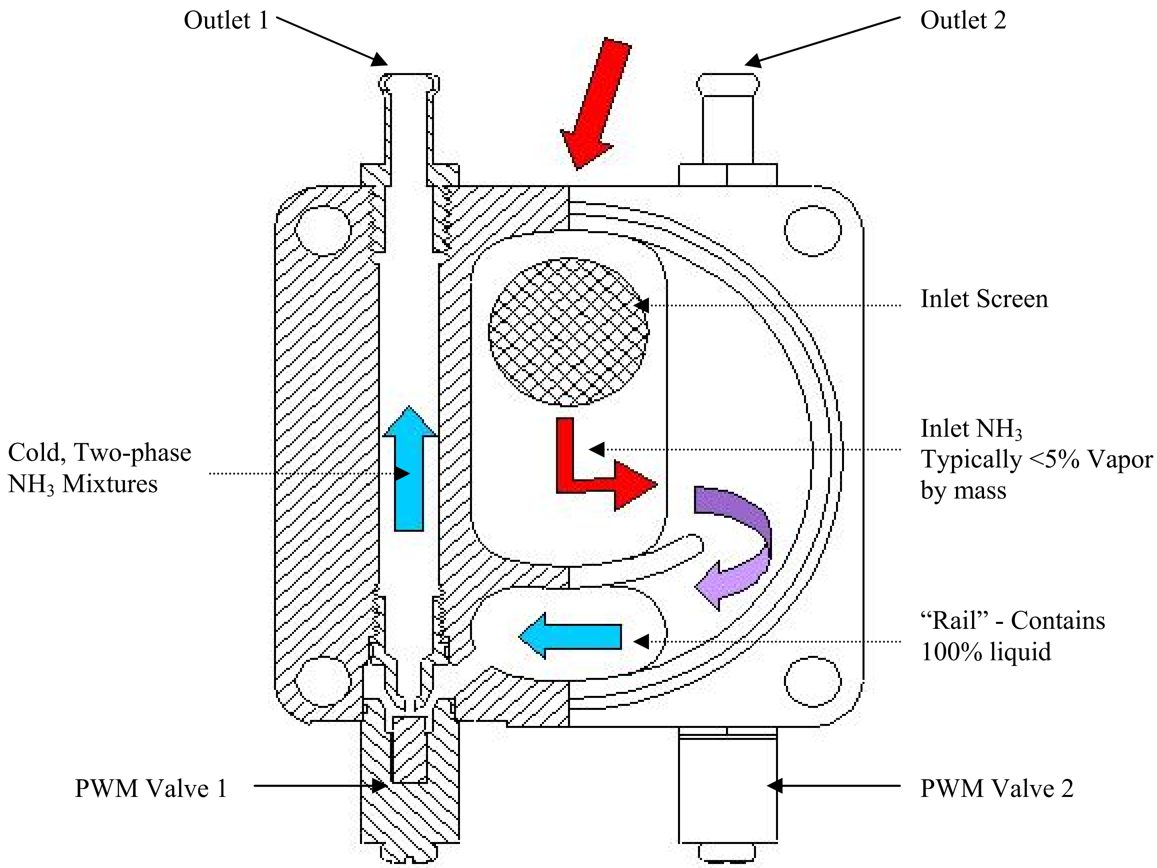


Figure 1. Cross-Section of Aluminum Valve Segment.

The inlet side of the PWM valve operates very close to the tank pressure while the discharge side is intended to operate at less than 400 kPa (60psia) even at very high flow. The manifold was instrumented for temperature and pressure sensing at various points. Figure 3 shows an external view of the manifold fitted with the gages and transducers.

