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RESEARCH ARTICLE

Dr.A.Z.A.Saifullah *et al*, The *Experiment*, 2014., Vol. 18(3), 1268-1283

Design, Construction and Performance Test of a Hydraulic Pressure Intensifier

ABSTRACT
In high pressure metal hydro-forming fluid pressure commonly exceeds 20000 Psi/1379 bar. This high intensity of pressure cannot be achieved by a pump directly. It can be provided by introducing a hydraulic pressure intensifier (HPI) between pump and the machine.
In this project a pressure intensifying machine has been designed and constructed. Such a machine is constructed mechanically by connecting two pistons each working in a separate cylinder of different diameters. The design of the pressure intensifier is based on diameter ratio of piston 2.5 and maximum pressure at inlet allowed to 5bar. Maximum input and out pressure has been controlled by a one way spring loaded non- returnable valve. This device was designed for intensifying the hydrostatic pressure equivalent to height of three-storied building. But its performance was tested by using a 0.85 Hp centrifugal pump by regulating its discharge through a by-pass line and input water pressure to the intensifier was varied. In performance test it was observed that maximum water pressure at outlet is 11.2 bar for the input pressure of 2.5 bar. Maximum intensify pressure had found 4.93 times of the input pressure and efficiency achieved is 78.88 %.

Keywords: Pressure Intensifier, Metal Hydro-forming, Hydrostatic Pressure, Centrifugal Pump

1. Introduction

An intensifier heightens the intensity of the meaning of an item. A hydraulic intensifier is a hydraulic machine for transforming hydraulic power at low pressure into a reduced volume at higher pressure [1]. It increases the intensity of pressure of the liquid by utilizing the energy of a larger quantity of liquid at low pressure. Such a machine is constructed mechanically by connecting two pistons, each working in a separate cylinder of different diameter. This concept is developed from Pascal's law for incompressible fluid. If the diameters of the pistons are different, the hydraulic pressure in each cylinder will vary with the area ratio of the pistons, the smaller piston giving rise to higher pressure intensity than the larger piston pressure intensity.

The increase in the intensity of pressure is generally required when the liquid supplied by the pump does not possess the required intensity of pressure [2]. The hydraulic intensifier is very important in the case of hydraulic machines, mainly hydraulic presses, which require water or hydraulic fluid at a very high pressure which cannot be obtained from the main supply directly**.** High pressure metal hydro-forming requires 20,000 psi or 1379 bar [3]. Definitely this pressure will require a massive construction of pump. But if there is a HPI, it is possible to raise the pressure by using a reasonable size of pump.

A machine which has come into general *use* very rapidly in the last few years is the high-speed forging press for casting and forming heavy and complicated shapes. The next broad step after the direct pump-driven press was the *hydraulic intensifier* which made it possible to raise the pressure which cannot be achieved directly by pumping action. To press two metals sheet adjacently and to lifting heavy load, as for example, bridge slab, it requires a device which is capable of heavy load carrying capacity and smooth operation. Again, it is hydraulic jack which possesses the capabilities of smooth operation and heavy load carrying behavior. But for its proper functioning it is necessary to supply the compressed fluid at high pressure and this can be done by using a HPI. Hydraulic intensifier is used in constructing water cutting jet machine. It is also used in mining and construction firms [4].

The objectives of the present work is to design and construct a automatic controlled reciprocating HPI which can maximize pressure 6.25 times the input pressure range of maximum 5 bar. In existing rotary type HPI critical intensification ratio is 2.5 and its efficiency is 45% [14].

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This mechanical device can be used in laboratories for testing bursting pressure of PVC pipe; it can also be used with Universal Testing Machine for testing high compressive and tensile strength. HPI can be used in Compressed Natural Gas (CNG) conversion station for converting natural gas into compressed liquid form. Using an intensifier in any mechanical circuit will reduce the cost of constructing pumping action. As a result it ensures a save of large amount of power which has a greater positive effect on personal economy as well as national economy. This type of HPI is only applicable where input pressure is not above 5 bar and output pressure requirements are within 11 bar. The celebrated mechanical engineer Harry Ricardo began his career by working in his grandfather, Alexander Randal's civil engineering practice [5]. At that time they were involved in the construction of bridges in India, which required hydraulic lifting, hoisting and riveting equipment. As the existing transport infrastructure was poor, all plant used on site needed to be lightweight and easily portable. Machines also needed to be connected to their hydraulic power source by flexible tubing, which limited their working pressure to around 500 psi. At this time, modern shipyard equipment was using pressures of up to 2000 psi. This high-pressure equipment was smaller and lighter than the bulkier low-pressure variety, a desirable feature for this construction work. Ricardo's innovation was to specify the use of portable hydraulic intensifiers for these tools, permitting the use of the improved high-pressure form, even where their supply was at low-pressure, through flexible hose [5].

