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# Alternate Design for Controlled Polymer Slurry Injection in Abrassive Water Jet Cutting

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**Abstract:** ***The water jet cutting technique is acknowledged as the most adaptable and rapidly evolving methodology globally. The capability of an abrasive-assisted water jet to penetrate both geological formations and metallic substances presents considerable prospects within the oilfield sector. Nevertheless, the dimensions of the cutting nozzle have precluded the application of water jet technology on a commercial scale for the drilling of reservoir rocks at depth. The ineffective transfer of momentum to abrasive particulates from pressurized water, coupled with the absence of abrasive feed rate regulation in commercially accessible devices, has further inhibited the adoption of water jet technology within the oil industry. Empirical research has demonstrated that the transfer of momentum can be markedly enhanced if abrasive particulates are introduced upstream of the nozzle. There exist limited methodologies whereby abrasives are initially suspended in a fluid medium and subsequently integrated into a high-pressure water stream prior to reaching the nozzle. However, previous investigations have been deficient in offering control over the abrasive feed rate. In the present study, an alternative design is proposed, which facilitates the provision of a regulated abrasive feed rate through the incorporation of a specially engineered Pressure Regulator-cum-Automatic Unloader (PRAU) Valve, thereby achieving precise regulation of pressure, while the injection rate is managed by a manually controlled Discharge Control (DC) Valve.***

**Keywords:** Abrasive Water Jet Cutting, Pressure Regulator cum Automatic Unloader Valve, Discharge Control Valve, High Pressure Triplex Plunger Pump

## 1. Introduction

Abrasive water cutting constitutes a non-conventional machining technique that employs a high-pressure stream of water combined with abrasive particles to erode and sever hard materials. The material removal efficiency of abrasive water jets significantly surpasses that of pure water jets. Within an abrasive water jet, the water stream serves to accelerate abrasive particles, which subsequently erode the material.

Various methods for abrasive injection have been developed, with several demonstrating commendable efficacy. Nonetheless, the challenges associated with controlled and efficient abrasive injection remain an ongoing issue.
When abrasives were introduced alongside water via a positive displacement pump, the process became economically unviable due to the rapid wear of pump liners and valves caused by the abrasives. Presently available commercial units are not adequately suited for application within the petroleum industry, particularly when the objective is to efficiently sever sub-surface rock utilizing water jet technology.

An in-depth examination of the complications related to the currently available abrasive injection systems is presented in Chapter 2; however, the fundamental principles, various types, applications, and advantages of water jet techniques compared to mechanical methods will be delineated in the subsequent sections.

### 1.1 Principle of Water Jet

Water jet is generated by pressurizing water to high-pressure levels using a high-pressure triplex plunger pump blaster, and then accelerating it through a small nozzle opening. Figure 1 depicts general flow diagram of water jetting component [5].

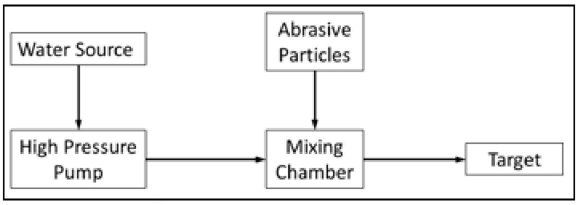


**Figure 1:** Abrasive water jetting Components

## 2. Literature Review

Many studies have been conducted to understand the effect of the amount of abrasives entrained in the high velocity water stream on cutting performance of abrasive water jet and it has been established that initially the abrasive flow rate and depth of cut follows a linear relationship [8]. However, beyond the optimum point any further increase in abrasive flow rate leads to a decrease in the depth of cut [8]. Based on theory of erosion, the depth of cut is proportional to a particle's kinetic energy and depends on the particle velocity exiting the nozzle [9]. Depth of Cut (h) α Kinetic Energy.

$$h \propto Mv^2 \quad (1)$$

where **m** is mass and **v** is exit velocity.

In terms of water jet velocity (vj) [9],

$$v \approx v_j \frac{1}{1+R} \quad (2)$$

Where, R is the loading ratio and can be described as the ratio of abrasive flow rate (m) over water flow rate ($m_w$).

$$R = \frac{m}{m_w} \quad (3)$$

Using equation (1) and (2), the depth of cut can be estimated based on erosion theory as:


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$$v = M\left(\frac{v_j}{1+R}\right)^2 \quad (4)$$

Where, the critical abrasive flow rate is obtained at $\frac{\delta h}{\delta R} = 0$

However, there is a discrepancy in the valves of critical flow rate obtained from Equation 3 and from experiments, which is usually attributed to mixing losses at the point of injection [9]. A plot between depth of cut and abrasive flow rate would generally yield results as shown in Figure 2.

