# OPTIMIZING A TEXAS INDUSTRIAL REMCOR SOLENOID VALVE FOR PULSE -WIDTH MODULATION APPLICATIONS

By

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Thesis Advisor

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# *Chapter I*

# *Introduction*

Today, a major push in farming industry is for the integration of new technology with farm equipment to increase the efficiency of the farming process (Anglund, and Ayers 2003). Many areas within the farming process should be analyzed for improvement in efficiency. One of these areas is in the application of agricultural chemicals.

## *Precision Agriculture*

Precision agriculture techniques are widely adopted to improve both quality and quantity of crop yields, eliminate costs of farming process, and decrease effects of applying fertilizer and pesticide to the crops (Bowers. et.al 2001). New equipment for precision agriculture is being developed in light of the existence of spatial variability of plant and soil attributes. This equipment applies crop inputs such as fertilizers, pesticides, etc, at variable application rates. This variability can be measured by using yield monitors, soil sampling, and optical sensing. Optical sensors provide a continuous stream of data to the controller so that inputs can be varied over small areas through out the field.

## *Challenges in Application*

There are some challenges associated with that method like accuracy of the data collected by the sensor, time required for transferring this data to the spraying system and then to the crops. This time is critical because any delay of the response may lead to misapplication of the treatment on targeted area. In this process, the time delay can be divided into three phases

1. The time delay associated with transferring the data to the spraying systems.
2. The time delay associated with the spraying system.
3. The time delay associated with the combination of vehicle speed, and fluid velocity.

To improve the variable rate applicator, this time should be minimized so that margin of error in applying the material becomes small and the accuracy and precision of the variable rate technology increased. Moreover, having a very high accuracy for applying chemicals will attract more farmers to adopt this technology.

**Solenoid Valve**

Solenoid valves are widely used in many fields whenever fluid flow has to be controlled automatically. The wide variety of different designs, which are available, enables the users to choose a valve specifically to suit virtually any application. The solenoid valve is a valve that is opened and closed by an electromagnetic forces. When the valve is energized, magnetic field builds up which pulls a plunger against the action of a spring.

**Time Response.**

An important factor that must be considered for the use of spraying system is the response time. The time to respond is the period of time between the emission of the control signal to actuate the valve and the effective corresponding change of application rate. This time depends on several essential system factors and can put the agricultural operation at risk if not considered (Baio and Balastererire, 2002). The faster a sprayer valve can open and close the smaller the area that the sprayer can treat precisely. Theoretically, the higher the frequency the valve is pulsed, the finer the application resolution achieved. Practically, valves have a maximum frequency at which they can pulse due to their physical characteristics (Holtz et al., 2000).

Selecting a valve or optimizing performance of an existing valve are two possibilities to obtain valves acceptable response times. This research investigates optimizing the performance of a commercially available solenoid valve for applying agricultural materials.

## *Objectives*

The objectives of this research are:

**1.** To model the dynamic response of a solenoid valve to explore the parameters that have some effect on the valve performance.

**2.** To modify, based on the dynamic model, the part(s) of the valve that have some influence on the valve performance.

**4.** To investigate about the effect of the operational conditions, like voltage and pressure, then to run a test to observe the results.

**4.** To compare the performance of the original valve with the modified valve in terms of response time.

# Chapter II

# REVIEW OF LITERATURE

## Modeling The Dynamic Response

Solenoid valve manufactures usually do not provide information on response time or frequency response. Further, it is only recently that the dynamic behavior of solenoid valves has been comprehensively studied. The electro - solenoid - hydraulic valve is an electro-mechanical interface, where the electric current is transformed into magneto-motive force acting on a spool. (Lu and Jensen 2003) presented a model of the dynamic response for a fast-action micro-solenoid valve for pulsed detonation fuel injection. They found that the valve opening lagged by a constant time delay for a range of frequencies from 50 – 110 Hz when excited at 12 volts. The magnetizing current lags the exciting current creating a phase delay at all frequencies.

Pohl et al. (2000) developed a semi-empirical dynamic simulation model of a fast 2/2 switching valve. The model predicted the valve characteristics for a widely range of working conditions in the form of supply pressure and voltage. The characteristics of the valve that they studied were current through the coil of the solenoid, magnetic flux density, and armature displacement. Zhang, et al. (2000), developed a mathematical model for a high speed digital valve.

Zheng (2001) presented theoretical and experimental study of the dynamic response of a cylinder deactivation hardware system. The dynamic response was characterized by a physical model. Through simulation and experimental data analysis, the effect of operating conditions on the dynamic response was captured and characterized over a wide range of operating conditions. Reed (2001) tested a Texas Industrial Remcor valve, with the objective of identifying the pressure response time. He found that the valves had a range of 20-50ms response time, which is the flow-opening time only.

Holtz, et al., 2000, evaluated the dynamic response of three commercially available sprayer valves used in variable rate application of fertilizer and pesticides. Also, the study identified the minimum treatment distances for different ground speeds for each valve.

**Design and Operation Criteria**

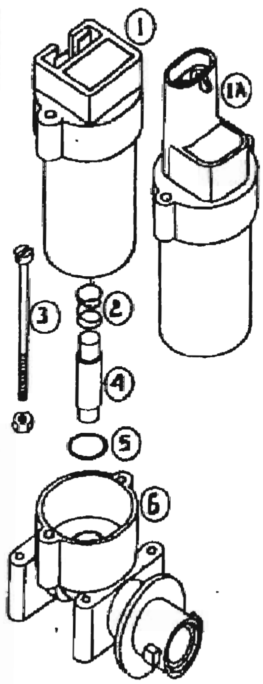
Zhang et al., 2000, identified the following design principles to optimize solenoid valve performance based on the mathematical model:

1. The voltage should be high (24 volts) and the current low,
2. A magnetic material with low conductivity is advantageous.
3. The magnetic path length should be shorter.
4. Stroke should be small to reduce the flow force.
5. Connecting coils in parallel allows high-speed operation.
6. Armature mass need to be small for higher acceleration.

# Chapter III

## *MATERIALS AND METHODS*

A Texas Industrial Remcor 2602 (International Corporate Offices and Manufacturing, P.O.Box 3704, Temple, TX 76505) solenoid valve was used in this study (Figure1). The valve contains a coil, a spring, and a plunger with a viton seat.




**PARTS LIST**

| Ref. | Part No. | Description | No. Req. |
|---|---|---|---|
| 1 | 2188 | Coil............................ | 1 |
| 1A | 2477 | Coil w/Weather Pack Connector.... | 1 |
| 3 | | 6-32 x 2 Screw w/ Hex Nut........ | 2 |
| 4 | 2239 | Plunger w/Viton Seat............. | 1 |
| 5 | 1977 | "O" Ring, .014 Viton............. | 1 |
| 6 | 2488 | Valve Body, .148 Orifice......... | 1 |

**Figure 1. A Disassemble 2602 Solenoid valve. (Source: Texas Remcor valve's Specification sheet).**

The Viton O-ring in this valve had a 1/4 in NPT female inlet and a standard agriculture nozzle body outlet. The body of the valve was made of nylon with 30% glass fibers. The coil was made of 304 and 430 F stainless steel. The valve was a direct lift type, i.e. the coil pulled the plunger to a stop in the coil housing acting against the pressure of the liquid plus the spring compression force. The coil was completely sealed and it has 59 turns/layer. The total turns was1030, and the coil wire length was 5.461 m. The plunger moves 1.24 mm from closed to open. The diameter of the orifice of the valve was 7.8 mm. The maximum operating pressure of the valve is 551.6 kPa (80 psi). The manufacture's specification for operation states that the voltage should be 12 volt, maximum pressure 862 kPa (125 psi), and a current of 0.85 amperes.

The source of the pressure in this experiment was the air pushed into the pressure container to force the liquid to flow under the desired pressure. The pressure container has been used as a pressurized reservoir for this project. The brand name of this container is Spartan NSDA-VS-O made by Cornelius Co. Anoka, MN USA, serial number 84003478. Four Ashcroft pressure gauges were used to measure the pressure in the test apparatus. They are made by Delavan – Delta Inc. The gauge connection is ¼ NPT, 100-psi maximum pressure; the serial number is 481010-5-32781-7-30-G-1 (Industrial Instrument Operations, Berea, Kentucky, 40403). A simple function generator was applied to generate the solenoid drive signals. This generator was fabricated in the Biosystem and Agricultural Engineering laboratory by the electric technician Mr. Michael Veldman. It has the ability to vary the signal frequency and the pulse width. It required a 12 VDC power supply, and was connected directly to the solenoid valve. A variable voltage power supply was used as a source of power for the solenoid valve, (809A Model), Harrison Laboratories Inc, (Berkeley Heights. N.J.). Power supply had a voltage range from 0 to 40 volt, and from 0 to 10 amperes. The voltage applied to the solenoid was measured with a Fluke 77 III multemeter made by Fluke Corporation USA (serial number 72850460). A digital balance was used to measure the mass of the original and modified plungers. This balance is made by Denver Instrument Company (TR-8102D). The pressure waveform was sensed with a pressure transducer made by MSI (Measurement Specialties Inc), Fair Field. New Jersey 07004, USA. In order to obtain the valve response to an input signal, a pressure transducer was installed near to the nozzle in each tested valve. That was done by drilling into the valve body until reaching the fluid chamber. Two pressure transducers (MSP-400-250-P-4-N-1) were used in this study. The pressure range for this transducer is 0-250 psi, the output from 1-5 volts with 10-30 V supply, and pressure port using 1/4 NPT threads. It has an accurate to ±0.5% of full-scale output at room temperature. For accurate measurements, the pressure transducers were installed in the flow path near to the nozzle. Signals produced by the solenoid valve – solenoid voltage, and pressure were captured by a digital oscilloscope Tektronix Inc. (Beaverton, OR. USA (TDS 210 serial number C038140). This oscilloscope equipped with one of the 200 series extension modules (071-0409-00). The oscilloscope has two channels and the sampling rate is 1 GS/s and 2,500 samples could be stored. This extended module has the feature of transferring the captured signal from the oscilloscope to a computer using text capture software. Also, the oscilloscope could directly print traces through the RS232 communication port. This study required precise time measurements capturing the moment the plunger started its movement to pen or close the valve and the time when flow reached its highest or the zero level. The oscilloscope had some limitations. For example, when collecting measurements at the very high frequencies, the oscilloscope may not capture and display the complete waveform. As a result, one must use the decrease sampling frequencies to capture the entire pattern, which diminishes time accuracy. Time measurements depended in some part on the personal judgment when manually positioning the cursor to obtain time. The improvement in the valve performance (if any) will be in milliseconds therefore, it became a must to have an accurate method to observe this improvement. The digital waveform data as record of points enabled to sight any change of the time and made the measurements more accurate and reliable.

One of the objectives of this study was to investigate the behavior of the solenoid valve in terms of the time delay for reaching the full flow rate value, and time to shut-OFF the flow completely. For this purpose, two different types of nozzles were tested. Three orifice diameters were used for each nozzle type. Those six nozzles are currently in use for some PWM applications at Oklahoma State University. The first type, the Quick Tee Jet included Quick Tee Jet TP00015-SS, TP0003-SS, and TP0006-SS. The flow rates of those nozzles are 0.568 liter/min (0.15 GPM), 1.14 liter/min (0.3 GPM), and 2.27 liter/min (0.6 GPM) respectively (Spraying Systems Co information sheet). This type of nozzle contains of a cap, (Spraying System Corp, Wheaton IL) made of Silicone, A Tee jet sprayer tip made of stainless steel, and seat gasket, made of EPDM rubber. The other type of nozzle called Stream Jet by NTech Inc. has three different sized nozzles. Those nozzles were made from a Spraying nozzle System Co. custom drilled for three orifices by NTech Industries, Inc. Ukiah, CA. To distinguish between them they were labeled by their flow rate; i.e. the first nozzle with a yellow cap and orange tip was labeled as Modified Stream Jet 0163, since its flow rate is 0.617 liter/min (0.163 GPM). Second one with blue cap and orange tip was labeled as Modified Stream Jet 0360, as its flow rate is 1.36 liter/min (0.360 GPM). Finally, the third nozzle with green cap and yellow tip was labeled as Modified Stream Jet 0667, with flow rate of 2.52 liter/min

(0.667 GPM). This type of nozzle has a cap and tip made of silicone, seat gasket made of EPDM rubber. The cap is designed with grooves that fit locating lug on the nozzle body. Three solenoid valves (2602) were installed in the test apparatus. One of them was assigned to the original valve; another the modified valve, and the other one was used to do the quick tests like new plunger or volume designs. The test apparatus included a pressure vessel valve to adjust the pressure, a pressure container connected to the air pressure supply, three solenoid valves, four pressure gauges, and four fluid valves (Figure 2).

**Figure 2. Test apparatus including air supply, pressure regulator, pressure gauges, Remcor solenoid valve, and nozzles.**

**The Solenoid Valve Dynamic Model**

The PWM technique uses digital signals as its input to the solenoid. The signal is nearly instantaneous, but the critical issue after the signal is applied is the time it takes the solenoid valve to actuate the order i.e. the time between when the signal is applied and the valve action is complete. Clearly, the PWM procedure requires a very fast response from the solenoid valve to be effective. Therefore, solenoid valve behavior needs to be carefully analyzed in order to identify the major affective variables. Then, the next step will be to explore possible ways to improve those variables for better performance. In short, modeling the dynamic response for the solenoid valve is the key point in improving the valves performance. As a result, a dynamic model has been written for the solenoid valve (Texas Industrial Remcor 2602), considering both the electrical, mechanical, and the hydraulic forces. Equation 1 describes this model.

$$m\ddot{y} + C_d\dot{y} + F_s = F_e + F_f \qquad \text{.............. (1)}$$

$$m\ddot{y} + C_d\dot{y} + K\,y = \frac{2\mu_o\,\pi\,N^2\,i^2}{\dfrac{4x}{d} + \dfrac{y}{d+y}} + A_p\,\frac{\rho\,\dot{y}^2}{2C_d} \qquad \text{......... (2)}$$

Nomenclature

| | | |
|---|---|---|
| m | [kg] | Plunger mass |
| $C_d$ | [kg/sec] | Damping coefficient |
| k | [N/mm] | Spring constant |
| y | [m] | Variable gap length in the direction of the magnetic flux path (m) |
| $F_s$ | [N] | Spring Force |
| $F_e$ | [N] | Electromagnetic force |
| $F_f$ | [N] | Fluid force |
| $\mu_o$ | [Wb/A.m] | The permeability of free space |
| N | [-] | Number of turns per unit length |

| | | |
|---|---|---|
| i | [A] | Current |
| d | [m ] | Diameter of the plunger |
| x | [ m] | The plunger displacement. |
| $A_p$ | [$m^2$] | Area of surface of the plunger subject to the pressure |
| ρ | [$kg/m^3$] | Mass density of fluid |
| p | [pascal] | pressure. |

After modeling the dynamic response, it can be seen that there are several parameters that have influence in the valve performance. Although this study had not addressed all of those factors due to some limitations, it has covered, the most important ones. One of the critical issues of the performance of the solenoid valve is the opening and closing time for the plunger. During the opening operation, equation (1) can be rewritten as

$$F_e = F_f + m\ddot{y} + C_d\dot{y} + F_s \qquad \text{.....................} (3)$$

In this equation it can be seen that electromagnetic force needs to overcome the fluid, and the mechanical forces. Therefore, in order to move the plunger faster against all these forces, the electromagnetic characteristics need to be changed. In general, the magnetic field about a wire can be describe simply as:

$$F_e = L * B * I * \sin\theta \qquad \text{...............................} (4)$$

where L is the wire length (m), B is the intensity near a current (Wb/m), and I is the current (A). Apparently, increasing the current in the solenoid coil will increase the magnetism and will linearly increase the solenoid force. Also the solenoid magnetic force increases proportionally to the number of coil turns.