2. THEORETICAL STUDY

HPI is a mechanical device which is used for increasing the intensity of pressure of the liquid by utilizing the larger quantity of liquid at low pressure. Often hydraulic machines such as press, etc., require liquid at high pressure which may not be directly available from a pump. It can, however, be provided by introducing an intensifier between the pump and machine. It consists of several kinds of mechanical and electrical equipments.

2.1 Classification

Basically there are only two types of hydraulic intensifier namely single action and double action intensifier [6]. These two principal types of hydraulic intensifier have been modified in so many ways as per requirements of industry. Some of them are described as follows:

Classification based on body construction of Hydraulic intensifier:

2.1.1 Tie-Rod Construction

This type of construction is most widely used in industry. ISI standard also generally refers to one of this type of construction. As all the components are only machined and assembled together and not welded. Hence planning manufacturing, quality control assembly and maintenance are more convenient than other types of construction. As long as tie-rods are used to hold the entire components together, special care is required to tighten them and safe-guard against loosening in operation. Figure 1 shows Tie-Rod Construction HPI.

2.1.2 Threaded Construction

This construction is similar to tie-rod construction, but more compact, stronger, and requires more accuracy and care in manufacturing and quality control. In this design, both ends are assembled with cylinder-tube by threading, as shown in following design. These are used for medium to heavy-duty operation, and widely used in earth-moving purpose. Figure 2 shows Threaded Construction HPI respectively.

2.1.3 Bolted Construction

This type of construction involves welding of flanges to cylinder tube, and bolting of end- cover to the welded flange. Similar to tie rod construction these are also designed and manufactured as standard hydraulic component and widely used in industry. Figure 3 shows Bolted Construction HPI.

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2.1.4 One Piece-Welded Cylinder

Similar to shock absorber, in this design the end-covers and cylinder tube are welded together. These are economical but cannot be repaired. These are used for low pressure agriculture machinery application. Figure 4 shows One Piece-Welded HPI.

2.1.5 Custom Build HPI

In this type of cylinder, various type of construction is mixed together to suit the requirement. One of the most widely used combinations is welded cap-end cover, bolted head-end cover with front tube flange mounting. In case of high capacity cylinder when it is steel cast or machined from solid steel forging, then end cover and front flange may be integral part of cylinder tube. Cylinder with this type of construction is widely used in hydraulic press. Figure 5 shows Custom Build HPI.

2.2 Main Parts

A hydraulic pressure intensifier consists of several kinds of mechanical and electrical components. There are two main parts in the hydraulic intensifiers to be noted [1]. These are Piston and Cylinder.

2.3 Working Principle of HPI

Figure 6 shows a HPI.

The working principle of HPI is described below [10]:

1. Initially valve 1 and 3 are opened and valve 2 and 4 are remain closed, which permits the supply of low pressure liquid into the small cylinder through valve 1 and exhaust of liquid from large cylinder through valve 3.
2. After fully discharge from large cylinder valve 3 and 1 remain closed, and when the position of the piston is at the bottom of the master cylinder then valve 2 is opened The low pressure liquid enters the master cylinder and presses the piston to the upward direction.
3. Due to area difference in the piston, high pressure intensity will be achieved in small area portion of the cylinder because pressure is inversely proportional to the area.
4. As a result, spring loaded control valve will open after achieving definite pressure intensity. After that it will allow discharging full-pressurized fluid and close again due to spring action.
5. Again valve 1 and 3 are opened to allow entry of liquid from low pressure reservoir and valve 2 and 4 are kept closed.

2.4 Mathematical Formulation

Figure 7 shows Free Body Diagram of Piston.

Let "A "and "a" be the external areas of the large and small end of the piston respectively and "p "and **P** respectively be the intensity of pressure at large and small ends. Now

Upward direction Force, F_1 = Pressure × Cross sectional Area

or, F_1 = p × A

Downward direction Force, F_2 = Pressure × Cross sectional Area

or, F_2 = P × a,

For equilibrium condition,

Total upward force = Total downward force

or, $F_1 = F_2$

or, P × a = p × A,

or, P = p × (A/a)

If diameter of the large and small ends of the piston be D and d,

then cross sectional area, $A = \pi D^2/4$

Small area, $a = \pi d^2/4$

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High pressure, P = p × $(D/d)^2$…(1)
Further, if L is the stroke length or lift of the piston then in one stroke of the piston,
Volume of water supplied to the cylinder, $Q_1 = A \times L$ … (2).
Volume of water supplied from the cylinder, $Q_2 = a \times L$ … (3).
Dividing equation (2) by (1) we get, $Q_1 / Q_2 = a / A$
or, $Q_2 = Q_1 \times (d/D)^2$ … (4).