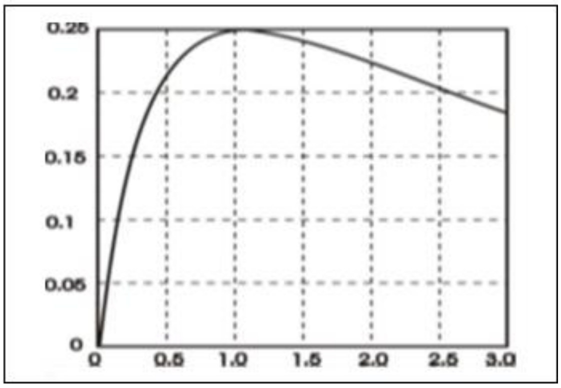


**Figure 2:** Effect of mixing ratio on cutting ability.

It has been proved that maximum depth of penetration($h_t$) occurs at $R$ = 1. The variation in $h_t$ with $R$ is shown in Fig.2. But, in practice maximum $h_t$ is obtained at $R$ = 0.5 to 0.6 for all other parameters remaining same.

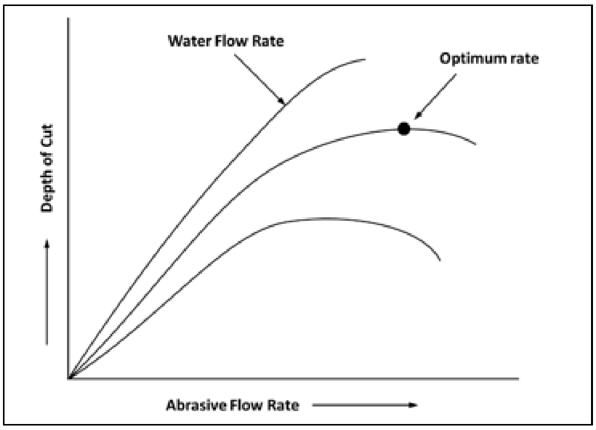


**Figure 3:** Optimum Abrasive Feed Rates [9]

If, abrasive flow rate is less than optimum amount, sufficient cut may not be achieved and on the contrary if it were too high, abrasives would be wasted. Since the beginning of abrasive assisted water jetting, various techniques have been employed to gain effective and efficient control over abrasive feed rates. Presently available techniques are

### 2.1 Abrasive Injection Techniques

#### 2.1.1 Post-Orifice Injection

As pressurized water is forced to pass through a small opening or an orifice the resulting pressure drop creates suction in a mixing chamber that allows abrasive entrainment.

The amount of suction and abrasive entrainment is proportional to the pressure drop. The mixing of abrasive and water takes place in a mixing chamber and the slurry is transferred to a focusing nozzle by a collimating or discharge tube.

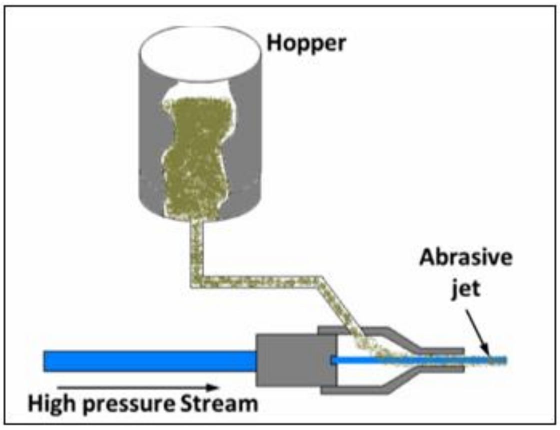


**Figure 4:** Hopper and Cutting Head used in Post-Orifice Abrasive Injection

#### 2.1.2 Pressurized Hopper

Pressurized hopper prevents liquid build up in abrasive feed line by applying air pressure on top of the dry abrasives inside the hopper. Abrasives are stored in a hopper, which is pressurized using compressed air. A slipstream of compressed air carries the abrasives from the bottom of the hopper to the mixing chamber. Pressurized hopper takes care of liquid hold up problem by not allowing water from mixing chamber to enter back in the abrasive feed line, but adds to the problem of air entrainment. Air entrainment causes critical impact on the performance of water jet by expanding the jet as it leaves the cutting nozzle. As an air bubble expands it disintegrates the jet and causes poor precision.

