DESIGN OF A HIGH SPEED, SELF-SWITCHING VALVE

BY

CALVIN BEWSKY

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

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University of Manitoba
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ABSTRACT

The intermittent injection of high speed liquid jets into the ground has been shown to increase plant quality and productivity. However, to overcome the poor reliability and slow switching nature of the solenoid valves used on currently available injection equipment, a self-actuating valve has been developed that transforms a constant 28 MPa pressure supply into a pulsating output of variable pulse duration and frequency. The prototype valve, which is a 35 mm diameter poppet valve with stellite seating surfaces and a stroke of 0.127 mm, opens in 0.8 ms, closes in 1.3 ms, and is audibly quiet, insensitive to hammer blows and orientation and simple in construction with only a single moving part. However, it can achieve a minimum open time of only 12 ms (5 ms is required) and a maximum operating frequency of only 16 Hz (20 Hz is desired). Additionally, cavitation damage on the stellite surfaces has caused a small leakage during the valve's 8 hours of operation but it has almost been eliminated by the inclusion of a machined profile on the poppet face. The valve's operation was simulated with a computer program which predicted the behavior closely to the measured values enabling the program to be used as a design tool. Although further refinements are necessary to meet the design criteria, the valve operates repeatably (+/- 1 ms/cycle), has an estimated seating speed comparable to that of the valves in automobile engines and has an estimated production cost of $145 (based on 500 valves). Furthermore, its simple timing control system, which consists of two needle valves, can be automated easily for the intended ground injection application.

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NOMENCLATURE

dBA	decibels on the A-weighting scale
ft-lbs	foot pounds (force)
kN	kilo (1000) newtons
lbs	pounds (force)
MPa	mega (10^6) pascals
Nm	newton meter
psi	pounds per square inch
μm	micro (10^{-6}) meters

1. INTRODUCTION

The intermittent injection of liquid jets into the ground creates pockets of moistened and loosened soil that promote root growth as well as water and nutrient uptake of plants. This process can be used to inject a variety of liquid mixtures that can increase plant quality and productivity through the cultivation, nourishment and reconditioning of the soil. Moreover, the process is more effective, efficient and environmentally friendly than many conventional plant management practices. Furthermore, the process can be used to effectively reclaim land for new vegetation growth such as grass in urban regions.

The injection process requires the generation of a pulsating high pressure, by means of a fast-acting on-off valve, to produce the high speed liquid jets that penetrate the ground and laterally fracture the soil to a depth of up to 20 cm [1]. This process can cultivate, aerate and moisturize the soil with no physical ground contact and with minimal surface disruption [2]. For these reasons, the process has found widespread use for turf management on golf courses to alleviate dry spots and rejuvenate compacted areas with water injections [3,4]. However, available injection equipment is handicapped currently by inadequate valve hardware that prevents the extension of this technology beyond the golf green [5]. If alternative valve gear becomes available, the injection of a host of aqueous solutions can be used to increase the productivity and quality of a wide range of plants, including forage crops and pastures that feed livestock as well as vegetable and cereal crops that feed people. For example, it would be possible to annually cultivate and fertilize perennial forage crops to increase the overall yield and support more livestock. Aside from placing the aqueous solutions directly to the required area, amidst the roots where they are utilized [6], to make more efficient and effective use of the fertilizers than broadcasting, the injection process also creates less drift than conventional spraying.

Thus, this direct ground application can lead to substantial reductions in environmental contamination due to surface run-off from rainfall, less chemical exposure to humans and animals, and a decrease in the overall amount of chemicals spread throughout the world [7,8,9].

The injection process can also be used to reclaim land in urban regions for grass cover [5]. Aside from its recreational and aesthetic benefits, grass serves many important functions such as the control of soil erosion, retention of rainfall for ground water recharge, and the catchment and filtration of polluted run-off waters [10]. Grass can be grown on roadsides and around newly constructed buildings by using the injection process to relieve compaction, and to condition the ground with nutrients, moisture and even soil amendments before and after seeding. The process can also be used to inject saturated water-retaining polymers and reclaim highly permeable ground such as sand, which would otherwise be incapable of supporting plant growth [11]. A grid of pockets of slowly released moisture and nutrients would be suspended below the surface (similar to hydroponics) making possible plant growth above. Currently, a dry polymer is ploughed into the sand which is irrigated later [12]. Injecting a slurry would save one pass, minimize disruption of the growing bed and, conceivably, reduce evaporation compared with conventional irrigation, making more efficient use of dwindling fresh water supplies. Furthermore, as opposed to ploughing, injection technology would permit subsequent applications until sufficient root growth and organic matter has formed, permitting the vegetation cover to hold its own moisture and continue to grow naturally [13]. This land reclamation process would be similar to nature's but at an accelerated rate to keep abreast of continuing urban development.

The applications cited previously cannot be applied satisfactorily with currently available injection equipment primarily due to inadequate valve gear [5]. Problems relate to either limited or no control of the frequency and duration of the injections. These two parameters correspond to the injection spacing and quantity, respectively, and, ideally, they should be changeable and independent of ground speed to allow the operator to adjust the operation to match the application. These difficulties have been addressed by replacing ground driven, mechanically operated, on-off valves with electrically actuated solenoid valves [14]. By changing the nature of the electrical excitation with a key-pad control set up, for example, the frequency and open time of the valves can be altered conveniently and easily [5]. However, many difficult problems and deficiencies still hinder the effectiveness and reliability of solenoid valves. The injection process needs fast switching of the jets to allow suitably fast implement travel speeds and it also requires a high operating pressure to attain adequate ground penetration. These extraordinary operating requirements call for special solenoids and custom timing control hardware which, even after several years of research and development, still have problems of too slow switching action and frequency. Additional problems include a generally poor reliability due to circuit failures and leaky valves and, consequently, an unacceptably short service life.

The purpose of this project is develop an on-off valve that is free of the limitations of mechanically operated valves as well as the difficulties and problems associated with electrical devices and their actuation hardware. In other words, a non-electrically actuated, possibly a self-switching valve is desired. If this is accomplished, the need for an external power source to operate the valves would be eliminated. Consequently, a reduction in the number of system components could offer an increase in reliability and a significant cost reduction of the overall injection system.

The objectives of the thesis include:

1. developing an on-off valve that switches with minimal or no electrical control and has satisfactory operating characteristics and service life for a commercial, ground injection application;
2. constructing a cost effective prototype valve having as many commercially available components as possible and verifying its operation and performance; and
3. assessing the economic viability of the concept by carrying out a preliminary production survey and cost estimate.

2. VALVE HARDWARE FOR A LIQUID PULSE INJECTOR (LPI)

2.1 Functions of a LPI

As stated in the introduction, present day injection equipment is designed and used primarily on golf courses for turf management [3,4,5,14]. Consequently, this equipment has a small 1 to 1.5 m width and typically travels at speeds less than 3 km/h which makes it unsuitable and impractical for use on golf course fairways, large playing fields and farm fields. Presuming that improved valve hardware can be developed, this section describes the duties of a conceptual injection implement, a LPI, and the valve gear needed for larger-scale, commercial use. The design criteria and ideas presented in this section were set at the beginning of the project and were based on desired improvements to existing injection equipment as well as the envisioned use of the improved, enlarged LPI [5].

The ground injection process can be performed by a LPI, which is a tractor-drawn implement that intermittently injects high speed liquid jets beneath the surface. Figure 2.1 illustrates the injection process and shows the main components of a LPI. They include a tank for the aqueous solution, a high pressure pump, and multiple on-off valves that feed a row of nozzles. The on-off valves transform the constant, high pressure supply from the pump into a pulsating output which forces the liquid through the small orifices to create intermittent, high speed liquid jets. These jets penetrate the ground's surface and laterally fracture the soil to create pockets of moistened, loosened earth. (Note the absence of external actuation for the valves so that they are implicitly self-operating.) A supply pressure of 28 MPa (4000 psi) has been found suitable for ground penetration [3,4,14] and is the chosen design pressure for the thesis.

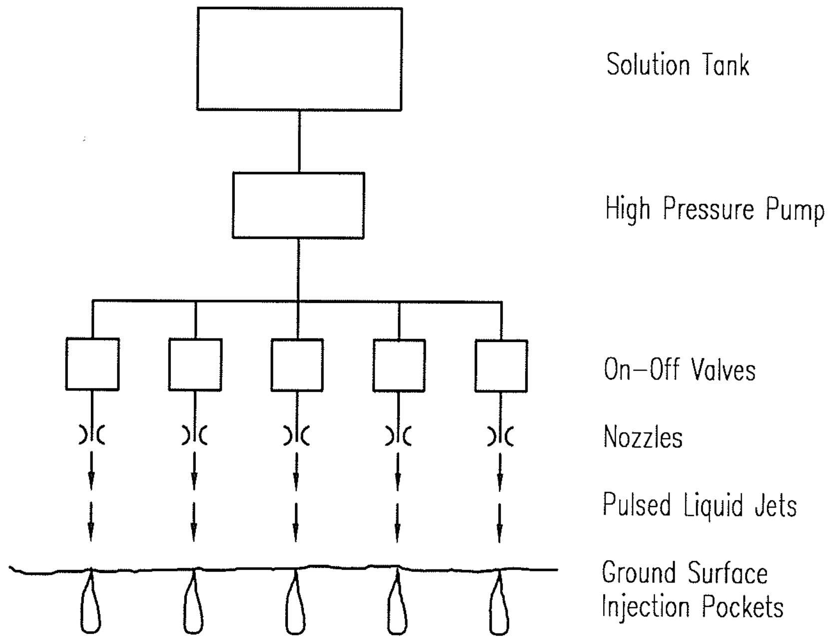


Figure 2.1 The ground injection process

A LPI can be used to inject a variety of aqueous solutions to aerate, cultivate, moisten and nourish the ground and, consequently, increase plant productivity. Materials such as fertilizers and pesticides can be injected directly to the plants' roots where they are required. Soil amendments and water-retaining hydrogels can also be installed to alter the condition of the ground. In addition to applying solutions that can be corrosive (fertilizer), abrasive (soil amendments) or viscous (hydrogel slurry), the LPI must be capable of applying the solutions at different coverage and application rates and in a multitude of environments. For example, it may be desired to apply pesticides into turf with closer, smaller and shallower injections at higher travel speeds than saturated polymers into sand. This suggests, in turn, that the LPI can be expected to operate in a hot, dusty environment and travel over rough terrain so that all hardware must be robust and insensitive to vibrations.

The LPI must be able to operate at different travel speeds and provide a variable injection spacing and depth as well as solution quantity to match the injected materials with the ground and vegetation conditions. The implement can be expected to travel at ground speeds up to 15 km/h (9 mph), whilst the LPI should provide a repeatable injection spacing of 10 - 20 cm and from 1 to 5 cc/injection. To satisfy these requirements, the LPI must produce between 5 and 20 injections per second with an injection lasting from 5 to 30 ms. Desired injection depths range from 1.5 to 20 cm depending upon the injection time and orifice size, both of which also affect the injection quantity. Orifice sizes ranging from 0.3 to 2 mm (0.015 to 0.80") have been found suitable [3,4,14].

The valves regulate the frequency and duration of the injections. They should be reliable and be controllable regardless of ground speed in order to maintain a desired injection spacing over the entire speed range. The valves must operate at 28 MPa and, according to the operating parameters cited above, must be capable of switching at up to 20 Hz with a variable open time of from 5 to 30 ms. The timing of the valves must be accurate, repeatable and insensitive to ground induced vibrations in order to apply the specified amounts of a wide range of corrosive, abrasive and viscous injection fluids. They must switch in less than 5 ms, with no dripping when closed, and have a long service life. The following sections review available on-off valve technologies and discuss their suitability and limitations for a LPI.

2.2 Electromechanical On-Off Valves

Electromechanical devices convert electrical energy into a mechanical function. Two common examples are the electrical motor and the solenoid. An electrical motor rotates its shaft whereas a solenoid, a two position device, moves its plunger axially. The basic advantage of using electromechanical devices is the convenience and ease of supplying (preconditioned) electrical signals to achieve a desired mechanical response. For instance, step changes in either a voltage or current applied to a solenoid, can be generated readily to open or close an on-off valve. This section describes three classes of on-off valves that are actuated by solenoid, piezo-electric elements and a torque motor.

A solenoid is an electromagnetic actuator which is conventionally made of a cylindrical coil of wire that surrounds a movable iron rod or plunger. When the coil is energized, a magnetic force is produced which attracts the plunger and moves it. The speed at which the solenoid responds to an electrical signal, viz its switching time, is influenced by the time constant of the coil and the ratio of the magnetic traction force to the mass of the plunger [15]. The time constant determines the delay in increasing the magnetic force to the critical magnitude, whereas the force to mass ratio governs the acceleration of the plunger.

Since the advent of electro-hydraulic systems, many new and unique solenoids having quicker response and higher traction forces have been developed to achieve faster switching times and permit higher operating pressures. For instance, Tanaka [16] has developed a high speed poppet valve with a switching time of 0.8 ms. However, it has been tested at only 14 MPa and requires a 120 V excitation. A 12 V excitation is preferred because this lower voltage is common to electrical systems on engines. Consequently, many solenoids have been designed specifically for use on automobile engines so that they operate at 12 V. Barkhimer et al. [17,18] have developed a solenoid actuated, ball poppet valve assembly for fuel injected gasoline and diesel engines. This valve features a response time of less than 3 ms, positive sealing at shut off, excellent repeatability, but it has operated at only 10 MPa and produces a traction force of merely 15 N. This last value is far too low a force for operation at 28 MPa. For example, a 400

N force would be required to move a 4 mm diameter plunger against a 28 MPa pressure. Rapid acceleration of the plunger would require an even higher traction force. The Diesel Kiki Co., Ltd. [19] has developed a powerful and simple Disole solenoid actuator that switches in less than 1 ms and generates over 200 N. Although it is compact and has a simple construction with great potential for reliability and low manufacturing cost, this force is still too low. On the other hand, Lucas Industries Ltd. has developed extremely fast response solenoids called Helenoids and Celenoids [20,21] that switch in less than 1 ms and develop up to 400 N. However, the high power requirement of 4000 W could create the need for either liquid or forced air cooling which would add significant complexity and cost to a LPI system. Cooling would also be required for the "multipole" solenoid produced by the Ford Motor Company [15] making this valve also unsuitable. A 12 V solenoid valve has been custom made specifically for a LPI but still requires considerable improvement [14]. This valve can operate at 28 MPa with switching times of 2 ms for opening and 4 ms for closing, but it can attain only a minimum 8 ms open time. Furthermore, the valve cannot operate faster than 18 Hz and generally leaks. It is believed that improvements are required to both the solenoid and control circuitry before the desired operating characteristics can be satisfied and the valve becomes reliable [5].

Piezoelectric elements are special crystals, such as quartz, that have the unique characteristic of rapidly expanding over a small distance (tens of micrometers) upon electrical excitation. Hence, if used for on-off valve control, fast switching times would be possible. Yokota et al. [22] have used dual, multi-layered piezoelectric elements on a poppet valve assembly to achieve a switching time less than 0.1 ms. However, this set up requires a 100 V excitation and has operated only at pressures up to 10 MPa. The authors claim that pressure cancellers in the valve can increase the upper operating pressure. Even if this claim were proven, the elements' 15 μm (0.0006") short stroke is suspected to provide insufficient flow area and, consequently to produce an unacceptably large pressure drop. Stone [23] has invented a high speed, amplitude variable, thrust control that switches in less than 0.5 ms but it requires up to 300 VDC to reach a maximum open position which is unsuitable for the desired LPI.

A valve actuated with a single-step, torque motor has been developed by Cui et. al. [24]. The motor, when subjected to an electrical pulse, turns a shaft which opens a gallery. This action exposes, in turn, a piston to the operating pressure so that the valve opens rapidly. Switching times between 2 and 3 ms have been achieved but only at pressures up to 9 MPa. The authors also describe other fast-acting valves that were developed in the 1970s. However, none have operated above 10 MPa.

2.3 Fuel Injection and the Poppet Valve

The fuel injection system (FIS) and the poppet valve, both of which are used extensively on the internal combustion engine, serve functions relevant to the needs of a LPI. The mechanical FIS, particular to the diesel engine, intermittently injects small quantities of liquid fuel at high pressure into the engine at (variable) frequencies that change with the engine speed. The poppet valve, which is found in almost all gasoline and diesel engine heads, opens and closes to permit the flow of gases to and from the engine. Both mechanisms have been improved over the past 100 years [25,26] to the point of high reliability and low cost due to mass production. For example, a service life in excess of 5000 hours (i.e. 150 to 300 million cycles) is not uncommon for either of these mechanisms in present day commercial engines [26,27,28].

A FIS includes a pump, injection line and nozzle. Instead of creating a pulsating pressure from a constant pressure supply, like an on-off valve, the injection pump itself provides a pulsed output. The pump pressurizes a controlled amount of liquid fuel which is injected into the engine at the correct time, frequency and rate. The pump, which is cam driven off the engine, has a plunger that compresses fuel on its up stroke to a pressure that opens the injection nozzle to begin the injection. The plunger has a helical cut around its side so that, when the bottom of the helix passes a port in the cylinder, the pressure drops rapidly and the injection stops. Rotation of the plunger (and the bottom of the helix) varies the effective stroke and, hence, the quantity of fuel delivered. The shape and rotational speed of the cam determine the flow rate and frequency of the injections, respectively. Common injection pressures range from 14 to 70 MPa (2,000 to 10,000 psi), and they are set by adjusting the spring force in the injector nozzle.