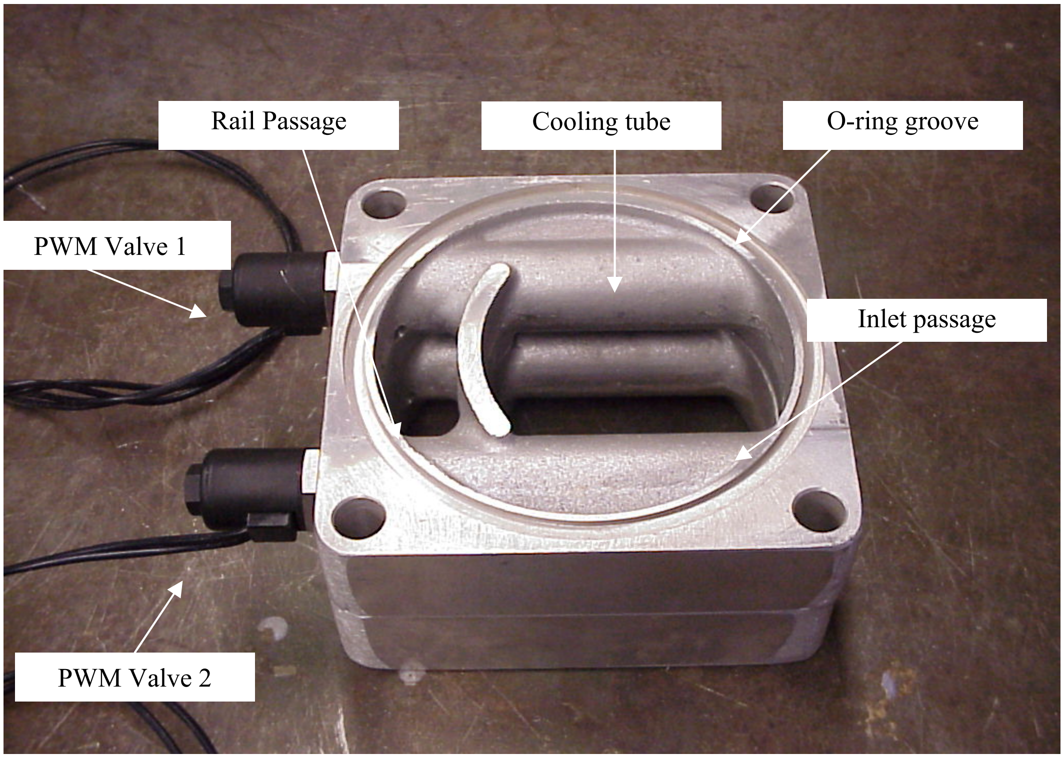


Figure 2. Aluminum plate with valves

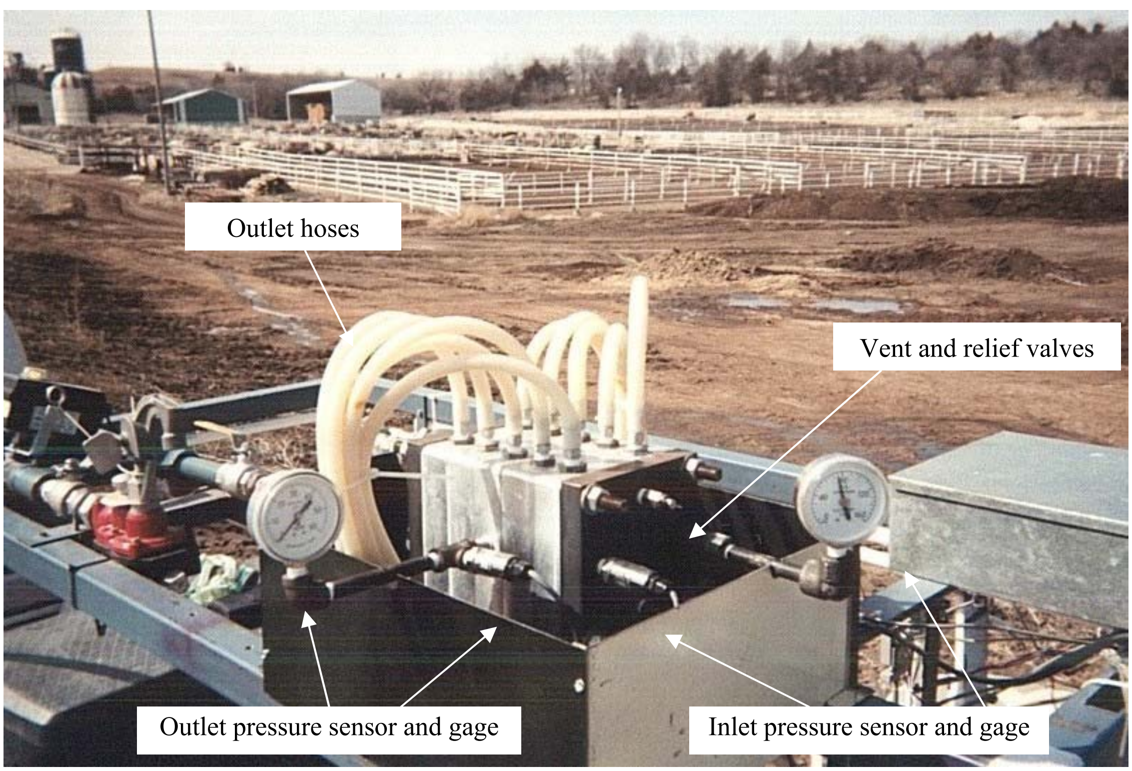


Figure 3: MP-PWM Manifold with instrumentation

**2.2 PWM Valve**

The valve used in this study has a Teflon seal on the plunger, which seals against a stainless steel seat that is integrated into the valve base. The valve orifice is 2.36 mm (0.092 in) in diameter. The diameter of the outlet increases from the 2.36 mm (0.092 in) valve orifice to the 6.35 mm (0.25 in) valve outlet passage to the 12.7 mm (0.50 in) outlet passage in the aluminum segment. A disassembled valve is shown in Figure 4. Each valve plunger is lifted by a 14 Watt, 12-vdc coil. The coils are actuated by a 3 Hz Capstan Sharpshooter PWM driver circuit. Three Hz valve frequency is selected as a compromise between valve wear and concern for uneven longitudinal distribution caused by pulses of $NH_3$ at lower frequency. The driver circuit produces duty cycles from 3% to 100%. Commercial 9.5 mm (3/8 in) hoses of equal length [2.1 m (7ft)] were used to discharge the $NH_3$ from the valve outlet to the steel knife tubes. Tube ends were flattened and cross-drilled with two 4 mm (0.16 in) holes by the manufacturer.