#### 2.1.3 DIAjet (ASJ) Solution

DIAjet utilizes a slipstream of the motive fluid to inject abrasives. Usually 10% of the motive fluid is directed to a vessel where it mixes with the abrasive particles. The mixture of water and abrasive is delivered to the cutting head without any air entrainment. In order to ensure that pressure of the main stream at the injection point is less the pressure of the slurry in the vessel, a small restriction is usually placed downstream of the slipstream. This design eliminates air entrainment as no air is introduced in the system, but the problem of controlling abrasive feed rate still exists as there is no way to ensure that the slip stream would deliver same concentration of abrasives throughout the injection cycle.

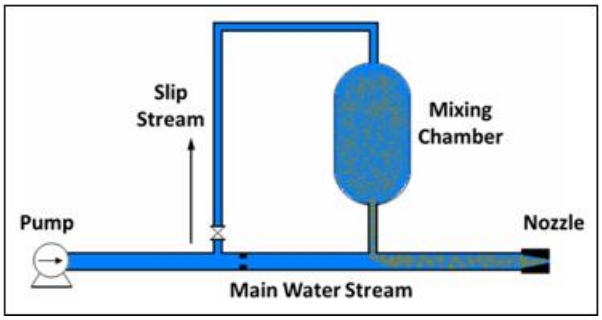


**Figure 5:** Schematic of DIAjet Technique [15]

#### 2.1.4 Bladder Transfer System


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The approach to abrasive injection discussed above is indeed a dilution process, as there is no barrier between the abrasives being injected and water entering the vessel as slipstream. So, with time, the amount of abrasives being injected decreases, because the water flow rate to the vessel is constant, but abrasive contents with-in the vessel decrease continuously.

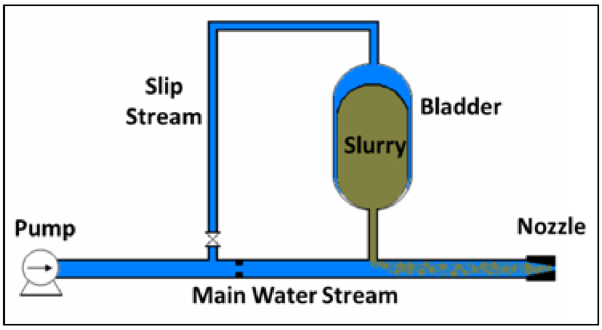


**Figure 6:** Schematic of Bladder Transfer System [16]

### 2.1.5 Piston Transfer System

A piston assembly as shown in Figure 7 is based on the same principle as the bladder discussed in the preceding. The only difference is that it uses a piston to separate the abrasives slurry added to the high-pressure water stream. This design was tested at Rock Mechanics and Explosive and Research Centre at The University of Missouri-Rolla, Missouri. The piston assembly included a polished cylinder and a floating metallic disc or a piston head without rod. Metal to metal seal between polished cylinder and piston avoids abrasive dilution. O-ring seal is not recommended in an abrasive environment, as abrasive particle would wear it very rapidly.

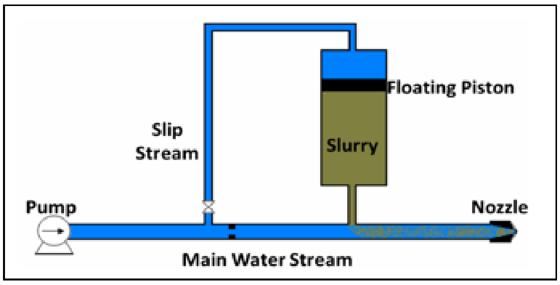


**Figure 7:** Schematic of Piston Transfer System

## 3. Alternate Design for Controlled Abrasive Injection

Considering the limitations of existing abrasive injection systems and the dependence of water jet quality on abrasive feed rate, there is a need to design and develop a system that would provide improved water jetting results.

The objectives of improved slurry injection techniques are summarized below:

1) To achieve the flexibility to adjust abrasive flow rate depending on application.
2) To maintain constant slurry concentration without dilution.
3) To achieve the largest pressure, drop at the cutting nozzle.
4) To eliminate any air entrainment at the point of abrasive injection.

The proposed system is expected to achieve control over abrasive feed rate by controlling the delivery rate of the slurry system. This chapter concentrates on relative merits and feasibility of two designs utilizing an external source to deliver abrasives at controlled rates.

