DESIGN AND CONSTRUCTION OF AN EDUCATIONAL PUMP BENCH WITH OPERATIONAL CONTROLS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE
OF
MASTER OF SCIENCE

IN

MECHANICAL ENGINEERING

DECEMBER 2004

Approval of the Graduate School of Natural and Applied Sciences

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ABSTRACT

DESIGN AND CONSTRUCTION OF AN EDUCATIONAL PUMP BENCH WITH OPERATIONAL CONTROLS

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December 2004, 159 pages

System characteristics of automated pumping systems may change due to wear, aging of piping, and accumulation of deposits in the system and/or due to configuration changes. Such changes might result in conflicts between the controlling algorithms and the actual system requirements for each particular case. The said mismatch between the actual physical system and the software controlling it, may result in inefficient operation of the pump which may even lead to total system failures (overpressurization of instrumentation and sensing elements etc.) due to temporary malfunctioning of the system components or permanent damages incurred by them during operating under unsuitable conditions.

It is intended in this study to design and construct an experimental automated pump bench with operational components (mechanical, electronical and instrumentation etc.), serving in a system introducing multiple geometric heads and its controlling and monitoring software in order to visualize effects of the above-mentioned cases for education and training purposes.

System characteristics data acquisition module (system test module) provides the means of recognizing new pump and system characteristics, provided that they were changed due to some reason (throttled valve, changed pump speed, changed flowrate or elevation of discharge etc.). Then the pump operation module enables users to make comparative judgments by observing the effects of the above-mentioned changes.

Above-mentioned testing sequence and monitoring of changing physical quantities were achieved by employing four *pressure transducers*, a *custom made DC motor operated -throttling valve with position feedback* which was designed and constructed specifically for this study and a *variable frequency drive (VFD)* which were all connected to a *custom made Main Control Circuit (MCC) Board*.

Keywords: Automated pumping system, educational pump setup, variable geometric head, throttling control, variable frequency drive, VFD, pump speed control.

ÖZ

EĞİTİMSEL BİR POMPA DÜZENEĞİNİN OPERASYONEL KONTROLLERİ İLE DİZAYNI VE YAPIMI

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Aralık 2004, 159 sayfa

Otomatik pompa sistemlerine ait sistem karakteristiklerinin , yıpranma, borulardaki eskime ve sistemde toplanan tortu ve/veya konfigürayon değişikliklerinden kaynaklanan nedenlerle değişikliklere uğraması söz konusu olabilir. Bu tip değişiklikler, her durum için kendine has şekilde, asli fiziksel sistem gereksinimleri ve kontrol algoritmaları arasında bağdaşmazlıklara neden olabilmektedir. Fiziksel sistem ve onu kontrol etmekte olan yazılım arasındaki sözkonusu uyumsuzluk, pompanın verimsiz çalıştırılmasına hatta sistem bileşenlerinde geçici olarak meydana gelen aksaklıklar yada sistem bileşenlerinin uygun olmayan koşullar altında çalıştırılmaları esnasında meydana gelen kalıcı hasarlar nedeniyle, bütün sistemin çalıştırılamaz hale gelmesine yol açabilir.

Bu çalışmada yukarıda bahsedilen durumların eğitim ve öğretim amaçlı olarak görselleştirilebilmesi için değişken tahliye yüksekliklerinde çalışan otomatize edilmiş bir deneysel pompa düzeneğinin operasyonel bileşenleri ile birlikte (mekanik, elektronik, enstrümantasyon), tasarımı, üretimi ve düzeneğe ait denetim ve kontrol yazılımlarının hazırlanması amaçlanmıştır.

Yazılımın sistem karakteristiklerine dair verilerinin toplanmasını sağlayan modülü (sistem test modülü) pompa ve sistem karakteristiklerinin herhangi bir nedenden dolayı değişmesi durumunda (kısılan vana, pompa hızının değişmesi, debinin veya tahliye yüksekliğinin değişmesi v.b) yeni pompa ve sistem karakteristiklerinin tanımlanmasını mümkün kılmaktadır. Daha sonra pompa operasyon modülü, kullanıcının yukarıda belirtilen nedenlerden dolayı meydana gelen değişiklerin etkileri hakkında karşılaştırmalı yargılara varmasını sağlamaktadır.

Yukarıda bahsedilen test aşamalarının ve denetiminin gerçekleştirilmesi amacına, hepsi *özel olarak yapılan bir Ana Kontrol Devre (AKD) Kartı*'na bağlanmış, 4 adet *basınç transdüseri*, *bu çalışma için özel olarak üretilen pozisyon geri beslemeli DC motor kontrollü kısma vanası* ve bir *değişken frekans sürücüsü (DFS)* kullanılmak suretiyle ulaşılmıştır.

Anahtar kelimeler: Pompalama sistemlerinde otomasyon, eğitim amaçlı pompa düzenekleri, değişken tahliye yüksekliği, kısma kontrolü, değişken frekans sürücüsü, VFD, pompa hız kontrolü.

ACKNOWLEDGMENTS

Firstly, I would like to express my gratitude to my Thesis Supervisors Prof. Dr. Kahraman ALBAYRAK and Prof. Dr. Cahit ERALP for their most valuable guidance as well as for their patience and encouragement during my thesis studies.

I would like to cordially thank to my second parents Mr. Fatih ÖCAL and Mrs. Buket ÖCAL who have made the real contribution to each and every piece of this material since the beginning.

I am also thankful to the Head of Engineering Department of BTC Crude Oil Pipeline Project, my superior, Mrs. Fügen KALKANLI for her incredible patience, support and for her belief in my studies.

I would like to express my cordial gratitude to my dear brother Mechanical Engineer Güray GÜNER for his valuable help and support during the hard times of my studies.

Finally, I would like to express my deepest cordial gratitude to my dearest parents Dr. Seyfettin GÜNER and retired teacher Mrs. Bülent GÜNER who have made their all facilities available for my future, and for their infinite love and devotion.