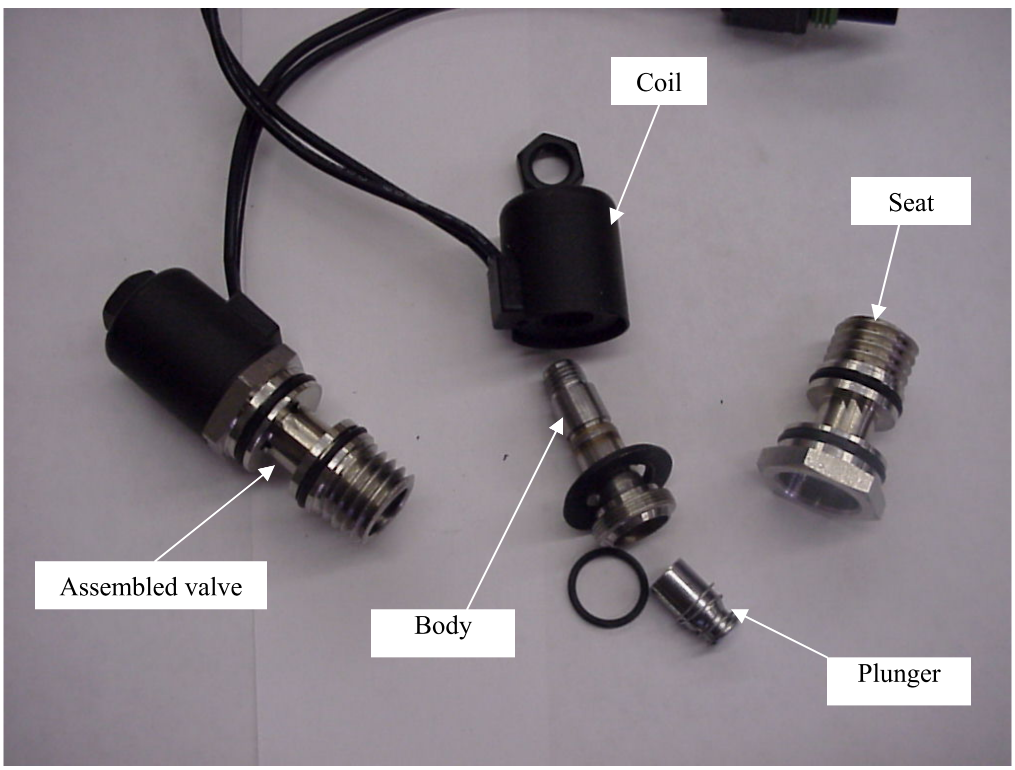


Figure 4. PWM Valve; nut, coil, body, o-ring, plunger and seat

**2.3 Distribution Test**

The distribution was tested on a trailer using a dynamic water absorption technique to measure the $NH_3$ flow per knife. The test set up (Figure 5) has ten water buckets and each weighed by load cells as $NH_3$ was discharged. All necessary safety precautions for $NH_3$ handling were followed. The strain-gage load cells, with a rated capacity of 220N (50 lb) sensed the weight of the bucket. Signal noise caused by turbulence and vibration was addressed by sampling each channel by 50 readings per second and using this one second average. Data were logged to a personal computer and the raw data were post-processed to yield results immediately after each test run using MathCad (Mathsoft Engineering & Education, Inc., Cambridge, MA). The mass flow rate of $NH_3$, the pressure readings and the knife to knife coefficient of variation (CV) were noted from the data analysis. CV is the statistical measure of deviation of a variable from its mean and is calculated by dividing standard deviation by the mean value. The test runs were sequenced at a 10 minute interval to obtain consistent manifold temperature. This also reduced data handling errors and exposure of personnel to $NH_3$.

Absorption buckets of 26.5 liter (7 gallons) nominal capacity were used and they were filled to about 15 liter (4 gallons) level with fresh tap water after each test run by a water line connected to a nearby source. Buckets were emptied by a vacuum cleaner and the solution was discharged in a nearby livestock waste treatment lagoon.