Although the duties of a fuel injection system suit the needs of the LPI, the rugged construction and high precision of the components make pumps and injectors very costly. For example, a single plunger pump having a 18 mm bore and 10 mm stroke, which would be suitable for feeding only one nozzle of a LPI, costs over $2500 [29]. In addition to multiple pumps being required (one for each nozzle), a modified variable speed, cam driven system and injectors would make adaptation of the fuel injection system to a LPI far too costly.

The poppet valve consists of a rod attached to a thin disk which covers a hole. Axial movement of the disk to lift it off its seat creates a flow path past the poppet and into the outlet hole. The poppet valve has been universally accepted in the internal combustion (IC) engine due to its many advantages [30,31]. For example, the poppet valve has a high flow to displacement ratio, an excellent flow coefficient if designed properly, a self-cleaning capability that promotes reliable shut-off and a low manufacturing cost due to its simple construction. Furthermore, its construction enables easy repair or replacement, and its axial movement within the guidebore involves very little friction so that minimal lubrication is required. Automotive research over many years has produced valve and valve seat materials (eg. stellite) that resist the high temperature and corrosive nature of exhaust gases as well as seating wear due to the impacts created at closures [25,26,27].

The poppet valve is ideal for on-off flow control but it requires actuation. The cam system used in an IC engine provides frequency control of the poppet but does not allow adjustment of closed or open times. This last deficiency can be overcome, however, by using a sliding wedge between the cam and poppet stem to vary the valve's lift and, hence, the open time. In fact, this principle is used to control the duration that injectors remain open on common rail fuel injection systems [32]. However, similar to the FIS, the cost of adapting a variable speed, cam drive system with a wedge to control the open time would be excessive for a LPI application.

2.4 Other Switching Devices

There are several switching devices that do not rely on electrical signals for activation. One such device is called a bi-stable, fluidic amplifier or flip-flop. A fluidic flip-flop is a valve, typically the size and shape of a small matchbox, with one inlet that merges into two diverging outlets [33]. In operation, flow attaches itself to the outside wall of either outlet by a natural phenomenon known as the Coanda effect [34]. Flow can be switched to the other outlet by providing a short, sharp pulse of fluid from a control jet that enters from the side adjacent to the active outlet. The momentum of the pulse shifts the flow to the other outlet where it remains until a control jet pulse issues from the other side. Flow will flip, thereafter between the outlets, by applying alternating pressure pulses to the control ports at a controlled timing. The fluidic flip-flop can be connected to an appropriate closed loop, fluid circuit that controls the time each outlet is active [33,35]. With one outlet feeding a nozzle on a LPI (and the other returning to the tank), the frequency and duration of the nozzle's output could be regulated. This arrangement could be very reliable because the flip flop has no moving parts. Although these devices were developed primarily for use with gas at pressures around 0.001 MPa (5 psi), efforts were made with larger versions, the size of a shoe box, to switch liquid at 14 MPa (2000 psi) [36]. However, large pressure drops were encountered which made the device relatively inefficient. A pressure drop of up to 50% could be expected with an operating pressure of 28 MPa [36,37]. This means that, to get 28 MPa pressure at the nozzle, a minimum 56 MPa supply pressure would be required. This, of course, is unacceptable.

A liquid operated oscillator was developed and tested in the early 1970s [38]. The oscillator makes use of diaphragms and the inertia of fluid flowing through a fixed length, outlet tube. Although the oscillator has been adopted as a pulsating shower head and, at higher pressures, as a pulsating car washer, it has not been tested at pressures above 1 MPa (140 psi). Moreover, it has a fixed frequency which depends primarily on the length of the outlet tube. The same inventor also developed a fluid oscillator in the early 1980s [39]. This device includes a ball contained in a conical chamber that has two circular outlets which feed separate outlet tubes of any length. The fluid flow through the cone causes the ball to alternately block the two outlets. The time the ball remains over a port depends primarily upon the length of the tube so that the frequency of operation is difficult to adjust [40]. Furthermore, the mechanism has been tested at pressures up to only 0.7 MPa (100 psi).

An extremely fast opening, high pressure valve has been developed to generate hydraulic pulses at 400 MPa (60,000 psi) for fragmenting rock [41,42]. This hydraulic pulse generator consists of an inlet chamber which is pressurized to force a poppet (in the form of a short cylindrical metal rod) over the outlet of an accumulator pressure vessel. Quick release of the inlet pressure by activating a two-way servo-valve (operated electrically or manually) removes the closure force and the pressure in the accumulator vessel instantly lifts the poppet off the outlet hole to fully open the valve. The device can generate pulses at only 1 Hz but the pulse time is dictated by the volume of the accumulator and, thus, cannot be adjusted easily. However, the concept of using the accumulator pressure to snap open the valve is clever. The opening is very rapid (although no specific times are given) and requires very little energy so that the device is very efficient.

2.5 New Approach

A thorough review of existing technology has revealed no mechanism that satisfies all the requirements of a LPI. However, several mechanisms and concepts can be used, with ingenuity, to develop a new and effective solution. For instance, the poppet valve, because of its many advantages over other valves, is an ideal on-off valve [43]. Moreover, in a similar fashion to the hydraulic pulse generator [42], the pressure could help to rapidly open a poppet valve. However, as mentioned in Section 2.3, controlling the position of the poppet remains a problem. Although a solenoid is a likely choice for actuation, its capabilities have been found insufficient for the LPI's high operating pressure and fast switching requirements. The system of using a cam and wedges has been discussed already and it is considered infeasible due to the high complexity and cost. On the other hand, using the energy available in a pressurized operating fluid to control the position of the poppet should be possible [37]. A logical approach is to attach a disk or switching piston to the end of the poppet stem, as shown in Figure 2.2, and control the pressure acting on the piston. With this arrangement, the inlet pressure, Pi, would keep the poppet sealed against its seat until the switching pressure, Ps, acting on the piston is sufficient to lift the poppet off its seat. The poppet valve would remain open until Ps vanishes to permit the remaining pressure, Pi, to close the valve. In a similar manner to the operation of the fluidic flip-flop, by connecting the switching chamber to an intermittent pulsating pressure circuit, the valve could conceivably open and close at a controlled timing with no electrical actuation.

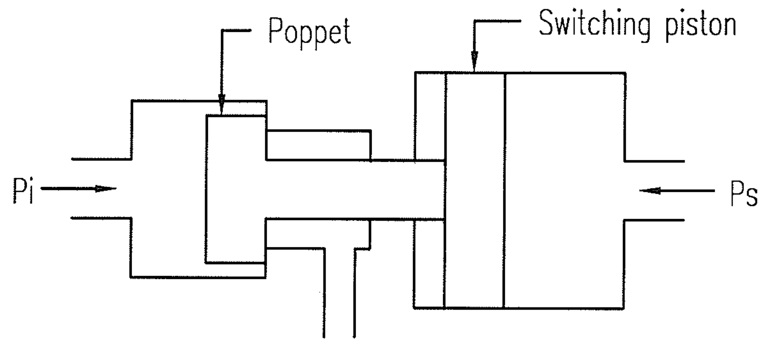


Figure 2.2 Arrangement of the poppet valve and switching piston

The remainder of this thesis describes a circuit that regulates Ps in order to operate the poppet valve according to the requirements of the LPI. Before the circuit is presented, however, a detailed description of the requirements of the on-off valve is given.

3. VALVE REQUIREMENTS

The on-off valve described in this thesis is designed to meet the requirements of a LPI outlined in Section 2.1. Table 3.1 summarizes, for convenience, the specific requirements set at the beginning of the project [5].

Operating pressure	28 MPa (4000 psi)
Operating fluids	Aqueous solutions: corrosive, abrasive, viscous
Switching time	< 5 ms (drip-free when closed)
Operating frequency	Up to 20 Hz
Open time	5 - 30 ms (independently adjustable)
Closed time	20 - 200 ms (independently adjustable)
Timing control	Repeatable, accurate, easily automated
Other features	Insensitive to shocks and orientation, quiet, maintainable
Expected service life	> 500 hrs (maintenance-free)
Manufacturing cost	< $100.00

Table 3.1 Valve requirements

To satisfy the design criteria given in Table 3.1, the pressure-actuated poppet valve that was presented in Section 2.5 (and Figure 2.2) should have the following physical characteristics. The valve must be robust to withstand a high operating pressure. The poppet must be light and have a short stroke to achieve a fast switching time. Because the valve may be far from the operator's reach, remote timing control must be accommodated. Furthermore, the valve must be durable and dependable during a long service life. Its construction must be simple and have as many as possible, commercially available parts to reduce manufacturing and developmental costs. To simplify the design, it was decided to initially limit liquids to merely water with the intent of introducing subsequent alterations to make the valve compatible with other required fluids. Finally, because current ground injection equipment uses nozzles having orifices ranging from 0.3 to 2 mm [3,4,14], a midrange orifice size of 1 mm was chosen [5].

4. SELF-SWITCHING CONCEPT

4.1 Development

The pressure-actuated poppet valve design that was shown in Figure 2.2 of Section 2.5, included a switching piston connected rigidly to the end of a poppet. It was explained that, by controlling the switching pressure "seen" by the piston, the position of the poppet could be controlled and maintained. This section describes a circuit that controls the switching pressure and gives the valve a self-switching capability. Note that the valve requirements listed in Table 3.1 are implicit to all later discussions.

Figure 4.1 shows a pressure-actuated, on-off valve in the (a) closed and (b) open positions required to produce intermittent, high speed liquid jets. The illustrations indicate that Ps must be low for the valve to close and remain closed and high to initiate and maintain the open position. The exit chamber pressure, Pe, also plays an important role in the switching and (position) control of the poppet. As soon as Ps is sufficiently high to lift the poppet off its seat, flow into the exit chamber causes Pe to increase rapidly and snap open the valve. Conversely, when the poppet seats at closure, Pe drops immediately to atmospheric pressure to keep the poppet valve closed. More specifically, Ps initiates both the opening and closing of the valve whilst Pe assists in completing and maintaining the transition. Therefore, to control the timing of the switches, the rise and fall of Ps must be controlled. The time for Ps to rise to the opening pressure corresponds to the closed time and the time for Ps to fall to permit closure corresponds to the valve's open time. To be self-switching, the valve itself must control the variations in Ps with either Pi or Pe as the pressure source. Ps must rise when the poppet valve is closed, when Pe is zero, and must drop when the valve is open, i.e. when Pe is maximum. Consequently, more difficulty is likely encountered if Pe is the pressure source because it is out of phase with Ps. This leaves Pi. As shown in Figure 4.2, Pi feeds Ps through a needle valve that controls the flow rate into the switching chamber and, hence, the rise time of Ps. The larger is the flow area past the needle valve, the higher is the flow into the switching chamber and the shorter is the closed time.

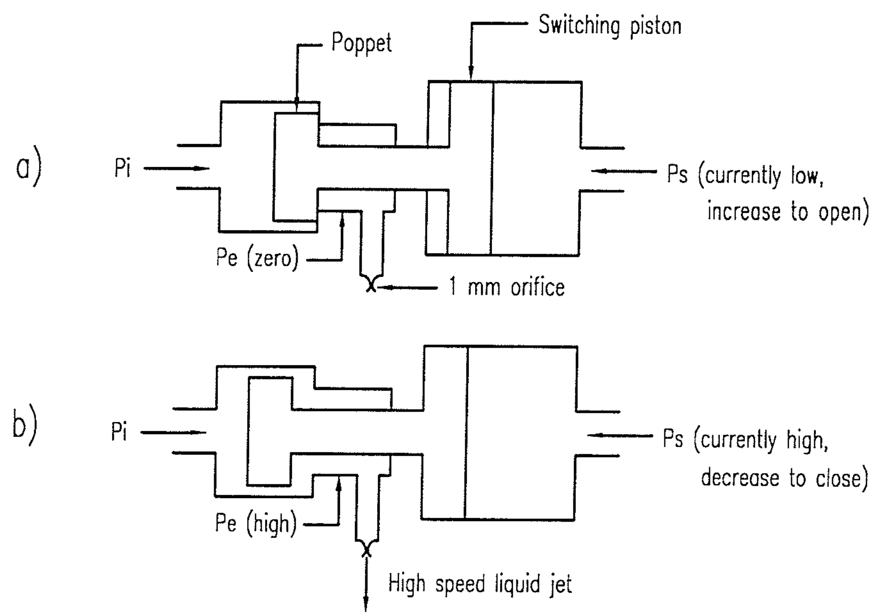


Figure 4.1 Pressure-actuated poppet valve (a) closed position, and (b) open position

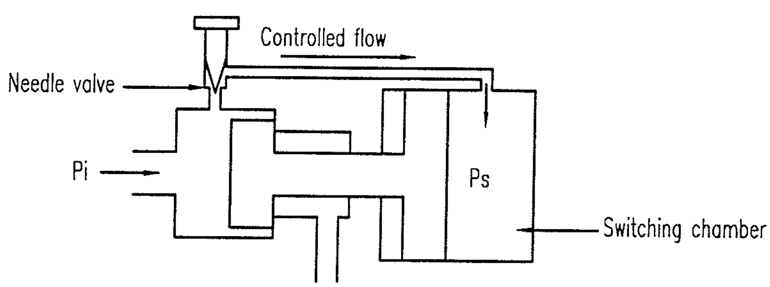


Figure 4.2 Flow circuit controlling the rise time of the switching pressure

The simple fluid circuit shown in Figure 4.2 controls the closed time as well as opens the valve but it does not have the capability to permit closure. This circuit would involve flow only until Ps equals Pi - a condition that would lock the poppet valve open. Still required is a means of exhausting the switching chamber to reduce Ps to a value that would permit closure. Figure 4.3 shows another needle valve, controlled circuit that can be used to release fluid from the switching chamber and permit Ps to drop, at a controlled rate, to permit closure. However, this arrangement would only involve continuous flow and would not provide the varying Ps necessary for both on and off switching functions. This observation indicates that a dual-purpose mechanism is required (i) to seal the switching chamber and permit Ps to rise when the poppet valve is closed and (ii) to allow flow out of the chamber to reduce Ps when the poppet valve is open. The seal-release mechanism can be coupled either to the exit chamber pressure, and be pressure-actuated, or to the position of the poppet valve assembly and be position-actuated. The latter approach was pursued because no off-the-shelf, pressure activated valve could be found and also it was considered an easy task to construct a sealing mechanism. Figure 4.4 shows the inclusion of a custom-made release valve that seals against the switching piston when the poppet valve is closed and separates from the piston when the poppet valve is open. In the closed position, Ps would increase at a controlled rate and, in the open position, the release valve would permit flow out of the switching chamber (at a rate greater than the in-flow) and cause Ps to decrease. This simple mechanism can provide the necessary variations in Ps with the rise and fall times controlled by the setting of each needle valve.

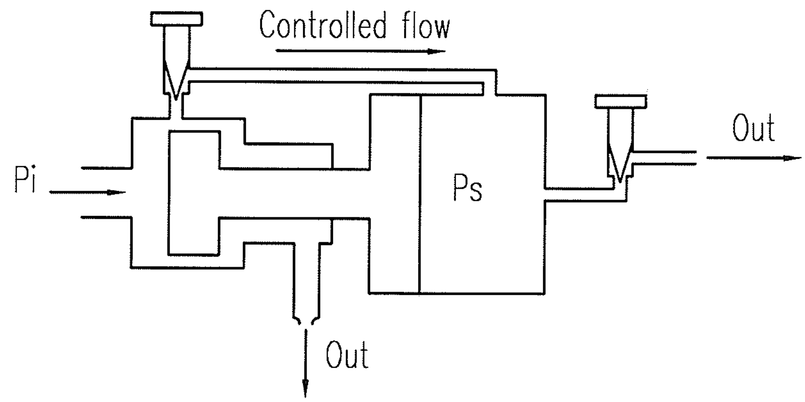


Figure 4.3 Addition of a pressure release circuit

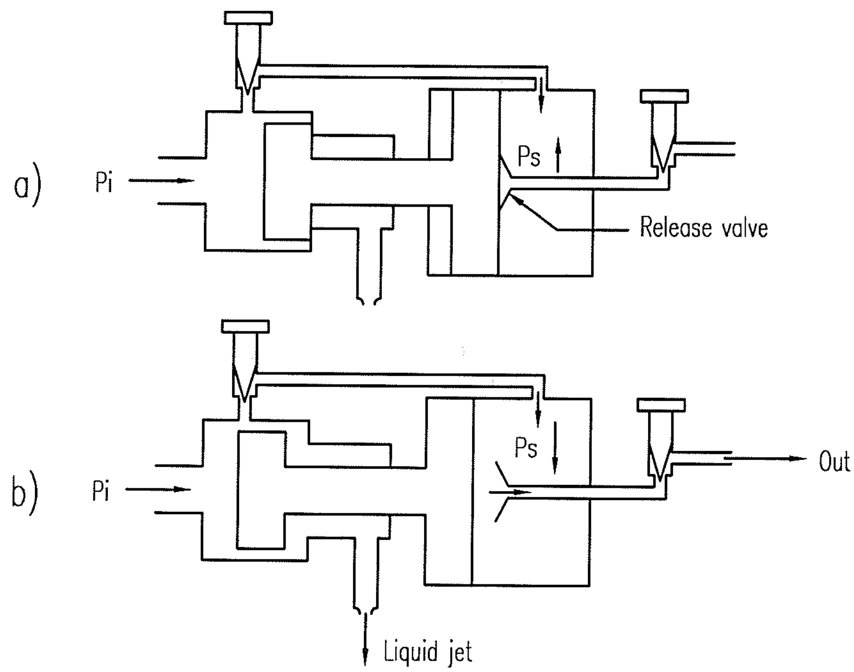


Figure 4.4 Complete switching circuit to control variations in Ps; a) release valve closed and Ps increases, and b) release valve open and Ps decreases

The arrangement shown in Figure 4.4 is intuitively self-switching but it is very difficult to hypothesize whether the arrangement would meet the requirements listed in Table 3.1. Many questions can be asked regarding the valve's operation. For instance, what sizes should the poppet valve, the switching piston, the pressure chambers and the needle valves be in order to meet all the design criteria? Also, how sensitive are the valve's switching and timing characteristics to changes in the physical parameters, such as the overall size or needle valve settings? Most importantly, what factors can be changed or controlled to provide repeatable and long lasting service? These and many other questions can be answered by the construction and testing of a prototype. However, such an exercise is not only time consuming and costly, it is also unlikely that an effectively working product would be produced at the first attempt. There is a preliminary cost effective exercise, however, that can provide much insight into the dynamic behavior of the valve's operation. A computer model can be used to simulate the operation of the valve based on given physical parameters that can be changed with little effort and time.