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NOMENCLATURE

SYMBOLS

H	Head (m)
Q	Flowrate (m^3/h)
C	Flow Coefficient
P	Power [(N×m)/s], Pressure, Flow Potential
n	Rotational Speed (rpm)
N	Rotational Speed (rpm)
g	Gravitational Acceleration [m/s^2]
D	Diameter [m]
v	Velocity [m/s]
f	Friction Factor
R	Resistance (Ohm), Flow Resistance (m)
L	Length [m]
K	Resistance Coefficient
e	Surface Roughness [m]
Re	Reynolds Number
μ	Absolute Viscosity [(N×s)/m^2]
β	Diameter Ratio
θ	Inclination Angle (Valve ports)
π	Pi
z	Elevation Difference
I	Current
V	Voltage

ABBREVIATIONS

MOV	Motor Operated Valve
HV	Hand Operated Ball Valve
RO	Restriction Orifice
OH	Open Header
Pxx	Centrifugal Pump
PMxx	Electrical Motor
Txx	Reservoir, Tank
PITxx	Pressure Transducer
VFD	Variable Frequency Drive
PWM	Pulse Width Modulation
PIC	Programmable Integrated Circuit
PCB	Printed Circuit Board
Op-AMP	Operational Amplifier
MCC	Main Control Circuit
MOSFET	Metal Oxide Silicon Field Effect Transistor
DC	Direct Current
AC	Alternative Current
VDC	Volts DC
VAC	Volts AC
CPU	Central Processing Unit
barg	Bar (gage)
mbarg	Milibar (gage)
I/O	Input – Output

CHAPTER 1

INTRODUCTION

1.1 Variable Speed Drives for Pumps

Up to about 1970's variable-speed drives in the water industry usually meant fluid couplings located between a fixed-speed motor and a variable-speed pump. The coupling is controlled electrically or hydraulically to allow a variable slip between the motor speed and that of the coupled load. These drives established a high order of reliability and are quite satisfactory for pump loads where in the torque requirements dropped off rapidly as the speed is reduced.

The loss of popularity of the mechanical drives is due to their lower efficiency compared to that for the Variable Frequency Drives (VFD's). Figure 1.1 provides a rough comparison of the efficiency of the VFD's and the mechanical drives. The energy consumption of the most mechanical drives is approximately double that for the VFD at 50 percent speed when applied to a variable torque machine such as a centrifugal pump. [1]

The other factor against the mechanical drives is first cost. These drives, being mechanical in nature, have not had the great reductions in cost that VFDs have done. This is due to the great advancements that are made in electronics during the last decade.

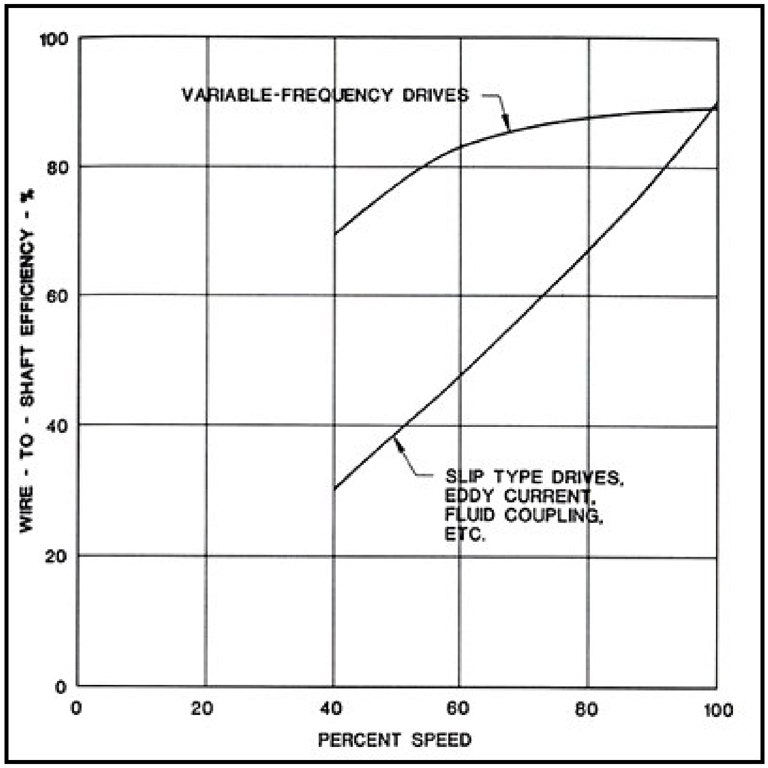

Fig 1.1: Efficiency Comparison of Mechanical Drives and VFD's

Mechanical variable-speed drives should still be used for applications that have environments harmful to VFDs. This includes dusty or corrosive atmospheres and high ambient temperatures where it is impossible to provide adequate cooling for the variable-frequency drive.

1.2 Variable Frequency Drives

The VFD is a device that varies the motor speed by changing the frequency of the power source applied to an electric motor. The speed of the motor is directly proportional with the frequency of this power source. This is the fundamental design basis of these drives.

The advantages of VFD’s for pumps have been known for many years. They permit the use of simple, reliable, and inexpensive induction motors, provide the operating economies of variable speed.

Variable-speed drives soon appeared for DC motors and shortly thereafter, for AC induction motors. The early variable-frequency, thyristor drives, which are mostly voltage source inverters, are sometimes less than ideal in their characteristics; but they opened up a huge new field of application in the water pumping industry. Now, drive designs have matured, but there are still important new developments which solve some of the major application problems on the electrical side. [1]

1.3 Pulse Width Modulation (PWM) Drives

The development of large power transistors in the 1980’s spawned a new type of VFD. The acronym, PWM, stands for “pulse width modulation”, for obtaining voltage control and a variable output frequency. PWM drives vary the output voltage by repetitively connecting and disconnecting a fixed voltage at rapid intervals. The ratio of "on" to "off" periods determines the voltage magnitude.