3. DESIGN AND CONSTRUCTION

3.1 Design Assumption

- Working fluid is water
- Water head is equivalent to height of three-storied building, 30 feet = 9.144m
- Flow through pipe is completely turbulent
- Pipe is smooth
- Pipe diameter taken, d = 1 inch = 0.0254 m

- Piston material is Aluminum because it is light weight and non-corrosive
- Intensifier piston diameter ratio is 2.5
- Water is discharged to the atmospheric pressure
- Pipe is steel mirror-lined
- Gray Cast Iron was chosen as cylinder material for its high compressive strength
- Cylinder bursts only along longitudinal section because transverse stress is twice of the longitudinal stress
- Ultimate strength of the Cast Iron ASTME SAE 35Ksi = 241.316Mpa [13]
- Diameter of the valve piston is taken, 1 inch = 0.0254m
- Spring length is 0.038 m
- Minimum valve opening pressure is 0.561 $\times 10^6$Pa
- Factor of safety for piston design is 3[14]
- Factor safety for cylinder design is 8[14]
- Coefficient of discharge C_d = 0.6
- Discharge way from the valve 0.25 inch = 0.00635m

3.1.1 Available Pressure Calculation

Height of the building, Δh = 30 feet = 9.144 m
Density of water, ρ = 1000 Kg/m^3
Gravitational acceleration, g = 9.81 m/s^2
Hydrostatic pressure at inlet of the machine,
ΔP = ρ × g × Δh
or, ΔP = 1000 × 9.81 × 9.144
or , ΔP = 89.7Kpa
Let piston large side and small side diameters be D and d respectively.
If piston diameter ratio is taken as 2.5,

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then D/d = 2.5.
Output Pressure, $P_2 = P_1 \times (D/d)^2$
or, $P_2 = 89.7 \times 10^3 \times (2.5)^2 = 0.561$Mpa

3.1.2 Discharge Calculation

Figure 8 shows the View for Simple Arrangement HPI
Applying Bernoulli's equation between point 1and 2, we get

$$p_1/\gamma + V_1^2/2g + Z_1 = p_2/\gamma + V_2^2 + Z_2 + h_f \text{ .... (1)}$$

where, $p_1 = p_2 = 0$ (considering) and velocity, V_1=0
Now according to Darcy-Weisbach equation friction loss due to flow through pipe can be found as $h_f = 4flV^2/2gd$
So equation (1) becomes

$$Z_1 - Z_2 = V_2^2/2g + 4flV_2^2/2gd$$

Static head, $H = Z_1 - Z_2$
or, $H = V_2^2/2g(1+4fL/d)$
Let constant $S = (1+4fL/d)$
or, $V_2 = \sqrt{2gH/S}$ ...(2)
Consideration: Pipe is smooth & flow through pipe is completely turbulent.
Pipe diameter was taken d = 1 inch = 0.0254 m
Now From Moody's diagram for steel mirror- lined pipe,
friction factor, f =.028 for roughness of the pipe, $\varepsilon = 0.1mm$
Considering length of the pipe, L = 13m
So constant, $S = 1 + (4 \times 13 \times 0.028)/0.0254$
or, S = 58.33
Now static head, H = 30 feet = 9.144m
From equation (2) we get,

$$V_2 = (2 \times 9.81 \times 9.144)/58.33$$

or, V_2=1.753 m/s
Discharge to the pressure intensifier, $Q_1 = C_d \times A \times V_2$
Here $A = \pi d^2/4$
or, $A = \pi \times 0.0254^2/4$
or, A = $5.067 \times 10^{-4} m^2$
Hence, $Q_1 = 0.6 \times 5.067 \times 10^{-4} \times 1.75 = 5.32 \times 10^{-4}\ m^3/s$ = 532ml/s
Now discharge to machine, $Q_2 = (d/D)^2 \times Q_1$ [2]
or, $Q_2 = (1/2.5)^2 \times 5.32 \times 10^{-4}$
or, $Q_2 = 85.126 \times 10^{-6}$
or, Q_2= 85ml/s

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3.1.3 Design of Piston

Figure 9 shows Free Body Diagram of Piston.

Force on Piston top, F= Pressure × Cross sectional area

or, F = P×A

Now Area, $A = \pi D^2/4$

or, $A = \pi \times 0.0508^2/4$

or, A=2.02 × $10^{-3} m^3$

Pressure, P =0.561× 10^6 Pa

Force, F=1137.05158 N.

For Aluminum compressive strength, σ_c = 470Mpa [12].

Load on piston is repeated one-directional and gradual.

Hence factor of safety is N = 3[11].