4.2 Computer Simulation

The plausibility of the self-switching concept was investigated by simulating the operation of the conceptual valve design with a customized computer program [44]. The program generated time histories of the pressures and flows through the chambers and valve circuits as well as the corresponding position and velocity of the poppet valve assembly. This exercise proved to be a valuable guide in assessing the dynamic behavior of the valve and in evaluating the effects of changing various physical parameters on the response of the poppet motion. After the results of the computer simulation were checked for accuracy with a simple pressure test and steady state flow measurement on a quick mock up, they were used to design the first version and also to provide key information toward subsequent design improvements. Furthermore, this exercise provided a cost effective means of testing ideas before the laborious tasks of construction and testing were performed. The computer program listing is included in Appendix A.

The simulation first required the development of mathematical equations to describe the behavior of each section and element of the valve based on several simplifying assumptions. Equations were developed to describe the flow across each restriction and the resulting pressure changes due to fluid compression, as well as the motion of the poppet valve assembly due to the interacting chamber pressures. To simplify the analysis, fluid density (across a restriction) was considered constant (i.e. negligible density change) all chambers were treated as rigid and the friction (due to seals) on the poppet valve assembly was neglected. After the final design was tested, dilation of the exit chamber was incorporated and friction was added to achieve better correlation with experimental results. Details of the mathematical modelling are presented more conveniently in Appendix B.

The computer program calculated the flowrate across each restriction, the pressure in each chamber and the position and velocity of the poppet valve assembly at 0.01 ms increments. The results were analyzed with particular interest in the switching times and corresponding impact speeds, the transient flowrates as well as the forces imposed on the poppet valve assembly. Quick checks were made to build confidence in the mathematical model before using it for design. The simulation results were compared with calculated estimates of the acceleration and switching times of the poppet valve and a measured flowrate through a mock up valve. Of course the results were expected to indicate a transient flow upon valve opening, flow stoppage after valve closure and matching steady state exit chamber flows (in and out). Once the results correlated well with the checks and were considered indicative of the real behavior, the computer model was used as a design tool by manipulating parameters to ascertain their effects.

The initial prototype design, that was simulated numerically with a 28 MPa pressure supply, included a 32 mm (1.25") diameter poppet valve with a 12 mm (1/2") diameter stem and a 0.127 mm (0.005") stroke. The size of the poppet valve was based on commercially available stellite collars which were intended to be incorporated into the valve (to keep manufacturing costs down and provide corrosion resistance and a long service life). The stem was sized to withstand the high compressive forces required to overcome the closure force (22 kN or 5000 lbs) and open the valve as well as to fit a commercially available stem seal. The short stroke was chosen to achieve a fast switching time. It also provided a flow area about 10 times that of the 1 mm orifice. The switching piston was set arbitrarily at 47 mm (1-7/8") diameter to give an area ratio of 2.25 relative to the head of the poppet. The mass of the poppet valve assembly was set at 0.2 kg (7 oz.).

The results of the computer simulation showed that the valve is, indeed, self-switching with an opening time of 0.4 ms and a closing time of 0.8 ms. As shown in Figure 4.5, these switching times correspond to the period it takes for the poppet to move through its stroke of 0.127 mm. Also indicated in the figure, are the opening and closing impact speeds of 170 cm/s and 50 cm/s (67 and 20 in/s), respectively. These estimated switching times suggested that the 5 ms switching time requirement was achievable and that the configuration modelled was worth pursuing. Additionally, the slower impact speed at closure, compared with the quicker opening, was considered desirable for a long seat life. In fact, the estimated closing impact speed is only 11% higher than the recommended seating speed for valves in internal combustion engines [27].

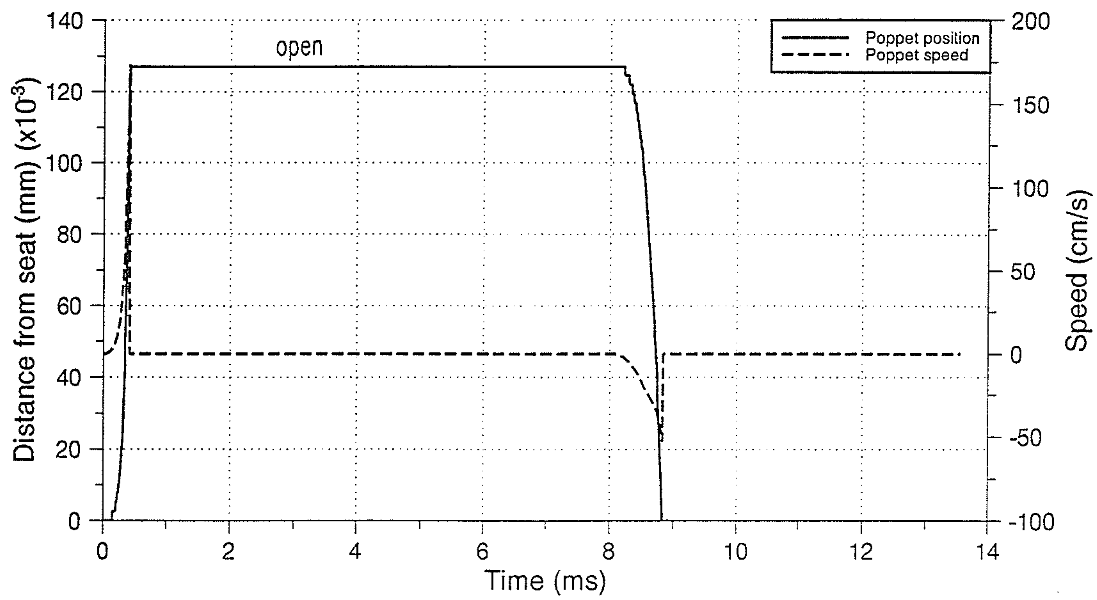


Figure 4.5 Simulated poppet motion

Figure 4.6 shows the simulated characteristics of the exit chamber pressure and flowrates in relation to the poppet's motion. As expected, the curves indicate that flow past the poppet valve exists only when the valve is open, flow out of the valve exists only when the exit chamber pressure is non-zero and that the steady state flows (after the transient spike at opening) are equal. Quantitatively, the pressure curve shows that a steady exit pressure of about 27 MPa (corresponding to a pressure drop of only 1 MPa or 140 psi) is reached in less than 1 ms, just shortly after the valve is fully open. If this 1 ms value is considered the switching time, it undercuts the required 5 ms. The curve also indicates that the fall time of this pressure is approximately 4 ms, which is also less than the desired value. Notice that the valve closes (i.e. re-seats) before much change has occurred to the exit pressure. Physically, this implies that the force due to the switching pressure dominates throughout the closing transition. On the other hand, Figure 4.6 suggests that the rapidly increasing exit pressure dominates the opening transition to produce an opening time that is half the closing time.

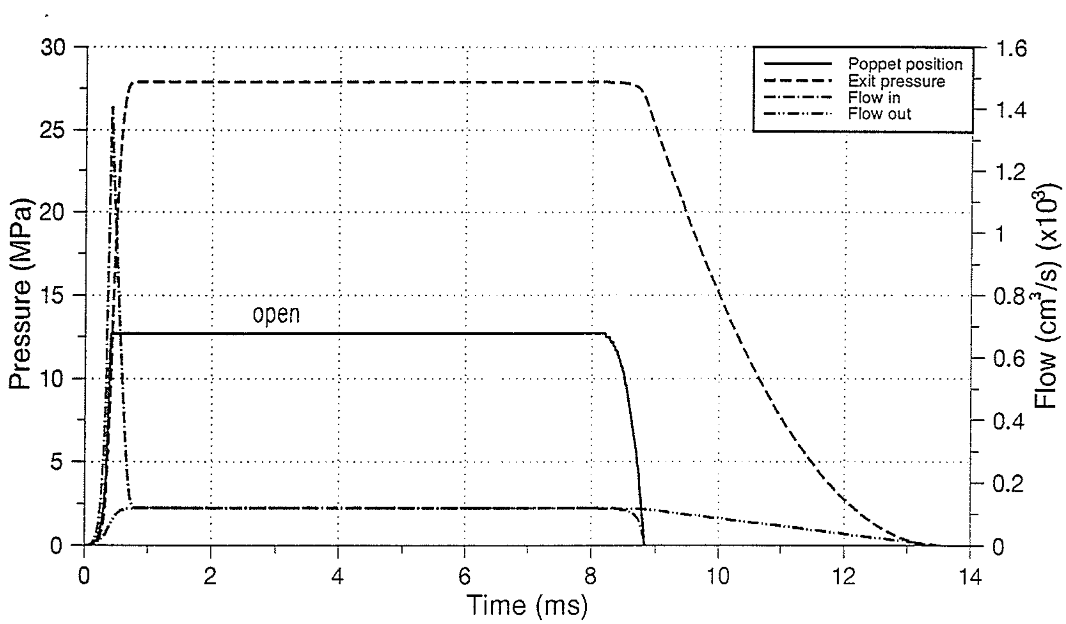


Figure 4.6 Simulated exit chamber pressure and flow characteristics

The estimated steady flowrate of 115 cm^3/s was found to be very close to the measured value of 116 cm^3/s with the valve mock up. Figure 4.6 shows that the transient flow during the opening of the valve is about twelve times the steady value. This ratio is considered reasonable because transient flow can be expected to be considerably higher than the steady state value in many fluid circuits [45]. Flow transients are critical because, for the short period they exist, the capacity of the supply pump may be exceeded. This could become a serious problem at higher frequencies of valve operation (or with many valves operating), which would increase the number of transient spikes per second, resulting in an overall increase in the average flowrate required by the pump. If the average flowrate exceeds the capacity of the pump, the pressure supply would reduce which, in turn, would reduce the amount of available (pressure) energy for the ground injection process.

The estimated switching and exit chamber pressures as well as the corresponding varying net force on the poppet valve assembly are shown in Figure 4.7. This graph starts at time zero (the instant that the supply pressure would be turned on) when the only active force acting on the poppet is due to the inlet pressure. The magnitude of the closure force shown in the figure is approximately 22 kN. The other chamber pressures are at atmospheric pressure at this time and, because atmospheric pressure is treated as the reference pressure, they are initially zero. The dashed curve indicates that the switching pressure increases almost linearly to its upper limit of 12.5 MPa (1800 psi) at which time the net force on the poppet valve assembly surpasses zero which causes the valve to open. (Note that this pressure corresponds to the inverse of the area ratio of 2.25.) The opening of the valve permits flow into the exit chamber which results in a rapid increase in the exit pressure and, hence, the net force which, in turn, rapidly accelerates the poppet and snaps open the poppet valve. Keep in mind that this transition is predicted to occur within 0.4 ms. After the valve opens, the release valve is separated from the switching piston (see Figure 4.4b) which permits the switching pressure to decrease non-linearly to its lower limit. At this time, the net force, which also has decreased in the same fashion, drops below zero which initiates valve closure. Figure 4.7 indicates that, because the valve closes before the exit pressure drops significantly, the net force does not change as much during closure as it does during opening. This corroborates the argument that the seating speed is less than the opening impact speed.

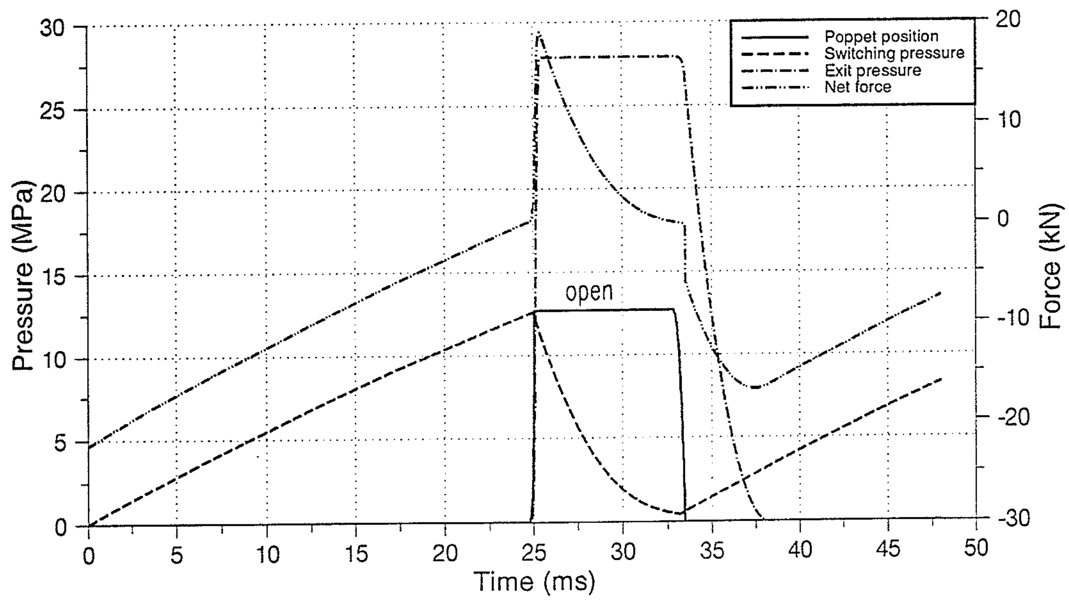


Figure 4.7 Simulated chamber pressures and resulting net force on the poppet valve assembly

After the reasonable results described previously were obtained, physical parameters like the mass or stroke of the poppet and the size of a pressure chamber were altered to ascertain their effects. It was found that increasing the stroke and the area of the base of the poppet head (exposed to the exit pressure) and decreasing the mass of the poppet valve assembly all contribute to undesirable increases in impact speeds. A larger exit chamber volume or a reduction in the fluid's bulk modulus was shown to increase the transient flowrate as well as the opening switching time by decreasing the rate of fluid compression and, hence, the pressure rise (and fall) times. To minimize the transient flow, it was decided to keep this chamber as small as possible. It was also found that a larger switching piston lowers the switching pressure and, hence, the amount of fluid to be compressed which would effectively increase the sensitivity of the timing control system.

On the other hand, a larger switching chamber volume decreases the sensitivity of the needle valve adjustments. Realizing these trends was very helpful in learning the behavior of the valve and also in designing the initial prototype and subsequent modifications.

5. FINAL VALVE DESIGN

5.1 Physical Description

The final valve design is a poppet valve with no external actuation that transforms a constant pressure input into a pulsating output. The valve operates with cold tap water pressurized to 28 MPa and supplies pressure pulsations to a nozzle with a 1 mm orifice to create intermittent, high speed liquid jets. The valve is designed in accordance with the requirements of a LPI that will be assisted to traverse the ground and automatically inject the liquid jets beneath the surface.

The prototype valve has a 35 mm diameter, stainless steel, poppet valve housed in a cuboid aluminum body. The valve body is 75 mm (3") square, 70 mm (2-3/4") long and is capped at each end with a 25 mm thick aluminum plate. Four Grade 8 bolts, each 9 mm (3/8") diameter and 140 mm (5-1/2") long, that run through the four corners of the valve body and the two end plates, hold the assembly together. The assembled prototype weighs approximately 2.5 kg (5 lbs). The valve has one inlet that feeds the two fluid circuits which include the main flow circuit that provides the pressure pulses to the 1 mm orifice in the nozzle and the switching circuit that controls the timing of the pulsations.

The main components of the valve are the poppet valve-switching piston assembly, the release valve and the closed stage and open stage needle valves. As shown in Figure 5.1, the poppet valve and the switching piston, which are attached rigidly together, are contained within the concentric bores of the valve body. The release valve screws through the end plate and butts up against the switching piston. The closed stage needle valve screws into the valve body at the inlet end and the open stage needle valve is in a small aluminum block that screws onto the end of the release valve rod.

