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Development of A Pressure Sensing Module and Flow Control System For A Prototype Pump Test Bed

Md. Rafsan Nahian[1*],Mohammad Sakalin Zaman[2],Md. Nurul Islam[3],Md. Rokunuzzaman[4]
[1] School of Engineering, University of Guelph, Guelph, Ontario, Canada N1G 2W1
[2, 3, 4] Department of Mechanical Engineering, Rajshahi University of Engineering & Technology, Rajshahi, Bangladesh - 6204
e-mail: [*1]**samsrafsan@gmail.com**, [2]zamansakalin@gmail.com, [3]nurul50.ruet@gmailcom, [4]rzaman_me.ruet@yahoo.com

Abstrak

Pompa test bed sangat penting untuk memastikan berfungsinya pompa. Namun, test bed pompa konvensional memiliki beberapa keterbatasan selama mengukur sifat aliran dan memvariasikan kecepatan pompa. Akibatnya, tempat tidur uji pompa digital dapat menjadi solusi untuk mengukur sifat aliran lebih akurat. Artikel ini menjelaskan proses konstruksi modul penginderaan tekanan untuk tempat tidur uji pompa digital dan kontrol aliran dengan memvariasikan kecepatan pompa DC prototipe. Sebuah modul penginderaan tekanan dan sistem kontrol aliran dibangun dalam penelitian ini untuk mengembangkan test bed pompa prototipe serta mengubah kecepatan pompa sentrifugal. Ditemukan bahwa dengan menggunakan sensor tekanan piezoelektrik dalam pipa pengiriman, kesalahan penginderaan tekanan hanya 6,3% pada kecepatan yang dirancang pompa dan dapat diminimalkan dengan kalibrasi sensor, memperbaiki masalah kebocoran dan meningkatkan tekanan aliran. Berbagai macam kecepatan pompa juga dapat diperoleh dengan menerapkan prinsip modulasi lebar pulsa tanpa menghentikan catu daya.

Kata kunci— *sensor tekanan, kontrol aliran, mikrokontroler, modulasi lebar pulsa, pompa test bed*

Abstract

Pump test bed is essential to ensure the proper functioning of a pump. However, a conventional pump test bed has some limitations during measuring the flow properties and variating the pump speed. As a result, a digital pump test bed can be a solution for measuring the flow properties more accurately. This article describes the construction process of a pressure sensing module for a digitalized pump test bed and control of flow by varying the speed of a prototype DC pump. A pressure sensing module and flow control system are constructed in this study to develop a prototype pump test bed as well as change the speed of the centrifugal pump. It is found that by using a piezoelectric pressure sensor in delivery pipe, the pressure sensing error is only 6.3% at the designed speed of pump and can be minimized by calibrating the sensor, fixing the leakage problem and increasing the pressure of flow. A wide variety of pump speeds can also be obtained by applying pulse width modulation principle without stopping the power supply.

Keywords— *pressure sensor; flow control; microcontroller; pulse width modulation; pump test bed.*

1. INTRODUCTION

Pumping systems are used widely. They provide domestic services, agricultural services, municipal water services and industrial services for processing, chemical,

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pharmaceutical, and mechanical industries [1]. Centrifugal pumps are turbo machines which convert mechanical energy into hydraulic energy by imposing a centrifugal force on the liquid. The liquid enters through a suction connection concentric with the axis of an impeller. Liquid flows outward in the spaces between the vanes and leaves the impeller at a considerably greater velocity than the entrance velocity. Input energy is applied to the fluid through the impeller. The impeller is directly connected through a drive shaft to an electric motor [2].