In this study, the solenoid valve was operated at three levels of voltage starting from 12 volt (the voltage recommended by manufacture), 24 and 36 volt. By doing so, an improvement would expect in the valve speed. Regarding the plunger closing operation, it has been assumed that the forces closing the plunger are spring force and fluid force. In this case, the spring pushes the plunger toward the orifice when the coil discharged. As a result, it has been assumed that by increasing the spring force, the valve would close faster.

**Modifying the plunger**

The relationship between acceleration and mass is given to be:

$$a = F/m \quad (5)$$

Where a is the acceleration [$m/s^2$], F is the force [N], and m is the mass [kg]. Accordingly, the option of reducing the plunger mass has been examined. This option should improve the plunger performance in both directions. So with respect to opening operation, the force in equation 5 becomes the electromagnetic force. Where as in closing the valve, this force becomes the spring force and the fluid forces. But, reducing the mass of the plunger might reduce the electromagnetic force, because the magnetic field will not be less sufficient to pull the "new" plunger open. Two plunger modifications were investigated. One modification was to drill a hole axially through the plunger from the top to the bottom, but not through the plunger rubber seat. After that, a piece of metal was used to cover the hole. Another modification perform by doing the same thing done to the first plunger except that instead of covering the plunger's head, a piece of iron as large as the original head was inserted inside the plunger to replace the old one. Finally, a third design has been implemented in which the weight of the plunger had reduced to 6.53g from the original plunger mass of 12.24g. This modification was accomplished by incising grooves on the six plungers sides. That avoided reducing the mass from the topside of the plunger, where the magnetic attraction primarily occurs. Also by incising the sides of the plunger, the fluid was expected to flow out faster around the plunger during the closing operation and resulting in an accelerate the closing process. The new plunger is slightly longer than the original one. This shortened the distance (the gap) that the plunger moved from closed to open position. The electromagnetic force is inversely proportional to the distance between the objects. In general, for the same speed, shortening the distance will reduce the travel time.

Figure 3 shows the dimensions of the original and the modified plungers and Table1 presents some comparisons between the two designs.

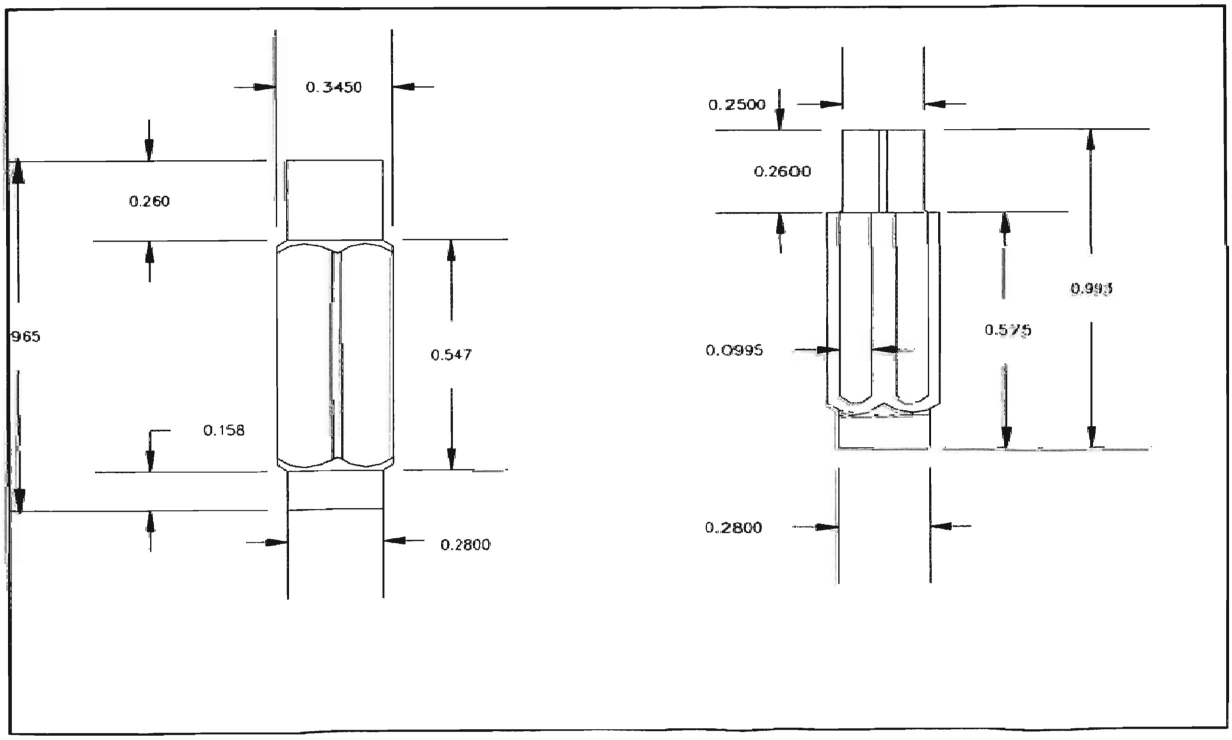



**Figure 3. The original (Right) and The modified (Left) plungers.**

**Table 1. Comparisons between the original and modified plungers**

| Measurement | Original | Modified |
|---|---|---|
| Length (in) | 0.965 | 0.993 |
| Weight (g) | 12.24 | 6.53 |

**Modifying the volume of the valve:**

As mentioned before, a primary objective of this study was to reduce the time delay of shut-OFF the flow. The mechanism of closing the valve starts when turning off the voltage to coil; after that, the flow decreases in a linear fashion decreasing faster as the plunger seals the orifice. This operation needs some time to be accomplished. However, one might think that this problem would be solved by increasing the speed of the plunger. But, during some initial testing of the solenoid valve, it was noticed that the shut-OFF time for the same valve varied from nozzle to another. Specifically, the time delay reaches its greatest value when spraying with lowest flow rate nozzles. Also, the same result was observed when replacing the original plunger with a modified one. As a result, it was concluded that part of this problem was due to the plunger's performance. Yet the valve design, particularly, the design of the fluid volume between outlet orifice and nozzle orifice could have a major effect. Although the plunger seals over the valve seat, the nozzle continues draining the remaining volume of liquid in the cavity of the valve seat and the nozzle. This problem appears clearly at lower flow rates where drainage takes a longer time since the nozzle's orifice is smaller. This assumption is supported by the results of the pre-testing observations. In order to prove this hypothesis, several modifications were evaluated to reduce the volume of the area after the valve orifice. The crucial issue while modifying the valve was that the nozzle's flow rate must be independent to the modifications; i.e. to ensure that the new valve design will provide the same flow rate as the original one. Therefore, flow rate calibrations have been performed on all designs. After testing the performance of several new modified valves, one design has been chosen to explore the effect of reducing the volume. This design was found to be performing at the same flow rate as the original valve. This design basically was done by installing a copper pipe into the valve. This pipe was inserted inside the outlet orifice carrying the flow to the nozzle directly. Details are shown in Figure 4.

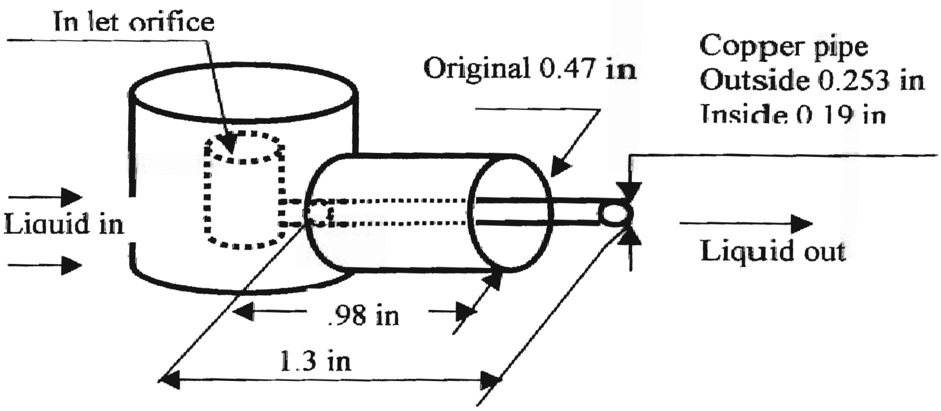



**Figure 4. Original valve seat with the copper pipe installed.**

In this figure it can be seen that the copper pipe basically replaces the original outlet. The (inside) diameter* of the copper pipe is 4.8 mm (0.19 in), and a length of 33.02 mm (1.3 in) which makes the total volume of the cylinder pipe equal to 0.037 $in^3$. However in the original valve the volume of the outlet tube is about 0.17 $in^3$, as the outlet

* All measurements were taken experimentally as the manufacture specifications were not available.

length is 24.9 mm (0.98 in) and the diameter is 11.9 mm (0.47 in). The volume of the new tube was 78% less than the original one. However, the new modified valve gives the same flow rate as the original.

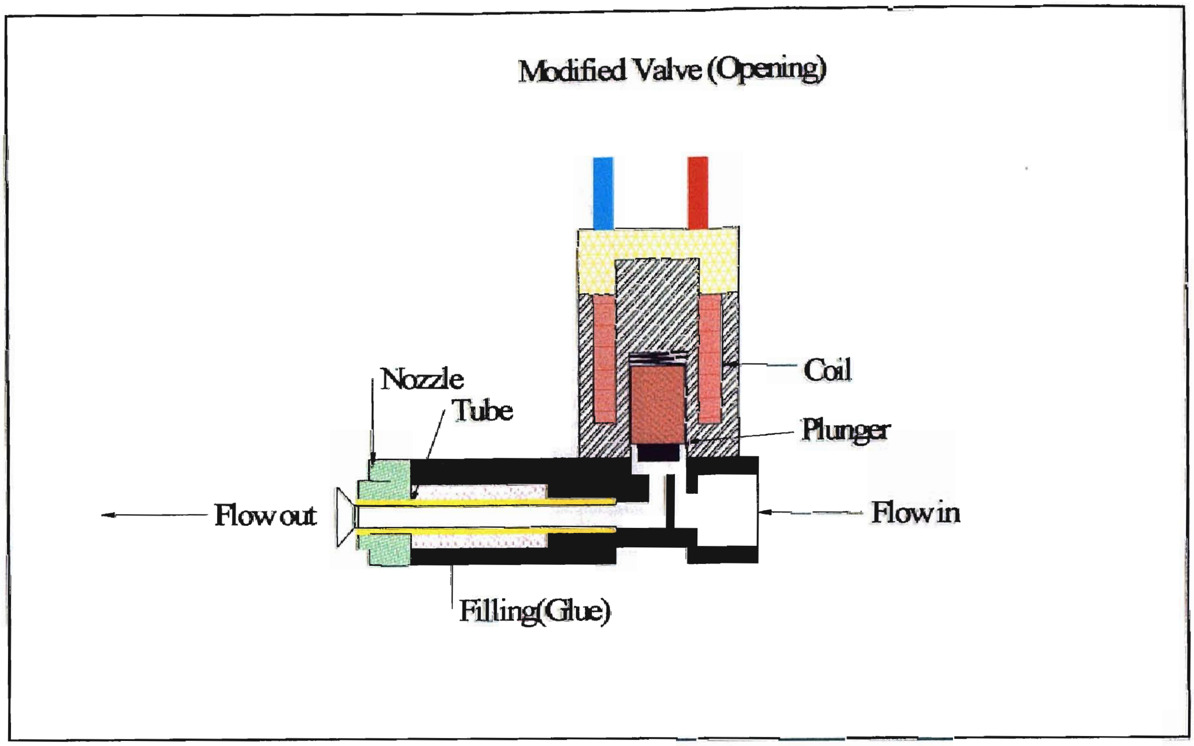



**Figure 4-A. The modified valve in the opening action.**

Figure 4-A shows the side view of the modified valve in the opening action. Here the plunger is being attracted by the electromagnetic field produced by the coil. Figure 4-B however, shows the closing action of the valve in which the plunger is sealing over the valve orifice.

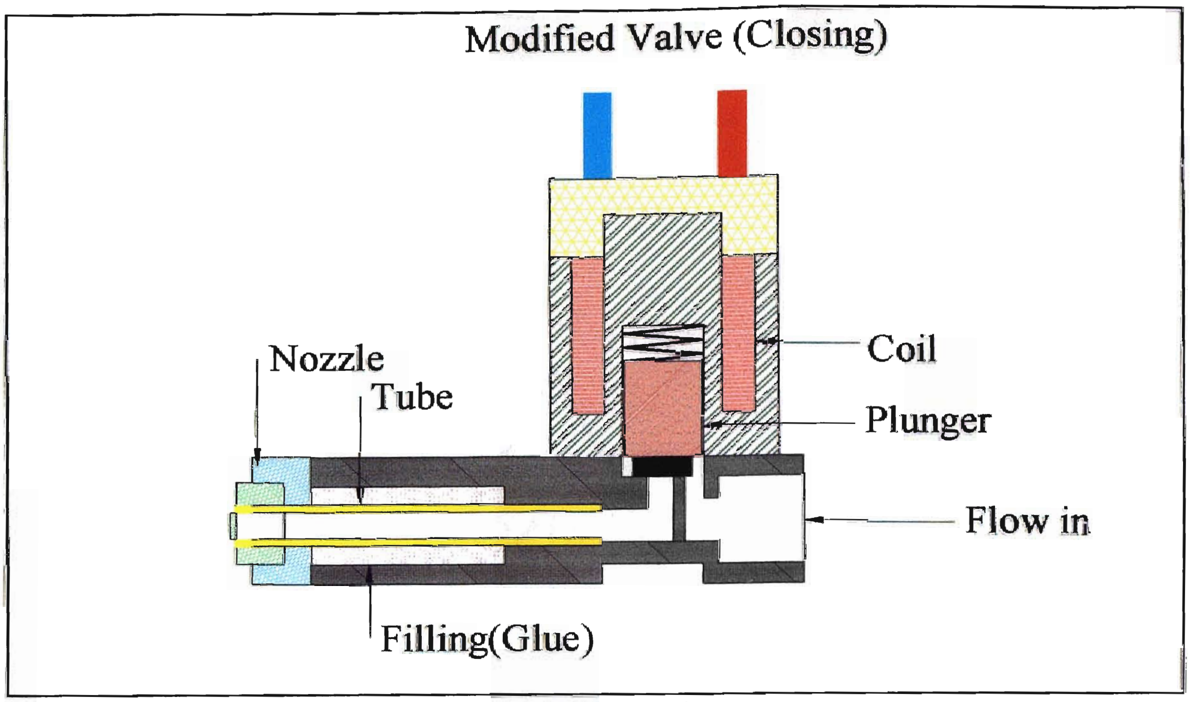



**Figure 4-B. The modified valve in the closing action.**

In conclusion, the modifications that had been done to the valve was as follows:

First: The plunger's weight has been reduced from 12.24 g to 6.53 g.