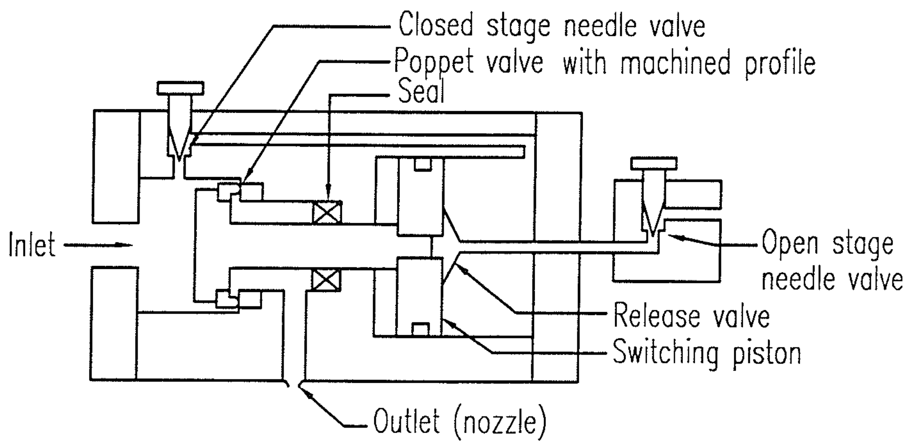


Figure 5.1 Configuration of the self-switching valve

The poppet valve-switching piston assembly, abbreviated later to the poppet valve assembly, is the only moving part in the valve and has a stroke of 0.127 mm (0.005"). The poppet valve consists of a poppet (and stem) machined from stainless steel and two stellite collars for the poppet and seat contacting surfaces. The collars are both 24 mm inside diameter, 35 mm outside diameter and 8 mm deep. As shown in Figure 5.1, one collar is pressed onto the poppet and the other into the valve body. The poppet collar has a rounded, raised profile running around the outside of its face that provides a line contact to the flat seat. The profile is rounded to provide a smooth flow path through the valve and to effectively reduce minor loss coefficients [45,46]. The collars are commercially available as valve seat inserts for automobile engine heads. They are designed for superior wear and corrosion resistance at high temperatures and are precision made as well as inexpensive ($10.00 each) due to mass production. The valve stem is 12.5 mm in diameter and slides into the smallest bore of the valve body to keep the stellite collars concentric and square. The valve stem, which determines the working stroke (i.e. travel distance) of the poppet valve by using the back side of the switching piston as the stop, is approximately 35 mm long and has a 15 mm long threaded extension. The switching piston is a 35 mm diameter by 19 mm thick aluminum disk with smooth flat faces and, as shown Figure 5.1, has a groove on its circumference to accommodate an o-ring that seals the piston to its bore. The piston screws onto the threaded extension of the valve stem and rests tightly against the stem's shoulder. A thin steel backing plate, glued to the back of the piston, protects the soft aluminum from the harder stainless steel shoulder of the stem to which it rests tightly.

The bores machined into the valve body, the poppet valve assembly and the two end plates compose three separate pressure chambers. The first is the inlet pressure chamber which receives the pressure supply from the pump and feeds the main pulsed flow circuit (through the poppet valve) and the switching circuit. It is 40 mm in diameter and 12 mm deep and is confined at its ends by the end plate (with a face seal o-ring between the plate and body) and a closed poppet valve. The second chamber is the exit pressure chamber which receives the pressure pulsations (when the poppet valve is open) and supplies them to the nozzle. This chamber is 25 mm in diameter, 16 mm long and is confined by the base of the poppet head and a seal around the valve stem. The seal prevents leakage from passing through the clearance between the stem and the valve guide and into the space behind the switching piston. The third pressure chamber is the switching chamber which receives fluid from the inlet chamber through the closed stage needle valve and repeatedly stores pressurized fluid and releases it to the atmosphere past the release valve and open stage needle valve. This chamber is confined by the other end plate and the outer face of the switching piston. A face seal o-ring between this plate and the valve body, as well as an o-ring between the piston and its bore and the release valve, seal this chamber.

The remaining components of the valve are the release valve and two needle valves. The release valve controls the direction of the switching by butting against the switching piston to seal the switching chamber when the poppet valve is closed, and by permitting the release of fluid (and pressure) from the chamber when the poppet valve assembly moves to the open position. The custom-made release valve consists of a flat-faced, circular plastic knob extending from the end of a 50 mm (2") long, fine threaded rod (1/4" NF) with a hole drilled through the center (for the flow of fluid). The plastic knob is 10 mm (0.400") in diameter and has a 0.38 mm (0.015") thin lip that extends 2 mm outward and around the end of the knob. The lip is sufficiently flexible to seal to the face of the switching piston (due to the switching chamber pressure) but rigid enough to separate from the piston when the poppet valve shifts to its open position. The threaded section, which screws through the end plate, provides an adjustment to lightly rest the release valve on the piston face.

The two needle valves control the duration of the open and closed periods of the valve. Both needle valves consist of a stainless steel, fine-tipped screw and a 0.76 mm (0.030") orifice. The screws are 25 mm (1") long with a 10 - 32 threaded section and a 9 mm (3/8") long tip that tapers from 2.5 to 0.64 mm (0.100" to 0.025"). Each tip fits into its orifice to regulate fluid flow through the switching circuit. The closed stage needle valve is machined through the side of the valve body and regulates flow from the inlet chamber to the switching chamber. The open stage needle valve is machined in an aluminum block that screws onto the free end of the threaded release valve rod. This needle valve regulates flow out of the switching chamber when the poppet valve is open and the release valve is separated from the switching piston. The screws, which were kindly donated to the project [47], are actually idle mixture screws for carburetors of small aircraft engines.

5.2 Description of Operation

The poppet valve repeatedly opens and closes by itself to transform a constant pressure input into a pulsating output pressure. The valve feeds its pulsating output to a nozzle with a 1 mm orifice that produces high speed liquid jets. Varying the time the valve remains open and closed alters the frequency and duration of the liquid jets.

The valve switches in sequence to a continually changing net force that acts on the poppet valve assembly due to the pressures in the three chambers. The three axial forces resulting from the three chamber pressures include a constant closure force, which pushes the valve to its seat, an oscillating switching force, which initiates the switch, and a bi-state (zero or high) exit chamber force, which helps complete the switching and maintains the new position of the poppet valve. The closure force, Fc, which equals 28 kN (6000 lbs), is the product of the constant inlet chamber pressure of 28 MPa (4000 psi), and the area of the top of the poppet head, which is 10 cm^2 (1.5 sq.in.). The oscillating switching force, Fs, is the product of the area of the switching piston, which is 20 cm^2 (2.75 sq.in), and the switching chamber pressure, which oscillates between 14 and 2 MPa (2000 and 350 psi). Thus Fs varies between 28 kN (which opens the valve) and 5 kN (which permits closure). The exit chamber force, Fe, equals the product of the exit chamber pressure, Pe, and the area of the bottom of the poppet head, which is 4.0 cm^2 (0.6 sq.in). With atmospheric pressure as the reference (i.e. Pe = 0), Fe alternates from zero, when the poppet is closed (and the exit chamber pressure is atmospheric) to a maximum of about 23 kN (5000 lbs) when the valve is open. After the poppet is lifted off its seat, due to Fs reaching its maximum value, Pe rises due to an in-flow from the inlet chamber, rapidly creating Fe, a new additional opening force, and the valve snaps fully open. After closure (due to Fs dropping), Pe returns to zero, thus removing Fe, and the valve remains closed.

The switching pressure oscillates by utilizing the compressibility of the working fluid in the switching chamber. A fluid is compressed, or squeezed, by either reducing its volume or by adding more fluid to a given volume. Both these procedures effectively produce a greater fluid pressure. Conversely, a reversal of either process reduces the pressure. The switching circuit, fed from the inlet chamber and eventually exhausted to the atmosphere, repeatedly adds or releases very small amounts of fluid to the switching chamber to create the oscillating pressure. This oscillating pressure, which acts over the surface of the switching piston, changes the net force acting on the poppet valve assembly. When the switching force, Fs, is sufficiently high, the poppet valve is forced open and, when the switching force is at its lower limit, valve closure is permitted. Controlling the time it takes for the switching pressure to reach its maximum and minimum values determines the instants the valve opens and closes, respectively.

The needle valves control the duration of the closed and open periods by governing the flow rate to and from the switching chamber. The more open is the closed stage needle valve, the faster the switching chamber pressure rises and the shorter is the closed time. The same principle applies to the open time. However, unlike the closed time which depends only upon the position of the closed stage needle valve (because the release valve deactivates the latter part of the switching circuit when the poppet valve is closed), the open time depends upon both needle valve positions. During the open stage, fluid flows into the switching chamber from the inlet chamber and flows out past the release valve and open stage needle valve making the open time depend upon the difference between the two flowrates.

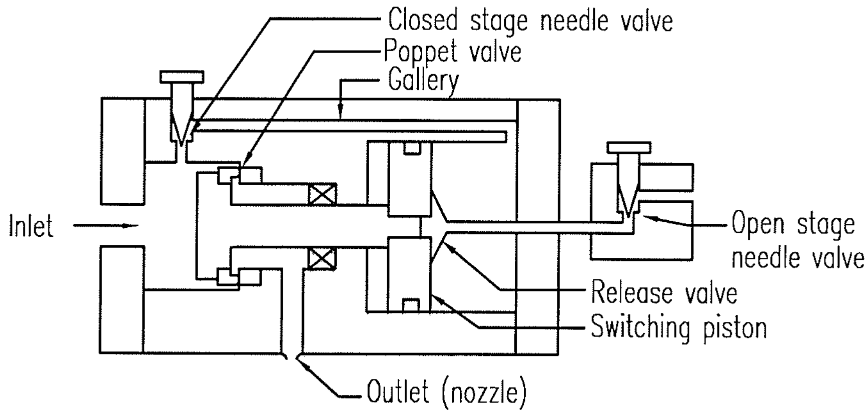
The following is a detailed description of the events that take place over one complete on-off cycle. The discussion is based on the sequential force diagram given in Figure 5.2 which shows the three axial forces that act on the poppet valve assembly and how they change with time and valve position. The various poppet valve conditions a) though h) shown in the figure correspond to the following sections.

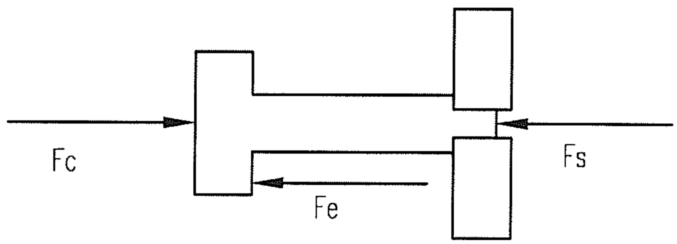
a) Closed: Start-up position:

When the system is pressurized, the inlet chamber pressure reaches its maximum value and the poppet valve assumes its normally closed position. At this time, both the exit and switching chambers, Pe and Ps, are at atmospheric pressure, making the closure force, Fc, the only contributor to the net force that closes the valve. In this closed position, the switching piston butts lightly against the release valve. The pressure differential across the closed stage needle valve causes fluid flow past the needle valve, down the gallery and into the switching chamber. This flow causes the fluid in the switching chamber to compress and the pressure to rise which pushes the lip of the release valve to the face of the switching piston, sealing the switching chamber. The continually increasing switching chamber pressure causes a proportionally larger switching force, Fs, which opposes Fc.

b) Initiation of opening:

When sufficient flow has entered the switching chamber, making Fs equal or slightly greater than Fc, the net force lifts the poppet off its seat. Ps has reached its maximum value.





Poppet Position	Active forces	Chamber Pressure
a) Closed (start-up)	$Fc-\cancelto{0}{Fe}-Fs>0$	$Pe=0$, $Ps\uparrow$
b) Initiation of opening	$Fc-\cancelto{0}{Fe}-Fs<=0$	$Pe=0$, $Ps=max$
c) Switch to open	$Fc-Fe-Fs<<0$	Pe-->max, RV opens
d) Open	$Fc-Fe-Fs<0$	$Pe=max$, $Ps\downarrow$
e) Initiation of closure	$Fc-Fe-Fs>=0$	$Pe=max$, $Ps=min$
f) Switch to close	$Fc-Fe-Fs>0$	$Pe\downarrow$, RV closes
g) Closure	$Fc-\cancelto{0}{Fe}-Fs>>0$	Pe-->0, $Ps\uparrow$
h) Closed	$Fc-\cancelto{0}{Fe}-Fs>0$	$Pe=0$, $Ps\uparrow$

Figure 5.2 Sequential forces acting on the poppet assembly

c) Switch to fully open position:

During this transition, three things happen before the poppet reaches the end of its stroke. First, the opening of the valve permits flow into the exit chamber. This transient flow rapidly increases the exit chamber pressure, Pe, and the resulting, additional force, Fe, snaps the valve to its fully open position. The rapid increase in Pe also starts a liquid jet to be emitted from the nozzle orifice which is the second event. The third event is the separation of the switching piston from the release valve (RV) which permits the compressed liquid to be released slowly from the switching chamber through the open stage needle valve.

d) Open position:

In the open position, the flow area past the poppet valve, the exit chamber pressure and the jet issuing from the nozzle are all at their maximum values and the two forces, Fe and Fs, maintain this condition. Fluid is released at a controlled rate from the switching chamber past the release valve and open stage needle valve causing the switching chamber pressure to drop. This declining pressure lowers Fs and, consequently, the net force holding the valve open.

e) Initiation of closure:

When the net axial force acting on the poppet valve assembly can no longer hold the valve open as a result of the switching chamber pressure reaching its minimum value, the valve begins to close.

f) Switch to closed position:

During the switching to the closed position, the poppet approaches the seat which reduces the flow area past the poppet valve. This reduction causes, in turn, the pressure in the exit chamber to begin to drop which increases the net closure force and permits the poppet to seat rapidly.

g) Closure:

At closure, the exit chamber pressure drops immediately to atmospheric pressure, which eliminates Fe and produces a large force imbalance that keeps the poppet seated. The closure also cuts off the liquid jet and sets the switching piston against the release valve to reseal the switching chamber.

h) Closed position:

With the exit chamber at atmospheric pressure and the release valve sealed against the switching piston, the switching chamber pressure begins to rise until it pushes the poppet valve open.

5.3 Operation and Design Modifications

The valve's operation identified design deficiencies that remained undetected in the computer simulation. Each new version of the valve was assembled, connected to an operating circuit and tested to assess the switching and timing behavior. After a short running period, the valve was disassembled and the components were inspected carefully for early signs of wear or damage. These observations led to modifications and improvements and, finally, to a longer, faster operation at higher pressures.

The valve was operated in a specially constructed, safe laboratory operating circuit that could be operated continuously. As shown in Figure 5.3, the operating circuit included a filtered, cold city tap water supply, a Wabesh, high pressure cleaning pump (see Appendix C for details) and a sealed test enclosure which contained the valve, nozzle and liquid jets. The test cell drained into the building's plumbing. The pump, which was a three stage (cylinder) positive displacement pump, featured a reservoir with a float, an adjustable pressure release valve, a pressure gauge (4000 psi scale) and a hose that led to the valve. The test cell was made economically from a salvaged 45 gallon drum cut along its axis into halves. The halves were hinged and sealed with foam gasket tape. The test cell also featured an inspection window of 17 mm (3/4") thick, clear acrylic sheet and an interior waterproof safety light which permitted safe viewing of the valve's operation. A cradle welded to the inner bottom surface of test cell restrained the valve.

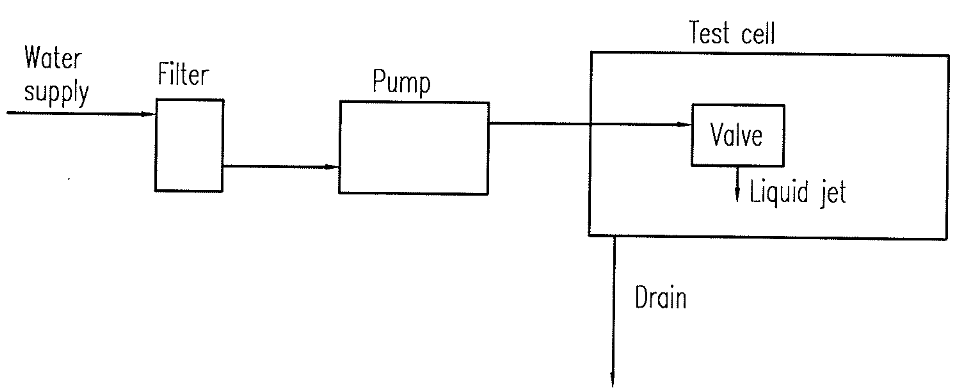


Figure 5.3 The valve's operating circuit

Operation of the valve first required the assembly, hook up, pressurization and tuning of the valve. Assembly involved installing all seals and o-rings, fastening the switching piston to the stem of the poppet valve and bolting the end plates to the valve body. After mounting the valve into the cradle of the test cell, the high pressure line was connected and the valve was pressurized with the test cell lid closed. The operating pressure was restricted to 3.5 MPa (500 psi) for the early valves and was increased incrementally with design improvements. After a quick check for leaks, the lid was opened to access the valve for tuning. The valve was tuned by opening both needle valves to create a high flowrate through the switching circuit that purged all the air trapped in the switching chamber. After an unbroken flow stream issued from the open stage needle valve block, the closed stage needle valve was screwed in until only a trickle of water issued from the switching circuit. The release valve was then screwed in until the valve began to switch and produce the liquid jets from the nozzle. Proper positioning of the release valve was maintained by tightening a lock nut to the end plate. The assembly process to this stage was timed at less than five minutes. With a tuned valve, the needle valves could be turned to manipulate the pulse timing and frequency and permit examination of the valve's operation.