A pump test bed is an environment used to verify the correctness or soundness of design a pump. When developing pumps and testing the finished products, it is essential to experiment on a pump test facility in. In order to measure and assess the operating behavior of pumps, a number of characteristic quantities must be measured or calculated from the measured values. This ensures that the following quantities can be determined during the performance test: pressure, flow rate, head, torque, power input, speed, drive rating and operating temperatures [3]. Pumping systems represent complicated electromechanical equipment including mainly the centrifugal pumps, variable speed drives, pipelines, and various types of sensors [4-5]. They are among the most significant power consumers and commonly work with variable loads those characteristics depend on many factors, such as pipe length and material, a number of pumps, valves, drives, etc. [6]. These systems increase the kinetic energy of the liquid running through the pump and thus create an appropriate pressure at the pump outlet. During the pump system study, the main focus is on the head, pressure, and flow control systems [7]. Different methods and approaches are used to explore pumping systems. Among the most efficient ways, the prototype models are presented [8-9]. A pump-based compensation method is proposed to improve the dynamic performance under different working conditions. A performance indicator is defined to evaluate the dynamic behavior under the load condition with wide variation range. The results indicated that the proposed compensator achieves better dynamic improvement than the traditional system [10]. These types of models are very useful tools for the pumping station testing and tuning. They allow replicating the processes that take place in real systems. The control systems developed with the help of the prototype systems can be applied for the process optimization and for the real-time management without expensive hardware prototyping. The construction of this prototype also appeared fundamental for a complete experimental validation [11].

Pressure, discharge, impeller speed, power, head are the key parameters for detecting and judging faults of a pump in pump test bed. But traditional measurement methods have many deficiencies [12]. Most of the time analog manometer or mechanical gauges are used to measure the head and pressure developed by pump. These instruments don't have much capability to determine the flow properties properly. Sometimes there are backlash errors which are occurred during taking the value in analog system. Besides to change the impeller speed (rpm) of pump the supply voltage is needed to be changed which is done by stopping the supply of power and then connecting to the desired voltage that will be supplied to the shaft of pump for a constant rpm. So, speed variations of pump can't be done without stopping the supplied power which is a major problem in a pump test bed.

2. METHODS

The developed program for this system is uploaded to microcontroller. The entire system is administered and controlled with the aid of the microcontroller. The pressure sensor senses water pressure through delivery pipe and sends a signal to microcontroller. The motor speed of centrifugal pump is also controlled by the motor controller driver. However, the motor controller driver is controlled by microcontroller and gives power to the motor according to the given signal sent by microcontroller. The LCD display module is connected to a microcontroller which displays the pressure and speed of the pump in KPa and rpm respectively. The whole architecture of the system is given in Figure 1.

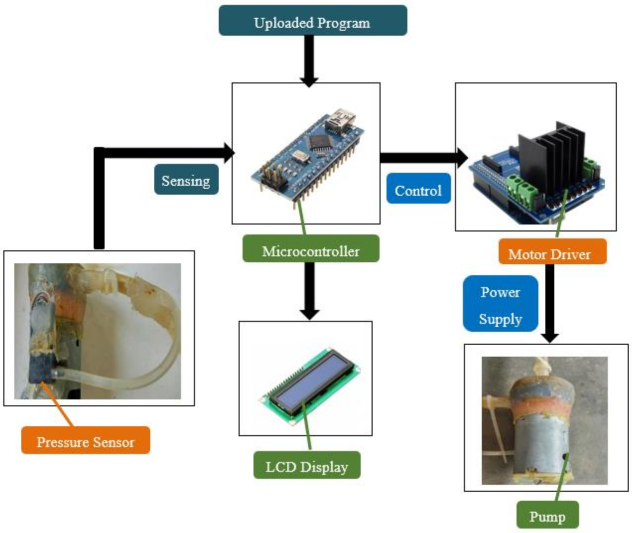

Figure 1 System architecture of pressure sensing module and flow control

For lifting water from a reservoir, a prototype DC pump is used. The supplied DC power run the microcontroller. Nylon 6 hose pipe is used as suction and delivery pipe, because its bending properties are suitable for the operation to be done and cost is low. As it is a prototype system, low range pressure sensors are suitable for this project. The piezoelectric pressure sensor is one kind of pressure sensor that can sense low range pressure more accurately. So, for sensing the pressure piezoelectric pressure sensor (MPXV5050GP) has been used in this system which is available in the market. The variations of pressure can be done by changing the speed of pump impeller, opening and closing the gate valve and changing the total head of the system. In this study, a control system for changing the impeller speed of pump and opening and closing of gate valve are developed for the variation of pressure. The speed of the pump impeller as well as shaft of motor depends on the supplied power to the shaft of motor. The voltage which will be supplied by the motor controller driver to the shaft of motor is controlled by microcontroller which can develop pulse width modulation (PWM) process. The average value of supplied voltage and current to the shaft of motor is controlled by turning the switch between supply and motor on and off at a fast rate. By following this method, the speed of motor shaft as well the pressure of flow can be varied easily without stopping the power of the system. The specifications of the system are given in Table 1.