1.4 Advantages of Variable-Frequency Drives

VFD’s are available for nearly any water pump application and have been the preferred means of varying the speed of a pump. They have become the drive of choice for new applications for many reasons. These are:

1. Lower first cost in most sizes compared to mechanical slip type drives

2. All are air cooled; larger slip-type drives require water cooling

3. Much higher wire-to-shaft efficiency than any slip-type drive

4. Easy to integrate drive control software into the control software of pumping systems

1.5 Efficiency of Variable-Speed Drives

The technology of VFD’s has advanced to the point that most of these drives have a full efficiency of 97 to 98 percent. The efficiency of the drive alone does not determine the input power and, by itself, is unimportant when operating pumps. The important efficiency is the one consisting of combined efficiencies of drive and the motor.

1.6 Aim of the Thesis Study

The adjustment of the flowrate to actual requirements using speed regulation is particularly useful if the system characteristics curve is steep (i.e. if the dynamic pump head is considerably greater than the geometric head) (Figure 1.2). In this case, the pump's efficiency is only altered slightly because the alteration of the operating point is effected approximately along a parabola.

For relatively flat system characteristics curves (geometric head H_{geo} is considerably greater than the dynamic head loss), the useful range of adjustment is small due to the fact that the small changes in speed results in sudden alteration of operating point as a result the efficiency of the pump also alters suddenly. Thus, economic operation must be reviewed for such applications. Throttling may possibly be more economical in the case of a flat system characteristics curve than speed control due to relatively higher initial investment costs.

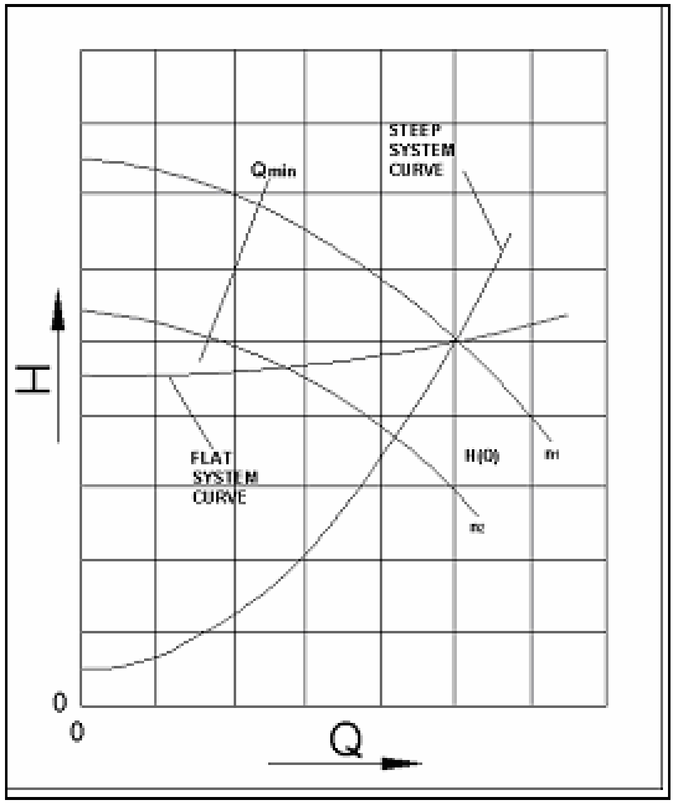

Fig 1.2: Speed control in the System

It is intended to design and construct an experimental pumping system which introduces more than one geometric head value combined in one system. In addition to the foregoing comparison between throttling and pump speed control as discussed above is demonstrated and visualized for educational purposes. Also wide coverage of the scope of this study is consisted of the design and construction of instrumentation and electronic control periphery adapted to the above-mentioned physical system. Nevertheless a test module is designed which computes the numerical model of system characteristics and pump characteristics for any kind of achievable configuration. This enables the automation algorithm to visualize the real-time operational parameters with flexibility in various systems to some extent.

During the initial phase of the study, complete design and construction of an operative, DC motor actuated throttling valve is finalized instead of using an off-the-shelf “motor operated valve” (MOV). The MOV is constructed of a manually operated gate valve and a DC motor furnished with a gearbox as the actuator. These two items are assembled together on a valve frame made of 4mm stainless steel plate, which is cut by the laser CNC lathe. Also an encoder is designed and mounted on the mechanical valve assembly in order to identify the valve position and provide feedback for the controlling algorithm. A disc made from printed circuit board and an IR photocell switch are used for the valve position encoder.

Above-mentioned design and construction steps also included the production of a fully operational Main Control Circuit (MCC) board consisting of 3 Programmable Integrated Circuits (Valve Controller Microchip, Motor Speed Controller Microchip and Main Controller Microchip). This part of the study also included the origination of PIC programming subroutines in order them to communicate among themselves and with the master PC (CPU) via RS – 232 asynchronous serial communication channel [11].

System characteristics of pumping systems change due to wear, aging of piping, and accumulation of deposits in the system and/or due to configuration changes. This may put any sort of controlling algorithm into a state where they become unsuitable for that particular case. The said mismatch between the physical system and software controlling the process may cause inefficient operation of the pump which may even lead to total system failures.

The software may be developed and modified such that the system testing module enables the control algorithms adapt themselves to the new system characteristics changed due to some reason (closed valve, changed equipment combination, changed elevation of discharge, aging in the piping network etc.). Testing sequence automation is achieved employing the custom made, motor-operated throttling valve with position feedback and variable frequency drive controlling the pump speed which provides the means of identifying new characteristics of the system using pressure transducers within the operating range of the pump.