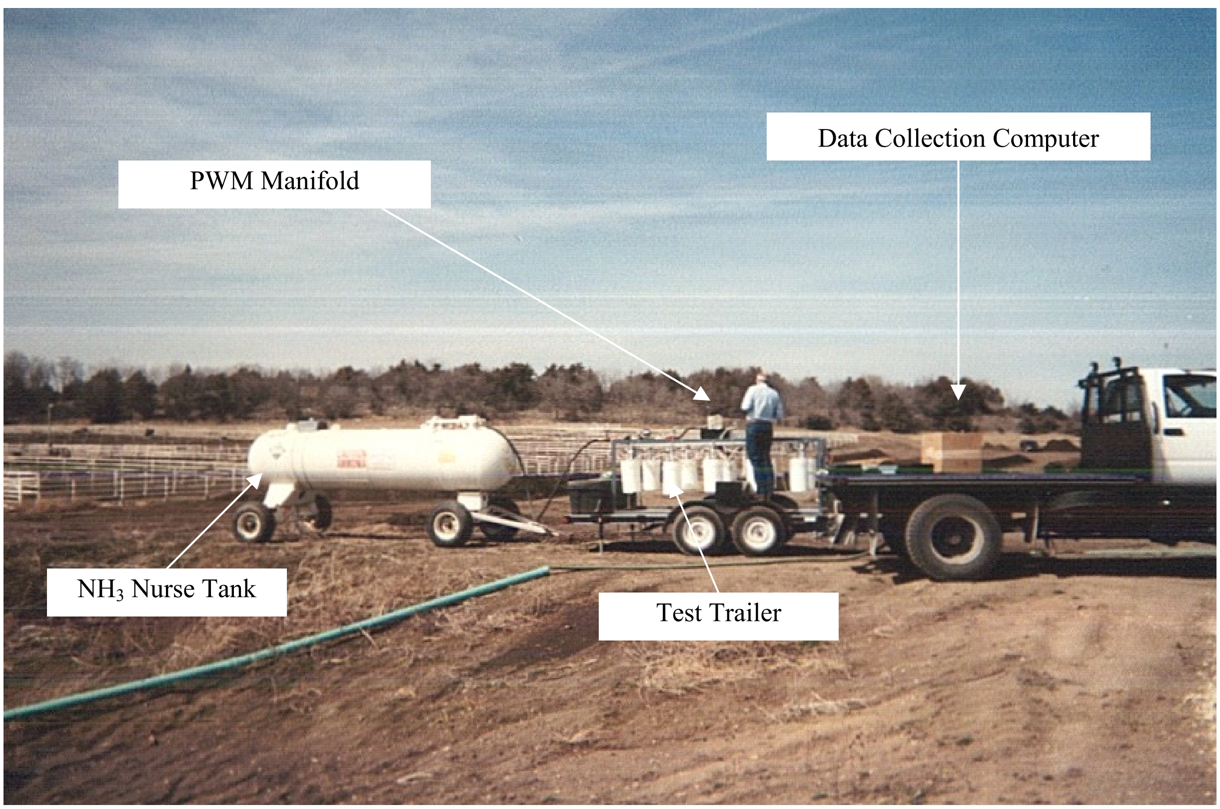


Figure 5. $NH_3$ distribution trailer

Temperatures were monitored at the rail, manifold inlet, manifold outlet, external body of the manifold, outlet hose and a knife by copper-constantan thermocouples. The pressure was monitored at manifold inlet, manifold outlet, rail and at a discharge knife by transducer MSP300-250-P-3-N-1 from Measurement Specialties, Inc., Hampton VA. Pressure transducers were calibrated against a manual gage. An IOTech DaqBook 100 (IOtech, Inc., Cleveland, Ohio) data acquisition system was used to communicate to a laptop computer over a parallel port. A DBK-13 expansion card was used to amplify the low-level load cells signals and a DBK-19 expansion card was used for amplification, cold-junction compensation, and linearization of the thermocouples. A DBK-11 expansion card was used to receive the pressure transducer.

To enable the accurate flow control in $NH_3$ application a functional relationship between DC, pressure and flow was needed. A physical flow model based on basic orifice flow equation was used to predict the valve flow (Schrock et al., 2001) and is given below:

$$F = C * DC * (\Delta P)^{0.5} \quad (1)$$

Where: F = $NH_3$ flow (kg/hr)
C = Regression coefficient
DC = Duty cycle of PWM coil pulse width (%)
$\Delta P$ = Pressure drop across the PWM valve (kPa)

## 3. RESULTS AND DISCUSSIONS

The data acquisition system was validated by running at 0% DC. The processed data indicated that three valves showed negative flow and seven of them showed positive data with average flow of 0.166 kg/hr (0.365 lb/hr) per knife, which is negligible. There were 6 replications of five DC for a total of 30 runs taken over three days. The results from the distribution test are summarized in table 1 and the values are the average of those 6 replications.

Table1. Test results for flow, pressure and distribution. Each row represents mean of six replications

| Duty Cycle (%) | Flow/knife (kg/hr) | CV (%) | Pin (kPa) | Pout (kPa) | High flow/low flow |
|---|---|---|---|---|---|
| 10 | 15.3 | 6.11 | 469.2 | 13.8 | 1.23 |
| 30 | 43.0 | 5.49 | 471.3 | 86.3 | 1.07 |
| 50 | 67.5 | 6.71 | 474.7 | 100.1 | 1.18 |
| 70 | 88.9 | 7.87 | 472.7 | 124.2 | 1.32 |
| 90 | 106.2 | 9.29 | 457.5 | 139.4 | 1.29 |

A graph of flow against flow parameter ($DC*\Delta P^{0.5}$) was drawn to establish the flow prediction model considering no flow at 0% duty cycle. The flow model in Figure 6 is quite linear with $R^2$ value of 0.9864 and given by F = 6.7756 ($DC*\Delta P^{0.5}$) with DC expressed in decimal form. The system has the capacity of flow rate of about 106 kg/hr (235 lb/hr) per knife at 90%DC. The knife-to-knife CV among 10 valves ranged from 4.2% in a run of 10% DC to 11.2% in a run of 70% DC as seen in the Figure 7. There is no consistence relationship between DC and knife-to-knife CV.