Table 1 Specifications of the system

Item	Specification
Pump	DC 7 W
Pressure sensor	Piezoelectric (0-50 KPa)
Microcontroller	Arduino Nano V3.0
Code development	Arduino IDE Platform
Pipe	Nylon 6 hose pipe

2.1 Calculation of pipe diameter

Pressure sensor measuring capacity, P = (0-50) KPa = (0-5.09) m head of water

Current flow to the motor, A = 400 mA = 0.4 A

Maximum voltage that can be supplied to the motor, V = 18 V

So, the maximum power that can be given by motor driver, P = $(18\times 0.4) = 7.2$ W

For 10% efficiency (small pump), the output power of pump = $(7.2 \times 0.1) = 0.72$ W

Now, Power P = γQH

So, Q= $\frac{P}{\gamma H} = \frac{0.72}{9810 \times 5.09}$ = 1.45 ×10^{-5} m^3/s

But, Discharge, Q = AV

For unit velocity, Cross sectional area of pipe, A = $\frac{Q}{V} = \frac{1.45 \times 10^{-5}}{1}$ = 1.45 ×10^{-5} m^2

Now, A = $\frac{\pi}{4} \times D^2$

So, Diameter, D = $\sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4 \times 1.45 \times 10^{-5}}{3.1416}}$ = 4.3 ×10^{-3} m= 4.3 mm = 0.17 inch

So, the pipe should have diameter more than 0.17 inch. The closest pipe diameter of designed parameter available in the market is 0.25 inch.

2.2 Experimental setup

This is the total experimental setup of digitalized pump test bed. However, this setup has two parts.

A. Pressure sensing module.

B. Flow control system.

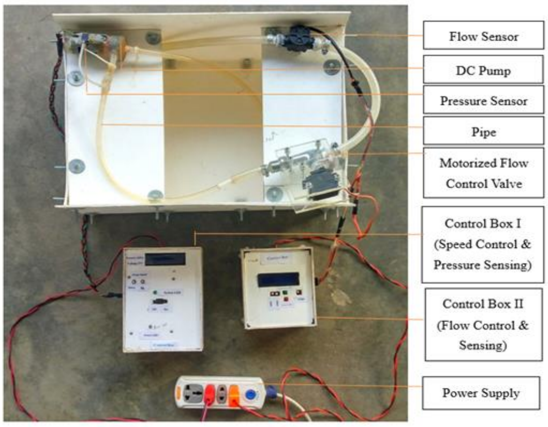

Figure 2 Experimental setup of a prototype pump test bed

When the control box I is switched on, DC pump is started. Water is flowed through the pressure sensor and pressure and voltage is displayed on the LCD screen. The pressure can be varied by changing the speed of DC pump. After passing through the pressure sensor water is entered into a motorized flow control valve which is controlled by Control box II. Flow sensor reads the value and it is displayed on Control box II. Water is finally discharged into the reservoir.

There are different sub systems of this project. These are:

A. Sensing system

B. Controlling system

C.

2.2.1 Mechanical systemSensing System

The sensing system includes pressure sensor, pin, connecting pipe etc. Figure 3. shows different components of the sensing systems.

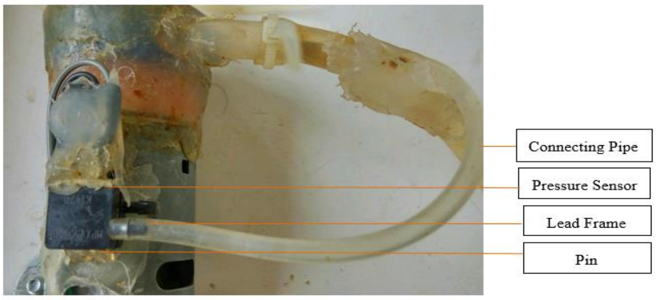

Figure 3 Pressure sensing system

The MPXV5050 series piezo resistive transducer is a state-of-the-art monolithic silicon pressure sensor designed for a wide range of applications, but particularly those employing a microcontroller or microprocessor with A/D inputs. This patented, single element transducer combines advanced micromachining techniques, thin-film metallization, and bipolar processing to provide an accurate, high level analog output signal that is proportional to the applied pressure [13]. The sensing signal is only used to measure the pressure of flow through pipe. For determining positive pressure Pin (1, 2, 3 and 4) are used and for negative pressure Pin (5, 6, 7 and 8) are used.