CHAPTER 2

OPERATIONAL ASPECTS OF PUMP SYSTEMS

2.1 Pump Performance Curves

The head that a pump can produce at various flow rates and rotational speeds is established in pump tests conducted by the pump manufacturer. During testing, throttling a valve in the discharge pipe varies the capacity of the pump, and the corresponding head is measured. The results of these tests and other tests with different impeller diameters are plotted to obtain a series of head-flowrate (H-Q) curves for the pump at some given speed. These curves are known as pump characteristics curves.

2.2 Pump Operating Characteristics

The operating characteristics of pumps depend on their size, speed, and design. Pumps of similar size and design are produced by many manufacturers, but they generally vary because of slight design alterations. Basic relationships can be used to characterize and analyze pump performance under varying conditions.

2.3 Pump Characteristics Curves

In most pump curves, the total dynamic head H, the efficiency, η (percentage), and the power input, P (kW), are plotted as ordinates against the capacity, Q (in cubic meters per second) as the abscissa.

2.4 Stable and Unstable Pump Curves

The head-capacity curves for radial-flow centrifugal pumps can be either stable (Fig 2.1a) or unstable (Fig 2.1b), whereas the pump characteristics curves for mixed-flow and axial-flow pumps are more stable (except for a small area of operation). With stable pump curves, there is only one flowrate for each value of head, whereas two discharge values are possible for a given value of head in unstable pump curves, as can be seen from Figure 2.1b. The use of pumps with unstable pump curves can lead to pumping instabilities at heads greater than the shut-off head.

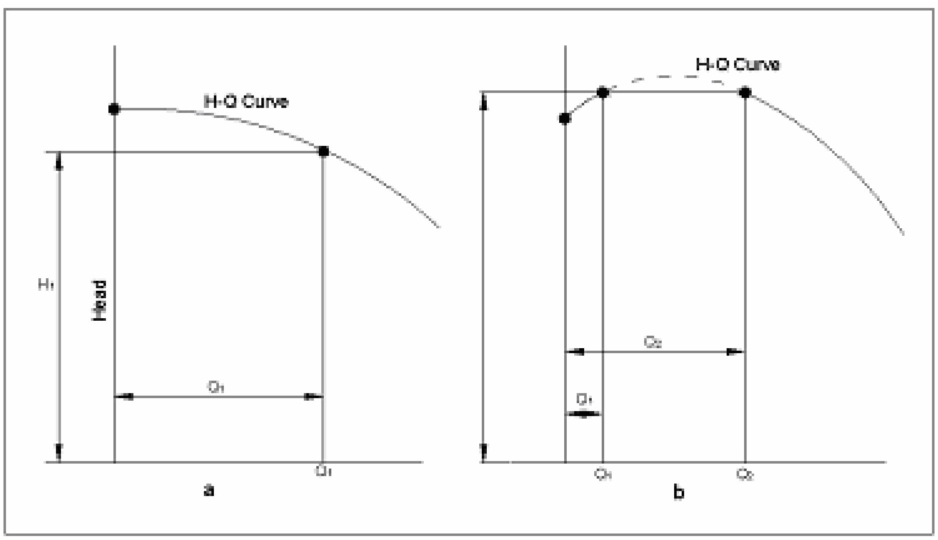

Fig 2.1: Stable (a) and unstable (b) pump H-Q curves

2.5 Pump Operating Ranges

Operating a pump near its best efficiency point, problems of cavitation and radial loads on the impeller are minimized by defining particular operating ranges [3]. Operating range of the experimental system is also limited by means of the concept explained in the upcoming sections.

2.5.1 Fixed Efficiency Loss

For a given impeller diameter, the operating range of a pump can be established by

1. Setting a limit on the minimum acceptable efficiency depending on the requirements of the process

2. Setting upper and lower limits on the allowable speed changes depending on the system availability

The operating range of a pump based on this criterion is illustrated in Fig 2.2

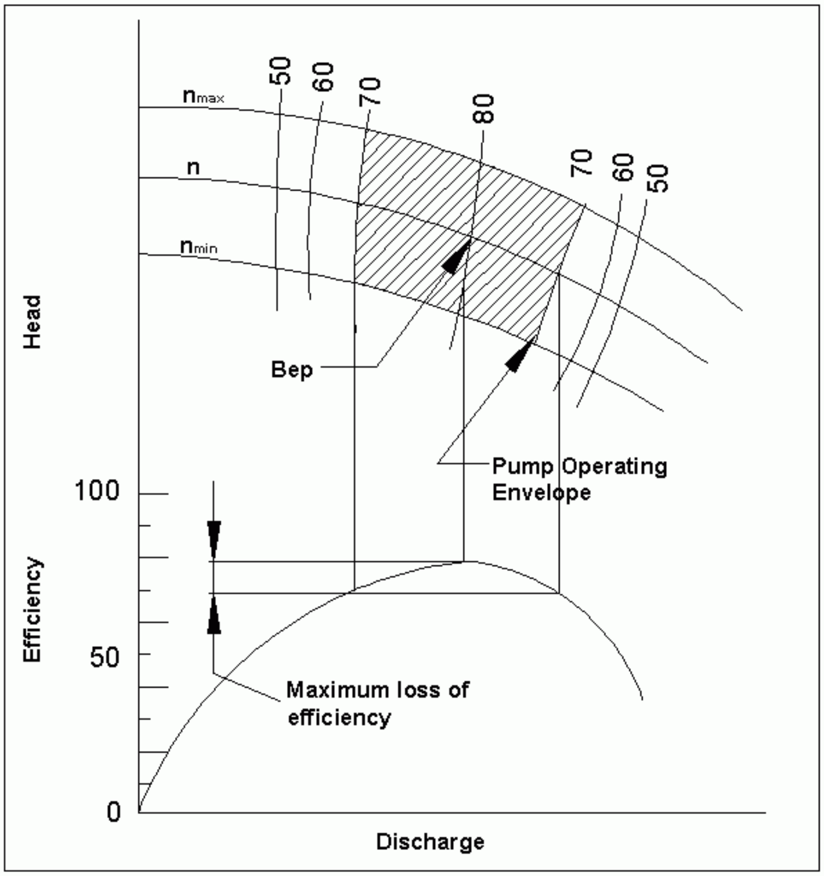

Fig 2.2: Fixed Efficiency Loss Criterion

2.5.2 Percentage of Flowrate

An alternative approach used to establish the pump operating range is to set limits on the pump discharge as a percentage of the best efficiency flowrate. Pump operating envelopes are defined using these values as illustrated in Figure 2.3 for changes in speed.