For design criteria, $\sigma_c = F/A \times$ N

or, $A = F \times N / \sigma_c$

or, A = 7.26× $10^{-6} m^2$,

Again piston rod area, A = $\pi d^2/4$

Hence, $\pi d^2 / 4$ = 7.26× 10^{-6}.

or, d = 3.04mm

Hence diameter of the piston rod required, d = 3.04 mm. Finally for construction, diameter of piston rod was taken to be 20mm.

3.1.4 Design of Cylinder

Figure 10 shows Free Body Diagram of Cylinder

Ultimate strength cylinder material, σ_t = 241.316Mpa.

For large diameter portion of the cylinder

Diameter, D = 121mm = 0.121m

Pressure in the large portion, P = 89.7×10^3 Pa.

Length of the large portion the cylinder, L = 118mm

Factor of safety, N = 8

Thickness of cylinder wall is t_1.

Now bursting force, F_1= Pressure × Projection area

or, F_1= Pressure × Diameter × Length

or, F_1= P×D×L

Again, resisting force, R_1= Stress × Area

or, $R_1 = \sigma_t \times t_1 \times L$

According to design criteria

Resisting force = Bursting force × Factor of safety

or , $R_1 = F_1 \times$ N

or, $\sigma_t \times t_1 \times L$ = 2 × P × D × L × N

or, $t_1 = 2 \times P \times D \times N / \sigma_t$

or, $t_1 = (2 \times 89.7 \times 10^3 \times 0.121 \times 8)/(241.316 \times 10^6)$

or, t_1= 0.72mm

Hence cylinder wall minimum thickness required is 0.72mm.
For construction, cylinder wall thickness was taken 5mm.

For small diameter portion of the cylinder
Diameter, d = 50.08mm = 0.058m
Pressure, P_1 = 0.561 × 10^6 Pa
Length of the small section L = 118mm.
Let cylinder wall thickness be t.
Now according to design criteria
Resisting force = bursting force × factor safety
or, R = F×N
or, $\sigma_t \times t \times L = 2 \times P_1 \times d \times L \times N$
or, $t = 2 \times P_1 \times d \times N / \sigma_t$
or, $t = (2 \times 0.561 \times 10^6 \times 0.058 \times 8)/(241.316 \times 10^6)$
or, t = 1.88 mm
or, t = 2 mm (approximately)
So cylinder wall minimum thickness must not be less than 2 mm
Finally for construction, cylinder wall thickness was taken **5** mm

3.1.5 Design of Valve
Figure 11 (a) and Figure 11 (b) show Nomenclature of One Way Spring loaded Non- Returnable Valve and Free Body of Valve Piston respectively.
Force acting in valve piston, F = Pressure difference × cross sectional area
or, F = (P - P_1) × $\pi D^2/4$
or, F = (0.561 × 10^6 - 101325) × $\pi \times 0.0254^2/4$
or, F = 232.92 N
Before compression, length of the spring is x.
After compression, length of the spring is x_1.

Displacement of the piston = (x - x_1)
Force exerted on the piston, F = spring constant × Piston displacement
or, F = K × (x - x_1)
or, $K = F/(x - x_1)$
or, $K = 232.92/0.006$
or, K = 38.82 KN/m
Finally for construction, valve spring constant was taken to be 32.5 KN/m

3.1.6 Design of Electrical Circuit
An electrical circuit is necessary for controlling the valve operation of the HPI. Main purpose of this circuit is to control the consecutive valve action of the solenoid valve [7]. An electrical circuit was designed for simultaneous valve action. When valve **2** is open, valve **1** and **3** must be kept closed and vice-versa. At TDC, valve V1 is open, and then piston starts to move from TDC to BDC. This piston position is sensed by a limit switch sw2 [8]. According to the signal of limit switch sw2, valve V2 will open which causes valve V1 and

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V3 to remain closed [9]. As a result, piston starts to move in reverse direction like BDC to TDC. This movement of the piston will increase the pressure of the fluid at smaller cross-sectional area of the cylinder. Valve 4, which open according to the predefined range of pressure intensity starts to supply fluid to the machine at high pressure intensity. At the same time small piston position is sensed by limit switch sw1. According to its signal, valve V1and V3 is opened and Valve V2 is closed. As the same sequence piston again starts to move from TDC to BDC. This sequential valve action creates a to and fro motion of the piston.
Figures 12 (a) and 12 (b) show Electrical Circuit Diagram and Layout of HPI respectively.