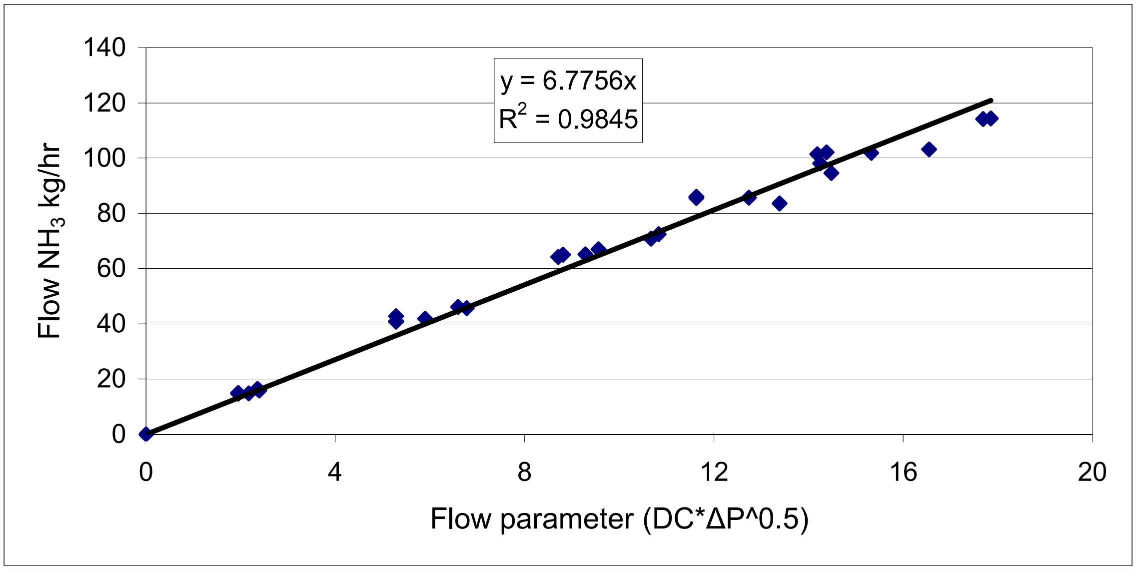


Figure 6. Flow versus flow parameter with regression

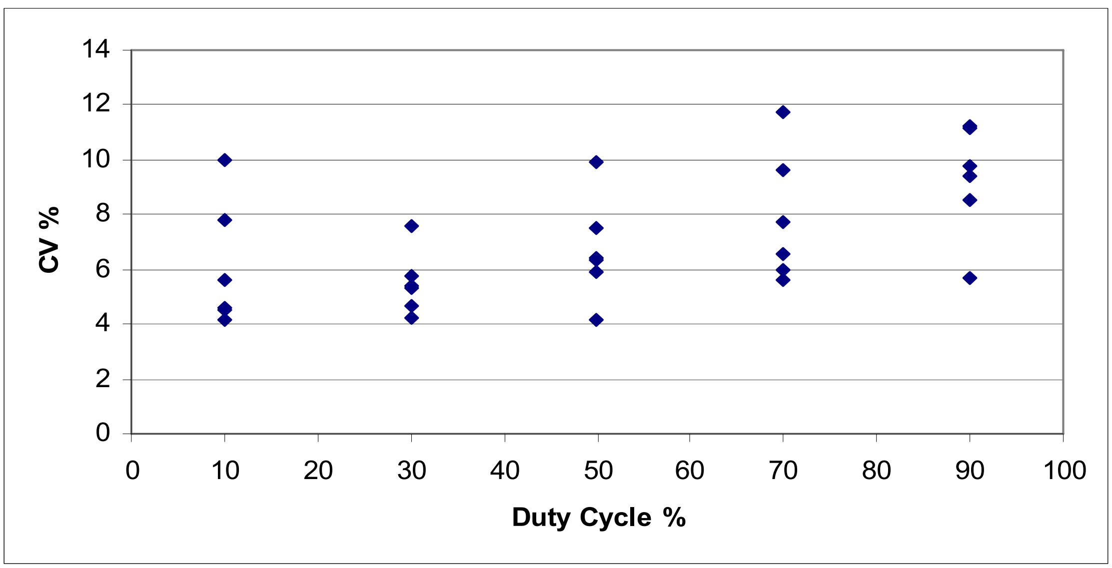


Figure 7. The knife-to-knife coefficient of variation in flow at different DC

### 3.1 Valve Modification

Due to a small diameter outlet passage in the valve body, it was believed that high back pressure was restricting the flow. Singh et al., (2001) studied mass flow rate of refrigerant R-134a through orifices tubes of different diameters and length and concluded that the flow rate was a strong function of diameter, inlet pressure, inlet sub-cooling and a relatively weak function of length.

They also developed a semi-empirical model and on the basis of that, the valve was modified and two new prototypes were built to increase the flow rate. For one, the valve orifice was enlarged to 3.97 mm (0.156 in) and the outlet passage was back drilled to increase the diameter. Second, keeping the same inlet orifice diameter of 2.36 mm (0.092 in) but the outlet passage was back drilled.