### 3.1 Design I

Design I utilize a reversible motor to provide a linear displacement to a threaded shaft attached to it by means of gear arrangement, as shown in Figure 8.

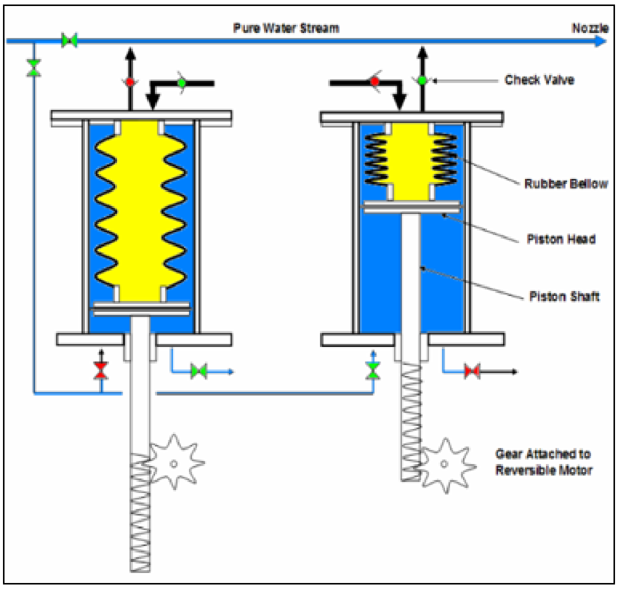


**Figure 8:** Schematic of Design I

The shaft forces the slurry contained in the bellow into the main high-pressure water stream. A slipstream provides force equilibrium across the piston and reduces the total load on the reversible motor. This arrangement still requires a slipstream, but would provide control over abrasive slurry injection rate by controlling the rpm of the reversible motor. It would take two such cylinder-motor combinations to accomplish continuous injection.

### 3.1.1 Process Description

Once the bellows are charged with slurry, opening the slipstream valves would pressurize the unit to mainstream pressure. Reversible motor would push piston upwards to begin injecting slurry to the main or pure water stream. Once the stroke is complete, closing the slipstream valves and bleeding pressure would allow the downward stroke. At the same time, the check valve on the slurry suction line would open in order to recharge the bellow.

### 3.1.2 Design Calculations for Design I

Force balance across the piston would yield,


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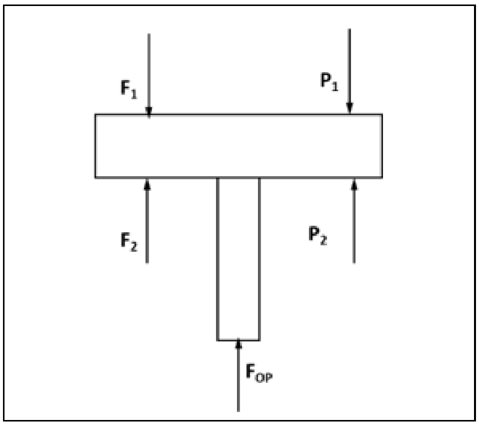


**Figure 9:** Force Balance Across Piston

$$F_1 = F_2 + F_{OP} \quad (1)$$

$$F_1 = \frac{\pi}{4} D^2 P_1 \quad (2)$$

$$F_2 = \frac{\pi}{4} (D - d)^2 P_2 \quad (2)$$

Where, D is the piston diameter, d is the piston rod diameter and FOP is the operating force required to push the piston and would essentially depend on the injection rate, but for simplicity it is assumed to be equivalent to the differential force across the piston as shown in Figure 10.

$$F_{OP} = F_1 - F_2 \quad (4)$$

$$F_{OP} = \frac{\pi}{4} (D^2 P_1 - (D - d)^2 P_2) \quad (5)$$

$$F_{OP} = \frac{\pi}{4} d^2 P_1 = \frac{\pi}{4} d^2 P_2 \quad (6)$$

Let Q $m^3/s$ be the desired slurry injection rate, then; injection velocity would be given by,

$$V = \frac{Q}{A} \quad (7)$$

Power required would be,

$$P = F_{OP} V \quad (8)$$

### 3.2 Design II

Design II utilizes a hydraulic pump based external system to control the slurry injection rate, as shown in Figure 10.