3.2 Construction

A HPI is an assembly of several components like Cylinder, Piston, Solenoid valve, Limit Switch and a one way spring loaded non-returnable valve. A construction of HPI is referring to construction of each component and assembling them properly. First of all cylinder construction was considered and then piston construction. For sensing the position of piston the location of limit switch was identified after constructing both piston and cylinder. After that limit switch and solenoid valve was connected with the circuit board. Then input water line for two solenoid valves was shorted together with a pipe which was connected with supply water line. Two Pressure gauges were installed for measuring the input and output pressure of the intensifier. One was placed at the beginning of the supply water line and another one at the position of the spring loaded one way non-returnable valve.
Figure 13 shows 3-D View of HPI Cylinder
Construction of hydraulic pressure intensifier includes

I. Construction of Cylinder
II. Construction of Piston
III. Construction of One way spring loaded non returnable valve
IV. Assembly of fittings and pipes

3.2.1 Construction of Cylinder

Cylinder construction consists of several steps like pattern making, casting and machining for getting the desired dimension. Cylinder was constructed by Cast Iron material. After machining the cylinder its dimension was kept at 5mm wall thickness. To reduce the machining complexity both small and large diameter portion were of same wall thickness. To connect the valve and pipe line, the upper and lower end of the cylinder was threaded. At the bottom of the cylinder there are two holes for preventing the piston jam due to air being trapped.
Figure 14 shows Cylinder with Dimension

3.2.2 Construction of Piston

Construction of piston also consists of several steps like cylinder casting. Piston was made by Aluminum. Before casting the piston a pattern was made by providing 3mm machining allowance. After casting the piston was machined in a CNC lathe machine. After that 3mm piston ring slot was cut on the both small and large surface of the piston.
Figure 15 shows Piston with Dimension

3.2.3 Spring Loaded Valve Construction

For constructing valve at first a 1 inch diameter 5 inch length seamless pipe was taken. Both ends of the pipe were externally threaded 0.5 inch. Than a 1 inch mild steel solid bar was machined to make it to the piston with piston rod form. Then a spring was made with Vn-Cr alloy having a spring constant of 32.5kN/m. After that spring, piston and seamless pipe was assembled. At the end two holes of 0.25 inch was made on the pipe for connecting a pressure gauge and output discharge line. Finally valve was connected with the output discharge line of the cylinder.
Figure 16 shows Nomenclature of One Way Spring Loaded Non- Returnable Valve

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4.1 Performance Test

Test was performed by using a 0.85Hp pump and observed values found are as shown in Table 1.
Figures 17 (a) and 17 (b) show Variation of Output Pressure with Input Pressure and Experimental Set-up respectively.

4.2 Discussion

A HPI has been designed which is capable of intensifying pressure 6.25 times of input pressure value within limit of maximum pressure input of 5 bar. An electrical circuit has been designed which can generate signal sequentially by sensing the piston position which allows solenoid valve to open one after another. This circuit makes the HPI automated in operation. This mechanical device can be used in laboratories for testing bursting pressure of PVC pipe; it can also be used with Universal Testing Machine for testing high compressive and tensile strength. It has a huge application in work holding, forklifts, injection molding, subsea ROV, hydraulic and demolition tools [15]. HPI can also be used in CNG conversion station for converting natural gas into compressed liquid form. Using an intensifier in any mechanical circuit will reduce the cost of constructing pumping action. As a result it ensures a save of large amount of power which has a greater positive effect on personal economy as well as national economy.

4.3 CONCLUSION

This HPI was designed to intensify the pressure 6.25 times than input pressure value within a limit of 5bar maximum. But on the performance test it was observed that maximum pressure at outlet was 11.2 bars for the input pressure value 2.5bar and maximum pressure ratio is 4.93 times than input pressure. Its overall efficiency found is 78.88% which is better than other types of construction. Main feature of this machine is its automatic valve control system. Its efficiency cannot be achieved 100% due to frictional loss in piston and cylinder. In analyzing graph it has been found that HPI is working much better efficiency at 1.5 bar input pressure and output pressure is maximized at almost 5 times to input value. In MP-T, MP-C, MP-F series pressure intensifier maximum pressure is up to 2000 bar [15]. But their operation and performance is different from this construction. The present design is automated controlled and unique in nature and performance.

5. TABLES AND FIGURES

Table 1 Performance Test with a 0.85Hp Pump

No. of obs.	Input water pressure (bar)	Output water pressure (bar) gauge Test-1	Output water pressure (bar) gauge Test-2	Output water pressure (bar) gauge Test-3	Average water pressure (bar) gauge	Average Intensified Times	Efficiency
1	0.5	2.3	2.4	2.3	2.33	4.66	74.56 %
2	1.0	4.7	4.9	4.8	4.8	4.88	78.08 %
3	1.5	7.5	7.4	7.3	7.4	4.93	78.88 %
4	2.0	8.9	9.1	8.7	8.8	4.55	72.80 %
5	2.5	10.9	11.2	11.2	11.13	4.45	71.20 %