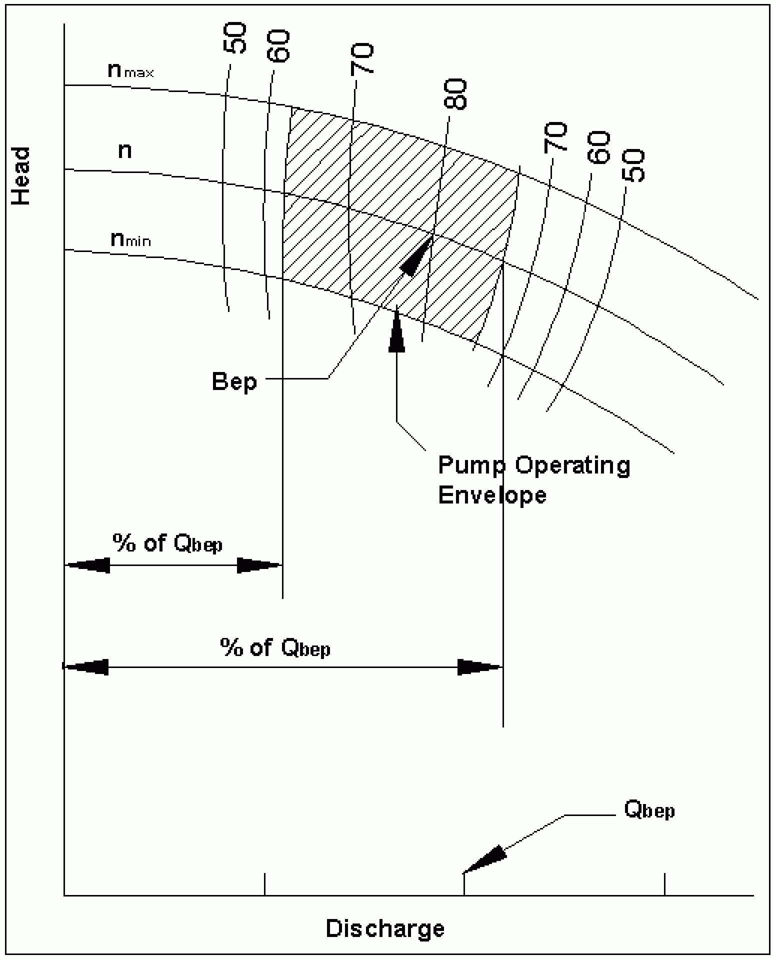

Fig 2.3: Percentage of Flowrate Criterion

2.6 Analysis of Characteristics of a Pumping System

The head developed by the pump must exceed the sum of geometric head and system friction losses in order to move the fluid in piping network.

Above-mentioned basic relationship determines the "*pump operating point*," a single point on both the pump characteristics curve and system characteristics curve. There are several ways of finding the pump operating point, including computer analysis and several graphical methods, but the simplest (for simple problems) and the most universally used method is H-Q plot. A different graphical approach, which is preferable for complex systems, is *Frey's analysis.* This method is also used for evaluating the losses in the actual physical system designed and constructed as a part of this study.

2.7 System Characteristics Curves

The systems served by the pump are represented by system characteristics curves (Fig 2.4 & 2.5). The head at any flowrate value is the sum of the geometric head and dynamic system losses.

The geometric head does not vary with flowrate, as it is only function of the elevation or back-pressure against which the pump is operating. A system characteristics curve tends to be fiat when the piping is oversized and steep when the pipe headers are undersized. The friction losses also increase with aging therefore, the system curve for old piping tends to be steeper than for new piping.

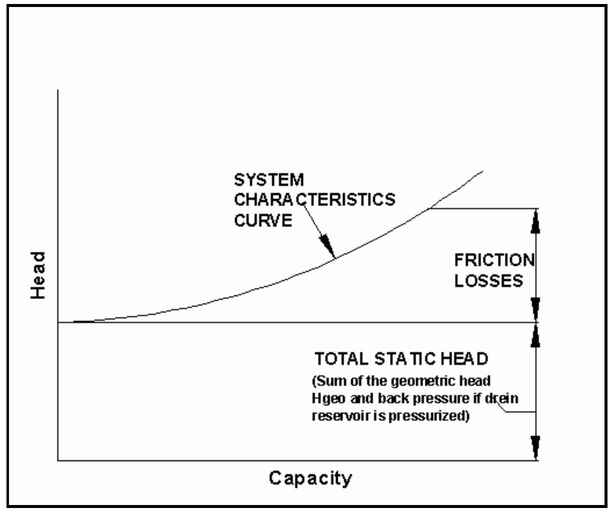

Fig 2.4: System Characteristic Curve (with static head)

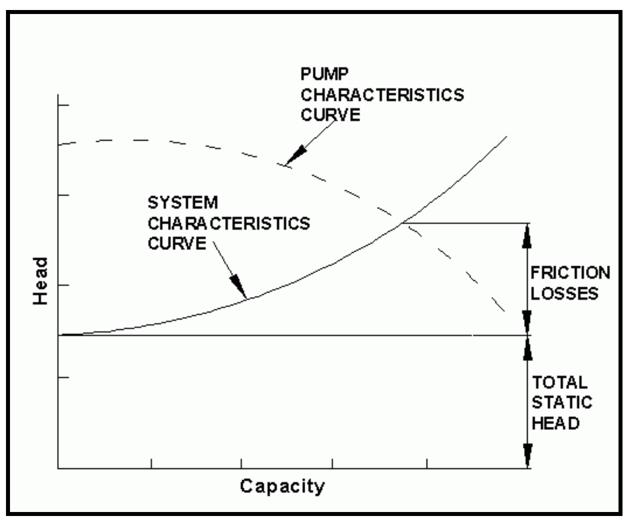

Fig 2.5: Pump & System Characteristic Curves

When the system curve is flat, there is little advantage for variable or multiple-speed pumping. Inversely, if the system characteristics curve is steep, substantial energy savings can be obtained by using the multiple or variable-speed pumps.