Operation of the valve focussed on the smoothness of operation, repeatability of the timing, the intensity and consistency of the impacts of the poppet valve assembly, and the range and sensitivity of the timing control. Initially, the valve was adjusted to operate at less than 5 pulses per second with a 30 to 50% open time. This slow speed made slight variations in the switching frequency detectable and allowed a careful examination of both opening and closing impacts. The impacts were examined most conveniently by placing the probe of a stethoscope on the valve body. A stethoscope enhances audible perception by amplifying sound waves transmitted through a solid body. The impacts of consecutive closures occurring at different frequencies and pulse times were also studied by using the stethoscope. Consequently, the needle valves were adjusted to change the switching times whilst quick but preliminary comparisons of the sound intensity were made. This timing adjustment also demonstrated the range and sensitivity of the timing control.

Although the sights and sounds of the operation provided valuable information, monitoring equipment was required to study the details of the valve's switching and timing characteristics. A Bruel & Kjaer Type 4344 accelerometer was mounted to an end plate to track the motion of the poppet valve assembly and a PCB Piezotronics 112A, miniature quartz, pressure transducer was used to separately monitor the exit and switching chamber pressures. These measurements helped quantify the switching times and impact speeds (which could not be measured directly with available equipment) of the poppet valve assembly, the smoothness of operation and the repeatability of the timing as well as operating limits such as the minimum pulse time and maximum operating frequency, the pressure drop across the valve and, finally, the switching pressure. As shown in Figure 5.4, the signals from both transducers were passed through dedicated conditioning amplifiers into separate channels of a digital storage oscilloscope. Appendix C includes a list of the monitoring equipment. The pressure and acceleration time histories were stored and analyzed on the screen of the oscilloscope and, if desired, were saved on floppy disk for future viewing. The time histories were captured and updated once every valve cycle at the precise instants initiated typically by the incoming signal from the accelerometer. With slow operating frequencies, the valve's operation could be checked with the continually updated pair of curves.

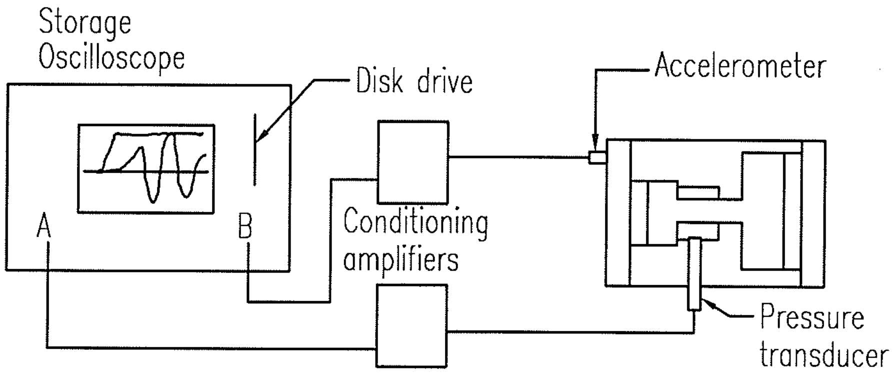


Figure 5.4 Monitoring equipment

The accelerometer detected the initial movement of the poppet valve assembly and the instant it stopped at the end of its stroke, which corresponded to an acceleration spike. The switching time was deduced from this data. This acceleration spike also provided additional qualitative information. The magnitude of the spike indicated the impact speed of the poppet valve assembly at the end of each of its strokes. It provided comparisons of opening and closing times and impact speeds as well as the smoothness of the valve's operation. Consistent, repeatable spikes of consecutive cycles indicated a repeatable performance of the switching circuit and, particularly, the release valve's operation.

The pressure transducer was installed through the valve body into either the exit or switching chamber. The exit chamber's pressure-time behavior was stored on the screen of the oscilloscope along with the acceleration information. The beginning of the pressure rise indicated the initiation of valve opening which substantiated the accelerometer's switching information. The measurement of the exit chamber's pressure also helped determine the rise and fall times of the output pressure pulse, the shortest pulse time (open time of the valve), and the pressure drop across the valve. By setting the oscilloscope to a longer time scale, a number of pulses could be displayed to determine the operating frequency. Therefore, by adjusting the needle valves, the sensitivity of the timing control system could be assessed quantitatively. This set up also permitted an accurate assessment of the repeatability of the valve's timing system over an extended period like 20 minutes. The switching pressures were determined by observing the measurement of the switching chamber's pressure.

After the operation was observed and several time history curves were saved, the pump was shut off and the valve was disassembled to inspect the components. Deficiencies in design, workmanship or materials were found by carefully inspecting the components. Contacting pairs of components such as the poppet and the seat, the switching piston and release valve, and the needles and their seats were checked continually for damage and wear. Seals and o-rings were also checked after each disassembly.

The assembly, operation, monitoring and inspection of the valve's components all contributed to the development of the valve up to its present configuration. The information obtained from these exercises helped to determine the precise size, construction materials and specific design details of the valve. The size of the prototype was set by the size of readily available, off-the-shelf stellite collars, which were the smallest that could be found. The collars determined not only the size of the poppet valve and the valve body but also the size of the switching piston, which had to be slightly larger than the poppet valve for the switching force to overcome the closure force. The collars were included because excessive damage from multiple indentations was observed on the integral poppet and seat of the first mock up which had all stainless steel parts. At the time, the impacts were excessive and thought to be the cause of the damage. However, after observing pin-head sized indentations in the stellite surfaces of the next valve version, after only several operation cycles at about 10 MPa operating pressure, cavitation was suspected [48,49]. Cavitation is a natural phenomenon that involves the formation and sudden collapse of tiny vapour bubbles in a liquid flow [50]. The bubbles form and grow in regions of low pressure and high flow speed, and they collapse after reaching a region of higher pressure. If the collapse occurs near a surface, as in Figure 5.5, the fluid replacing the bubble rushes in toward the surface and forms a liquid jet that impinges on the "solid" surface. This liquid jet can impose stresses up to 10^3 MPa (150,000 psi) over the area of a pin head and can erode even hard surfaces like stellite [52]. The entire process of bubble formation and collapse can happen in microseconds [53], which explains why the noise generated from the impacts could not be detected by ear [54]. Although the occurrence of the bubble formation cannot be prevented in certain flow regimes [43,55], the implosions can be directed by controlling the flow pattern with proper flow path design [51]. Consequently, the profile with the rounded raised ring (see Figure 5.1) was machined into the face of the poppet collar. However, bubbles were still believed to form during the transient in-flow when the valve opened. On the other hand, their number is likely much smaller because damage to both contacting surfaces (from operation at design pressure) has been reduced drastically. The odd indentation, however, can still be seen on the contact ring as well as on the poppet and seat surfaces inside the seating ring.

The use of aluminum also played a role in the sizing of the valve. Although aluminum is not resistant to corrosive fertilizer solutions, it was chosen in the prototyping stages for its higher strength-to-weight ratio and machinability and lower cost compared with stainless steel. Also, it does not rust like normal steel. The high internal chamber pressures dictated the wall thickness of the valve body and the thickness of the end plates. Although no problems were found with the strength of the valve body, provisions for the needle valve, the gallery leading to the switching chamber, and the four bolts made a square cross-section most convenient. During the operation of the earliest versions of the valve at pressures exceeding 10 MPa, bending and separation of the end plates from the valve body were observed. These problems were addressed by increasing the thickness of the plates to 25 mm and enlarging the diameter of the bolts to 9 mm (3/8") from 6 mm. The high operating pressures and plate separation also caused extrusion of the face seal o-rings. Therefore, their hardness was increased to 90 Durometer. Also, the bolts were torqued to at least 20 Nm (15 ft-lbs).

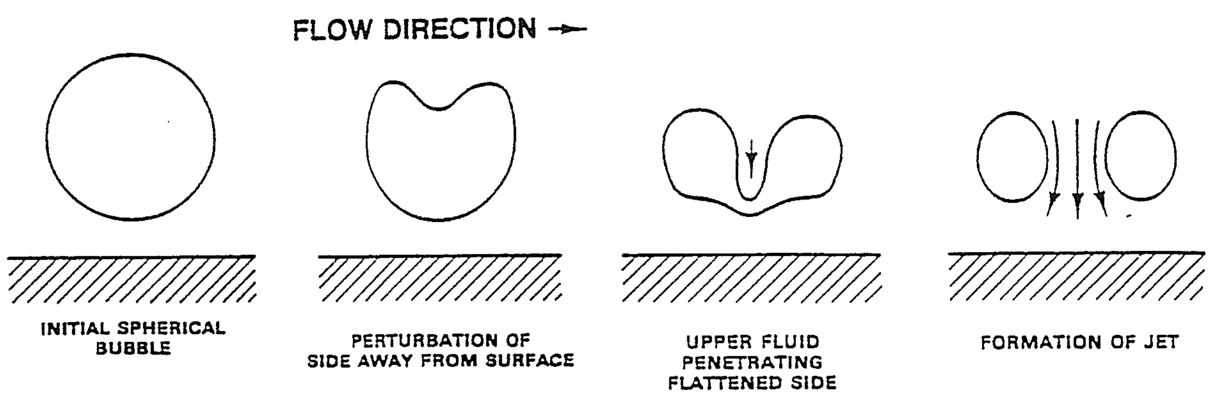


Figure 5.5 Collapse of a cavitation bubble near a surface [51]

The first mock up included external piping and flow control, needle valves to cheaply test ideas. These valves, although commercially available and inexpensive ($20.00 each), were too large to provide fine timing control. More importantly, a self-contained valve unit was required. This requirement led to the inclusion of the fine-tipped, in-body needle valve and gallery.

Aside from incorporating the needle valves to improve the sensitivity and consistency of the timing control, the release valve also required several minor modifications. The first design broke at the interface of the plastic and metal threaded rod. This failure led to a more robust design with thicker plastic and a stronger connection to the rod. The flat face was adopted because the outer edge of the plastic lip cut a ring into the switching piston. This deficiency prevented sealing of the chamber and caused the eventual loss of the switching function. The use of the release valve, which operates in conjunction with the movement of the switching piston, also restricted the stroke to no less than 0.076 mm (0.003") to permit sufficient separation of the flexible lip from the piston.

The switching piston also required slight modification. After several minutes of operation, damage was observed on the back of the switching piston where contact was made to the stem. This problem was solved by gluing a steel plate to the back of the piston to take the harsh, intermittent loading caused by the high switching speeds and corresponding impacts.

5.4 Operating Characteristics at Design Pressure

The final valve design has an accumulated operating time of approximately eight hours with water pressurized at 28 MPa, and meets most of the requirements listed in Table 3.1 of Section 3. The valve has operated with only a 1 mm orifice connected to the body which produced a measured steady flowrate of 116 cm^3/s. The prototype has operated continually for periods up to 30 minutes and performed repeatably and audibly quiet at all frequencies up to only 16 Hz. With a stroke of 0.127 mm, the poppet valve's switching times are 0.8 ms for opening and 1.3 ms for closing. However, the minimum achievable pulse (open) time is 12 ms and small signs of wear on the poppet and seat and the switching piston still exist. Also, the valve's timing is sensitive particularly to closed stage needle valve adjustments. However, a desired frequency can be set accurately and easily by turning the needle with two fingers. The operating and design deficiencies are considered solvable with further refinement and the overall effectiveness of the valve's operation suggests that it offers great potential for high pressure ground injection.

The valve opens in about 0.8 ms and closes in a much gentler 1.3 ms, with a small leakage when closed. Recall that the predicted switching times were 0.4 and 0.8 ms, which are about 30% lower than the measured values. Possible reasons for these slight differences could relate to immeasurable factors such as friction, bulk modulus and actual pressure and flow effects particularly in the poppet valve flow region. Notice, however, that the valve invariably opens in about half the time required for closing, as predicted by the computer simulation. The measured switching times are presented in Figure 5.6 which shows the acceleration and exit chamber pressure for the shortest attainable pulse time of 12 ms at a 2 Hz operating frequency. The opening switch time is determined from the time the exit pressure begins to rise to the point where the first negative acceleration spike occurs and begins to rise to the positive peak. The acceleration curve suggests that the valve begins to open and the poppet begins to accelerate in an increasing manner (in the negative direction) until the fully open position is reached and the back of the switching piston hits the valve body. This impact causes a sharp deceleration as indicated with the reversal of the -21 g peak. At this point the exit chamber has increased from atmospheric to about 10 MPa. It is this rapid increase in pressure, which acts on the back side of the poppet head, that rapidly opens the poppet valve. The closing time is determined from the instant when the exit pressure begins to drop to the instant when the positive acceleration peak occurs. This peak of +8 g is considerably lower than the -21 g at opening. This observation corroborates the simulation results which suggested a seating speed about one third the opening impact speed (50 and 170 cm/s, respectively). (It should be noted that a direct poppet speed measurement could not be made with available equipment.) Furthermore, because the measured switching times are longer than predicted, it is conceivable that the actual impact speeds are also less than the predicted values for a given travel distance so that the seating speed may be lower than the recommended 45 cm/s [27].

Another way of finding the switching time is from the difference between the rise and fall times of the exit pressure curve, the pressure that the nozzle "sees". The rise time is approximately 1 ms and the fall time is about 3.5 ms which are very close to the predicted times shown in Figure 4.6.

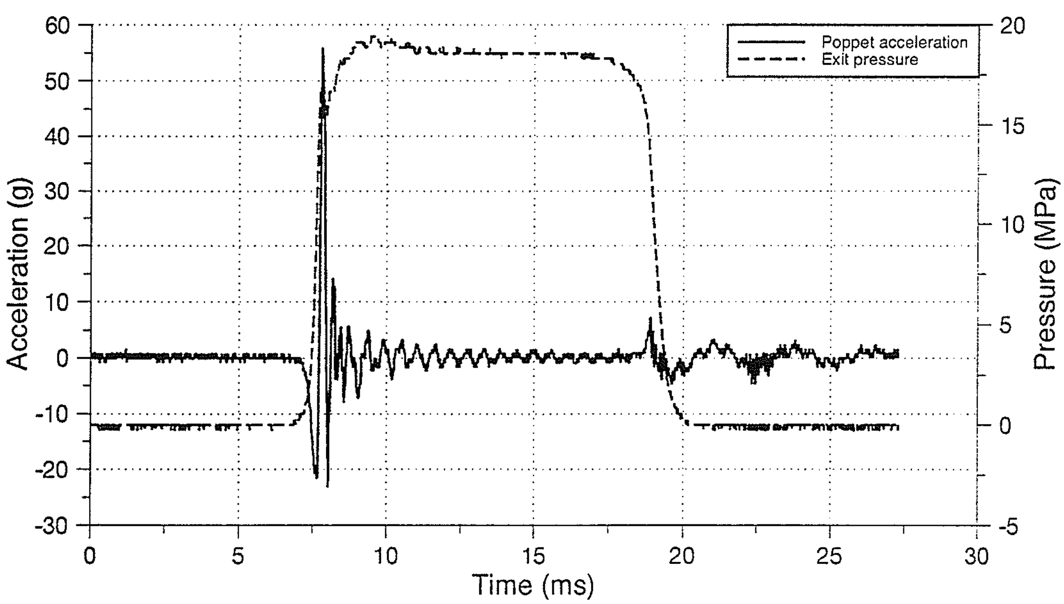


Figure 5.6 Measured poppet acceleration and exit chamber pressure at 2 Hz

The inherent and highly desirable feature of a longer closing time and, more importantly, a lower seating speed compared with the opening, is attributed to the nature of the exit chamber pressure during each transition. Recall that the exit pressure's main effect is to complete and maintain the transition that the switching pressure has initiated. Three observations can be made from the exit pressure curve of Figure 5.6 that support the longer closing time. First, the total fall time is longer than the rise time. Second, the slope of the linear portion of the drop off is less than the rise and, third, the time it takes to reach the linear portion from the steady state value is longer at valve closure. This last point is, perhaps, the main reason for the different switching times because the quickness of the pressure change will affect the nature of the changing net force during the completion of the switch.

Figure 5.6 also shows that the steady exit pressure is around 18 MPa, which produces an undesirably large 10 MPa pressure drop across the poppet valve. This detrimental pressure drop is the result of the profile cut into the face of the poppet collar to control cavitation. Before machining, a pressure drop of only about 1 MPa was measured. After the profile was machined, all the fine tool marks were not polished flat which left many tiny ridges and valleys perpendicular to the direction of flow. This surface roughness effectively increased the resistance to flow and, consequently, the pressure drop grew. Moreover, the seating surface of the raised contact ring, which was described in Section 5.1, is only 0.25 mm (0.010") higher than the flat portion of the collar (with the tool marks) inside the ring. This step or slight flow area expansion, compared with the previous flat surface, effectively added an additional minor loss to this flow section. In other words, the flat seating surfaces involved only one entrance and one exit going radially inward from the inlet chamber to the exit chamber. With the step, there is a similar entrance and exit with an additional expansion in between. Theoretically, this added expansion must increase the pressure drop. Because a negligible pressure drop existed previously, the step was not considered in the computer simulation. Reducing the effects of this additional expansion by increasing the size of the step to make it closer to the exaggerated view shown in Figure 5.1 and by further polishing of the collars, should enable the lost output pressure to be regained.