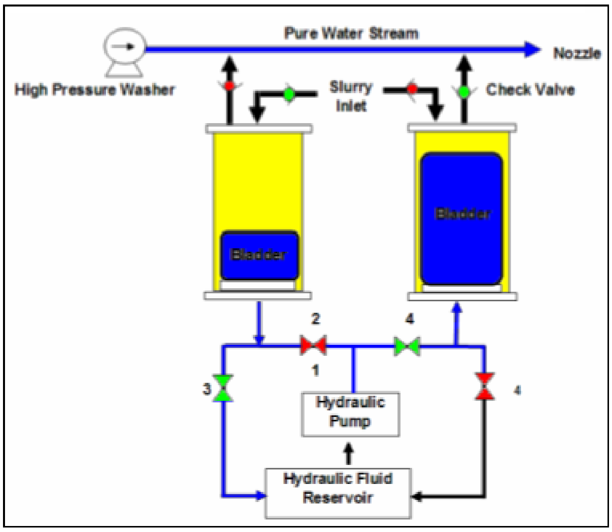


**Figure 10:** Schematic of Design II

In this design, a bladder contained in a high-pressure shell replaces the bellows. Slurry is charged to the shell side from pre-pressurized bulk storage tank and then injected into the high pressure water stream by pressurizing bladder using a hydraulic pump. Varying hydraulic pump rate could control slurry injection rate. It would take two bladder units to make the continuous. While one unit injects the slurry into the high-pressure water stream, the second unit recharges at the same time. The process can be automated by using solenoid valves in place of regular ball valves 1, 2, 3, 4 and 5. Process.

### 3.3 Advantages of Design II over Design I

1) Eliminates the need of a reversible motor.
2) No gear arrangements or complex moving parts are required.
3) Piston rod and matching stuffing box are eliminated.
4) Hydraulic pumps are readily available.

## 4. Experimental Setup

This chapter concentrates on relative merits and feasibility of proposed design. This Design utilizes hydraulic high pressure triplex plunger pump based external system to control the slurry injection rate, as shown in Figure 11. In this design, a bladder contained in a high-pressure shell replaces the bellows. Slurry is charged to the shell side from pre-pressurized bulk storage tank and then injected into the high-pressure water stream by

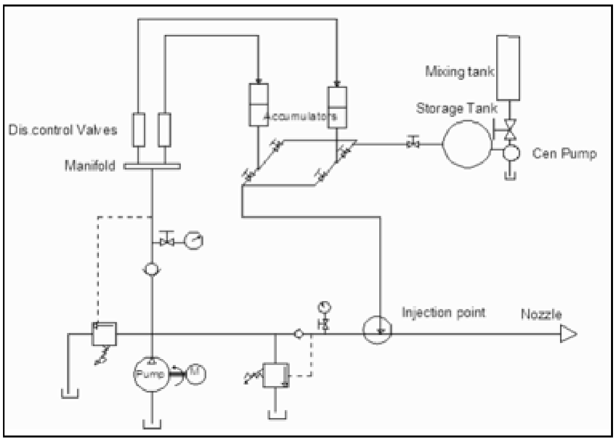


**Figure 11:** Schematic diagram of experimental Setup

pressurizing bladder using a hydraulic pump. Varying hydraulic pump rate could control slurry injection rate. It would take two bladder units to make the process continuous. While one unit injects the slurry into the high-pressure water stream, the second unit recharges at the same time. The process can be automated by using solenoid valves in place of regular ball valves 1, 2, 3, 4 and 5.

### 4.1 Pump Assembly unit

The assembly of pump unit consists of one High pressure triplex plunger Pump which is coupled to electrical motor through a reduction gear box of ratio 7.5:1. Water from the tank flows into the valve chamber through butterfly valve and strainer. At the delivery after the valve chamber, an Air Vessel and a Pressure Regulator-cum -Automatic Un- loader


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Valve is incorporated to maintain the pressure of the main stream line and one more pressure regulator-cum -Automatic un-loader valve is incorporated to maintain the pressure at slurry contained accumulators.

### 4.1.1 Pump Unit Design

The manufacturers usually develop and manufacture pump bodies for certain range of power to ensure quick delivery to the customers except for special requirements. For this design we selected a model which is suited to 20 HP.