2.2.2 Controlling system

The controlling system includes microcontroller, motor controller driver, display module, rectifier, switch etc. Figure 4 shows the different components of controlling system.

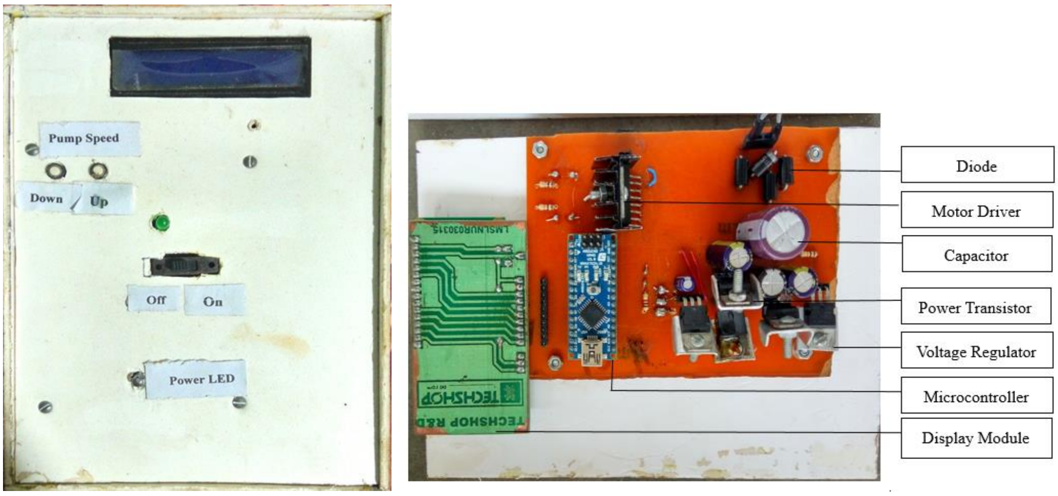

Figure 4 Control panel (Outside view- left side and inside view- right side)

2.2.2.1 Microcontroller

Arduino Nano V3.0 microcontroller has been used in this system. The Arduino Nano board is based on the ATmega328. The microcontroller consists of 14 input and output analog and digital pins, 6 analog inputs and remaining digital inputs. In this project PWM pins are vastly used. It has clock speed (20 MHz) higher than ATmega8, ATmega16 and ATmega32.This microcontroller has been chosen for its high electrically erasable programmable ROM (EEPROM) which is 1024B. It also requires the lowest supply voltage (1.8V) comparable to ATmega8, ATmega16 and ATmega32. The Arduino Nano is a small, complete, and breadboard-friendly board which works with a mini-B USB cable instead of a standard one [14].

Digital inputs can be either on state or in off state. Arduino Nano microcontroller also consists of 14 digital input pins. These ports receive the input and therefore the port can be used for both input and output process. The pin D3, D5, D6, D9, D10 and D12 have been used for pulse width modulation principle. Besides TX, RX and pin no 16, 24, 27, 28, 29 and 30 have been used for other applications.

2.2.2.2 *Motor controller driver*

Motor driver is used to control the flow of fluid by varying the impeller speed of pump. L298 motor driver controller has been used in this system. The L298 is an integrated monolithic circuit in a 15-lead multi watt. It is a high voltage, high current dual full-bridge driver designed to accept standard TTL logic levels and drive inductive loads such as relays, solenoids, DC and stepping motors. Two enable inputs are provided to enable or disable the device independently of the input signals. The emitters of the lower transistors of each bridge are connected together and the corresponding external terminal can be used for the connection of an external sensing resistor. An additional supply input is provided so that the logic works at a lower voltage [15]. L298 motor controller driver has 16 pins. Among them pin 1 to pin 9 have been used in this system.

2.2.2.3 *Circuit diagram of controlling system*

The circuit diagram of the controlling system is given in Figure 5.