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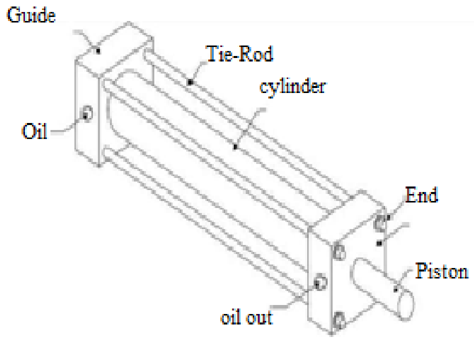

Fig.1. Tie-Rod Construction HPI

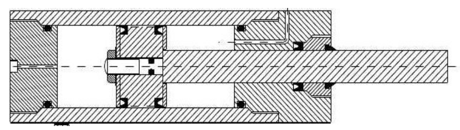

Fig.2. Threaded Construction HPI

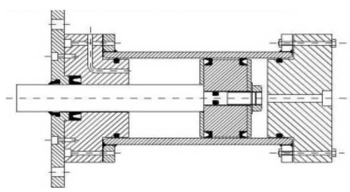

Fig.3. Bolted Construction HPI

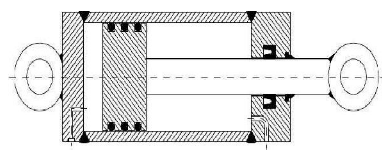

Fig.4. One Piece-Welded HPI

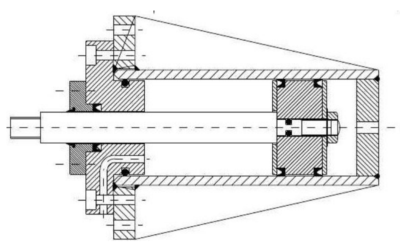

Fig.5. Custom Build HPI

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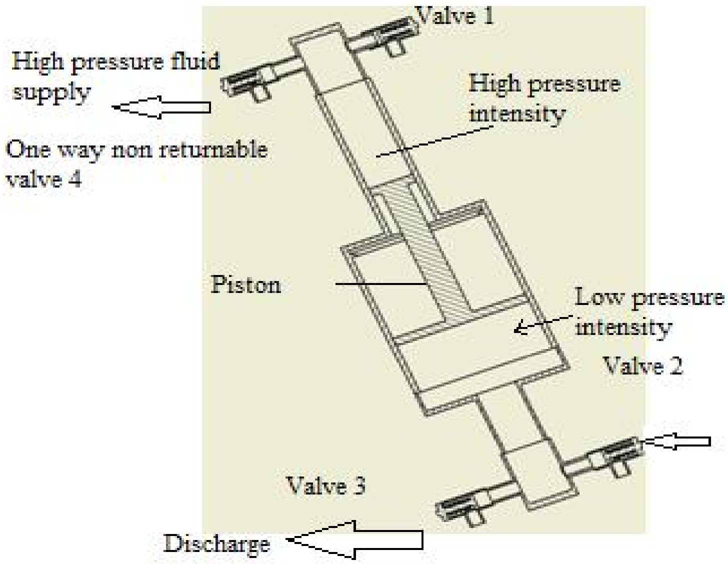

Fig.6. HPI

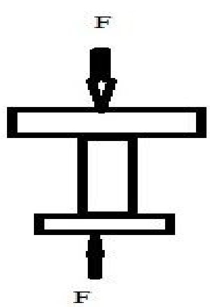

Fig.7. Free Body Diagram of Piston

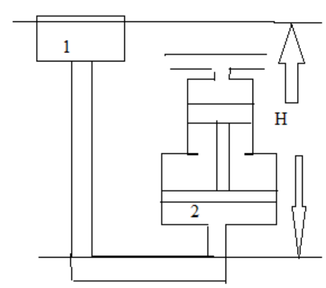

Fig.8. View for Simple Arrangement HPI

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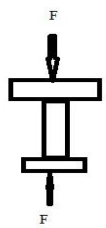