The two new valve designs were tested simultaneously with the old design in the same environment using the same manifold. The flow rates from the two new valve designs were expected to be higher and hence the flow from each valve was divided in to two buckets. This was done in order to reduce bucket motion at high DC which was experienced during initial testing. An unmodified valve was incorporated in the manifold keeping the earlier condition of one valve flowing to one bucket. In this distribution test we had one experimental unit for each valve and the data were taken from three replications at three different DCs.

The distribution results are tabulated in Table 2 and the graphs of flow versus flow parameters of each valve are shown in Figure 8. It was evident that both the increase in orifice diameter and back drilling substantially increased the flow. The new large valve achieved 170 kg/hr (375 lb/hr) at 90% DC, 450 kPag (65 psig) tank pressure. The back drilling helped the original valve substantially, increasing flow to about 147 kg/hr (325 lb/hr) at the same DC. Therefore it was decided to conduct a full set of tests with the larger orifice valve [i.e. 3.97 mm (0.156in)] and back drilled.

Table 2. The results of three different valve design (Average of 3 replications)

| | | 3.97 mm orifice new | | 2.36 mm orifice new | | 2.36 mm orifice old–split | | 2.36 mm orifice old–single | |
|---|---|---|---|---|---|---|---|---|---|
| DC % | Pin (kPa) | Flow (kg/hr) | Pout (kPa) | Flow (kg/hr) | Pout (kPa) | Flow (kg/hr) | Pout (kPa) | Flow (kg/hr) | Pout (kPa) |
| 20 | 483.0 | 49.0 | 23.0 | 37.9 | 36.8 | 36.8 | 18.4 | 36.9 | 20.7 |
| 50 | 425.5 | 103.3 | 39.1 | 83.8 | 69.0 | 77.3 | 48.3 | 78.4 | 85.1 |
| 90 | 460.0 | 174.2 | 96.6 | 150.0 | 108.1 | 124.9 | 78.2 | 118.8 | 179.4 |