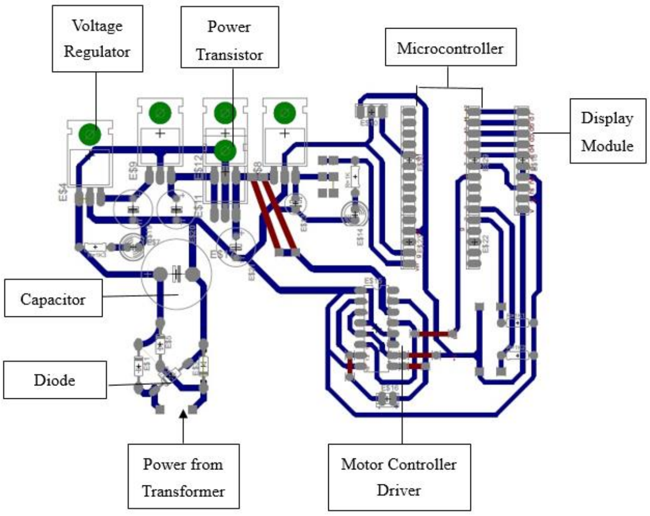

Figure 5 Circuit diagram of controlling system

When the system is plugged in with the main power socket and switch is turned on, 220V AC current comes to step-down transformer. It decreases the alternating current to 24 V. The system has a full bridge rectifier circuit which converts the alternating current to direct current. The current is passed to capacitor which stores the charge with a certain voltage level. Then the voltage is passed to voltage regulator and power transistor. Voltage regulator maintains a constant voltage of 18 V automatically. Transistors are composed of three parts a base, a collector, and an emitter. By sending varying levels of current from the base, the amount of current flowing through the gate from the collector may be regulated. In this way, a very small amount of current may be used to control a large amount of current, as in an amplifier. Voltage regulator supplies 18 V of voltage to motor driver and power transistor supplies 5 V of voltage to microcontroller. The power which will be transferred to the motor shaft from motor controller driver is controlled by the microcontroller through PWM method. Pulse width modulation (PWM) is a powerful technique for controlling analog circuits with a processor's digital outputs [16]. A microcontroller can only generate two levels on its output lines; high value is 5V and lower value is 0V. To generate any voltage between 0-5 volt outputs PWM is used. Microcontroller gives the signal of 0-5 V. Motor driver receives the signal and evolves it from 0 to 18 V. So, for increasing per unit voltage of the motor driver to run the pump, the microcontroller has to increase 0.2777 V signal.

2.2.3 Mechanical system

The mechanical system includes a centrifugal DC pump, suction pipe and delivery pipe. A centrifugal prototype DC pump is used in this project. Centrifugal pumps are mostly used for various types of pumping action. As this system is microcontroller based and pump motor is driven by the motor controller driver, a prototype DC pump of power 7 W has been used for this project. The different components of mechanical system are given in Figure 6.

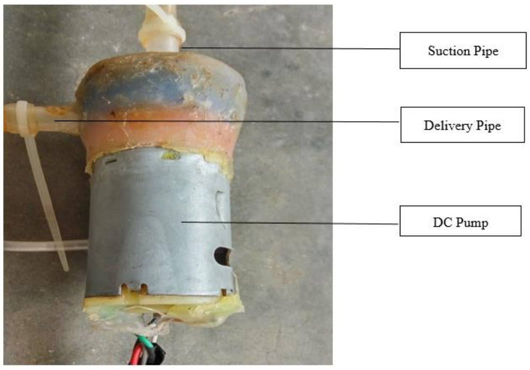

Figure 6 Mechanical system

3 RESULTS AND DISCUSSION

The experimental values are measured by the variation of pump speeds and gate valve openings at a constant height of 0.3 meter from the water level. 25%, 50%, 75% and 100% openings are maintained through motorized flow control valve. The experimental data for different operating conditions are given in Table 2.

Table 2 Experimental data

Gate valve position	Voltage (V)	Speed (rpm)	Pressure (KPa)	Discharge × 10^{-3} (m^3/s)
100% (full) opening	6	640	1.4	0.027
	8	760	2.7	0.032
	10	905	4.1	0.038
	12	1070	5.8	0.045
	14	1260	7.7	0.053
	15.8	1470	10.1	0.062
75% opening	6	640	2.3	0.022
	8	760	3.6	0.025
	10	905	5.4	0.029
	12	1070	7.6	0.035
	14	1260	10.2	0.042
	15.8	1470	13.2	0.051
50% opening	6	640	3.5	0.018
	8	760	5.3	0.021
	10	905	7.4	0.024
	12	1070	9.8	0.028
	14	1260	12.9	0.033
	15.8	1470	16.3	0.040
25% opening	6	640	4.9	0.016
	8	760	6.6	0.018
	10	905	9.4	0.020
	12	1070	12.3	0.023
	14	1260	16.0	0.027
	15.8	1470	20.1	0.032