Second: The shape of the plunger was changed by incising (by about 2.54 mm) on the plunger sides.

Third: the plunger's length for the modified (52.2 mm) is longer than the original (24.5 mm) which reduce the gap from 1.4 mm to 0.686 mm.

Fourth: the volume of the outlet area (area after the orifice) has been decreased by 78% (from 2.79 $mm^3$ to 0.606 $mm^3$).

In this experiment, three different levels of voltage were applied to the solenoid valves (12, 24, and 36 volt), however, the recommended voltage (by the manufacture) for operation is 12 volt. The wire electrical resistance increases with the wire temperature, and as a result of the temperature rise, the solenoid coil resistance will increase, which will in turn reduce the current draw resulting in lower available push or pull force. For this reason, and in order not to over heat the solenoids, the duty cycle for the valves in this experiment has been set for the on- time to be less than half second. Also, after running any of the tests, enough time (at least five minutes) was allowed before further testing to give the valves the chance to cool down.

**Pressure Effect on Operational Voltage**

The pressure force was described in the dynamic model (Eq.2). The model basically states increasing the pressure, while other variables remain constant, requires greater electromagnetic force to open the valve. In order to investigate this effect, a test has been carried out for both original and modified valves. As presented in Table 16.4 the valves were operated starting from of 69 kPa (10 psi) up to 552 kPa (80 psi) in increments of 69 kPa (10 psi). At each level, minimum voltage to open the valve was adjusted then recorded. The adjustment was obtained at each level of pressure by increasing the voltage from 0 to the value at which the valve would start to open.

**The Time Divisions for the Valve Performance**

In order to track any sign of improvement in the modified valve performance, in terms of time response, the valve time delay was divided into four phases Figure 5 describes the four stages of the valve time delay, and they are as follows:

First, the plunger opening time, which is the time between the coil being completely energized until the plunger starts to leave the closed position.

Second, the pressure opening time, which begins when the plunger moves off the valve

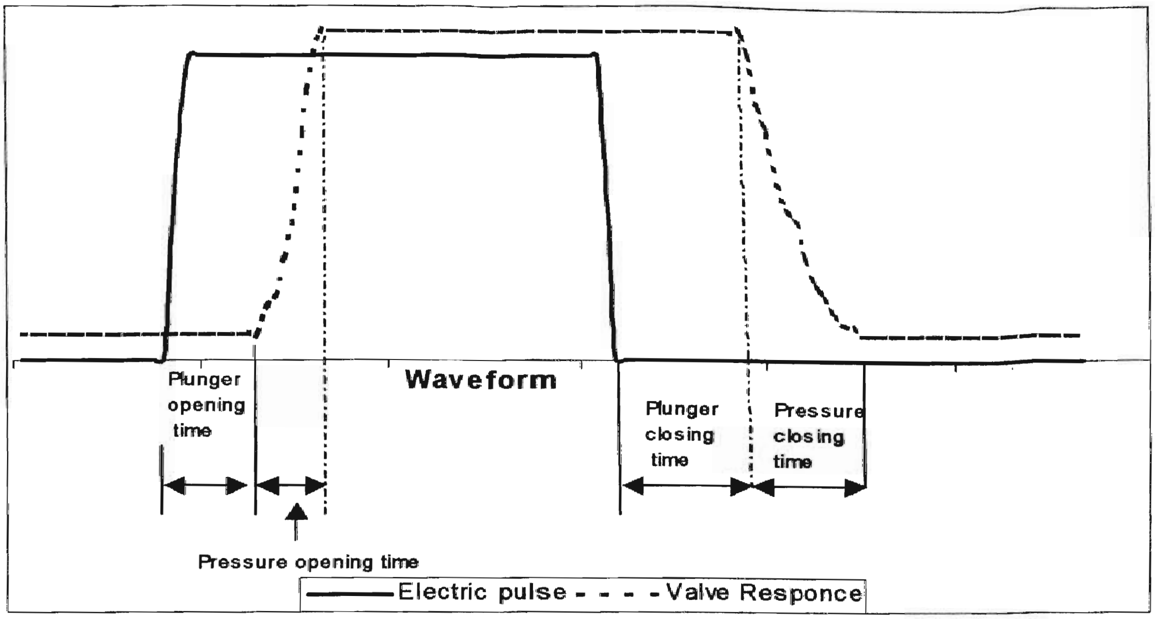



**Figure 5. A simulation of typical waveform for the input plus and the valve response**

seat until the pressure, reaches its highest value. Third, plunger closing time, that is the time period from turning off the voltage until the coil discharges enough so that the plunger would start to move toward the outlet orifice. Fourth, pressure closing time, which begins when the plunger begins to close until no flow comes out of the nozzle.

After adjusting the operational pressure to the desired level (207, 276, and 345 kPa), the system was ready to be tested. As shown in Figure 1, pressure gauges were installed at each valve to ensure the same pressure value to all valves. The test was performed starting with the original valve using six different nozzles (three nozzles for each type). The same test was repeated three times resulting in three replicates tests for each nozzle. The same sets of nozzles were used with the original and modified valve. The valve was set to perform at least three duty cycles before taking any measurements on the oscilloscope to assure as Table performance. Water was chosen to be the liquid used in this experiment.

## Springs Effect on Opening and Closing the Plunger

According to the dynamic model, the valve needs to overcome the spring force in order to open the plunger. Therefore, a spring with small constant K will help speeding up opening the valve. On the other hand, the spring force is the "main" force in closing the valve, so for faster closing, the spring force should be greater.

To investigate this issue five different springs with different spring constants were tested. Table 2 shows the springs' specifications. The test was conducted using the modified valve and operating at the voltage of 24 volts and 275 kPa (40 psi) pressure. The test was repeated three times for each spring.

**Table 2. Springs' specifications**

| Spring | Outside Dim. (mm) | Inside Dim. (mm) | Free length (mm) | Spring Constant | Weight (g) | Wire Diameter (mm) | Number of Turns | Material | Made by |
|---|---|---|---|---|---|---|---|---|---|
| Original | 11.43 | 9.398 | 14.859 | 362 | 0.40 | 0.6 | 6 | NA | Texas Remcor |
| NN - 47 | 9.906 | 8.5 | 20.6 | 240 | 0.49 | 0.7 | 7.75 | Stainless Steel | Century Spring |
| K - 64 | 9.906 | 8.5 | 14.3 | 565 | 0.59 | 0.7 | 7 | Music Wire | Century Spring |
| M - 84 | 9.906 | 8.7 | 15.9 | 512 | 0.69 | 0.6 | 8 | Music Wire | Century Spring |
| O - 49 | 9.906 | 8.3 | 11.1 | 1428 | 0.68 | 0.8 | 6 | Stainless Steel | Century Spring |

# Chapter IV

## Results and Discussions

### Introduction

The procedure for the measurements were discussed in chapter 3, where the interest of this study was in the opening and closing time for the plunger, plus the time for completely opening and shutting-OFF the flow determined by measuring pressure. For more accurate measurements, the waveform was captured by the oscilloscope in form of voltage and time. The sampling period was set to be two micro second (2μs), which had enabled tracking the minor changes in the valve performance. With this degree of accuracy, results of the comparisons tests are presented in appendix A (TableA-1 through A-12). A sample of the waveform of both the input and the valve response is shown in Figure 6.

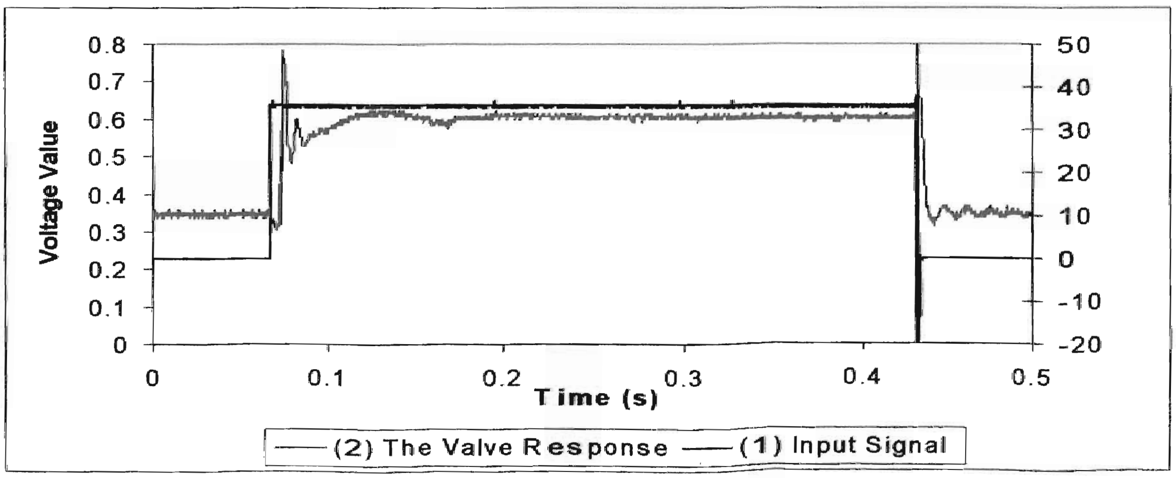



**Figure 5. Example of the valve response to an input signal.**

Analysis of the valve performance was approached from two standpoints. The first was to study the valve performance in regard to the plunger behavior. This included studying the valve performance when changing one or more of the operational variables, like voltage and current. The plunger's closing and opening time were measured for the original and the modified valve. The second aspect was to explore the effect of modifying the volume of the valve (reducing the volume of the cavity between the valve and the nozzle orifice) on the valve performance. In regard to this goal, the flow (pressure) opening and shut - OFF time were recorded.

## Plunger Opening Time

Concerning the solenoid valve performance when varying the voltage from 12 to 36 volt, the results strongly show the improvement of the valve performance in the plunger opening time. This improvement occurred in both original and modified valve. A separate detailed test was conducted on the original valve using a 00015 Quick TeeJet nozzle to show the effect of increasing voltage. The results are presented in Table 3 and plotted in Figure 6. Results of this test show the importance and the sensitivity of the performance to the solenoid voltage. For example, the opening time for the plunger at 10 volts was 27.6 ms. Increasing the voltage to 11 volts reduced the time decreased dramatically to 18.2 ms. Furthermore, in this observation, it can be concluded that the operational level of voltage used in the PWM application is NOT an appropriate one. That is because, in all tests (at 207 kPa), the average opening time for the original valve was found to be 14 ms when applying 12 volt. This time delay can be reduced by increasing the voltage of the valve (current) to a reasonable level. This level however, will depend on many aspects like, the valves limitations (wire's resistance, heat, etc) , and the machine capacity.

**Table 3 Voltage versus plunger's opening time**

| Voltage | Plunger's opening time (ms) |
|---|---|
| 10 | 27.6 |
| 11 | 18.2 |
| 12 | 18.6 |
| 14 | 11.4 |
| 16 | 10.8 |
| 18 | 10.6 |
| 20 | 7 |
| 22 | 7 |
| 24 | 5.3 |
| 26 | 5.1 |
| 28 | 5.1 |
| 30 | 5 |
| 32 | 5 |
| 34 | 5 |
| 36 | 3.6 |
| 38 | 3.6 |
| 40 | 2.28 |

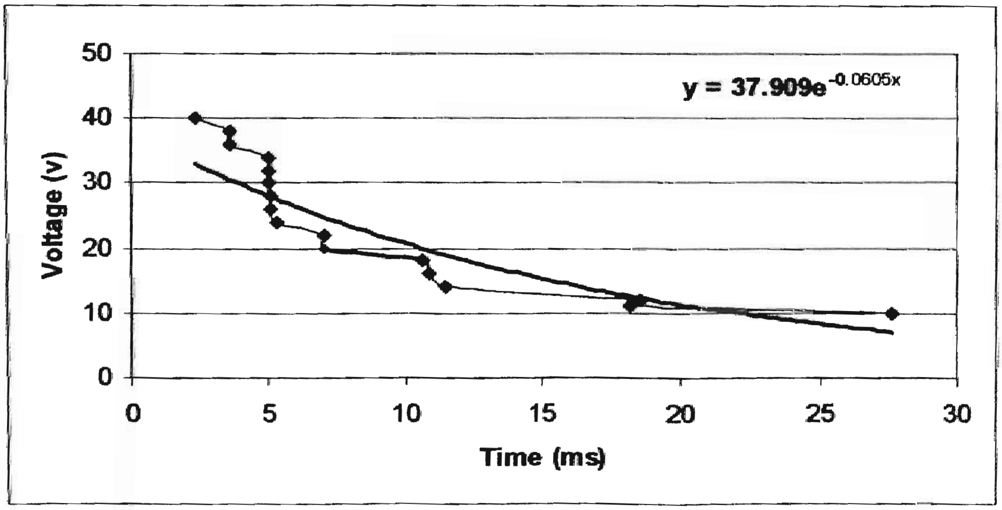



**Figure 7. The relationship between the voltage and plunger opening time**

In this study, the average plunger opening time at 24 volt for the original valve was found to be 6 ms and 6.4 ms for the modified one. Where the same average at 36 volt was found to be 4.6 ms for the original valve and 4.8 ms for the modified. This study, suggests that the Remcor solenoid valve should be operated at 36 volts if possible. This amount of voltage will be needed in opening the valve only, because holding the plunger requires a small amount of voltage. The following Table 4 presents the average of the plunger opening time at different level of pressure and voltage.