One last point can be made with reference to Figure 5.6 that relates to the repeatability of the valve's switching. Recall that the curves shown were updated every cycle because the signal from one of the transducers was used for triggering. This enabled observation of the variations in the magnitude of the acceleration spikes as well as the widths of the "square" exit pressure curve. It was found that the large 55 g positive spike at opening varied by only +/- 5 g and the acceleration curve at closing did not change greatly. Furthermore, the pulse time varied by only +/- 1 ms. These slight differences indicate again that the switching mechanism, particularly the release valve, functions consistently. However, the pulse time was found to be sensitive to release valve adjustments but, once tuned and locked, the release valve performed consistently.

It was stated in Table 3.1 of Section 3 that the minimum desired pulse time is 5 ms, which is much less than the measured 12 ms. This unacceptably large pulse time is caused by the restricted flow area between the switching piston and the release valve. The cylindrical flow area, which is at most 0.127 mm (0.005") long by 3 mm (0.125") in diameter (the size of the hole drilled though the center of the threaded rod), is obviously inadequate to permit a flowrate out of the switching chamber that is sufficiently large to allow the switching pressure to drop sufficiently quickly. Two changes can be made to correct this deficiency. Either the flow area of the release valve could be enlarged or the amount of fluid expelled could be reduced. The preferred choice is to enlarge the flow area because reducing the volume of the switching chamber would adversely increase the already marginal sensitivity of the closed stage needle valve. As stated at the beginning of this section, a desired frequency can be set with little difficulty but the entire frequency range, up to 16 Hz, corresponds to only 3/16 of a turn of the closed stage needle valve. This high sensitivity also suggests that a smaller tipped, custom made needle screw may be required. (Incidentally, the closed stage needle valve affects predominantly the operating frequency.) The flow area past the release valve can be enlarged by increasing the separation distance or stroke of the poppet valve, which is currently 0.127 mm, or by drilling a bigger center hole. Also, rounding the sharp corner along the outer edge of the lip as well as around the center hole could shorten the pulse times. All these suggestions are easy to undertake and they could have marked effect in reducing the open time to the 5 ms requirement.

The opening impact as well as the shortest attainable pulse time increases with increasing frequency. Figure 5.7, which is the poppet's acceleration measured at the fastest operating frequency of 16 Hz, shows that the negative spike increases to about 35 g from the 21 g observed at 2 Hz and the impact only slightly increases at closure to about 10 g from 8 g. This means that the closure time (seating speed) is affected less than the opening switch time, which, incidentally, has to decrease because a higher acceleration implies higher traverse speeds. The reasoning behind these faster switching times relates to the higher switching circuit flows which cause slight delays in reversing the direction of the switching pressure during the transitions. For example, consider a higher flowrate from the closed stage needle valve into the switching chamber. Although, theoretically, the pressure at which the initiation of the switch (to open) occurs should not change, the higher flowrate causes more fluid to enter the switching chamber during the transition (before the release valve fully opens), which effectively increases the maximum switching pressure and, hence, results in a slightly higher net force pushing the poppet valve assembly over. This increase in the maximum switching pressure with an increase in frequency is shown in Figure 5.8. This larger force, according to Newton's second law, must produce a greater acceleration. Nevertheless, the faster opening at higher frequencies is acceptable. The higher speed of the opening impact is not considered a problem because the back side of the switching piston (which impacts the valve body) has exhibited no signs of damage. The only potential problem associated with faster switching is an increase in the fluid's transient flow which would increase the chance of cavitation. This argument correlates well with the larger pressure peaks shown in Figure 5.9, which reach 21 MPa as opposed to the 19 MPa peak in Figure 5.6.

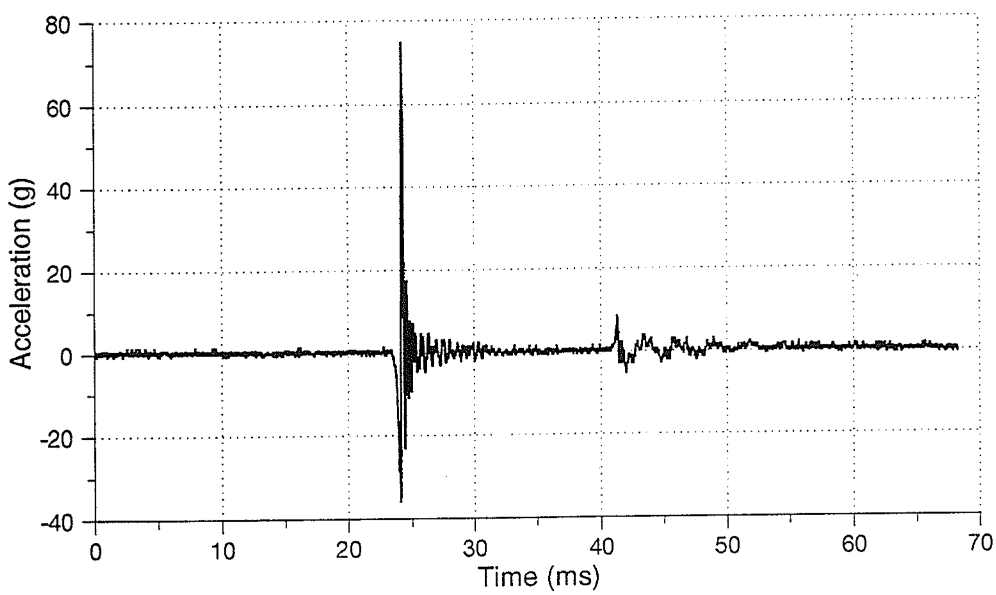


Figure 5.7 Measured poppet acceleration at 16 Hz

Figures 5.7, 5.8 and 5.9 also show that the shortest pulse time has increased from 12 ms at 2 Hz to 18 ms in Figure 5.7 and around 25 ms in the other two figures. The deviation may be explained by slight differences in the setting of the release valve position. The cause of the increased pulse width, however, also relates to the higher switching circuit flowrates. Recall that the open time depends on the difference between the flow out and into the switching chamber. This means that, to maintain the same pulse time, the flowrate past the release valve must increase accordingly. Because the flow area past the release valve is already inadequate, the increased minimum pulse time is inevitable with higher switching circuit flowrates.

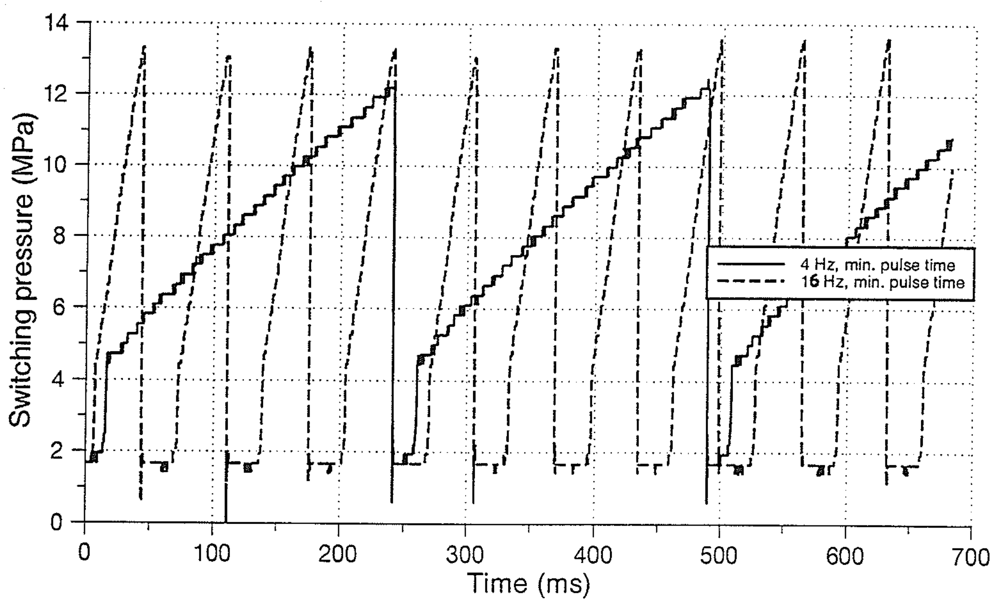


Figure 5.8 Measured switching pressure at 4 and 16 Hz

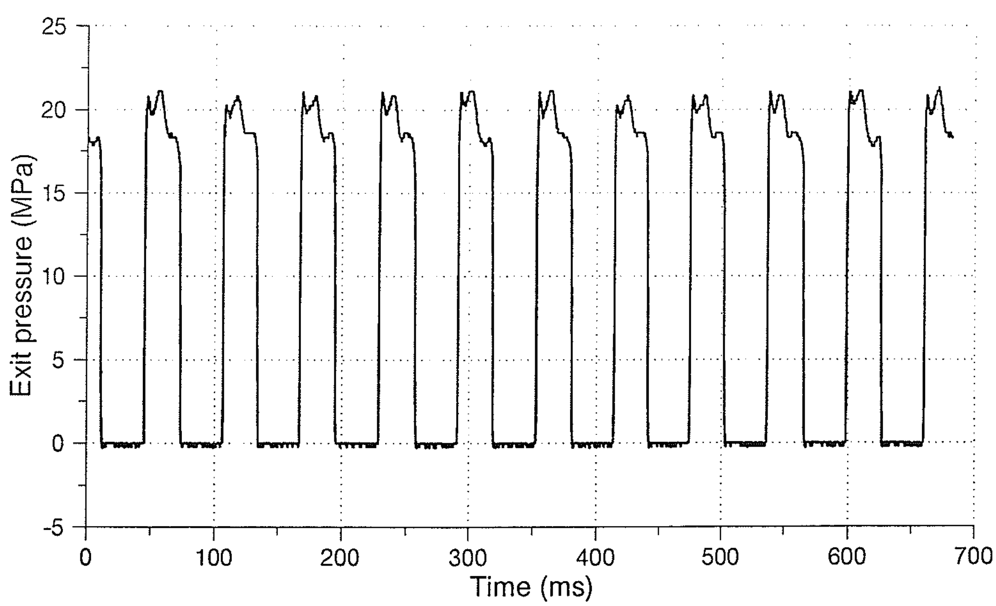


Figure 5.9 Measured exit chamber pressure at 16 Hz

The switching pressure curves given in Figure 5.8 deviate from the predictions shown in Figure 4.7. The pressure rise portions of the curves correlate well but the falling portion deviates considerably. It should be noted, however, that the switching pressure measurements on earlier versions of the valve followed the predictions very closely but they had a larger switching chamber than the final prototype. The addition of the steel backing plate behind the piston reduced the effective volume of the chamber which, in turn, made the chamber pressure much more sensitive to the piston's displacement. (Recall that a fluid pressure can be changed by changing either the amount of fluid in the container or the size of the container.) The sharp pressure drop shown in Figure 5.8 is a direct result of the poppet valve assembly moving to the open position, which makes the volume of the switching chamber increase. The subsequent sharp rise corresponds to the piston's displacement during closure. Although the discontinuities in the measured curves seem undesirable, the valve still switches consistently which is the primary concern. More work is needed, however, to fully explain the discrepancies between measurements and predictions.

The data files used to produce Figures 5.8 and 5.9 were analyzed for variations between consecutive cycle times. The analysis showed that the period of each valve cycle was repeatable to within +/- 1 ms. Furthermore, a test with the valve operating at 10 Hz revealed that the frequency remained constant for a period of 15 min. All these examples suggest that the release valve mechanisms operates consistently. However, this gives no indication of reliability. The switching function was lost completely on several occasions due to foreign debris, such as a piece of Teflon tape from the threaded fittings, lodging between the release valve and the piston, which broke the seal and prevented the switching pressure to rise. This strongly suggests a need for filtration, particularly at the entrance to the switching circuit.

As mentioned earlier, the poppet valve still shows small signs of cavitation damage on the stellite surfaces. The result of this damage is a leaky valve. Over the eight hours of operation, the valve's leak progressed from several drops per second to a trickle of water. After eight hours of service, the flowrate of the leak was measured at 20 ml/s for the first 30 s and 10 ml/s for the next 30 s - after 50 s the leaks reduces to a drip. The cause of the leaky condition is the pitting marks on the seating surfaces from cavitation. Although the profile that was cut into the poppet collar has almost eliminated the damage, a further design improvement is necessary. Cutting a larger step in the collar and machining the seat with a matching profile seems like a good logical choice. The effect of this change would likely be to allow cavitation bubbles the freedom to travel, as fast as possible, inside the contact ring before they collapse. Controlling where the bubbles collapse is crucial because cavitation is inevitable [43,55] under the opening conditions that correspond to a 28 MPa pressure differential. The increased step size, if placed on both seating surfaces, should also help regain the lost pressure drop.

Additional damage can still be 65
observed on the face of the aluminum switching piston from the outside of the release valve lip. Because aluminum is not corrosion resistant to many fertilizer solutions, the piston must be made of another material which makes this damage not a major concern. Incidentally, a stainless steel piston seems a likely choice.

Although minor deficiencies in the poppet valve and the open time require further attention before a long, effective and reliable service life can be attained, the valve is robust and has consistent timing. The valve's operation is insensitive to hammer blows and its orientation. The timing can be automated easily by incorporating small pressure sensors to indicate the state of the valve as well as small motors to turn the needle valves. The timing control system can be battery powered to permit operation in remote locations.

Therefore, the valve would require only a constant high pressure source to provide adjustable pressure pulsations anywhere.

5.5 Cost Estimate

A cost estimate for 100, 500 and 1000 valve assemblies has been performed. To make the valve compatible with the needs of the LPI (particularly corrosion resistance) and to simplify the assembly task, a few modifications were made to the design before assessing the updated drawings. This section describes the changes and gives an estimate of the material, machining, and assembly costs for production.

The valve has been changed to an all stainless steel construction for corrosion resistance. Type 316 stainless steel has been selected which also has acceptable machinability [56,57]. All internal dimensions and the length of the valve body remain unchanged but, due to the increased strength of stainless steel compared with aluminum, the outer dimensions of the square valve body have been reduced to 65 mm (2-1/2") and the two end plates have been reduced to a thickness of 12 mm (1/2"). To further simplify construction and assembly, the threaded stub extending from the end of the prototype poppet valve's stem has been replaced with a threaded hole for a screw. Assembly of the switching piston to the valve stem would involve sliding the two components into their respective bores and fastening them together with a screw through the piston and into the hole in the stem. The length of the stem would still determine the stroke of the poppet valve assembly. Furthermore, the faces of the two stellite collars have been made identical so that both have a raised outer contact ring, as discussed in the previous section. Having two identical collars also eliminates the chance of installation mix ups on the assembly line.

Table 5.1 gives a unit cost estimate of 100, 500 and 1000 valve assemblies. The approximate values given include machining and material costs [58,59] and assembly which accounts for $5/valve based on 1/2 hour of labour at $10/hr. This liberal assembly time includes assembly, tuning and testing of each valve. The estimated machine tooling cost is $2000 [58].

Quantity	Estimated $/unit
100	160.00
500	145.00
1000	144.00

Table 5.1 Cost estimates for mass production of valve [58]

Although the production cost per valve is about 50% higher than the desired value given in Table 3.1, the valve still may be feasible for high pressure ground injection with further refinement. It not only performs repeatably and meets most of the requirements listed in Section 3, but it also does not require an external power source to switch. Furthermore, being a self-operating on-off valve that can be manually operated or automated, it may be suitable for other applications that require an intermittent high pressure source.

6. CONCLUSIONS

A self-switching prototype valve has been developed that transforms a constant pressure supply into a pulsating output of variable pulse duration and frequency. The following conclusions are based on the valve exhausting through a 1 mm orifice.

1. The valve operates with water pressurized between 3.5 and 28 MPa (and a flowrate of 116 cm^3/s at 28 MPa).
2. The valve is simple in construction and operation, with only one moving part. It is deemed reliable.
3. The valve has operated for a total of approximately 8 hours with only minimal damage on the poppet valve seating surfaces due to cavitation. The damage produces a leakage flowrate of 30 ml/s over one minute. The profile cut into the poppet collar has almost completely controlled the cavitation but needs further refinement.
4. The machined profile increased the pressure drop to about 10 MPa. It was originally about 1 MPa with flat seating surfaces.
5. The valve's switching time is 0.8 ms for opening and 1.3 ms for closing.
6. The valve can operate at frequencies up to only 16 Hz with a shortest pulse (open) time of 12 ms at 2 Hz and 20 to 25 ms at 16 Hz.
7. The timing is repeatable and adjusted easily by fingertip turning two needle valves.
8. The timing is sensitive particularly to closed stage needle valve changes. The entire range of operation (up to 16 Hz) corresponds to 1/4 turn of this needle valve. The range covered by the open stage needle valve corresponds to about two turns.
9. The timing control system can be automated easily at little cost by incorporating a sensor to monitor the state of the valve and by turning each needle valve screw with a small motor.

10. The valve can be modified to be a manually operated on-off valve.
11. Valve operation is insensitive to hammer blows.
12. The valve can operate in any orientation.
13. The operation is an audibly quiet 77 dBA (slow) re 20 μPa at 1 m.
14. The seating speed at closure is estimated to be less than 18 cm/s (1.5 ft/sec) which is the maximum recommended value for valves in internal combustion engines.
15. The cost for materials, machining, assembly and testing of 500 valves is estimated at about $145 per valve.
16. An all stainless steel construction (with stellite seating surfaces for the poppet valve) would make the valve robust and resistant to the chemical solutions used with a LPI.
17. Filtration is required to prevent malfunction of the release valve.