Fig.9. Free Body diagram of Piston

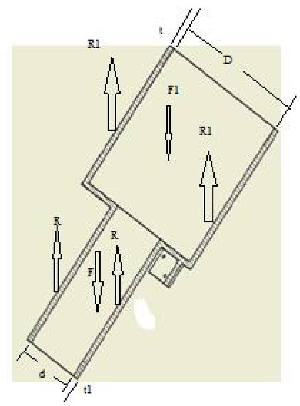

Fig. 10. Free Body Diagram of Cylinder

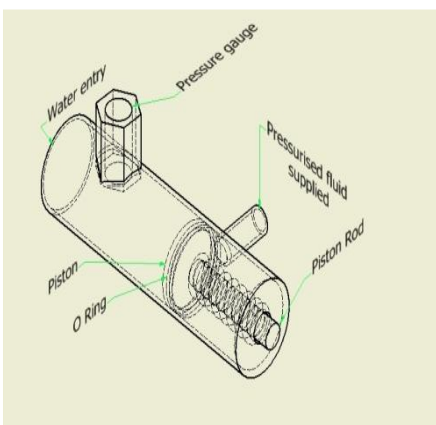

Fig.11 (a) Nomenclature of One Way Spring loaded Non -Returnable Valve

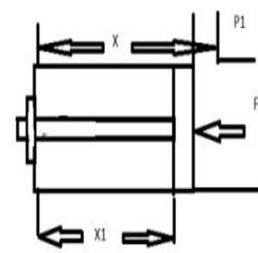

Fig.11 (b) Free body of Valve Piston

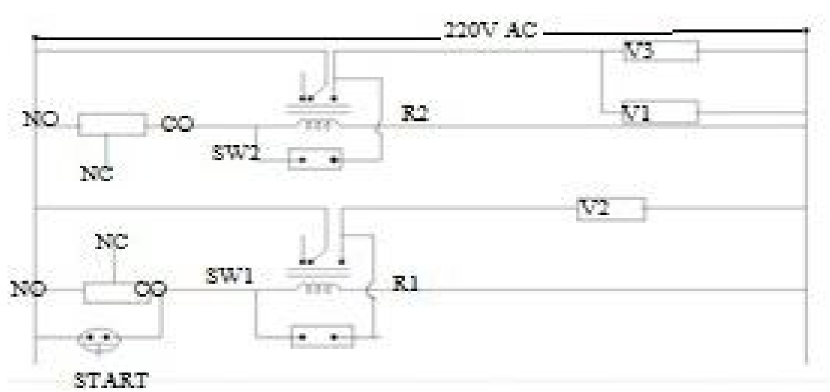

Fig.12 (a) Electrical Circuit Diagram

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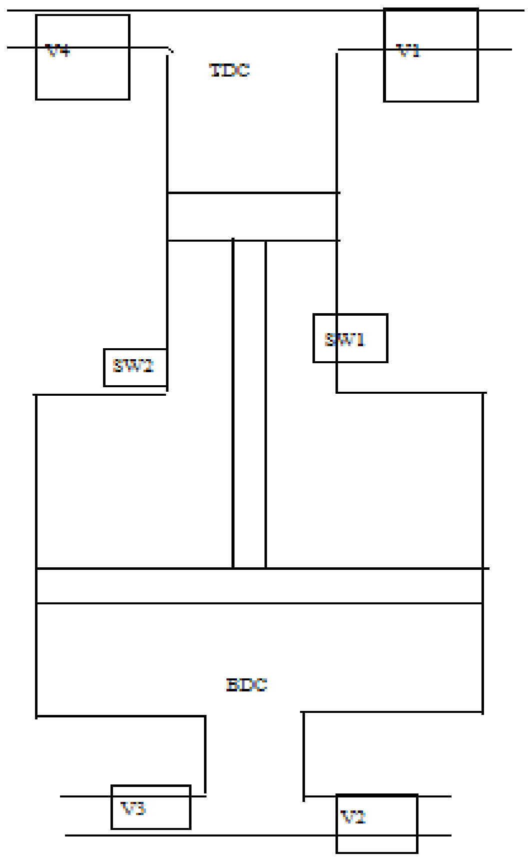