**Table 4. The plunger opening time average for original and modified valve***

| Voltage Volt | Pressure (psi) 30 | | 40 | | 50 | |
|---|---|---|---|---|---|---|
| | Original | Modified | Original | Modified | Original | Modified |
| | ms | | | | | |
| 12 (or minimum)* | 13.8 | 16.2 | 16.5 | 26 | 23 | 25 |
| 24 | 6 | 6 | 5.6 | 7.1 | 6.5 | 7.3 |
| 36 | 4.5 | 4.4 | 4.6 | 4.7 | 4.6 | 5.2 |

* All tests were obtained by applying 12v as a start voltage. However, this amount of voltage, some times was not enough to operate the modified valve, especially when operating at higher pressure. Therefore, the minimum here means the minimum voltage needed to operate the valve and it vary from12 to 20 volt.

These results clearly show the improvement of the valve performance as the voltage increased. The greatest concern when modifying the plunger was whether the new design would perform poorly at the lower voltage. It turned out that this is true not only for the modified valve, but also for the original valve. Moreover, the time delay in opening the valve (plunger) is “not acceptable “ in the PWM technique. That is because the minimum target area for treatment is 12 X 12 in, the common operational speed is 24.1 km/h (15 MPH), which is equal to 6.7 mm/ms (0.264 in/ms). As a result, for a time delay of 16 ms a distance of 107.4 mm (4.2 in) would be skipped without treatment. In other words, about 35% of the targeted area would have received no treatment. The problem will be come worse if the other time delays occur. It is worth mentioning that slight differences in opening time have been observed between the original and the modified valve. In particular, the original valve opens faster than the modified one by 0 to 1.5 ms. That is probably due to the shape of the new plunger design where the area of the plunger surface has been increased and as a result fluid pressure has more affect on the plunger.

Reducing the plunger's mass from 12.24 g to 6.53 g, by incising the sides of the plunger, so the fluid would flow out faster around the plunger during the closing operation, and using longer plunger (to reduce the distance that the plunger need to travel to close the valve) helped in increase the plunger acceleration and as a result reduced the plunger- closing time. Luckily, these modifications did not much affect the opening time. In conclusion, applying higher voltage to the solenoid valve improved the performance of the valve by reducing the time delay from 14 to 25 ms at 12 volt to 4.4 to 5.2ms at 36 volt. The plunger-opening time in Figure 8 is 25.4 ms at voltage of 20 volt and pressure of 344.5 kPa (50 psi). However, in Figure 9, the plunger opening time was remarkably decreased to 5.8 ms at the same pressure level and a voltage of 36 volt.

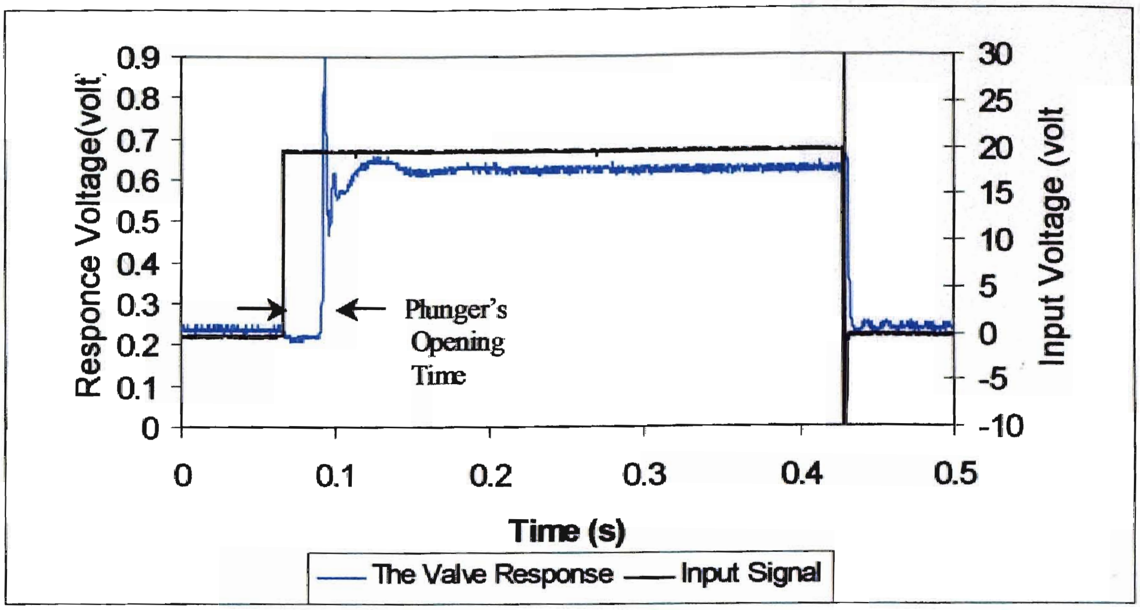



**Figure 8. The waveform of a modified valve (Quick TeeJet 0006), the time delay in opening the plunger 25.4ms when operated at 20volts and 50psi**

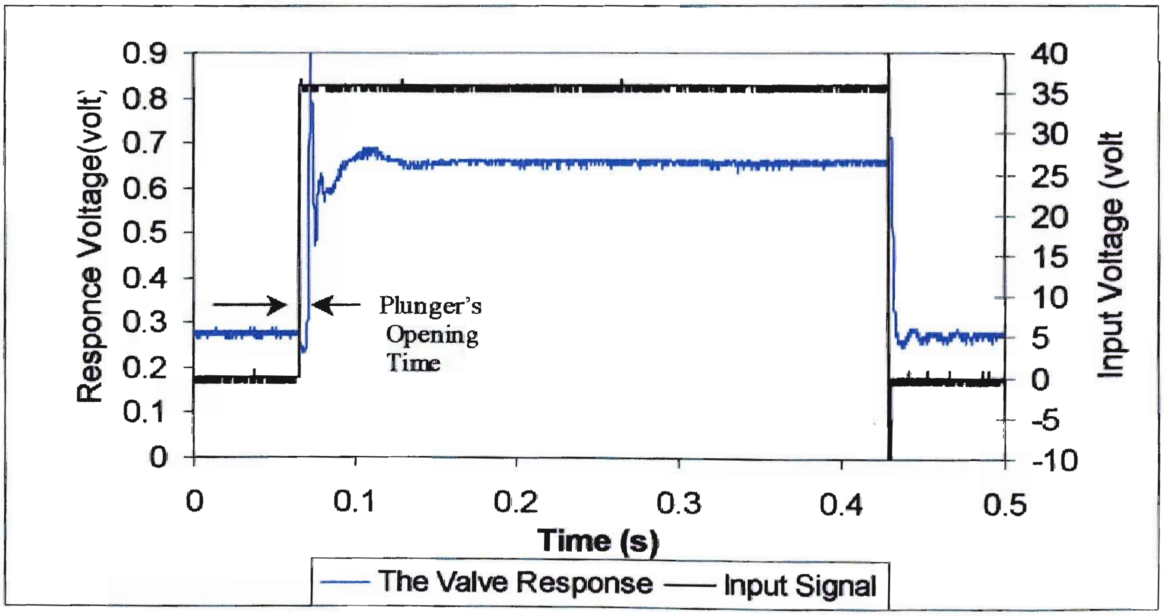



**Figure 9. The waveform of a modified valve (Quick TeeJet 0006), the time delay in opening the plunger 5.8ms when operated at 36 volts and 50psi.**

## Pressure Effect on Required Operational Voltage

The pressure force was described in the dynamic model (Eq. 2). The model basically states that increasing the pressure, while other variables remain constant, requires greater electromagnetic force to open the valve. In order to measure this effect, a test was conducted with both original and modified valves. As presented in Table 5, the valves were operated between 69 kPa to 552 kPa (10 psi to 80 psi) increments of 10 psi. At each level, minimum voltage was adjusted then recorded. The adjustment was obtained at each level of pressure by increasing the voltage from 0 to the value at which the valve would start to operate. In Figure 10, it can be seen that the minimum voltage increased in a linear fashion as the pressure increased for both original and modified valve. However, at the same level of pressure, the minimum voltage needed for the original valve was much less than the one needed for the modified valve. Moreover, the gap between the two valves in voltage requirement is widens as the pressure increases. This is, probably, due to the modifications done to the plunger in the modified valve and in particular to the shape of the modified plunger.

**Table 5. The minimum voltage needed to operate the valve at each level of pressure.**

| Pressure KPa (psi) | Minimum voltage (Volt) | |
|---|---|---|
| | Modified valve | Original Valve |
| 10 | 10.5 | 7.3 |
| 20 | 12 | 8 |
| 30 | 13.5 | 9.4 |
| 40 | 16.25 | 10.4 |
| 50 | 18.5 | 11 |
| 60 | 21.5 | 12 |
| 70 | 24.5 | 12.75 |
| 80 | 27.5 | 13.5 |
| 90 | 29.5 | NA |

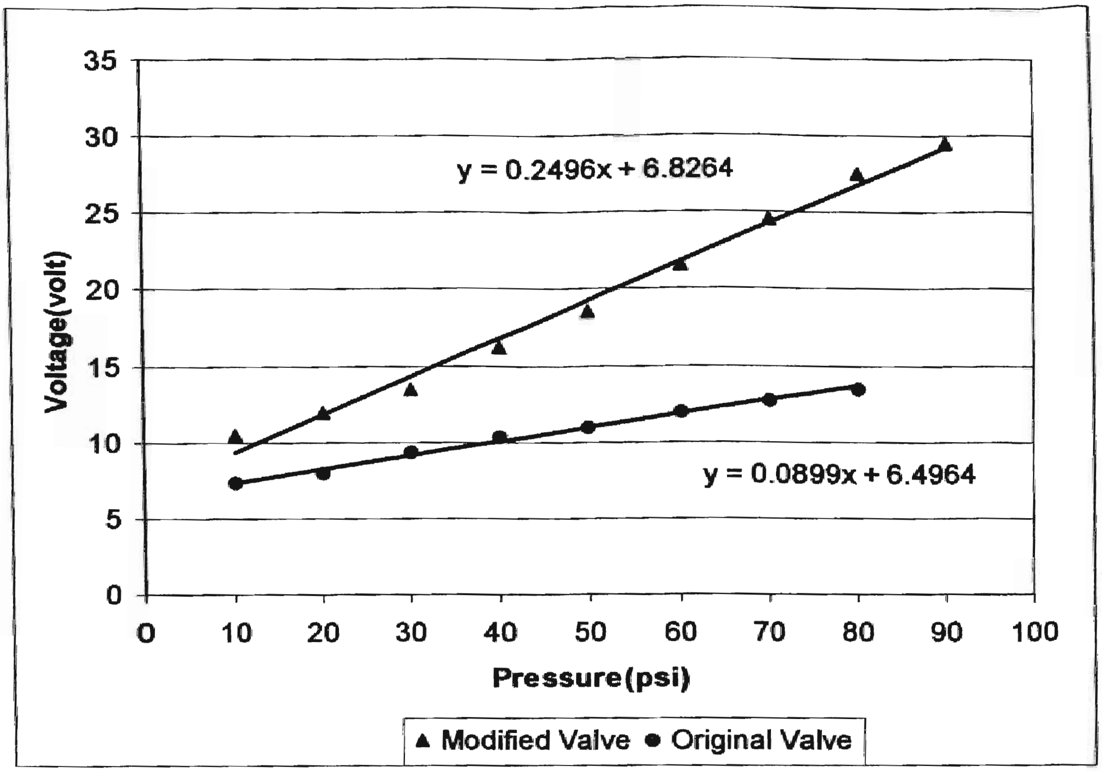



**Figure 10. The relationship between pressure and required voltage to open the valve for original and modified valve.**

With different applications of fertilizers and pesticide, it is probably possible that the spraying machine would need to operate at different levels of pressure. These results indicate that when changing pressure level, voltage needs to be adjusted. Therefore, this study recommends setting the operational voltage to be appropriate for the highest possible level of pressure. This, of course, will be limited by many factors like, the solenoid valve features (wire resistance, maximum heat, etc.), the power supply, and the cost, etc.

## Time Delay for Reaching the Maximum Flow

The time delay for reaching maximum flow is the period of time that is required for the flow to reach its maximum value after an "open" signal. It is the time that the plunger spends moving from closed to open position; also the time that takes the fluid to flow from the valve seat to the nozzle orifice. It is expected that the modified valve would perform better than the original as the volume of the new valve is being reduced by 78% of the original. However, it was observed that this time delay is relatively shorter than the other source of delay, is the plunger closing time delay. In particular, the highest value of this time delay was 5.2 ms, while the average time delay overall for the Quick TeeJet nozzles is 3.9 ms for the original, and 1.8 ms for the modified valve. Also the average for the Modified Stream Jet nozzles was 4 ms for the original valve and 2.5 ms for the modified valve. Table 6 presents comparisons between original and modified valve in terms of pressure opening time delay.

**Table 6. Complete pressure opening time comparisons between two different type of nozzles at different levels of pressure.**

| Pressure (psi) | Average Complete Pressure Opening Time (ms) | | | |
|---|---|---|---|---|
| | Quick TeeJet | | Modified Stream Jet | |
| | Original | Modified | Original | Modified |
| 30 | 4.6 | 2.1 | 4.4 | 2.8 |
| 40 | 3.7 | 1.8 | 3.8 | 2.5 |
| 50 | 3.4 | 1.6 | 3.9 | 2.4 |
| Average | **3.9** | **1.8** | **4.0** | **2.5** |

Figure 11 and 12 illustrate that using the modified valve improved the performance in terms of reducing the valve opening time as a function of opening pressure.