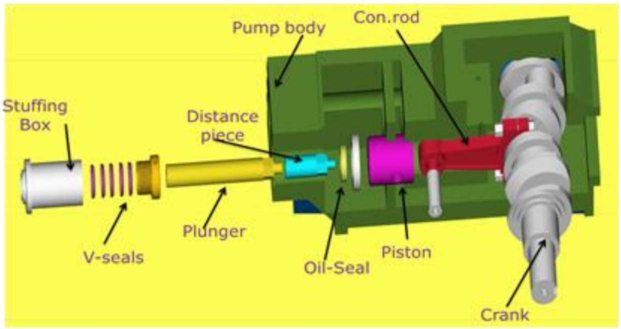


**Figure 12:** Exploded view of High- Pressure Triplex Plunger Pump

Based on the delivery size of the Plunger V- seal dimensions change. These V- seals has to be supplied by vendors. So, while deciding on the size of the plunger it is essential to select V-seals from the manufacturers data which is suited to designed diameter of the plunger and nearest discharge.,

**Table 1:** Technical data of pump

| Pressure (Bar) | Discharge (LPM) | Motor RPM | Power (HP) |
|---|---|---|---|
| 375 | 10 | 192 | 10 |

Power required = 375 x10/375 = 10 HP

Taking a factor of safety of 1.2 an Electrical Motor of 10 HP with 1440 rpm selected.

A suitable reduction gear box with 7.5:1 is selected. So, the pump runs at 192 RPM.

Discharge of the pump, Q = $= n\frac{\pi}{4}d^2LN$

n= no. of plungers (3);
d= diameter of the plunger;
L=Stroke length=40mm;
N= RPM of the pump =192;

Therefore, Q= $3 \times \frac{\pi}{4} \times 25^2 \times 40 \times 192 = 11.30\ lpm$
Nearest available inside diameter of the V-Seal is 25mm
Rate of flow = Q =11.30 lpm

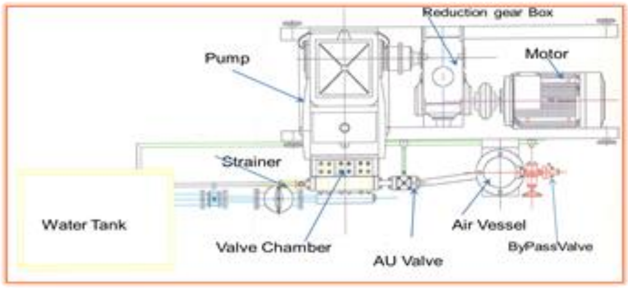


**Figure 13:** Layout of Pump unit

### 4.2 Pressure Regulator cum Automatic Unloader (PRAU) Valve

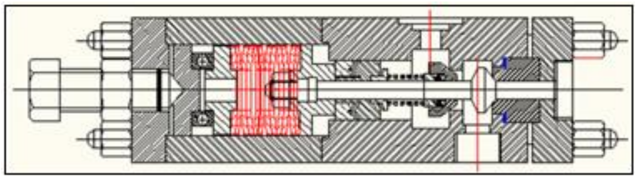

**Figure 14:** PRAU valve Construction

The PRAU valve serves three purposes:

1) Precise Pressure Regulation (Pressure setting)
2) Automatic unloading when system pressure exceeds set pressure Check valve to allow flow in one direction only. The design of PR-cum-Automatic Un-loader valve primarily depends on the selection of disc springs from the available manufacturer's data. To select the spring it is necessary to know the load coming on to them. Here the maximum working pressure is 750 bar.

Combination type of stacking gives both series and parallel benefits. So, we have selected combination type.

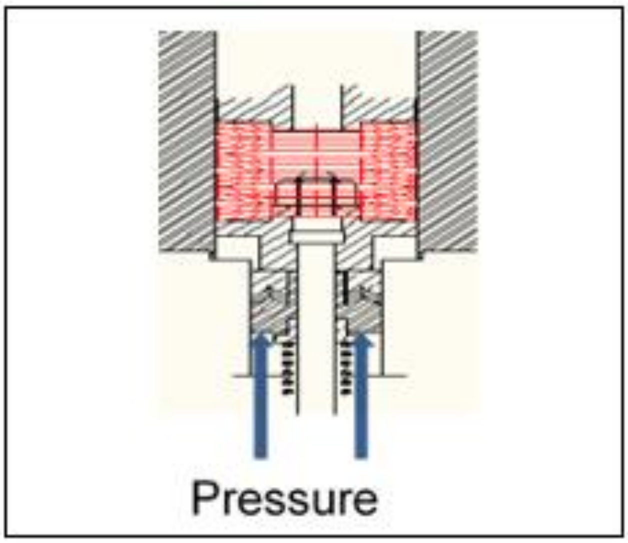


**Figure 15:** Disc washer setup

Load Acting on the springs due to pressure, F
Load bearing capacity of each spring = 9359 N
Because we have used two in parallel
Total load bearing capacity = 2 x 9359N = 19718N
Load Acting on the springs due to pressure
(15660 N) < Total load bearing capacity (19718 N)

### 4.3 Discharge Control Valves


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**Figure 16:** Photograph of Control valve set

Each accumulator is fitted with one control valve. Each of this valve consists two lines delivery line and return line. When the delivery line is opened the discharge starts flowing into the accumulator; once is filled with pressurized water we can cut off the supply. When charging the accumulator with polymer mixed abrasive slurry return line is opened. The following figure shows the details of the control valve.