Fig. 12 (b) Layout of HPI

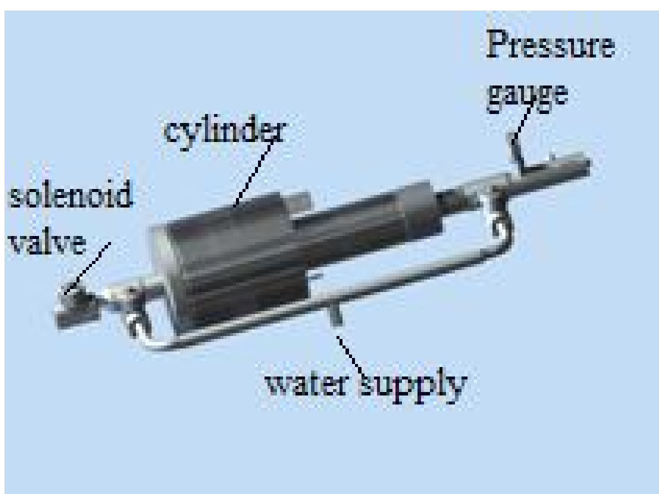

Fig.13. 3-D View of HPI Cylinder

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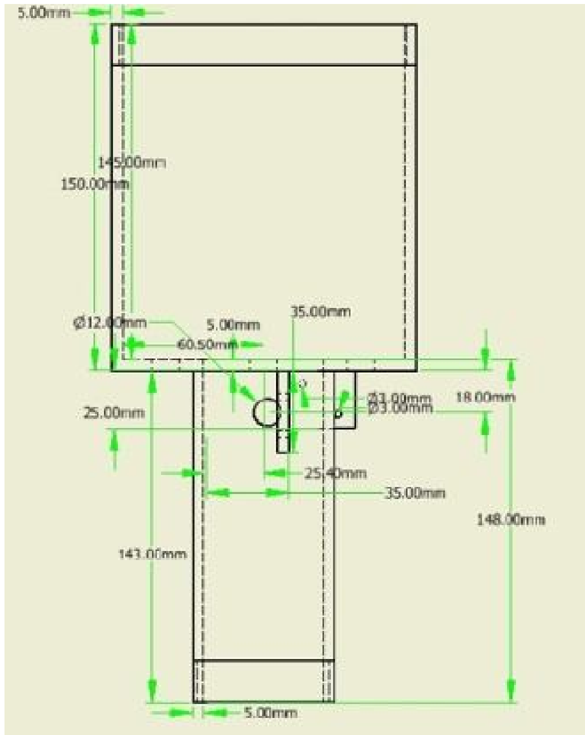

Fig.14. Cylinder with Dimension

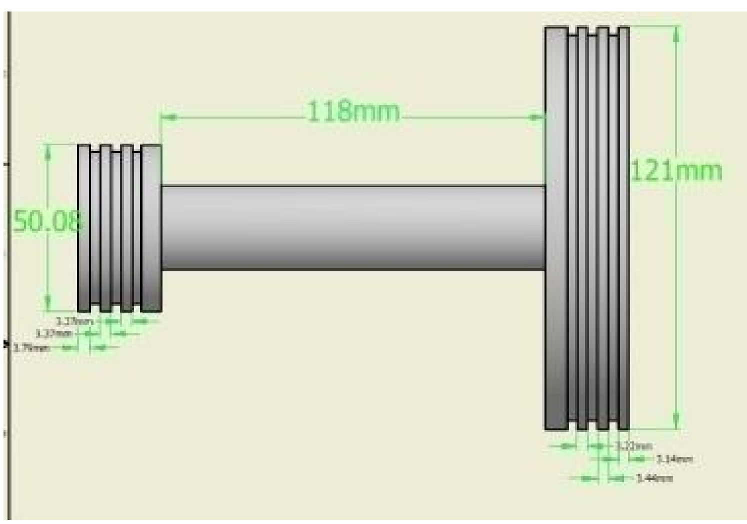

Fig.15. Piston with Dimension

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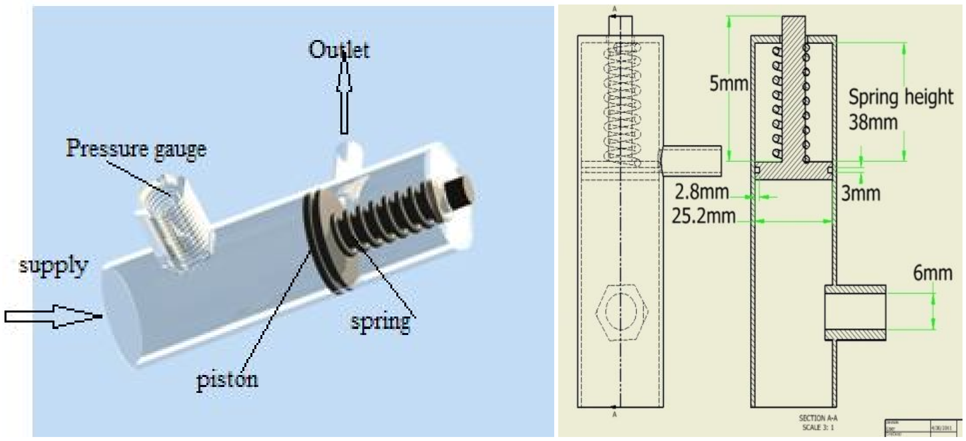

Fig.16. Nomenclature of One Way Spring Loaded Non-Returnable Valve

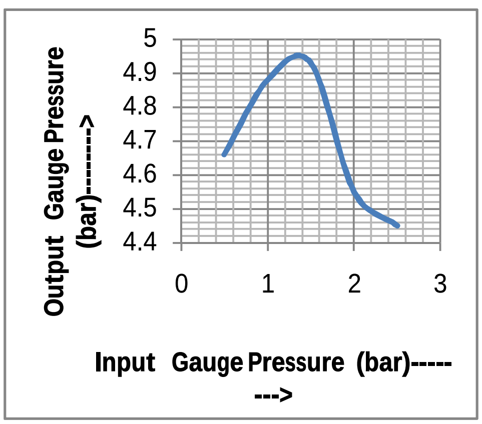

Fig.17 (a) Variation of Output Pressure with Input Pressure

Fig. 17(b) Experimental Set-up

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