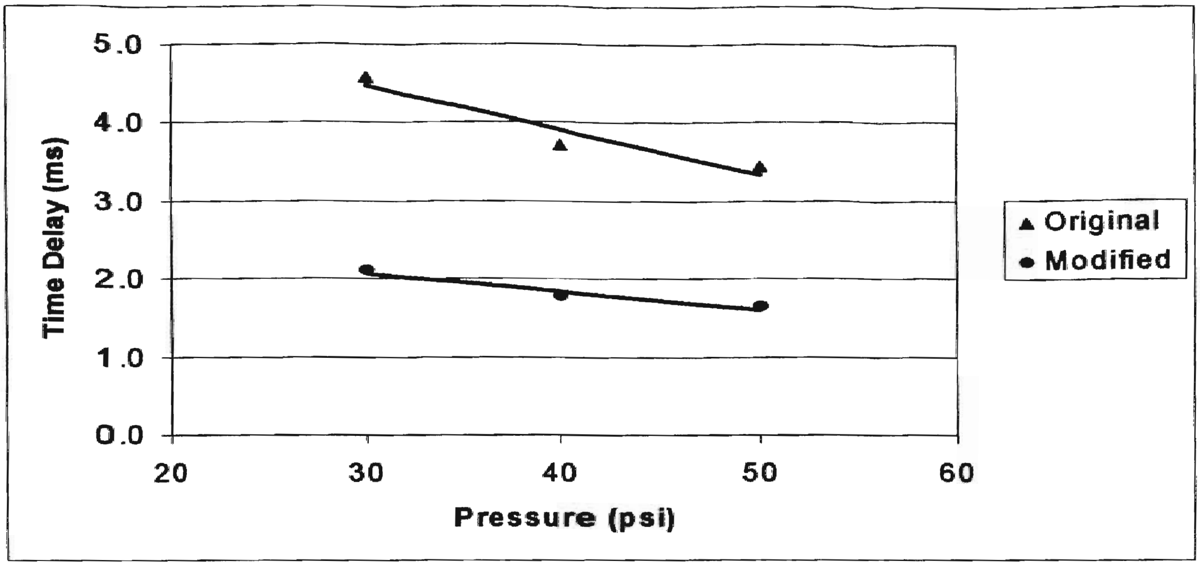



**Figure 11. The Flow- Opening time for original and modified valve at three levels of pressure, using Quick TeeJet nozzles.**

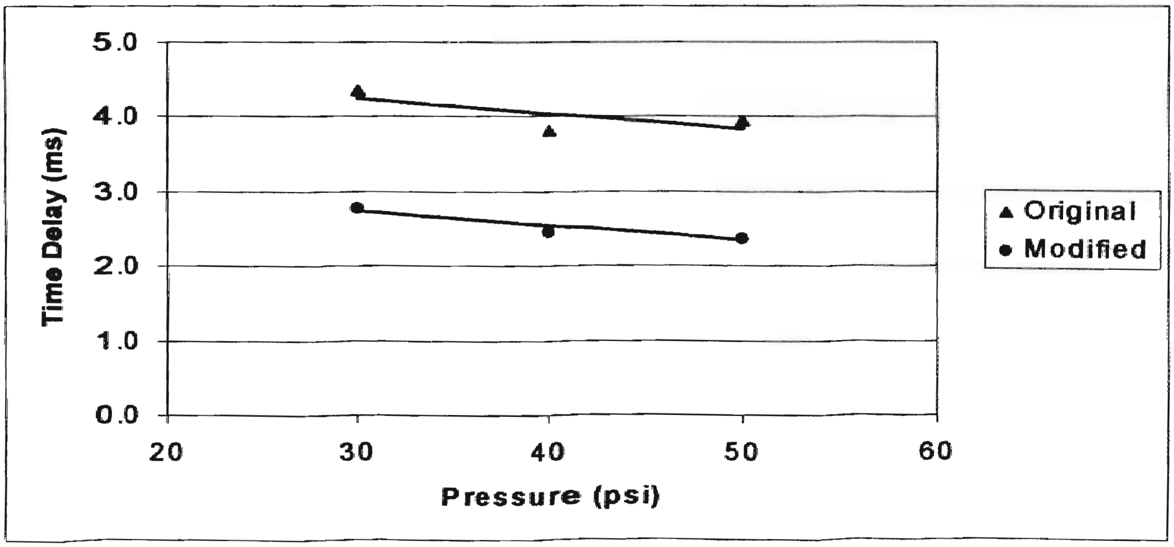



**Figure 12. The Flow-Opening time delay for original and modified valve at three levels of pressure, using the Modified Stream Jet nozzles.**

The flow- opening time has been reduced using the modified valve by 53% for the Quick TeeJet nozzles compared with original, and about 37% for the Modified Stream Jet nozzles. This improvement can be attributed to the valve modifications. That is, reducing the volume of the valve reduced the fluid cavity in the time that the fluid needed to fill the cavity before spraying.

It is expected that as the pressure increased, the opening time would decrease. This was confirmed in this experiment. For example, as shown in Table 6, the pressure opening time delay for the original (Quick TeeJet) decreased from 4.6 at 30 psi to 3.4 ms at 50 psi. This was also the case for both nozzles types. In general, operating at 50 psi reduced the pressure opening time by 10 to 25 % when operating at 30 psi. However, the Quick TeeJet nozzles showed better response to the increase in pressure.

### *Plunger Closing time*

Plunger closing time was defined as the time period from turning off the voltage to the solenoid valve until the coil completely discharges. As a result, the plunger would start to move toward the outlet orifice from its closing position. It is really hard to tell when exactly the plunger seal over the valve orifice. In this study however, there are some evidences that support the previous definition of the plunger – closing time. First, it was observed that this time would remarkably decrease once the plunger's weight reduces. This indicates that this time was for the plunger to travel from the opening position to the closing. Second, the plunger closing time as it was defined will never change when spraying with different nozzles rather the flow – shut OFF time is the one that will change. Therefore, it was assumed that the plunger – closing time (figure 5) is the time that takes the plunger to seal over the orifice.

The plunger – closing time is crucial for PWM applications. Because, during this time, the valve is operating at the full capacity while it is completely closed. The overall closing time average for the original valve (plunger) was found to be 13.5 ms with a standard deviation of 1.3 ms. This time delay is, in terms of travel distance at 24.1km/h (15 MPH), equal to 91.4 mm (3.6 in). Moreover, this time delay is about 30% of the PWM's target area 30 cm X 30 cm (12 in X 12 in).

Modifying the plunger significantly improved the valve performance in terms of plunger - closing time. The graph in Figure 12 is for an original valve with Quick TeeJet 00015 nozzles that operated at 36 volts and 40 psi. As shown in the graph, the plunger-time delay is remarkably longer (14.2 ms) than the one on Figure 13, the modified valve (3.4 ms) with the same nozzle and operational conditions. The overall average of the

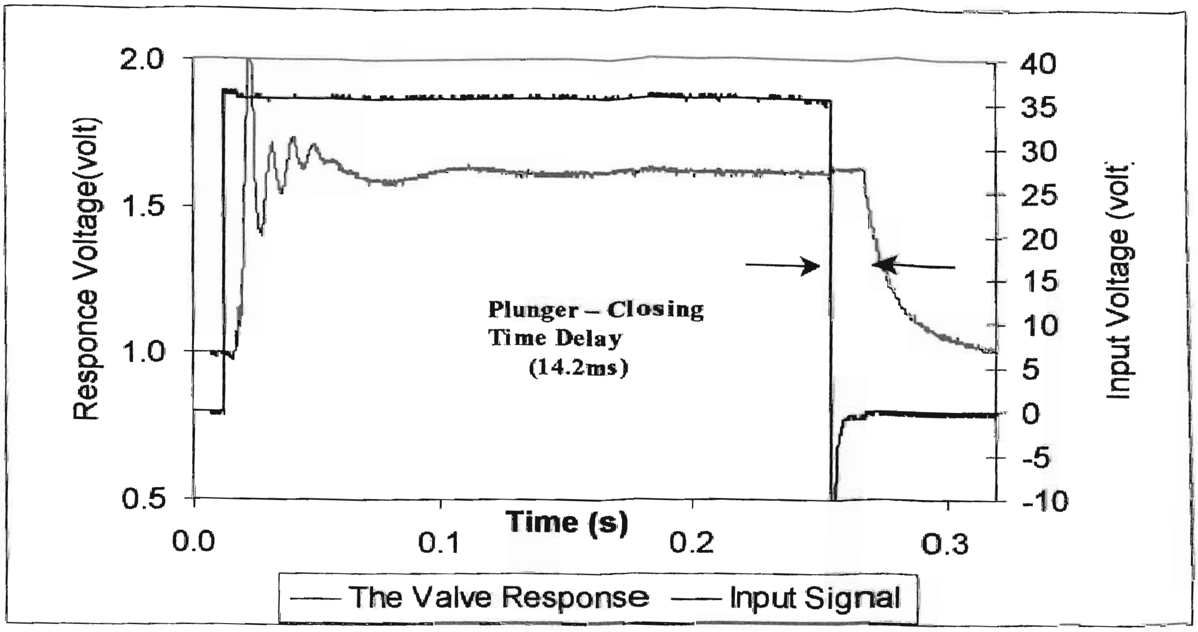



**Figure 13. The plunger Closing – time delay for an original valve, at 36 v and 40psi using 00015 Quick TeeJet nozzle, when operated at 36 volts and 40 psi**

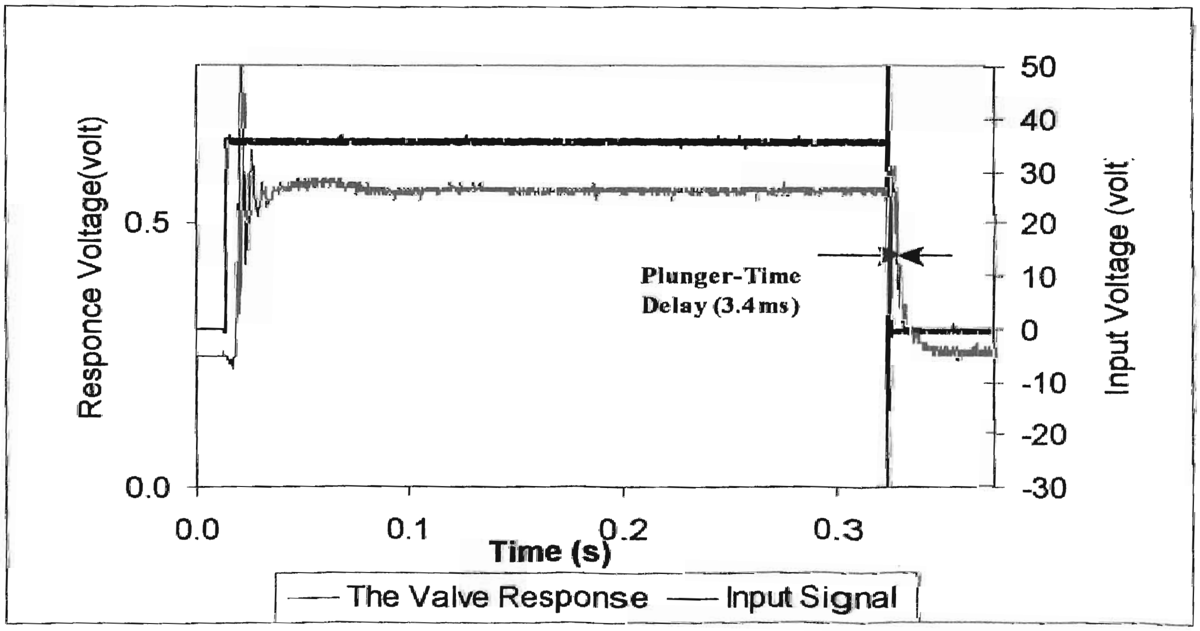



**Figure 14. The plunger Closing– time delay for the modified valve, at 36 v and 40 psi using 00015 Quick TeeJet nozzle, when operated at 36 volts and 40 psi**

plunger- closing time has been calculated to be 2.9 ms with standard deviation of 0.54 ms. As a result, the ratio of improvement was found to be 78.4%.

Figure 15 presents the average plunger-closing time (ms) for original versus modified valve for the six nozzles used in this experiment. About 79% or equivalently, the usual plunger – closing time has been reduced by 79% when using the modified plunger. An F test was made for these comparisons in which the F value was found to be 1348.2 while the $F_{1, 34, 0.05}$ value from the Table is 4.15. That is strongly leads to rejection of the null hypothesis ($H_o$ : $\mu_{original} = \mu_{Modified}$).

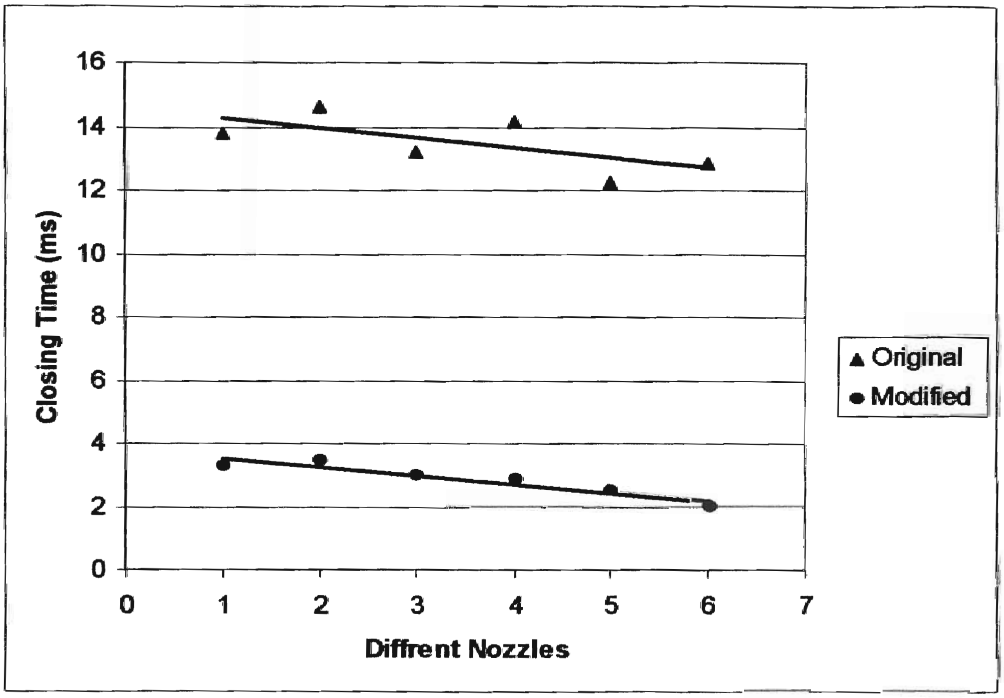



**Figure 15The average plunger-closing time for original versus modified valve using six nozzles.**

By general observation, the plunger- closing time appears to be independent of the change of the flow rate, voltage, and pressure, while the opening process for the plunger was affected by the voltage and the pressure.