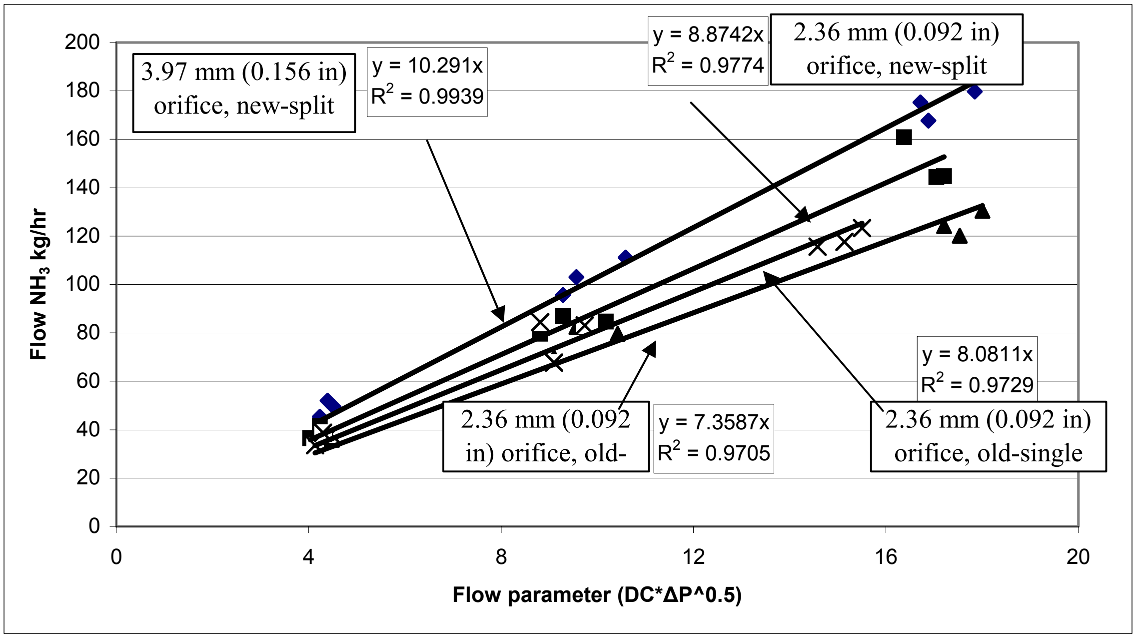


Figure 8. Flow graphs of valves of new and old designs

### 3.2 Full Distribution Test for the Large Valve

A full set of new design valves with the 3.97 mm (0.156 in) orifice was tested for flow distribution. The flow from each valve was divided into two buckets, so the test consisted of five valves in the manifold. The results from the distribution test are summarized in Table 3, and a graph of flow rate against flow parameter is shown in Figure 9. The flow reached 215 kg/hr (470 lbs/hr) per knife at 90% DC with 860 kPag (125 psig) tank pressure. The knife-to-knife CVs were low, ranging from 3.13% at 20% DC to 7.4% for 50% DC. The flow model for the larger valve found to be F = 8.9846 ($DC*\Delta P^{0.5}$) with $R^2$ value of 0.9906.

Table 3. Results of full test for the large valves (Average of 3 replications)

| DC (%) | Flow kg/hr | CV % | Pin kPa | Pout kPa | High flow/low flow |
|---|---|---|---|---|---|
| 20 | 50.1 | 5.27 | 924.6 | 43.7 | 1.31 |
| 50 | 120.1 | 6.22 | 922.3 | 112.7 | 1.30 |
| 90 | 214.7 | 4.28 | 920 | 250.7 | 1.15 |

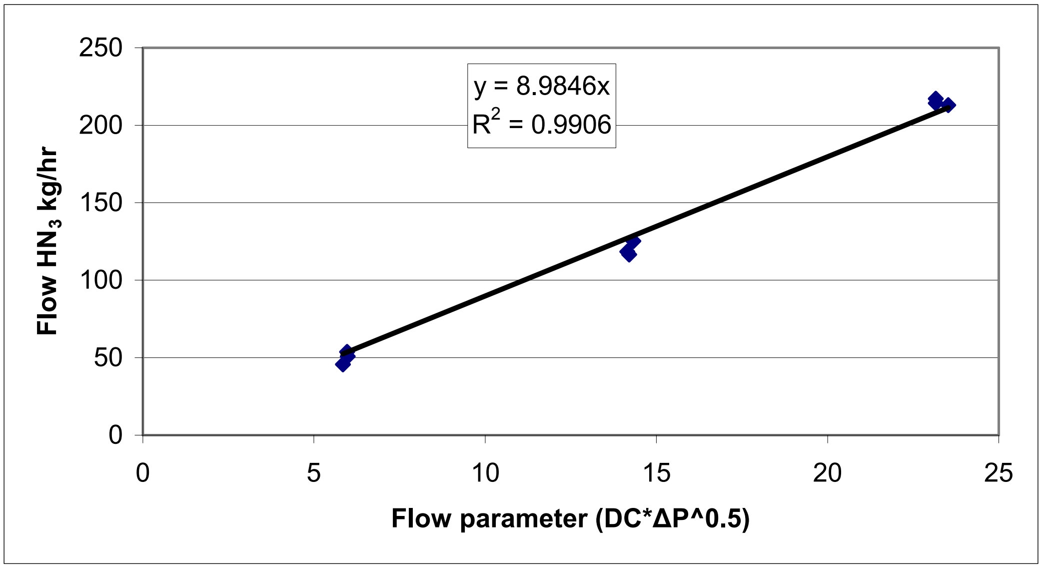


Figure 9. The graph for flow model of 3.97 mm back drilled valve

## 4. CONCLUSIONS

This study was undertaken to test the performance of a segmented multipoint PWM manifold with solenoid valves for variable rate anhydrous ammonia application. The following conclusions can be drawn from the study:

1. The system is capable of applying as high as 215 kg of $NH_3$ per hour per knife at 90% duty cycles and as low as 15 kg of $NH_3$ per hour at 10% duty cycles.
2. The knife-to-knife coefficients of variation were usually below 10%, with as low as 4% achieved at lower duty cycle.
3. A simple flow model, $F = 8.9846\ (DC*\Delta P^{0.5})$, can accurately predict the $NH_3$ flow rate based on the duty cycle of the PWM valve and ΔP across the valve.

## 5. ACKNOWLEDGEMENTS

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