7. RECOMMENDATIONS

Due to the valve's acceptable operating characteristics, versatility, robustness and production cost estimate of $145/valve for 500 valves, further development is recommended. The following work is recommended for adaptation of the valve for a LPI.

1. Modify the switching circuit to achieve a minimum pulse duration of 5 ms for all frequencies up to 20 Hz.
2. Optimize the profile of the poppet and seat to reduce the pressure drop and unconditionally eliminate cavitation damage. Tests must be conducted with all required fluids at all expected temperatures.
3. With cavitation controlled and eliminated, assess the plausibility of removing the stellite collars and machining the profile into the integral stainless steel seating surfaces of the valve body and poppet. Elimination of the collars would lower the cost by reducing the number of components and by a possible down-sizing that would also diminish the overall amount of material required. (The prototype is sized presently around purchased stellite collars.)
4. Automate the timing control system by incorporating a pressure sensor, two small motors and a microprocessor-based circuit to provide a closed loop control.
5. Consider replacing the machined poppet and stellite collars with a delivery valve from a fuel injection pump because the poppet and seat come as a pair. This miniature self-switching valve could be much cheaper to manufacture and may find other specialty applications.
6. Investigate the suitability of using instant set polymers as a construction material for the valve body.

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Appendix A: Simulation Software

```
/***************************************************************************/
/* VRSIM1.C */
/* Simulation of Valve operation at 28 MPa */
#include <stdio.h>
#include <math.h>
#include <malloc.h>

float P1,trav,mv,Qis,Qos,Pes,Pss,pos,vel,Q12,Q23,Q14,Q45,Ac,Ao,sumf,sumff;

FILE *out1;
/***************************************************************************/
main( )

{
int i;
int n=4;
float *y,*dy,*yout;
float h,t;

void rk4(),derivs();
float *vector();

out1=fopen ("out1.dat","w");
y=vector (1,n);
dy=vector (1,n);
yout=vector (1,n);

P1=28E6;
trav=0.000127;
mv=.2;

h=0.00001;    /* time increment */
t=0.0;
y[1]=0.0;    /* P2: Pressure in exit chamber */
y[2]=0.0;    /* P4: Pressure in switching chamber */
y[3]=0.0;    /* pos: Position of poppet relative to seat */
y[4]=0.0;    /* vel: Speed of poppet */

(*derivs)(t,y,dy);

rk4(y,dy,n,t,h,yout,*derivs);

for (i=1;i<=4800;i++)
{
t=i*h;
(*derivs)(t,yout,dy);

Qis=Q12*61024;     /* This block converts all values to standard units */
Qos=Q23*61024;
pos=yout[3]/0.0254;
Pes=yout[1]/6940;
Pss=yout[2]/6940;
vel=yout[4]/0.0254;
sumff=sumf/4.5;
```

```
fprintf (out1,"%.5f\t %5.1f %3.1f %6.4f %4.0f %4.0f %5.1f %5.1f\n",t,Qis,Qos,
          pos,Pes,Pss,vel,sumff);

rk4(yout,dy,n,t,h,yout,*derivs);

}

fclose(out1);

}

/************************************************************/
void derivs(t,y,dy)
float t,y[],dy[];
{
float A,B,C,D,E,F,G,H,F1;

A=0.00258;  /* Constants determined in Appendix B */
B=2.22E-8;
C=10E-15;
D=0.0365;
E=6.65E-4;
F=1.78E-3;
G=6.67E-15;
H=1E-4;
F1=22200;
Ac=.2E-7;
Ao=2E-7;

if (y[3] < 0.0)  {
  y[3]=0.0;  }

Q12=A*y[3]*sqrt(P1-y[1]);  /* CALCULATES FLOW THROUGH POPPET VALVE */

if (y[1] < 0.0)  {
  y[1]=0.0;    }

Q23=B*sqrt(fabs(y[1]));  /* FLOW OUT THROUGH ORIFICE */

dy[1]=(Q12-Q23)/C;      /* PRESSURE CHANGE IN EXIT CHAMBER */

Q14=D*Ac*sqrt(P1-y[2]);  /* FLOW THROUGH CLOSED STAGE NEEDLE VALVE */

if (y[3] == 0.0 || y[4] > 0.0)  {        /* VALVE IS CLOSED OR OPENING */
  sumf=(-F1)+(E*y[1])-(H*y[1])+(F*y[2]);  } /* FORCE ON POPPET ASSEMBLY */

if (y[3] == trav || y[4] < 0.0)  {        /* VALVE IS OPEN OR CLOSING */
  sumf=(-F1)+(E*y[1])+(H*y[1])+(F*y[2]);  } /* FORCE ON POPPET ASSEMBLY */

if (sumf < 0.0)  {
  if (y[3] <= 0.0)  {  /* VALVE FULLY CLOSED */
    Q45=0.0;        /* NO FLOW THROUGH OPEN STAGE NEEDLE VALVE */
    dy[2]=Q14/G;    /* PRESSURE CHANGE IN SWITCHING CHAMBER */
```

```
    y[3]=0.0;
    y[4]=0.0;
    dy[3]=0.0;
    dy[4]=0.0;  }
  if (y[3] != 0.0)  {          /* VALVE CLOSING */
    if (y[3] > 102E-6)  {
          Q45=D*Ao*sqrt(y[2]);  }  /* FLOW THROUGH OPEN STAGE NEEDLE VALVE */
    else  {
          Q45=0.0;  }
    dy[2]=(Q14-Q45)/G;
    dy[3]=y[4];        /* Speed of poppet (dx/dt where x = position) */
    dy[4]=sumf/mv;  }  /* Acceleration of poppet */
}

if (sumf > 0.0)  {
  if (y[3] >= trav)  {  /* VALVE FULLY OPENED */
    Q45=D*Ao*sqrt(y[2]);  /* FLOW THROUGH OPEN STAGE NEEDLE VALVE */
    dy[2]=(Q14-Q45)/G;
    y[3]=trav;
    y[4]=0.0;
    dy[3]=0.0;
    dy[4]=0.0;  }

  if (y[3] != trav)  {  /* VALVE OPENING */
    if (y[3] < 25.2E-6)  {
          Q45=0.0;
          dy[2]=Q14/G;  }
    else  {          /* Ps BEGINS TO DROP */
          Q45=D*Ao*sqrt(y[2]);
          dy[2]=(Q14-Q45)/G;  }
    dy[3]=y[4];
    dy[4]=sumf/mv;  }
}

}
/************************************************************************/
void rk4(y,dydx,n,x,h,yout,derivs)
float y[],dydx[],x,h,yout[] ;
void (*derivs)() ;
int n ; {
  int i ;
  float xh,hh,h6,*dym,*dyt,*yt,*vector();
  void free_vector();

  dym=vector(1,n);
  dyt=vector(1,n);
  yt=vector(1,n);
  hh=h*0.5;
  h6=h/6.0;
  xh=x+hh;
  for (i=1 ; i<=n; i++)  yt[i]=y[i]+hh*dydx[i];
  (*derivs)(xh,yt,dyt);
  for (i=1 ; i<=n; i++)  yt[i]=y[i]+hh*dyt[i] ;
  (*derivs)(xh,yt,dym);
```

```
  for (i=1; i<=n;i++) {
      yt[i] = y[i]+h*dym[i] ;
      dym[i] +=dyt[i];
                 }
  (*derivs)(x+h,yt,dyt) ;
  for (i=1 ; i<=n ; i++)
  yout[i]=y[i]+h6*(dydx[i]+dyt[i]+2.0*dym[i]);
  free_vector(yt,1,n) ;
  free_vector(dyt,1,n) ;
  free_vector(dym,1,n) ;
}

/* ****************************************************************** */
void free_vector(v,n1,nh)
float *v;
int n1,nh; {
  free((char*) (v+n1));
}

/* ****************************************************************** */
float *vector(n1,nh)
int n1,nh; {
   void nrerror() ;
   float *v ;

   v=(float *)malloc((unsigned) (nh-n1+1)*sizeof(float));
   if (!v) nrerror("allocaton failure in vector ()");
   return v-n1 ;
}

/* ****************************************************************** */
void nrerror(error_text)
char error_text[] ; {
  void exit() ;

  fprintf(stderr,"Numerical Recipes Run-time error...\n");
  fprintf(stderr,"%s\n",error_text) ;
  fprintf(stderr,"...now exiting to system...\n") ;
  exit(1) ;
}
```

Appendix B: Mathematical Modelling

page

B.1 Introduction

This appendix presents the mathematical equations used to describe the dynamic behavior of the prototype valve operating at 28 MPa, the design pressure. The analysis makes use of three different equations which are overviewed next.

1) Bernoulli's equation with minor losses [1,2,3] is used to calculate the flowrate across each of the following constrictions:

   i) the poppet valve,

   ii) the nozzle (orifice),

   iii) the closed stage needle valve, and

   iv) the open stage needle valve.

   Bernoulli's equation relates a pressure change to velocity (and elevation) changes along a streamline (a curve drawn in a flow field that is tangent to the direction of flow at every point in the flow field). Minor losses are (energy) losses due to entrances, fittings, area changes, etc. that result from violent mixing and flow separation at these locations in the flow field [1].

2) A compressibility equation [4] is utilized to calculate the pressure change (associated with fluid compression) resulting from the addition or release of fluid from each of the pressure chambers. Chambers include:

   i) the exit chamber, and

   ii) switching chamber.

   Note: The inlet (supply) chamber is assumed to be at a constant at 28 MPa so that no pressure change occurs during operation.

3) Newton's second law [5] is employed to calculate the acceleration of the mass of the poppet valve assembly according to the axial forces applied to it arising from the three pressure chambers.

B.2 Formulation of General Flow and Pressure Equations

B.2.1 Bernoulli's Equation with Minor Losses Applied Across a Flow Restriction

Applied to the constriction between points 1 and 2 shown in Figure A1, Bernoulli's equation can be written to include minor losses in the form [1]:

$$\frac{\mathbf{P1}}{\rho}+\frac{\mathbf{V1}^2}{2}+\mathbf{gz}_1=\frac{\mathbf{P2}}{\rho}+\frac{\mathbf{V2}^2}{2}+\mathbf{gz}_2+\mathbf{h}_{\mathbf{lm}} \qquad (1)$$

where

$$\mathbf{h}_{\mathbf{lm}}=\mathbf{K}\frac{\mathbf{V}^2_{\mathbf{orifice}}}{2}=\mathbf{K}\frac{\left(\mathbf{Q12}/\mathbf{A}\right)^2}{2} \qquad (2)$$

and

$P1, P2$ = pressure, $[N/m^2]$ or [Pa],

ρ_1, ρ_2 = fluid density, $[kg/m^3]$,

$V1, V2$ = average fluid velocity, [m/s],

g = acceleration due to gravity , 9.81 $[m/s^2]$,

z_1, z_2 = elevation from reference point, [m],

h_{lm} = minor loss term, $[m^2/s^2]$,

K = minor loss coefficient, [dimensionless],

$V_{orifiice}$ = average fluid velocity through flow area, [m/s],

Q12 = volumetric flowrate, [m^3/s], and

A = flow passage area, [m^2].

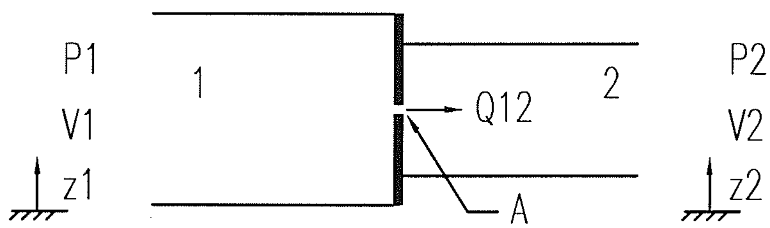

Figure B1 Flow across a constriction

Assumptions [3]:

1. $\rho_1 \cong \rho_2 = \rho$ = constant = 1000 kg/m^3: the variation of fluid density at points 1 and 2 is considered negligible, thus the density is constant.
2. V1 ≅ V2: the incoming and outgoing fluid velocities are roughly equal.
3. $z_1 = z_2$: elevation changes are negligible.
4. The flow passage through the poppet valve is treated as an equivalently sized orifice [2,4].
5. Only minor losses due to flow area changes are considered. Major losses due to wall friction in a fully developed flow are considered inapplicable in constant area portions of the flow.

6. The loss coefficient, K, is the sum of both the entrance and exit losses so that K= 1.5 because $K_{entrance} = 0.5$ and $K_{exit} = 1.0$ are the "worst case" values for sudden area changes [1,2].)
7. A change in flowrate through a restriction, due to pressure differential changes or flow area changes, are considered to happen instantaneously due to the high rigidity (low compressibility) of water.

Based on the foregoing assumptions equations (1) and (2) simplify to:

$$\frac{\mathbf{P1-P2}}{\rho} = \frac{\mathbf{K(Q12/A)^2}}{2} \tag{3}$$

or

$$\mathbf{Q12} = \left(\frac{2}{\mathbf{K}\rho}\right)^{1/2} \mathbf{A(P1-P2)}^{1/2}. \tag{4}$$

B.2.2 Compressibility Equation Applied to a Pressure Vessel

Applied to flow in and out of the rigid vessel shown in Figure A2, the corresponding pressure change due to the fluids compressibility can be calculated as:

$$\mathbf{Qi = Qo + q_c} \tag{5}$$

where

$$\mathbf{q_c = \frac{V}{\beta}\frac{dP}{dt}} \tag{6}$$

and

Qi = volumetric flowrate into the container, [m^3/s],

Qo = volumetric flowrate out of the container, [m^3/s],

q_c = volumetric flowrate [m^3/s] associated with fluid compression to obtain a pressure change,

V = volume of vessel, [m^3],

β = effective bulk modulus (of fluid and container) [N/m^2] which is the reciprocal of compressibility, and

$\frac{dP}{dt}$ = pressure change over unit time, [N/m^2s].

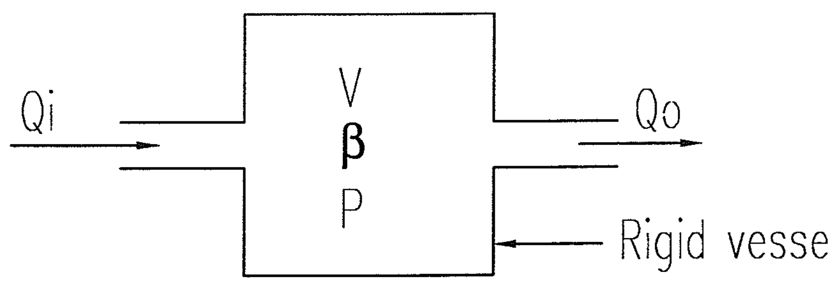

Figure B2 Net flow in a rigid vessel causing a pressure change

Combining equations (5) and (6) and solving for $\frac{dP}{dt}$ yields:

$$\frac{dP}{dt} = \frac{Qi - Qo}{(V/\beta)}. \tag{7}$$

B.3 Analysis of Each Valve Section

The following elements shown in Figure A3 are treated separately.

i) Poppet valve: The flow from the inlet chamber, 1, to the exit chamber, 2, is calculated. Flow depends on both the pressure differential across the poppet valve and the poppet valve's flow area, Av(x), which depends on the valve's displacement, x, from its seat.

ii) Exit chamber: The pressure change in the exit chamber due to fluid compressibility is calculated.

iii) Nozzle orifice: The flow from 2 out through a nozzle having flow area, An, to atmosphere, 3, is calculated.

iv) Closed stage needle valve: The flow from 1 to the switching chamber, 4, through valve flow area, Ac, is determined.

v) Switching chamber: The pressure change in the switching chamber due to fluid compressibility is calculated.

vi) Open stage needle valve: The flow from 4 out to atmosphere, 5, past a valve having flow area Ao is computed.

vii) Poppet valve assembly: The motion of the poppet valve assembly is calculated.

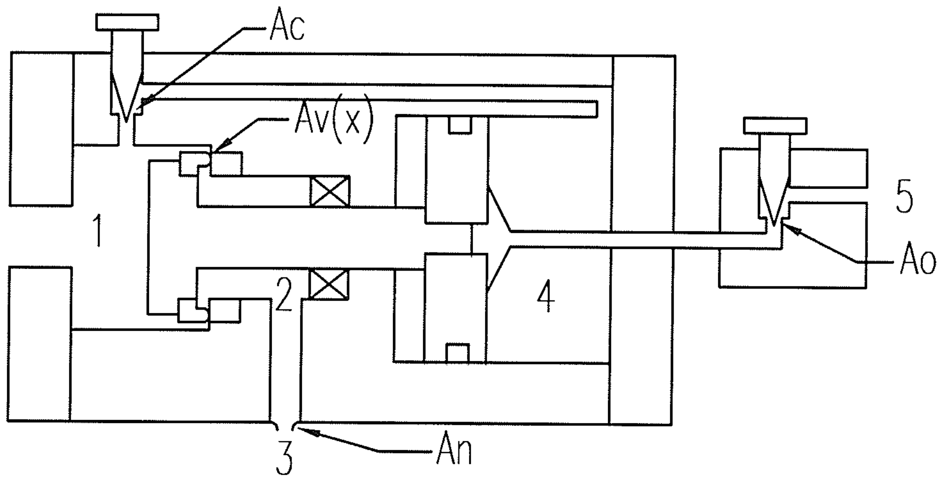

Figure B3 Modelled prototype valve

B.3.1 Poppet Valve

Flow Q12 through the poppet valve flow area, Av(x).