In Figure 16, the average plunger-closing time appeared to be independent to the change in pressure. This is the case for the two types of nozzles and for the original and

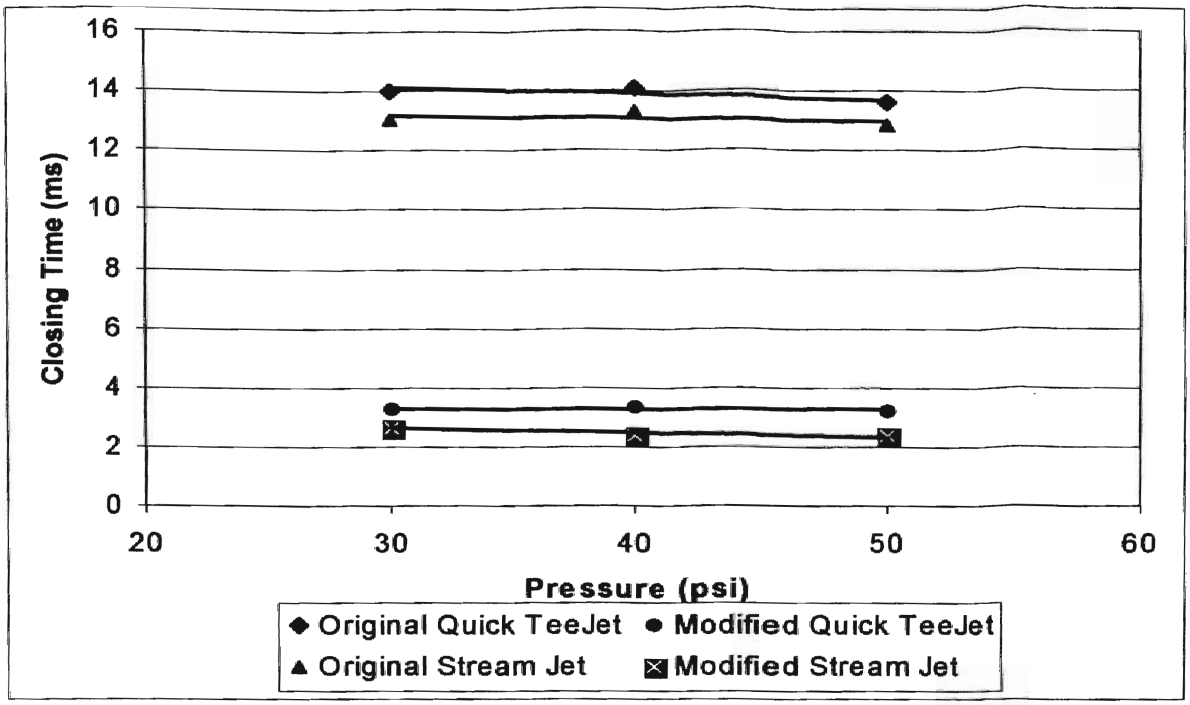



**Figure 16. The average of plunger-closing time for two nozzle nozzles using original and modified valve versus the pressure.**

modified valve. Previously, when discussing the pressure effect on minimum operational voltage (page 13 and 14), it has been observed in that increasing the pressure required higher voltage to overcome the "extra force".

That effect was more distinct in the modified valve, which was attributed to the plunger's new design - reducing the plunger weight- and partly to the new shape. In order to investigate this result, the average closing time at each pressure level was compared with others. Using the analysis of variance method the test has been set as follows:

The null hypothesis states that no difference in the mean of closing time for the three treatments (30, 40, and 50 psi) and the alternative hypothesis states that the difference among the three treatments exists or equivalently:

$H_o : \mu_{30} = \mu_{40} = \mu_{50}$

$H_a$ : the $\mu_i$ are not equal

The average of the plunger- closing time at each level of pressure was taken for the original and modified valve and listed in the following Table:

**Table 7 The average plunger-closing time of the six nozzle nozzles at each pressure.**

| Nozzle Type | Pressure (psi) | | | | | |
|---|---|---|---|---|---|---|
| | 30 | | 40 | | 50 | |
| | Original | Modified | Original | Modified | Original | Modified |
| 00015 | 14.2 | 3.2 | 14.2 | 3.3 | 13.0 | 3.4 |
| 0003 | 14.5 | 3.5 | 14.5 | 3.5 | 14.9 | 3.4 |
| 0006 | 13.4 | 3.1 | 13.5 | 3.1 | 12.9 | 2.9 |
| 0163 | 14.3 | 3.0 | 14.3 | 2.8 | 13.9 | 2.9 |
| 036 | 11.4 | 2.8 | 12.6 | 2.4 | 12.7 | 2.4 |
| 0667 | 13.5 | 2.2 | 13.0 | 1.9 | 12.1 | 1.9 |

The Following is the analysis of variance (ANOVA) for this hypothesis

**Table 8. ANOVA Table for original and modified valve.**

| Source | DF | | SS | | MS | | F | | α |
|---|---|---|---|---|---|---|---|---|---|
| of variation | Orig. | Mod. | Orig. | Mod. | Orig. | Mod. | Orig. | Mod. | **0.05** |
| Treatment | 2 | 2 | 0.591 | 0.081 | 0.3 | 0.041 | **0.306** | **0.136** | |
| Error | 15 | 15 | 14.5 | 4.475 | 0.97 | 0.298 | | | |
| Total | 17 | 17 | 15.1 | 4.556 | 1.26 | | | | |

The F value for the original and the modified valve are less than the $F_{2,\,17,\,0.05}$ table that found to be 3.59; as a result the null hypothesis cannot be rejected. In another words the there is not enough evidence in this experiment at the 5% significance level that the averages of the plunger- closing time are different when operating at different level of pressure for original and modified valve. This result has been obtained also when the flow rate was varied. In Figure 17, the original and the modified valves do not respond to the flow rate change.

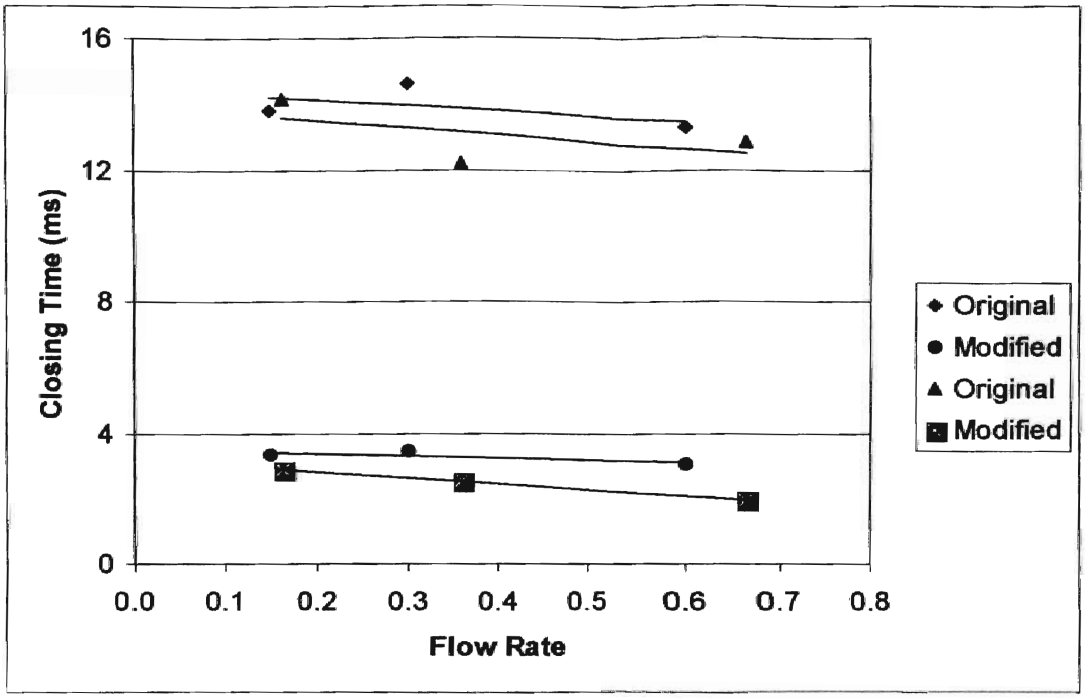



**Figure 17. The average of plunger-closing time for two nozzle nozzles using original and modified valve versus the flow rate.**

In conclusion, the plunger - closing time delay has been significantly decreased from an average of 13.5 ms when using the original valve to 2.9 ms with the modified valve. The plunger - closing process in this valve shows no significant response to the change in voltage, pressure, or flow rate. This result is true also for the modified valve in which it has been predicted that the new shape of the plunger would increase the effect of the pressure as the plunger moves to the valve seat. It turned out however, that the pressure effect is observable in the opening process in which the minimum voltage for opening the valve increases as the pressure increases. That is probably because when the plunger is seated, the fluid pressure plus the spring force are holding the plunger closed. However, with the plunger in the open position, pressure is equal on the plunger's sides, top and bottom. There is no pressure differential trying to close the valve. Then when the coil is discharged, the spring pushes the plunger "faster" toward the orifice than the fluid. Or in another words, the spring action achieves the mission before the pressure starts to act. That is because the distance the plunger needs to travel is only 1.4 mm for the original and .74 mm for the modified valve. As a result, the closing movement was limited to the effect of the spring force only. This result may help in designing or modifying solenoid valves.

**Flow – shut OFF time delay**

Shut – OFF delay is the time that takes nozzle to discharge the fluid from the valve. When the current plunger seals over the outlet orifice to stop the fluid, the cavity between the valve seat and nozzle still contains some of the fluid. The flow-shut OFF time depends on the flow rate of the nozzle. This relationship is presented in Figure 18, in which the time delay dramatically decreases as the flow rate increases. Obviously, to discharge the same volume of fluid, to close the valve, a large nozzle orifice allows the fluid to discharge more quickly at a constant pressure. Therefore, after reducing the volume of the cavity of the area after the outlet orifice by 78 % (from 2.8 $cm^3$ to 0.61 $cm^3$) some improvement has been achieved in reducing this time delay.

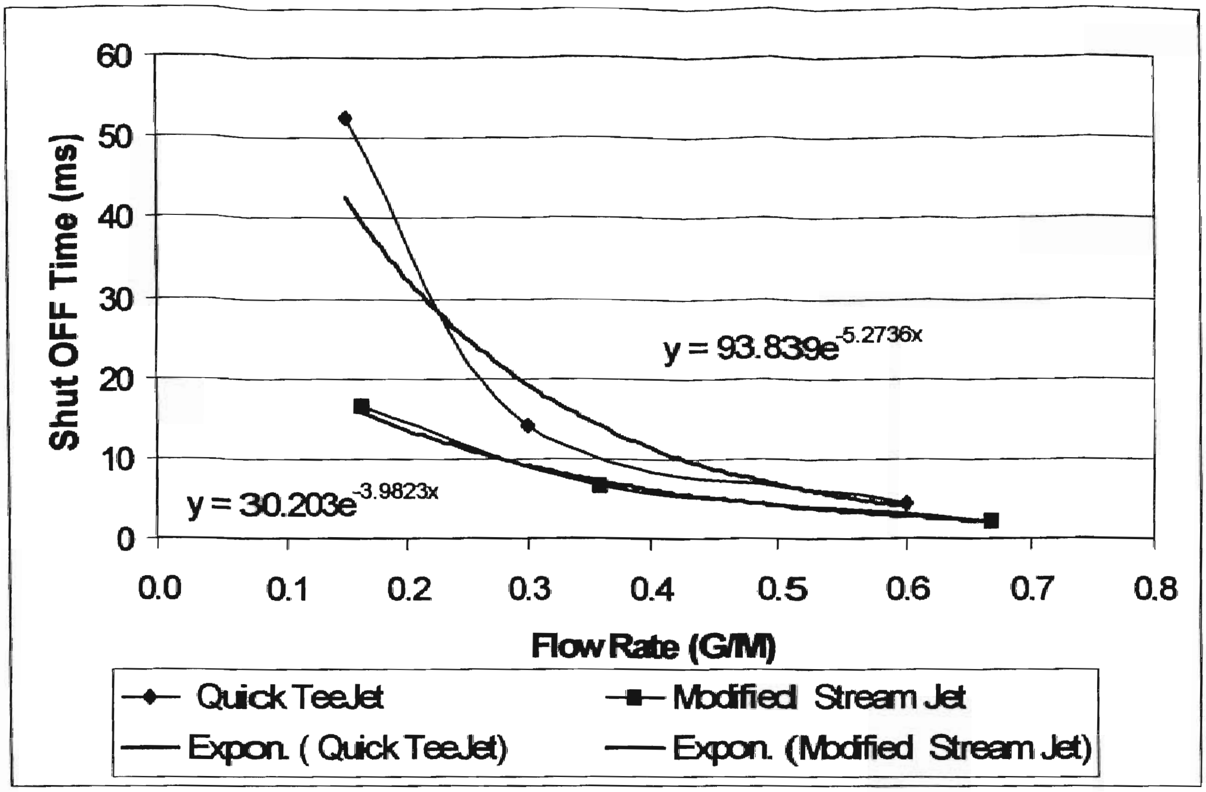



**Figure 18. The relationship between the flow rate and the flow –shut OFF time using the original valve**

The highest time delay was recorded to be 62.6 ms when spraying with Quick TeeJet 00015. As shown in Figure 19, the time for shut OFF the flow when operating with original valve is greater than the time in Figure 20, when using the modified valve. . Figure 20 illustrate the improvement that has been achieved by using the modified valve (with the new volume) during this time the fluid start to wane gradually. The amount of fluid applied after closing the plunger is not the same as before closing it, because the valve is not spraying at its normal flow rate. However, this time delay may cause some misapplications treatments.