2.8 System Characteristics Curves and Operating Point

The system characteristics curves in Fig 2.6 are indicated over a range of flowrates from zero (where the only head is due to the total static head consisting of the sum of geometric head and the back-pressure at the discharge point) to the maximum expected (which also includes all friction, fitting, and valve losses). Because the system characteristics curves are approximate functions of $v^2/2g$, the curve is a parabola with its apex on the zero Q line.

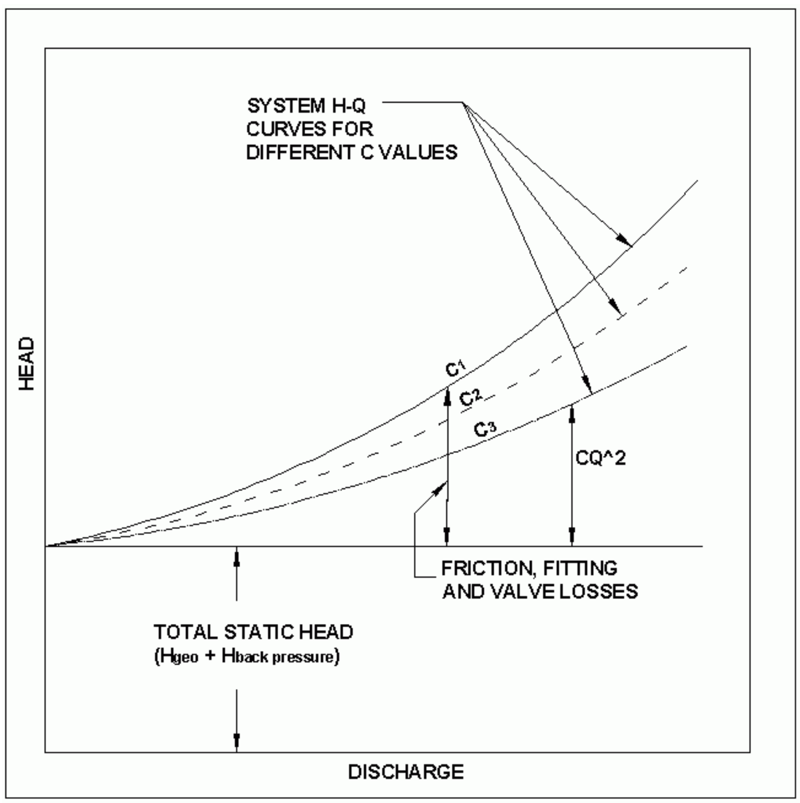

Fig 2.6: Typical system characteristics curves

New pipe is expected to be very smooth, but bacterial slime, other deposits result in a steeper system characteristics curve. The simplest system curve, one in which the water level at the suction inlet remains constant, is shown in Figure 2.6.

2.8.1 Single Pump, Single-Speed Operation

The point on the system characteristics curve at which a single speed pump must operate is determined by superimposing the pump characteristics curve on the system characteristics curve as shown in Figure 2.5 and 2.7. The point of intersection is the *pump operating point*. As the pipe ages and the system characteristics curve rises, the operating point moves up and to the left along the pump characteristics curve.

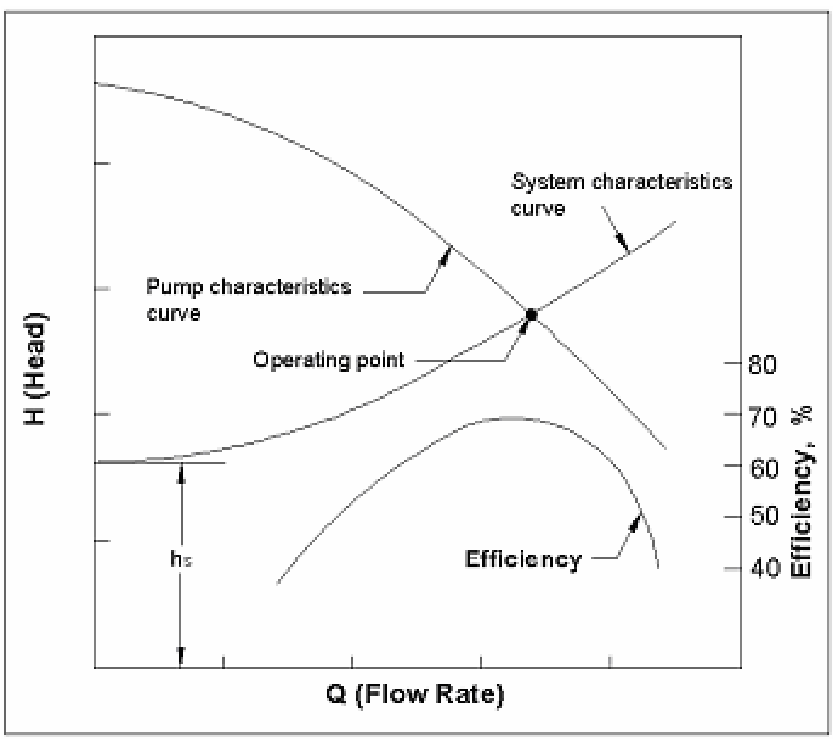

Fig 2.7: Operating point for fixed speed application

In this regard investigated automation of defining pump and system characteristics thus the automated real-time determination of operating point offered in this study, which is discussed in detail through the following sections, will provide the means of flexible and effective operation of the pump bench used in the educational setup as well as for practical applications.