3.1 Calculation of pressure sensing error

Experimental value of pressure:

At, 15.8 V (1470 rpm and 100% opening of gate valve) Experimental value of pressure= 10.1 KPa (gauge)

Theoretical value of pressure:

Here,
Z= 0.30 m
Length of pipe, L= 0.55 m

Area of pipe:
Pipe Diameter, D= $\frac{1}{4}$ inch = 0.635 cm= 0.00635 m.
So, Area of Pipe, A = $\frac{\pi}{4}\times D^2 = 3.167\times 10^{-5}$ m^2

Discharge:
Volume of Container = 1.5 Liter
Time required to fill up the container = 24 sec
So, discharge, Q= $\frac{1.5}{24}$ = 0.0625 liter/sec = 6.25×10^{-5} m^3/sec

Velocity:

Q= AV
So, V= $\frac{Q}{A}$ = 1.973 m/sec

Pressure measurement:

Static head:
Z= 0.30 m

Dynamic head:
$\frac{V^2}{2g} = \frac{1.973^2}{2\times 9.81}$ = 0.199 m

Frictional head:
Re= $\frac{\rho VD}{\mu} = \frac{1000\times 1.973\times 0.00635}{.000798}$ = 15700
[For 30°C, μ= $.798\times 10^{-3}$ Ns/ m^2]

So, the flow is turbulent.

For smooth pipe and Re < 100000 (Prandtl equation) [17]
$\frac{1}{\sqrt{f}} = 2.01 \log \left[\frac{Re\times\sqrt{f}}{2.51} \right]$

By this equation, f= 0.029
Frictional head, $h_f = \frac{flv^2}{2gd} = \frac{0.029\times 0.55\times 1.973^2}{2\times 9.81\times 0.00635}$ = 0.5 m

Bending head:

$H_b = \frac{Kv^2}{2g} = \frac{0.5\times 1.973^2}{2\times 9.81} = 0.099$ m

Now, Total pressure head, H_t = Static head+ Dynamic head+ Frictional head + Bending head

$H_t = \frac{P}{\rho g}$

So, $\frac{P}{\rho g}$ = 0.3+ 0.199+ 0.5+ 0.099 = 1.098 m

So, P = (1.098× 9.81× 1000) = 10777.96 Pa = 10.78 KPa

So, the theoretical pressure is 10.78 KPa (gauge)

Sensing error = $\frac{\text{Theoretical value} - \text{Experimental value}}{\text{Theoretical value}} = \frac{10.78 - 10.1}{10.78}$ = 0.063 = 6.3 %

As pump speed is controlled in this system, the performance can be evaluated according to main characteristics curve of pumps. The performance of pressure sensing module and DC pump at different operating conditions is given below.

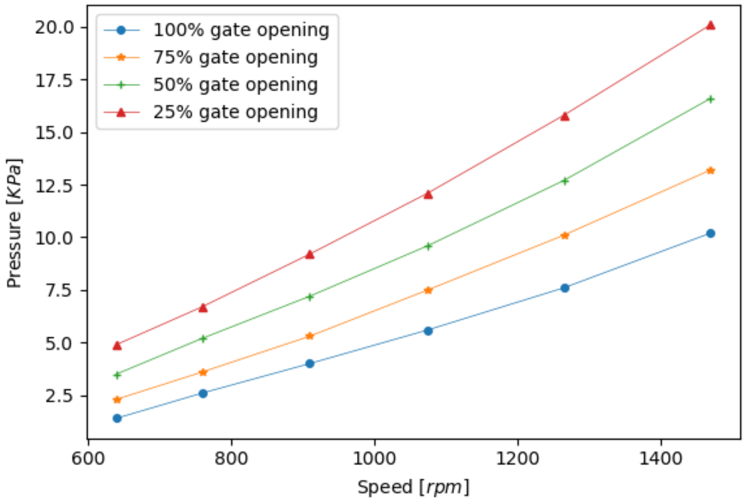

Figure 7 Variation of pressure in pipe with respect to pump speed and gate valve opening