A simplified diagram of this flow section is shown in Figure A4 and the general governing equation (4) becomes:

$$\mathbf{Q12} = \left(\frac{2}{\mathbf{K\rho}}\right)^{1/2} \mathbf{Av(x)(P1 - P2)}^{1/2} \qquad [m^3/s] \qquad (8)$$

where

P1 = inlet pressure, constant at 28 MPa,

P2 = exit chamber pressure, [MPa],

Q12 = flow through poppet valve, [m^3/s], Av(x) = cylindrical flow area, [m^2], through poppet valve which is a function of the distance, x, of the poppet from the seat (see Figure A3),

Av(x) = circumferential distance * x

$$= \pi 0.03175\mathbf{x} = 0.0997\mathbf{x} \qquad [m^2]$$

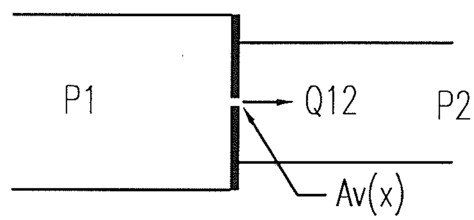

Figure B4 Simplified flow past the poppet valve

Substituting known values into equation (8) yields:

$$\mathbf{Q}12 = \left(\frac{2}{1.5*1000}\right)^{1/2} 0.0997\mathbf{x}(\mathbf{P}1 - \mathbf{P}2)^{1/2}$$

or

$$\mathbf{Q}12 = 0.00258\mathbf{x}\left(\mathbf{P}1 - \mathbf{P}2^{1/2}\right) \qquad [\mathbf{m^3/s}]. \qquad \mathbf{(9)}$$

B.3.2 Exit Chamber

Pressure change $\frac{\mathbf{dP2}}{\mathbf{dt}}$ due to fluid compressibility.

A simplified diagram of this section is shown in Figure A5. The general governing equation (7) becomes:

$$\frac{\mathbf{dP2}}{\mathbf{dt}} = \frac{\mathrm{Q12} - \mathrm{Q23}}{\mathrm{V2}/\beta 2} \quad [\mathrm{N/m^2 s}] \tag{10}$$

where

P2 = exit chamber pressure, [N/m^2],

Q12 = flow through poppet valve, [m^3/s],

Q23 = flow through nozzle, [m^3/s],

V2 = volume of exit chamber, [m^3],

V2 = cross sectional area * length of exit chamber

= $5.97 * 10^{-6}$ [m^3]

$\beta 2$ = effective bulk modulus of V2, [N/m^2]

= $6 * 10^8$ [N/m^2] (see below)

Note: β_{water} = $21 * 10^8$ [N/m^2]

β will be reduced if [2,4]:

i) the container (vessel) dilates upon pressurization, or

ii) free air is present in the water (fluid).

$\beta 2$ is set to $6 * 10^8$ [N/m^2] in the computer program to achieve predicted exit pressure rise and fall times close to the measured times. This manipulation of $\beta 2$

is considered reasonable because the poly pak seal [6] around the valve stem, which is made of neoprene (90 Durometer), would result in significant dilation of V2 with an increase in P2. Additionally, from observation of the liquid jets during the valve's operation, free air is believed to be present in the exit chamber. Although free air may not affect β significantly at high pressures like 28 MPa [2], both factors are lumped in the reduced bulk modulus.

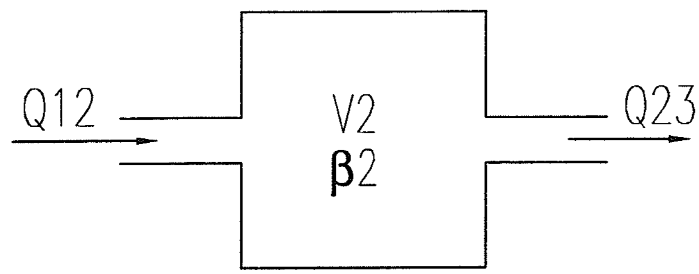

Figure B5 Flow through exit chamber

Substituting known values into equation (10) yields:

$$\frac{\mathbf{dP2}}{\mathbf{dt}} = \frac{\mathbf{Q12 - Q23}}{5.97*10^{-6}/6.0*10^{8}}$$

or

$$\frac{\mathbf{dP2}}{\mathbf{dt}} = \frac{\mathbf{Q12 - Q23}}{1.0*10^{-14}} \quad \mathbf{[N/m^2 s].} \qquad \mathbf{(11)}$$

B.3.3 Nozzle Orifice

Flow Q23 through nozzle flow area, An.

A simplified diagram of this flow section is given in Figure A6 and the corresponding governing equations (1) and (2) becomes:

$$\mathbf{Q23} = \left(\frac{2}{(\mathbf{K}+1)\rho}\right)^{½} \mathbf{A_n P2}^{½} \quad [m^3/s] \qquad (12)$$

where

Q23 = flow through nozzle, $[m^3/s]$,

A_n = flow area through nozzle orifice, $[m^2]$

$A_n = \frac{\pi}{4} 0.001 = 7.85 * 10^{-7} \quad [m^2]$

P2 = exit chamber pressure, [MPa],

P3 = atmospheric pressure = Patm = 0, [MPa]: assumed zero because P1 >> Patm,

V3 = speed of liquid jet, [m/s],

Note: Because this flow section creates a high speed liquid jet, assumption 2 in Section A.2.1, which states $\mathbf{V1 \cong V2}$, is not considered valid. Therefore, V2 of equation (1) is retained to yield the (K+1) term shown in equation (12) (as opposed to only the K in equation (4).

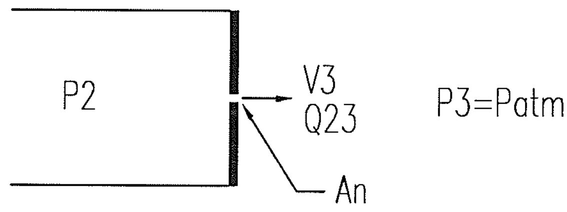

Figure B6 Simplified flow through nozzle orifice

Substituting known values into equation (12) yields:

$$\mathbf{Q23} = \left(\frac{2}{(1.5+1)1000} \right)^{1/2} (7.85*10^{-7})\mathbf{P2}^{1/2}$$

or

$$\mathbf{Q23} = 2.22*10^{-8}\mathbf{P2}^{1/2} \qquad \mathbf{[m^3/s].} \qquad \mathbf{(13)}$$

B.3.4 Closed Stage Needle Valve

Flow Q14 through valve flow area, Ac.

A simplified diagram of this flow section is shown in Figure A7. The general governing equation (4) becomes:

$$\mathbf{Q14} = \left(\frac{2}{\mathbf{K\rho}} \right)^{1/2} \mathbf{Ac(P1-P4)}^{1/2}\,[\mathrm{m^3/s}] \qquad (14)$$

where

Q14 = flow through closed stage needle valve, [m^3/s],

Ac = flow area past closed stage needle valve, [m^2],

(Ac is set arbitrarily in the computer program to Ac = 0.2 * 10^{-7} m^2)

P1 = inlet pressure, [MPa], and

P4 = switching chamber pressure, [MPa].

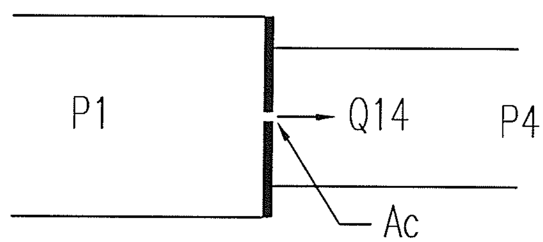

Figure B7 Simplified flow past closed stage needle valve

Substituting known values into equation (14) yields:

$$Q14 = 0.0365Ac(P1 - P4)^{1/2} \ [m^3/s]. \qquad \textbf{(15)}$$

B.3.5 Switching Chamber

Pressure change $\frac{dP4}{dt}$ due to fluid compressibility.

A simplified diagram of this flow section is shown in Figure A8 whist the governing equation (7) becomes:

$$\frac{dP4}{dt} = \frac{Q14 - Q45}{V4/\beta4} \quad [N/m^2s] \qquad (16)$$

where

P4 = switching chamber pressure, [N/m^2],

Q14 = volumetric flowrate into switching chamber, [m^3/s],

Q45 = volumetric flowrate out of switching chamber past the open stage needle valve, [m^3/s],

V4 = volume of switching chamber, [m^3],

V4 = area of chamber bore * length

$$= \frac{\pi}{4} 0.0476^2 * 0.00787 = 1.4 * 10^{-5} \quad [m^3], \text{ and}$$

B4 = bulk modulus of fluid within switching chamber (rigid) = $21 * 10^8$ [N/m^2].

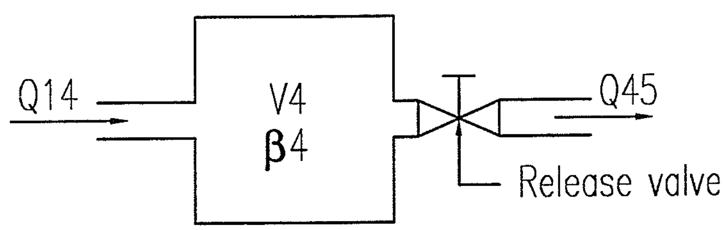

Figure B8 Flow into switching chamber

Substituting known values into equation (16) yields:

$$\frac{dP4}{dt} = \frac{Q14 - Q45}{1.4 * 10^{-5} / 21 * 10^8}$$

or

$$\frac{dP4}{dt} = \frac{Q14 - Q45}{6.67*10^{15}} \quad [N/m^2 s]. \tag{17}$$

Notes:

1. There are only two cases considered in the computer program when using equation (17). They are:
   i) when the release valve is closed, flow Q45 = 0, and
   ii) when the release valve is fully open, Q45 > 0 and Q45 is also dependent only on the flow area past the open stage needle valve assuming a sufficient flow area past the release valve.
2. The volume change, as a result of the switching piston's displacement during the transition of the poppet valve, is not considered in the computer simulation. Although this neglect created a significant discrepancy between the simulated and measured switching pressures of the prototype (compare, for example Figures 4.7 and 5.8 in the main text), the simulation results are still considered indicative of the real situation because measurements of the switching pressure on an earlier version correlated very closely to the predicted nature. The change in the measured pressure can be attributed to the addition of the steel backing plate to the switching piston (see Section 5.3) which decreased the volume of the switching chamber by about half making pressure changes more sensitive to movement of the poppet valve assembly.

B.3.6 Open Stage Needle Valve

Flow Q45 through valve flow area Ao (non-zero only when release valve is fully open).

A simplified diagram of this flow section is shown in Figure A9 and the general governing equation (4) becomes:

$$\mathbf{Q}45 = \left(\frac{2}{\mathbf{K}\rho}\right)^{1/2} \mathbf{Ao}(\mathbf{P}4 - \mathbf{P}5)^{1/2} \qquad [m^3/s] \qquad (18)$$

where

Q45 = volumetric flowrate through the open stage needle valve, [m^3/s],

Ao = flow area past the open stage needle valve, [m^2],

Ao = 2.0 * 10^{-7} [m^2] (in the computer program)

P4 = switching chamber pressure, [MPa], and

P5 = Patm = 0, [MPa].

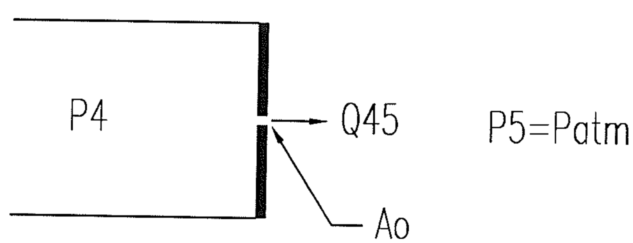

Figure B9 Simplified flow past open stage needle valve

Substituting known values into equation (18) yields:

$$\mathbf{Q}45 = 0.0365\mathbf{Ao}(\mathbf{P}4)^{1/2} \qquad [\mathbf{m^3/s}]. \qquad \mathbf{(19)}$$

B.3.7 Equation of Motion of the Poppet Valve Assembly

The poppet valve assembly moves in sequence to a changing net force acting on it due to the pressures in the three chambers. These pressures create the three axial forces shown in Figure A10. They include F1 due to the inlet pressure, F2 due to the exit pressure and F4 due to the switching pressure. The additional force, Ff, shown in the figure is due to friction between the poppet valve assembly and the seals around the valve stem and switching piston. Note that friction always opposes motion so that its direction reverses.

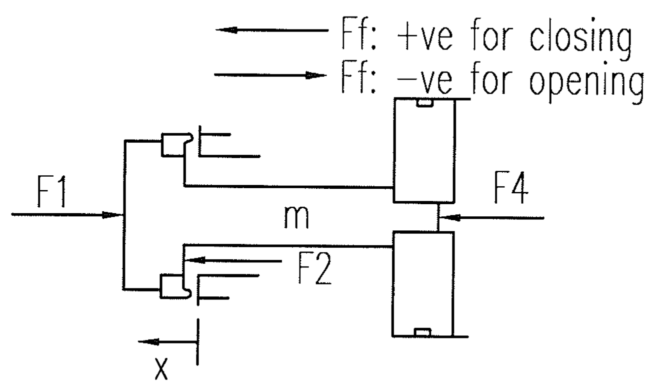

Figure B10 Forces acting on the poppet valve assembly

Using Newton's second law which states:

sum of forces = mass * acceleration [N]

or

$$-\mathbf{F1}+\mathbf{F2}+\mathbf{F4}\pm\mathbf{Ff}=\mathbf{ma} \tag{20}$$

where

$$\mathbf{F1}=\mathbf{P1}*\mathbf{A1}=28*10^{6}\frac{\pi}{4}0.03175^{2}$$

so that

$$\mathbf{F1}=2.22*10^{4}\,\mathbf{[N]}\qquad \mathbf{(4940\ lbs)} \tag{21}$$

$$\mathbf{F2}=\mathbf{P2}*\mathbf{A2}=\mathbf{P2}\frac{\pi}{4}\left(0.03175^{2}-0.0127^{2}\right)$$

or

$$\mathbf{F2}=6.65*10^{-4}\,\mathbf{P2}\qquad \mathbf{[N]} \tag{22}$$

$$\mathbf{F4}=\mathbf{P4}*\mathbf{A4}=\mathbf{P4}\frac{\pi}{4}0.0476^{2}$$

or

$$\mathbf{F4}=1.78*10^{-3}\qquad \mathbf{[N]} \tag{23}$$

and

$$\mathbf{m = 0.2\ [kg]\quad (7\ oz)} \tag{24}$$

As an approximation Ff is considered to be proportional to P2 and it is estimated to reach 2.8 kN (620 lbs) at a presumed maximum exit chamber pressure of P2 = 28 MPa (4000 psi). This approximation is considered plausible [7] because a higher pressure exerted on a poly pak stem seal leads to a greater pressure (and frictional force) being exerted by the seal on the shaft. Moreover, the higher is the pressure differential across an o-ring, the more the o-ring extrudes between the piston and bore and the larger is the pressure (and frictional force) acting on the bore of the switching chamber. Furthermore, this approximation yields simulation results (switching times) in good agreement with experimental values. Thus, the frictional force, Ff, is calculated as:

$$Ff = Cf * P2 \tag{25}$$

where

Cf = frictional proportionality constant, [m^2].

Solving for H yields:

$$H = Ff / P2 = 2800\ N / 28 * 10^6\ N/m^2 = 1 * 10^{-4}\ [m^2]$$

or

$$\mathbf{Ff = 1 * 10^{-4}\ P2 \qquad [N].} \tag{26}$$

Equation (21) can be used now, with the calculated pressure values, to obtain the acceleration of the poppet valve assembly, if a net force exists to initiate the transition.

B.4 Closing Statement

The mathematical formulations, indicated by equations in bold print, are complete now and they are used in the computer program given Appendix A. This program calculates, incrementally at every 0.01 ms, the values of the flow, pressure, net force and the resulting poppet position and speed.

B.5 References

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5. Beer, F.P. and Johnson, E.R., "Vector Mechanics for Engineers - Statics and Dynamics", Fourth Edition, McGraw-Hill, Inc., 1984.
6. Kepco Sealing Supplies Inc., Winnipeg, Canada, 1995.
7. Armstrong, K., Personal communication, 1995.

Appendix C: Operating Equipment and Instrumentation

This appendix lists the operating and monitoring equipment used in the thesis.

Water filter:	Aqua Pure AP101B
Pump:	Washex Model S57-5/3 driven by 5 HP Lincoln electric motor
Accelerometer:	Bruel & Kjaer Type 4344
	B & K Type 2626 conditioning amplifier
Pressure transducer:	PCB Piezotronics, Inc. 112A
	PCB 426A charge amplifier
Digital oscilloscopes:	Nicolet Instrument Corporation 204-A for experimental observations
	Hitachi VC-5430 for data acquisition