2.8.2 Single Pump, Variable-Speed Operation

The point on the pump characteristics curve at which a variable-speed pump must operate is determined as described previously for the single-speed pump. The affinity laws are used to determine the rotational speed at any other desired operating point on the system curve as seen in Fig 2.8.

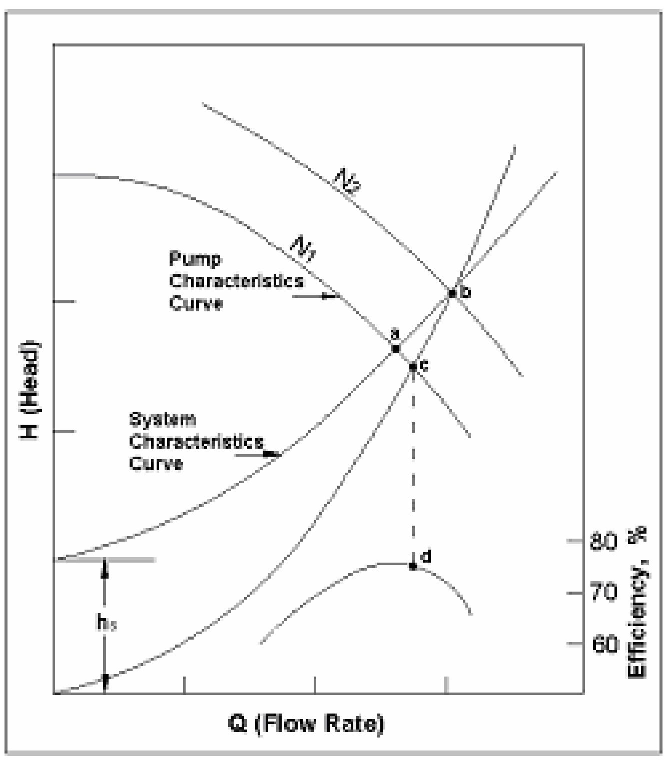

Fig 2.8: Determining operating point for a variable speed pump application

2.9 Complex Pumping System H-Q Plots

The most commonly used method for drawing system characteristics (H-Q) curves is described in foregoing sections, in which the H-Q curve of the pump (pump characteristics curve) and the H-Q curve of the piping system (system characteristics curve) are plotted with positive ordinates and abscissas (as in Figure 2.9b). The intersection of the two curves is taken as the operating point. This method of analysis is not handy if the system contains widely separated pumps and/or reservoirs. A computer is usually used to model such complex systems, but a graphical method, practical for such problems, is developed by Frey; although it offers no advantage for simple systems, it is superior for complex systems.

2.10 Frey's Method

Frey's method consists of drawing H-Q plots in terms of flow potentials and flow resistances. Flow potentials are plotted as positive ordinates and flow resistances are plotted as negative ordinates. Flow potentials (pumps and/or gravity when gravity induces flow) enhance discharge, whereas flow resistances (pipe friction and gravity when flow is against gravity) resist flow. As shown in Figure 2.9c, ordinates for the pump curve, P1, are plotted above the axis and ordinates for the pipe resistance (both static lift and friction), R1, are plotted below the axis. The net curve is P1-R1 and the system discharge point is its intersection with the axis. The discharge, OA, and the head, OC, are the same in Figures 2.9b and 2.9c.

2.10.1 Coordinates

In the coordinate system shown in Figure 2.9c, a positive head *(+ H)* represents a potential. A negative head *(-H)* represents a resistance. Positive discharge *(+Q)* is flow in the assumed direction, whereas negative discharge *(-Q)* represents flow opposite to the initial guess.

2.10.2 Basic Construction

In the H -Q curves of Figure 2.9c, the curve labeled P1 is a flow potential, whereas the curve labeled R1 is a flow resistance. Graphical addition of P1and R1 produces curve P1- R1, where "-" means "in series with (and *not* "minus"). Note that because the ordinates of R1 are negative, they are arithmetically subtracted from P1 ordinates. To find the operating point for the pump, a line AB to curve P1 should be drawn. Point B is the operating point of the pump, which shows the head as ordinate and the flowrate as abscissa.

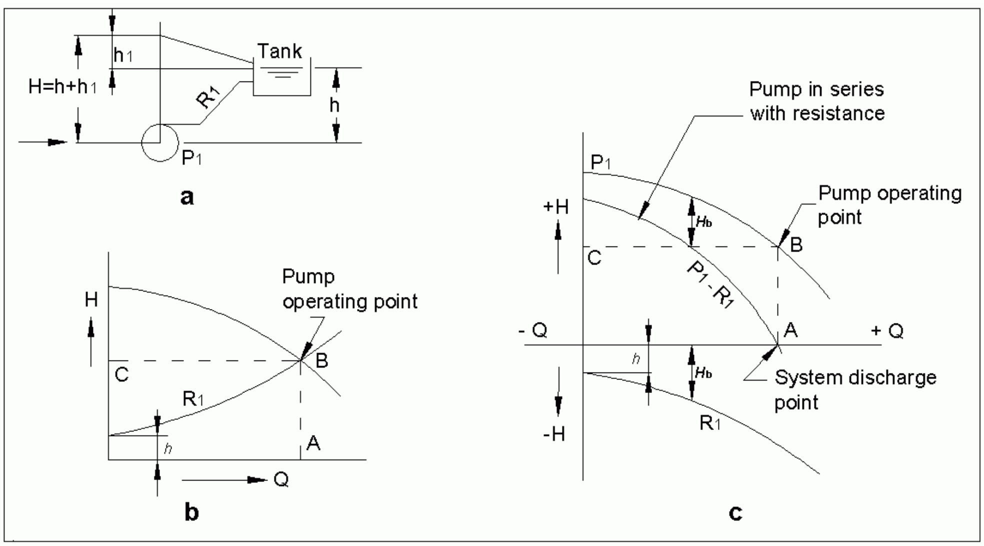

Fig 2.9: (a) Configuration (b) standard method (c) Frey's method

2.10.3 Single Pump and Reservoir in Parallel

Frey's method works for problems in which either potentials or resistances must be varied to produce a required performance. Such a system is illustrated in Figure 2.10, in which flow from the gravity supply system must be boosted to a given value, by adding pump P1.