**4.4 Accumulators**

Pressure accumulators serve as critical components of the experimental apparatus used for high-pressure polymer injection. Two units of 40 LPM each and maximum working pressure of 400 bar have been incorporated for this study.

Both units were charged with polymer slurry on the shell side and, water was pumped inside the bladder using high pressure pump with controlled water by Control vale. The bladder provided an impermeable barrier between polymer slurry and water, preventing any dilution of the polymer slurry before the injection point. This would be critical if polymer slurry consisted of suspended sand. Significant dilution could cause the sand to settle out permanently and block flow lines, thus causing serious safety hazards.

## 5. Experimental Apparatus and Operating Procedure

Experimental investigations can be divided into two segments. First segment is to develop performance curves for a 10-HP power high pressure pump. These curves can later used in second segment (System Design Testing) for continuous and controlled slurry injection upstream of the nozzle.

### 5.1 Experimental setup for pump performance curves

Experimental setup to develop pump performance curves consisted of 10 HP powered high pressure triplex plunger pump coupled through reduction gear box of 7.5:1 ratio with two PR-cum-Automatic Unloader valves and one air vessel, three high pressure ball valves, two 500 bar pressure gauge, a tachometer, a rotameter and essential piping. The setup was assembled as shown in Figure. All the piping and fittings used for this experimental setup were rated for 300 bar working pressure.

Pressure was regulated downstream of the pressure pump by operating the Pressure regulator cum Automatic Unloader valve. Flow rates were recorded using rotameter, by adjusting the control valve. Flow rate and rpm data were recorded for six different pressure settings, starting from zero bar to 300 bar with, 50 increments. Pressure data was recorded using a pressure gauge which was mounted upstream of the control valve. A piece of reflecting tape was placed on the shaft coupling which couples pump and gear box and one shaft coupling which couples gear box and electrical motor and tachometer was used, in optical mode, to measure Pump rpm and motor rpm was recorded as the instantaneous tachometer readings fluctuated over a range of ±10%.

#### 5.1.2 Procedure

1) Assemble setup as shown in Figure 13.
2) Make sure all the valves are open before starting the pump and allow for stabilization. Read both motor and pump rpm and measure discharge.
3) Adjust PR-AU valve to get desired pressure reading on the gauge and let it stabilize and record discharge after the control valve. This flow of discharge can also be controlled by control valve.
4) Read and record pump rpm using a tachometer.
5) For next reading repeat step (4) & step (5).

### 5.2 Experimental setup for testing of new design

Experimental setup for testing of Design consisted of a electrical motor driven high pressure triplex plunger pump set, two pressure accumulators, two rotameters, pressure gauges, two discharge control valve, and 300L spherical tank for bulk storage, a mixing tank, a centrifugal pump, essential piping, high pressure hoses, ball valves and fittings. The experimental setup was designed for a maximum working pressure of 300 bar, which included a safety factor of 1.5.

#### 5.2.1 Description of Apparatus

The components were assembled as per the schematic diagram shown in Figure 16. In the there are two pressure lines; one line is for accumulators which is having discharge control valves set and second line (main water jet stream) is to deliver straight to nozzle. Abrasive slurry coming from the accumulator would join the second line after PRAU valve. Each accumulator is provided with one discharge control valve which consists two lines; delivery line and return line. Polymer solution (1% w/w) was prepared in the mixing tank and was pumped to the bulk storage tank where it was pressurized by compressed air to pressure level between 7 bar to 8 bar. Pressure accumulators were charged from bottom with pressurized polymer solution by operating appropriate valves. Water from the pump, will flow into the pressure regulator there pressure is set to required pressure and then moves into discharge control valve, was pumped into the bladder of either of the pressure accumulator by rotating the handle wheel and lever of discharge control valve. This discharge control valve precisely controls the flow into the bladder of the accumulator. Polymer solution was injected into the main water stream, upstream of the nozzle by the expanding bladder.