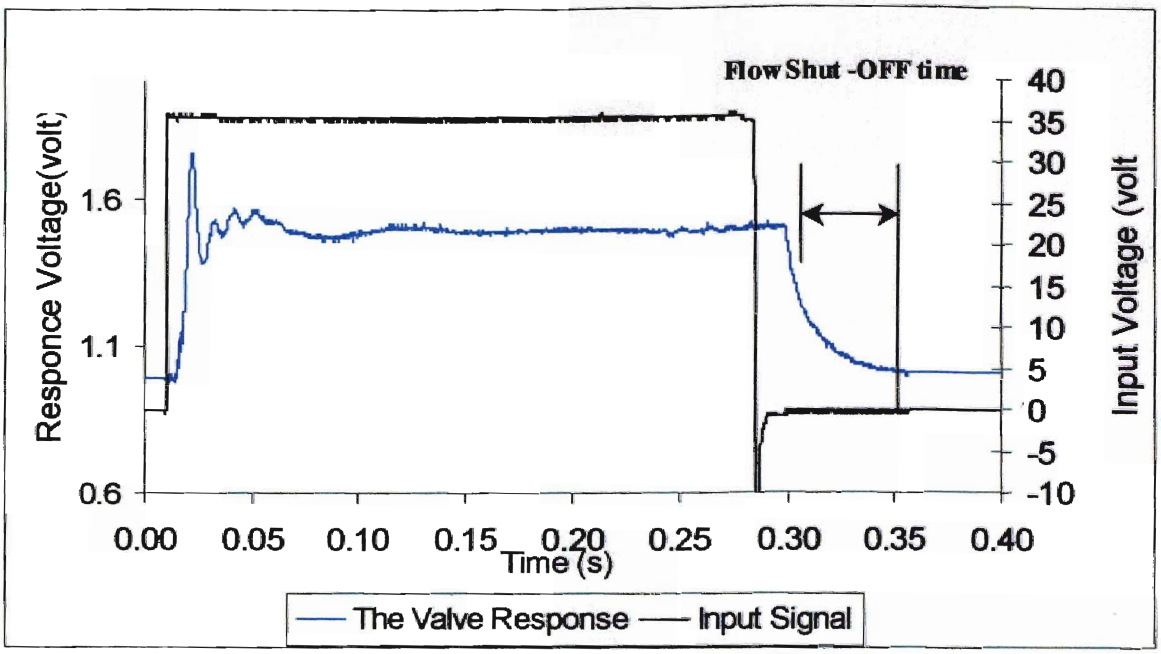



**Figure 19. The Waveform of the Original valve (Quick TeeJet 00015 at 36 volt and 30psi) performance.**

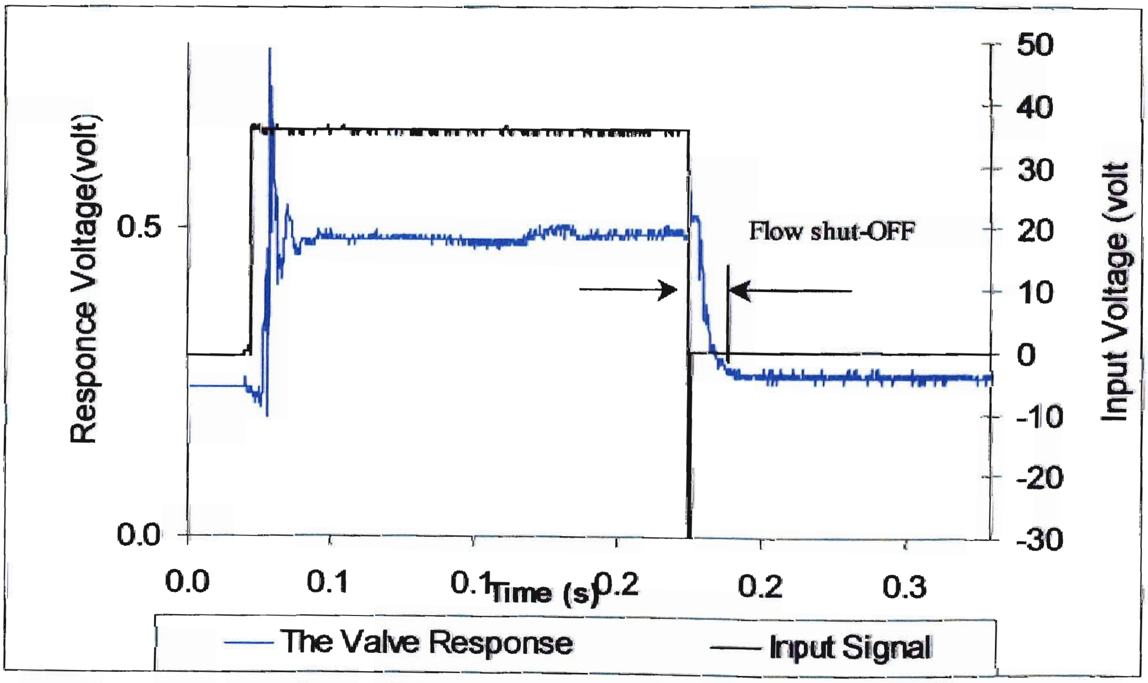



**Figure 20. The Waveform of the Modified valve (Quick TeeJet 00015 at 36 volt and 30psi) performance.**

Table 9 summarizes the results of the original and modified valves performance in terms of shut – OFF the flow time delay.

**Table 9. A summary of the average of shut-OFF delay for the original and the modified valves**

| Flow rate (L/M) | Quick TeeJet Time Delay (ms) | | Flow rate (L/M) | Modified Stream Jet Time Delay (ms) | |
|---|---|---|---|---|---|
| | Original | Modified | | Original | Modified |
| 0.606 | 52.4 | 14.1 | 0.617 | 16.7 | 7.5 |
| 1.14 | 14.1 | 6.2 | 1.36 | 6.6 | 3.9 |
| 2.27 | 4.4 | 2.8 | 2.52 | 2.2 | 2.0 |

To investigate the significance of these improvements, F tests have been driven to all nozzles individually since the main affect is the flow rate, and the result is presented in Table 10.

**Table 10. A summary of the F test derived for the valves performance for each type of nozzle.**

| Nozzle Type | F statistic value | $F_{1, 16, 0.05}$ Table | Significance* | Ratio of improvement % |
|---|---|---|---|---|
| (QTJ) 00015 | 169.91 | 4.49 | Significant | 73 |
| (QTJ) 0003 | 413.83 | 4.49 | Significant | 56 |
| (QTJ) 0006 | 96.89 | 4.49 | Significant | 37 |
| (MSJ) 0163 | 127.73 | 4.49 | Significant | 55 |
| (MSJ) 036 | 59.631 | 4.49 | Significant | 40 |
| (MSJ) 0667 | 2.2857 | 4.49 | Not Significant | 9 |

* Significant level of 0.05

It was observed that the time delay to shut the flow OFF has been reduced for all nozzles by using the modified valve. However, this improvement is not the same for all nozzles. In particular, nozzles with low flow rates had the greatest improvement. Moreover, according to the F values calculated (Table 21.4), all nozzles – except the Modified Stream Jet 0667 – had significantly improved in performance when using the modified valve. The Modified Stream Jet nozzles had shorter shut- OFF times compared with the Quick TeeJets nozzle, which may attribute to the design of the nozzles design. That is the Modified Stream Jet nozzle contains three nozzle orifices, whereas the Quick TeeJet has only one. As shown in the previous results, there is some need for improvement in shortening the time delay especially at lower flow rates.

In conclusion, the time delay depends on the nozzle's flow rate. Some significant improvement had been accomplished in reducing the time delay of flow shut - OFF. Although, the time delay has been reduced in all nozzles, the ratio of improvement was found to be very high (73% - 55%) at the lower flow rate. The Modified Stream Jet nozzles had significantly better performance in terms of flow shut - OFF time than the Quick TeeJets. That is probably due to the nozzle design in which the Modified Stream Jet nozzle has three orifices where the Quick TeeJet has only one.

## Performances comparisons

Four sources of time delay have been identified in this study, however, they do not sufficiently to describe the performance of the valves. For example, when discussing the shut - OFF delay the Quick TeeJet 00015 nozzle with the original valve has an average of 52.4 ms time delay and about 14.1 ms with the modified valve. But the question would be what is the flow rate during this time period? That is, during the 52.4 ms the nozzle still giving some flow, yet, it is not at the maximum flow. So how important is this time or can it be ignored? To answer all these questions and for better judgments on the valves performance, the area under the flow response curve was found to be the "best" criteria to compare the performance of the valves using different nozzles. This procedure allows knowing exactly what amount of fluid had been delivered in certain period of time. This "actual" area will be compared with what it should be or with the "ideal" area in which no time delay has taken place.

To achieve this goal, the area under the response curve (pressure) was measured using the simple integration in which the sampling period (2 μs) was considered as the width and the voltage value the height. This measurement is called the total actual area here. This area starts from opening the valve until the valve is fully closed (flow = 0). The actual area within the ideal operational time spans from opening the valve until the time that the voltage becomes zero. On the other hand, the ideal area is the area calculated by multiplying the ideal time with the ideal voltage. The ideal time is the input signal time with no delay. The ideal voltage is the stable value of the voltage after reaching the maximum flow. Basically the ideal area represents the ideal case of a valve without time delay. The results of those calculations are presented in Table 11. The ratio of error in Table 11 describes the of difference between the actual area, which represents the amount of the fluid applied to the targeted area, and the ideal area, which represents the exact amount of fluid required for the same area. Clearly, the results show that the original valve applies more fluid to the targeted area than required. The probable source of these misapplications is that this valve remains open longer than it should.

Specifically, this occurs during the plunger- closing time delay and flow-shut off time delay. However, this ratio of error decreases as the flow rate increases.

**Table 11. Comparisons between the valves performance in terms of area**

| Nozzle Type | Original | | | | | Modified | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Ideal Area | Total Actual Area | Act. Area within ideal time | Ratio of error % (area) | Ratio of error % (Spraying outside the targeted area) | Ideal | Total Actual Area | Act. Area within ideal time | Ratio of error % **(area)** | Ratio of error % (Spraying outside the target area |
| QTJ 00015 | 0.393 | 0.461 | 0.385 | **15** | **16.5** | 0.172 | 0.178 | 0.171 | **2.9** | **3.4** |
| QTJ 0003 | 0.460 | 0.492 | 0.457 | **6** | **7.0** | 0.221 | 0.222 | 0.217 | **0.5** | **2.0** |
| QTJ 0006 | 0.518 | 0.533 | 0.509 | **3** | **4.5** | 0.221 | 0.220 | 0.216 | **-0.5*** | **1.6** |
| MSJ 63 | 0.644 | 0.684 | 0.641 | **6** | **6.3** | 0.271 | 0.270 | 0.268 | **-0.3*** | **0.9** |
| MSJ 36 | 0.579 | 0.600 | 0.570 | **4** | **4.9** | 0.237 | 0.238 | 0.235 | **0.3** | **1.5** |
| MSJ 067 | 0.528 | 0.542 | 0.519 | **3** | **4.2** | 0.239 | 0.236 | 0.234 | **-1.1*** | **0.9** |

* The negative sign here indicates that the actual area is less than the ideal.

Moreover, in this table, the ratio of error in the modified valve performance is relatively smaller than the original one. In fact this improvement has been tested for significance using an F test. The F value was found to be 9.24 where the $F_{1, 10, 0.05}$ is equal to 4.96. As a result, it can be stated that this data is evidence that the valve performance has been improved using the modified valve.

The previous result described in general the valve performance in terms of the actual amount of fluid applied to the targeted area in response to an input signal. But, it did not specify where exactly this amount of fluid was applied. In other words, what does the targeted area receive from the total actual amount of treatment?

Also in Table 11, the ratio of error represents the percentage of the actual flow that is applied after the target area. For example, using the QTJ 00015 nozzle, it can be noticed that with the original valve 16.5% of the treatment will be applied after the targeted area, and 3.4% with the modified valve. Usually, as the flow rate increased (flow- opening time becomes shorter) the ratio of misapplication decreased. The modified valve performed better than the original valve. This improvement has been tested for significance using F test. The F value was found to be 8.148, which compared with $F_{1, 10, 0.05} = 4.96$, from F Table. Therefore, it can be concluded that there are some significant improvement in performance with the modified valve.

**Optimizing the Spring**

Although reducing the mass of the plunger has reduced the plunger – closing time, the modified valve required greater voltage for opening the plunger. The K constant can be defined as:

$K = (M * g)/(L1 - L2)$ ..............................................................................(6)

Where M is the weigh (kg), g is the earth gravity ($m/sec^2$) , L1 is the free length of the spring (mm), and L2 is the compressed length of the spring (mm). For each spring was determined experimentally by putting a weight on the spring then measuring the compressed length of the spring. The Table 4 shows that the average time for opening the plunger decreased as the voltage increased.

This data suggests that the valve should not be operated at less than 24 volts because of the poor performance at lower voltage. On the other hand, the best result was found when operating at 36 volts. However, solenoid valves have some limitations in terms of wire resistance. The other alternative was to find "better" spring that can reduce the time delay for opening and closing the plunger. For this purpose five different springs were tested at 24 volts and 40 psi using the modified valve with 0003 Quick TeeJet nozzle and the results is presented in Table 12. The different between the spring with the greatest and smallest spring constant K is 0.6 ms only. This indicates that almost all the springs in this experiment tend to have the same plunger - closing time.

**Table 12. Opening and closing-plunger time using the modified valve for several springs at 24 volts and 40 psi.**

| Springs | K (N/mm) | Opening ms | Closing ms |
|---|---|---|---|
| NN-47 | 240 | 4.3 | 3.4 |
| ORIGINAL* | 362 | 8.2 | 3.4 |
| M-84 | 512 | 8.2 | 2.7 |
| K-64 | 565 | 8.4 | 3.3 |
| O-49 | 1428 | 8.5 | 3.0 |

* Original spring is the spring that comes with the Texas Remcor In valve.

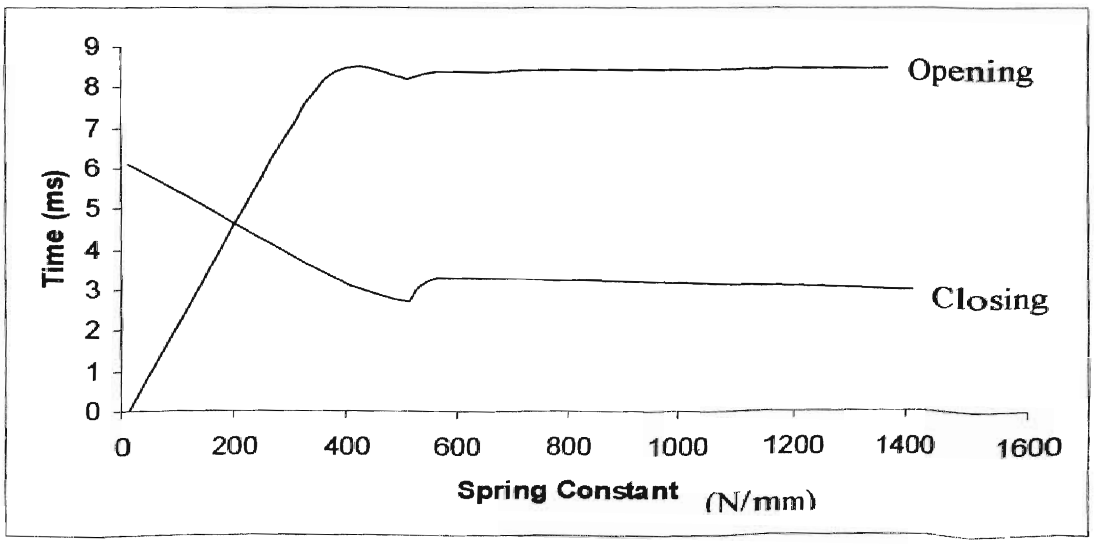



Figure 21. The plunger Opening and closing - time versus the spring constant (N/mm).

Thus, a spring with the lower K constant will be in demand because it will reduce the plunger – opening time. The best performance of the modified valve was found when using the NN- 47 spring with the lowest K constant. The total time delay associated with plunger when using this spring was found to be 7.7 ms, whereas this time (at the same level of voltage 24 volts, and pressure 40 psi) was found to be 11.6 ms when using the original spring. That is about 34 % improvement of the time delay. Moreover, the plunger - time delay using the NN-47 spring (4.3 ms) is shorter than when using the original spring (8.9 ms) at higher voltage and lower pressure. In another words, the performance of the modified valve with the NN-47 spring at lower voltage, is better than what it is with the original spring at higher voltage. Figure 21 shows that the intersection point for the opening and closing time occurred at the spring constant of 200 N/mm, which considered as an optimum value of the spring constant.

This improvement will hopefully help in matching the valve performance with the PWM technique requirement. Also, it will enable precision agriculture to achieve part of its goals in reducing the effect on environment by applying the treatments wisely.