The variation of pressures in delivery pipe with respect to pump speed are shown in Figure 7 for different position of gate valve. When the speed of pump is increased, the value of pressure is also increased. As the speed of pump impeller is increased, the pump delivers more water at higher voltage. As a result the pressure is higher at high voltage. For 100% opening of gate valve the pressure is lower than 75%, 50% and 25% opening of gate valve. On the other hand for 25% opening of gate valve the pressure is higher than 50%, 75% and 100% opening. This is because of the frictional head of water in the pipeline. For 25% opening of gate valve the friction is higher. The water is delivered slowly for a fixed speed than the other openings. As a result the pressure in the pipeline is got increased. But when the gate valve is full (100%) opened, there is less friction of flow to deliver water through the pipeline. As a result the pressure is minimum for full opening at a fixed speed of pump impeller. So, pressure is proportional to speed of pump and inversely proportional to the opening of gate valve.

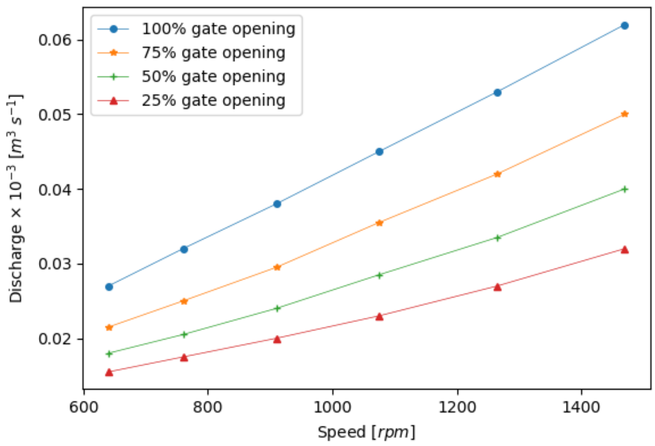

Figure 8 Variation of discharge with respect to pump speed and gate valve opening

The variation of discharges with respect to pump speed and gate valve opening are shown in Figure 8. When the supplied voltage is increased, the speed of the pump is also increased. As a result the pump delivers more water at higher speed. Besides, it also depends on the opening of gate valve. Discharge of the pump is maximum when the gate valve is fully opened. For a fixed speed at 100% opening of gate valve there is less restriction as well as less friction of water in the pipeline. More water is delivered through pipeline at full opening of gate valve. As a result the discharge is maximum for full opening of gate valve. But the 25% opening of gate valve the discharge is the lowest. This is because of the more restriction as well as more friction in the pipeline and the water is delivered slowly through the pipeline and needs more time to deliver a fixed amount of water. As a result the discharge is the lowest at 25% opening of gate valve. So, Discharge is proportional to the pump speed and opening of gate valve.

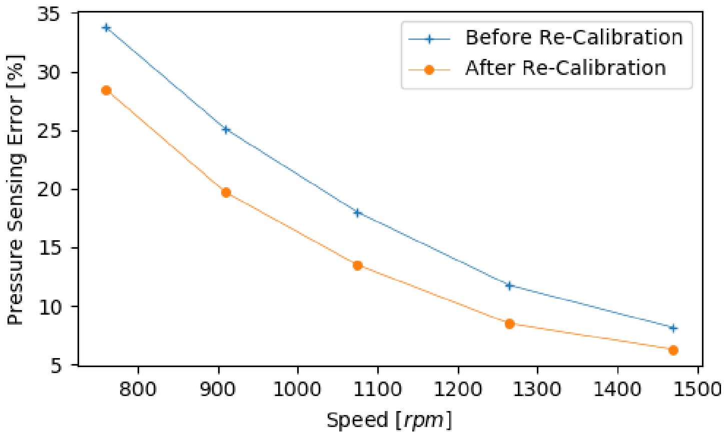

Figure 9 Graphical representation of pressure sensing error with respect to pump speed at full opening of gate valve

Figure 9 shows the graphical representation of pressure sensing error with respect to pump speed before and after re-calibration. When the speed is low, there is more error during sensing of pressure. But when the speed is increased there is less error of pressure sensing and at maximum speed of pump the errors are almost become constant. This is because of the leakage problem of the DC pump. When the speed is low there is less discharge of water and a great portion of the suction water is leaked out thorough the pump before sensing the delivery pressure of total supplied water. But when the speed becomes higher, there is more discharge of water and the portion of leakage through the pump is smaller compared to the total supplied water. That is why the pressure sensing error is less at maximum speed of pump.