#### 5.2.2 Safety Considerations

To ensure proper safety the experimental setup was equipped with safety relief valves and bypass lines. Although, the storage tank was rated for 300 bar working pressure, but still


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another spring-loaded safety relief valve set at 10 bar was mounted on it to avoid over pressurizing the Schedule-40 recharging line, in case of pressure leakage while polymer was being injected into the high-pressure water stream. Recharging lines were equipped with check valves just upstream of the pressure accumulators. Main water stream was equipped with a bypass line upstream of the injection point.

#### 5.2.3 Experimental Procedures

##### 5.2.3.1 Operating Procedures for Charging Cycle

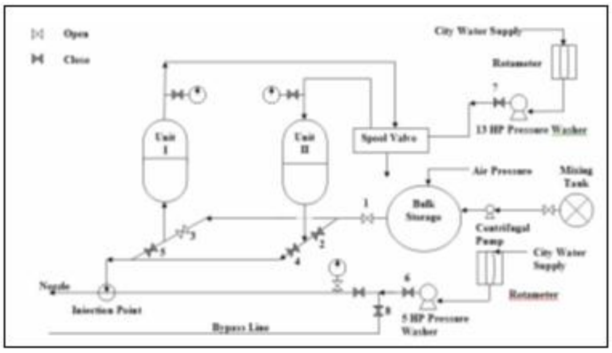


**Figure 16:** Schematic of Expt. Setup while Unit I being charged with Polymer Slurry

Following procedure is to be followed while charging the pressure accumulators with polymer solution from pressurized bulk storage tank as illustrated in Figure 16.

1) The bulk storage tank is filled with polymer solution and is pressurized to7 bar minimum, to overcome the friction in recharging lines and to open the check valve.
2) To charge pressure accumulator unit I, open valve-1 and valve-3 and rotate the wheel and levers of the control valve-I connected to it accordingly. While doing so make sure valve-2 and valve-5 are closed.
3) To charge pressure accumulator unit II, close valve-3 and valve-4, and open valve-2.
4) Rotate the wheel and levers of the control valve-I I connected to it and close valve-2.

##### 5.2.3.2 Operating Procedure for Injection Cycle

The following operating procedures to be followed to inject polymer solution from pressure accumulators to the high-pressure water stream.

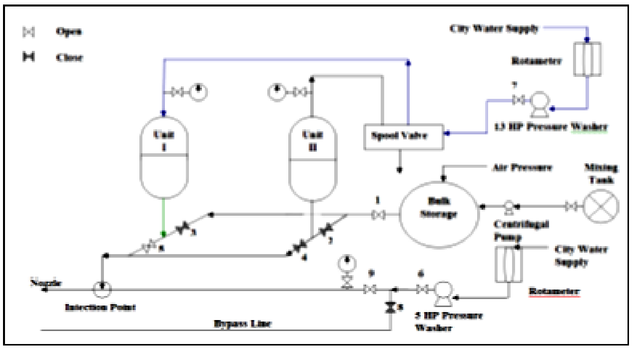


**Figure 17:** Schematic of Expt. setup while Unit I is injecting Polymer Slurry

1) Close valve-2, valve-3, and valve-4 and open valve-5.
2) Slowly open the delivery line so that water flows into the bladder of the accumulator and slurry starts flowing down into the main stream line which is carrying pure water stream to the nozzle.
3) To inject polymer solution from unit II, follow step (5) through step (9).

## 6. Conclusions

1) In this design the pump runs at low RPM i.e.,200 RPM and produces constant flow rate of 10 LPM. An Air Vessel is incorporated to avoid fluctuation in the discharge.
2) Pump running at low RPM avoid large vibrations which reduces the life of the bearings
3) Instead of two pumps, one for pressurizing the bladder and one for main stream flow, one for hopper line. In this design one pump with two control valves and two PRAU regulators will serve the purpose.
4) Injection flow rate is controlled by a Discharge control valve**.**
5) Pressure regulator-cum -Automatic Unloader valve a precise change in pressure is possible.
6) Use of manual operated Control vale eliminates hydraulic power pack which runs directional control valve.

## 7. Future Scope

In regard to the continuation of this project, the following recommendations are made:

1) Performance of this Design should be evaluated
2) Performance of this Design should be evaluated, at higher pressures, to drill oil well casing and pressurized reservoir rock samples to simulate down-hole conditions.
3) Design should be improved to an extent where the hole drilled is large enough so that the cutting nozzle can follow the drilled hole. Experiments should be conducted to record frictional pressure drop for different lengths of piping between injection point and cutting nozzle.

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