# Chapter V

## *Summary and Conclusion*

This research presents a theoretical and experimental study of the dynamic response of a 2602 Texas Remcor solenoid valve. The dynamic response is characterized by a physical model. The model identifies the effective parameters on the valve performance. It has been found that current, pressure, flow rate, spring force, and plunger mass have some effect on the valve performance. Based on the dynamic model analysis, some operational conditions, like pressure and voltage, have been varied. Also some modifications have been applied to the original valve. The valve has been operated at 30, 40, and 50 psi and at 12, 24, and 36 volt. The valve modifications include the weight and the shape of the plunger and the volume of the cavity after the outlet orifice.

In order to track any sign of improvement, the valve response has been divided into four phases:

i. Plunger- opening time.

ii. Flow- opening time.

iii. Plunger- closing time.

iv. Flow - shutting off time.

For each phase, the performance of original and modified valve has been tested. For the first phase, a significant improvement has been achieved in which the time delay has been reduced from the average of 17.8 and 25.1ms to 4.6 and 4.8 ms for original and modified valve respectively. Furthermore, it was observed that the valve required more voltage as the fluid pressure increased. Reducing the volume of the valve had helped in reducing the time for the flow to reach its maximum value into half (from3.95 to 2.15 ms). The plunger - closing time was found to independent to the flow rate, pressure, and voltage. It depended only on the spring force; thus, by reducing plunger's weight significantly reduced the closing time. The average closing time for the original plunger is 13.5 ms where it is equal to 2.9 ms for the modified valve. The time delay in the final phase depends on the ability of the nozzle to drain the remaining fluid in the valve after closing the plunger. The time is varied from 62 ms at the lowest flow rate to 1.6 ms highest flow rate. Reducing the volume of the valve cavity significantly decreased this time delay. The valve performance in general has been measured for the original and the modified valve in terms of area under the response curve. The modifications reduced the application error and brought the performance closer to the ideal situation.

Several springs were tested for performance, the time delay of opening and closing the plunger was improved by 34% when using the NN – 47 spring. However, the optimum spring constant K in which the opening and closing time of the plunger were the shortest was found experimentally to be 200 N/mm.

## Recommendations and Further study

This study recommends applying the modifications presented previously. Further study is recommended for different types of solenoid valves. It can be suggested to further investigate about the effect of dynamic response parameters on performance and possibilities of modifications. The coil design and materials is another subject of further study. This study did not cover the time delay associated with the input signal itself, therefore it is maybe an alternative for future research.

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# Appendix A

**Table A – 1. Results of a test on the Original Remcor valve with 00015 nozzle. (Average of three replications)**

| Pressure | Voltage | Plunger Time Delay | | Pressure Time Delay | |
|---|---|---|---|---|---|
| | | Opening | Closing | Opening | Closing |
| psi | V | ms | | | |
| 30 | 12 | 15.2 | 14.2 | 5.2 | 62 |
| 30 | 24 | 6 | 13.8 | 4.4 | 61 |
| 30 | 36 | 4.6 | 14.6 | 5.2 | 55.8 |
| 40 | 12 | 17.2 | 14.2 | 4 | 50.8 |
| 40 | 24 | 3.4 | 14.2 | 3.8 | 44.8 |
| 40 | 36 | 4.4 | 14.2 | 4.4 | 62.6 |
| 50 | 12 | 25 | 14 | 4.6 | 47.4 |
| 50 | 24 | 6.6 | 12.4 | 3.2 | 43.6 |
| 50 | 36 | 4.2 | 12.6 | 4 | 43.6 |

**Table A-2 Results of a test on the Modified Remcor valve with 00015 nozzle (Average of three replications)**

| Pressure | Voltage | Plunger Time Delay | | Pressure Time Delay | |
|---|---|---|---|---|---|
| | | Opening | Closing | Opening | Closing |
| psi | V | ms | | | |
| 30 | 14 | 6.8 | 3.2 | 2.8 | 11.6 |
| 30 | 24 | 5.4 | 3.2 | 2.8 | 16 |
| 30 | 36 | 4 | 3.2 | 2 | 9.8 |
| 40 | 16 | 8.6 | 3.4 | 1.5 | 11.8 |
| 40 | 24 | 6.6 | 3.2 | 2.2 | 12.8 |
| 40 | 36 | 4.4 | 3.4 | 2 | 15 |
| 50 | 19 | 5.8 | 3.4 | 1.64 | 13.4 |
| 50 | 24 | 4 | 3.4 | 2 | 14.6 |
| 50 | 36 | 4.8 | 3.4 | 1 | 22 |

**Table A-3. Results of a test on the Original Remcor valve with 0003 nozzle. (Average of three replications)**

| Pressure | Voltage | Plunger Time Delay Opening | Plunger Time Delay Closing | Pressure Time Delay Opening | Pressure Time Delay Closing |
|---|---|---|---|---|---|
| psi | V | ms | | | |
| 30 | 12 | 14.4 | 14.8 | 4.6 | 14.2 |
| 30 | 24 | 6.8 | 14.8 | 4.4 | 14.2 |
| 30 | 36 | 4.4 | 13.8 | 4.6 | 15.8 |
| 40 | 12 | 16 | 13.8 | 3.4 | 12.8 |
| 40 | 24 | 6.4 | 15.6 | 3.6 | 13.8 |
| 40 | 36 | 4.4 | 14 | 3.8 | 13.6 |
| 50 | 12 | 23.8 | 14 | 3.6 | 14.6 |
| 50 | 24 | 7 | 15.2 | 3 | 13 |
| 50 | 36 | 4.8 | 15.6 | 3.4 | 15 |

**Table A-4. Results of a test on the Modified Remcor valve with 0003 nozzle. (Average of three replications)**

| Pressure | Voltage | Plunger Time Delay Opening | Plunger Time Delay Closing | Pressure Time Delay Opening | Pressure Time Delay Closing |
|---|---|---|---|---|---|
| psi | V | ms | | | |
| 30 | 14.5 | 22.8 | 3.2 | 2.1 | 7.4 |
| 30 | 24 | 7 | 3.6 | 1.8 | 6.4 |
| 30 | 36 | 5.2 | 3.6 | 1.6 | 6 |
| 40 | 18 | 30.8 | 3.4 | 2.4 | 5.8 |
| 40 | 24 | 8.2 | 3.4 | 1.4 | 5.8 |
| 40 | 36 | 5.4 | 3.8 | 1.4 | 5.4 |
| 50 | 20 | 28.2 | 3.4 | 2.4 | 5.8 |
| 50 | 24 | 9.2 | 3.2 | 1.4 | 6 |
| 50 | 36 | 5.6 | 3.6 | 1.4 | 7.2 |

**Table A-5 . Results of a test on the Original Remcor valve with 0006 nozzle. (Average of three replications)**

| Pressure | Voltage | Plunger Time Delay Opening | Plunger Time Delay Closing | Pressure Time Delay Opening | Pressure Time Delay Closing |
|---|---|---|---|---|---|
| psi | V | ms | | | |
| 30 | 12 | 14.2 | 12.8 | 3.6 | 4.4 |
| 30 | 24 | 6.2 | 14 | 4.8 | 4.6 |
| 30 | 36 | 4.8 | 12.4 | 4.4 | 4.8 |
| 40 | 12 | 16.4 | 13.8 | 4 | 4.6 |
| 40 | 24 | 6.4 | 14.4 | 3.2 | 4.2 |
| 40 | 36 | 4.8 | 14.6 | 3.2 | 3.6 |
| 50 | 12 | 22.6 | 10.1 | 3.4 | 4.2 |
| 50 | 24 | 6.4 | 14 | 3 | 4.2 |
| 50 | 36 | 4.8 | 12.8 | 2.8 | 5 |

**Table A-6. Results of a test on the Modified Remcor valve with 0006 nozzle. (Average of three replications)**

| Pressure | Voltage | Plunger Time Delay Opening | Plunger Time Delay Closing | Pressure Time Delay Opening | Pressure Time Delay Closing |
|---|---|---|---|---|---|
| psi | V | ms | | | |
| 30 | 15 | 18.4 | 3.2 | 2.6 | 2.8 |
| 30 | 24 | 7.2 | 3 | 1.8 | 3.2 |
| 30 | 36 | 5.2 | 3.6 | 1.6 | 2.6 |
| 40 | 18 | 23 | 3 | 1.8 | 2.6 |
| 40 | 24 | 8.4 | 2.8 | 1.6 | 3.2 |
| 40 | 36 | 5.6 | 2.8 | 1.6 | 2.6 |
| 50 | 20 | 25.4 | 3 | 1.8 | 2.4 |
| 50 | 24 | 9.6 | 2.8 | 1.4 | 2.8 |
| 50 | 36 | 5.8 | 2.8 | 1.6 | 2.8 |

**Table A-7. Results of a test on the Original valve with 163 nozzle. (Average of three replications)**

| Pressure | Voltage | Plunger Time Delay Opening | Plunger Time Delay Closing | Pressure Time Delay Opening | Pressure Time Delay Closing |
|---|---|---|---|---|---|
| psi | V | ms | | | |
| 30 | 12 | 12.8 | 12.8 | 4.6 | 17.2 |
| 30 | 24 | 5.8 | 16.2 | 4.2 | 16.4 |
| 30 | 36 | 4.4 | 14 | 3.8 | 18.4 |
| 40 | 12 | 17 | 15.2 | 4 | 13 |
| 40 | 24 | 5.6 | 13.8 | 3.6 | 17.8 |
| 40 | 36 | 4.6 | 13.8 | 3.8 | 18.6 |
| 50 | 12 | 21.2 | 14.2 | 4.2 | 15.8 |
| 50 | 24 | 6.2 | 14 | 3.8 | 17.2 |
| 50 | 36 | 4.6 | 13.4 | 3.2 | 16 |

**Table A-8. Results of a test on the Modified valve with 163 nozzle. (Average of three replications)**

| Pressure | Voltage | Plunger Time Delay Opening | Plunger Time Delay Closing | Pressure Time Delay Opening | Pressure Time Delay Closing |
|---|---|---|---|---|---|
| psi | V | ms | | | |
| 30 | 12 | 16.6 | 3 | 3.4 | 9.4 |
| 30 | 24 | 5.6 | 2.8 | 2.6 | 7.8 |
| 30 | 36 | 3.8 | 3.2 | 2.6 | 8.4 |
| 40 | 12.5 | 33.6 | 3 | 3.4 | 8 |
| 40 | 24 | 6.4 | 2.4 | 2.2 | 7.2 |
| 40 | 36 | 4 | 3 | 2.6 | 8.4 |
| 50 | 15 | 47.4 | 2.4 | 3.4 | 8 |
| 50 | 24 | 6.6 | 3 | 2.2 | 7 |
| 50 | 36 | 5 | 3.2 | 2 | 3.2 |

**Table A-9. Results of a test on the Modified valve with 667 nozzle (Average of three replications)**

| Pressure | Voltage | Plunger Time Delay Opening | Plunger Time Delay Closing | Pressure Time Delay Opening | Pressure Time Delay Closing |
|---|---|---|---|---|---|
| psi | V | ms | | | |
| 30 | 12 | 12.8 | 13.4 | 4.4 | 8.9 |
| 30 | 24 | 5.6 | 13 | 4 | 8.2 |
| 30 | 36 | 4.6 | 14 | 4 | 8.1 |
| 40 | 12 | 15.6 | 13 | 4.4 | 8 |
| 40 | 24 | 6 | 13 | 3.6 | 10.5 |
| 40 | 36 | 4.4 | 13 | 3.4 | 8 |
| 50 | 12 | 21.8 | 12 | 3.8 | 7.6 |
| 50 | 24 | 6.4 | 11.5 | 4.2 | 7 |
| 50 | 36 | 4.8 | 12.8 | 2.4 | 9.2 |

**Table A-10. Results of a test on the Modified valve with 667 nozzle. (Average of three replications)**

| Pressure | Voltage | Plunger Time Delay Opening | Plunger Time Delay Closing | Pressure Time Delay Opening | Pressure Time Delay Closing |
|---|---|---|---|---|---|
| psi | V | ms | | | |
| 30 | 12 | 17.4 | 2.4 | 3 | 2 |
| 30 | 24 | 5.6 | 2.2 | 2.6 | 1.6 |
| 30 | 36 | 4 | 2 | 2.6 | 2.4 |
| 40 | 13.5 | 30 | 2 | 1.4 | 1.8 |
| 40 | 24 | 6.6 | 1.8 | 2.4 | 2.2 |
| 40 | 36 | 4.6 | 1.8 | 2.4 | 2 |
| 50 | 16.5 | 19.2 | 1.8 | 2.8 | 1.8 |
| 50 | 24 | 7 | 1.8 | 2 | 2.2 |
| 50 | 36 | 5 | 2 | 2.4 | 2 |

**Table A-11. Results of a test on the Modified valve with 360 nozzle. (Average of three replications)**

| Pressure | Voltage | Plunger Time Delay Opening | Plunger Time Delay Closing | Pressure Time Delay Opening | Pressure Time Delay Closing |
|---|---|---|---|---|---|
| psi | V | | | ms | |
| 30 | 12 | 13.6 | 10.2 | 2.6 | 6.6 |
| 30 | 24 | 5.4 | 11.6 | 2.4 | 5.4 |
| 30 | 36 | 4.4 | 12.4 | 2.4 | 6.4 |
| 40 | 12 | 16.8 | 10.4 | 2.4 | 5.6 |
| 40 | 24 | 5.8 | 13.2 | 2.4 | 6.6 |
| 40 | 36 | 4.8 | 14.2 | 2.2 | 6.4 |
| 50 | 12 | 23.4 | 10.2 | 2.6 | 6.6 |
| 50 | 24 | 6.2 | 13.8 | 2.4 | 7.6 |
| 50 | 36 | 4.6 | 14 | 2.2 | 7.8 |

**Table A-12. Results of a test on the Modified valve with 360 nozzle. (Average of three replications)**

| Pressure | Voltage | Plunger Time Delay Opening | Plunger Time Delay Closing | Pressure Time Delay Opening | Pressure Time Delay Closing |
|---|---|---|---|---|---|
| psi | V | | | ms | |
| 30 | 12 | 15.2 | 2.8 | 2.4 | 3.8 |
| 30 | 24 | 5.2 | 3 | 2 | 3 |
| 30 | 36 | 4.2 | 2.6 | 1.8 | 3.2 |
| 40 | 13 | 30 | 2.4 | 2 | 3.8 |
| 40 | 24 | 6.4 | 2.4 | 1.6 | 3.4 |
| 40 | 36 | 4.2 | 2.4 | 1.8 | 4.6 |
| 50 | 15.5 | 23.8 | 2.4 | 2 | 4.4 |
| 50 | 24 | 7.4 | 2.4 | 1.2 | 4.4 |
| 50 | 36 | 4.8 | 2.4 | 1.6 | 4.8 |

# Vita

(2)

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