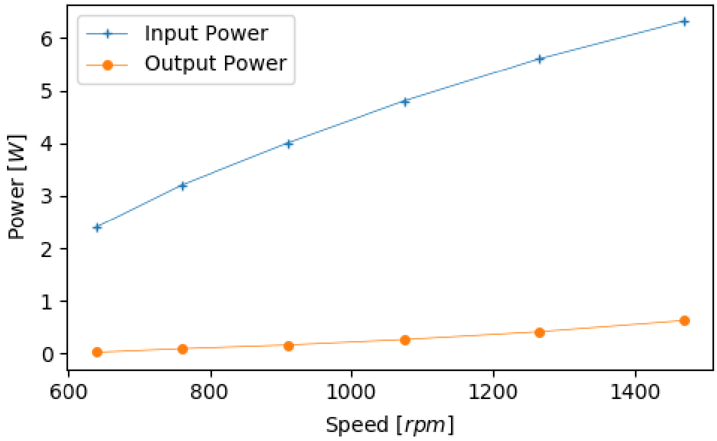

Figure 10 Variation of input power and output power with respect to pump speed

The variation of input and output power of pump with respect to pump speed are shown in Figure 10. For a constant supply of current of 400 mA, the input power is varied by the variation of supplied voltage. So, the input power is proportional to the supplied voltage as well as pump speed. For output power, the discharge and pressure head vary with respect to pump speed. As discharge and pressure head is almost proportional to the pump speed, the output power of pump also increases by increasing the pump speed.

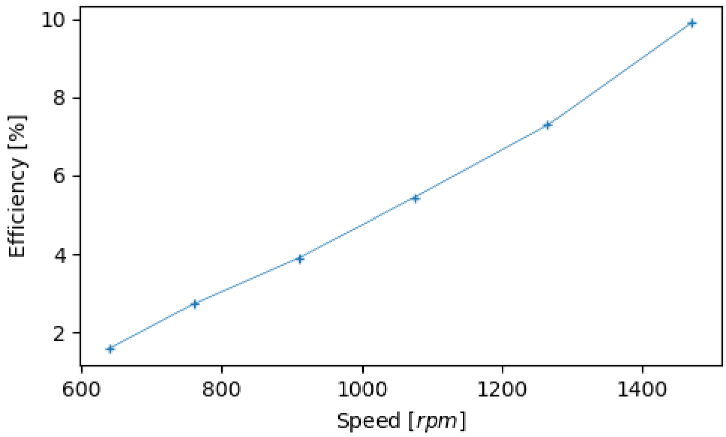

Figure 11 Variation of overall efficiency of pump with respect to speed

The variation of overall efficiency of pump with respect to the speed of pump impeller are given in Figure 11. So, the efficiency also varies by increasing and decreasing the speed. As the discharge and pressure head are increased by increasing the pump speed and there is less leakage of water compared to the total supplied water, the efficiency becomes maximum at maximum speed. But when the pump speed is low there is a great portion of leakage compared to the total supplied water and discharge is also minimum. That is why the efficiency of pump is less at minimum speed.

The sensing pressure and speed are shown in the LCD display. As the display is digital type, it changes the value randomly from time to time. For this reason there have occurred some errors during taking the value of pressure from LCD display. Besides the opening of gate is controlled manually. So they might not be fitted accurately to the desired positions. The discharge of water through the pump is determined by a stop watch and there are also some errors during taking the time to fill up a container having fixed volume. The pump has leakage problem. As a result the characteristics curves that have been drawn are not almost similar to the theoretical one.

4 Conclusion

In this work the main concern is to construct a pressure sensing module and change the speed of pump at wide variety of ranges which can be installed in the prototype pump test bed to develop a large model. The followings are the specific conclusions that could be drawn from the experimental results.

1. The delivery pressure is measured successfully by using a piezoelectric pressure sensor having an error only 6.3% at the designed speed of pump.
2. The pressure sensing error can be minimized by re-calibrating the pressure sensor, fixing the leakage problem of pump and increasing the pressure of flow.
3. By applying PWM principal wide variety of pump speeds have been achieved without stopping the power supply.

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