First, the known quantities are drawn

1. H1-R1
2. Resistances R2 and R3
3. Required performance at point A (from point "O" to point "A") through which the curve of [(H1-R1) II (P1-R3)]-R2 passes (where "II" sign means in parallel).

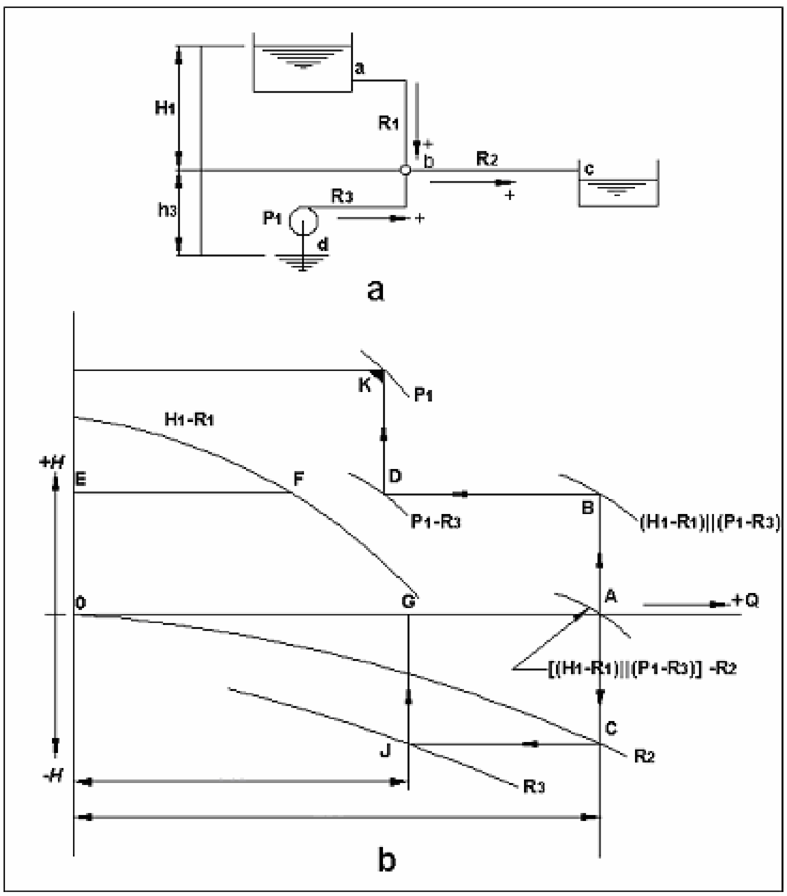

Fig 2.10: Single pump and reservoirs in parallel (a) configuration (b) pump & system H-Q curves

To find the performance at point **b** in Figure 2.10a, R2 is subtracted by drawing AB equal to AC. The curve (H1- R1) II (P1- R3) passes through point B. BD is drawn equal to EF. Because point F lies on the curve of H1 – R1, point D therefore lies on the curve of P1-R3. [This construction can also be explained by reasoning that the pressure at point **b** in Figure 2.10a must be the same whether derived from route **ab** or from route **db**; therefore the ordinate of point F (route **ab**) must equal the ordinate of point D (route **db**).] R3 is subtracted by constructing DK = GJ. Point K is on the operating curve of P1 so pump P1 must produce a flow magnitude of the length of OG line at a head value located at the point of intersection of horizontal line from K to Q=0 line.

CHAPTER 3

DESIGN CALIBRATION AND OPERATION OF THE SETUP

3.1 Hydraulic Design of the "Operational Pump Control" Setup

In this chapter the basis for the determination of flow resistances and flow potentials within the educational pump and piping system are presented. Also the system is evaluated by means of a set of empirical correlation and assumptions in order to obtain a numerical model of the system as well as to identify whether the pump and piping system together are capable of presenting the required performance for the aim of this study or not. This is required to ensure that the system properly displays the required operational performance where it also responds to users' inputs accordingly provided that the limits of components pertaining to the physical setup allows them to do so (maximum differential head that the pump could deliver and the maximum resistances which are likely to be encountered within the system).

In addition to the preceding, the equations obtained from physical and geometrical properties of the actual experimental setup consisting of piping, fittings and the pump are evaluated using the Frey's graphical method. Results and computations presented in this section constitute the worst case design basis of the actual layout of the setup and its components which are constructed and adapted to the requirements of this study within its scope.

Flow through a valve or fitting in a pipe line may be expressed in terms of velocity head and the corresponding head loss may be expressed as $h_L = K\frac{v^2}{2 \cdot g}$, where K is the resistance coefficient, v is the velocity of the flowing fluid and g is the gravitational acceleration.

In most valves or fittings, the losses due to friction (Category 1 mentioned above) resulting from actual length of flow path are minor compared to those due to one or more of the other three categories listed.

The same loss in straight pipe is expressed by the Darcy-Weisbach equation as $h_L = (f\frac{L}{D}) \cdot \frac{v^2}{2 \cdot g}$ where $K = f\frac{L}{D}$ and "*f*" is the friction factor.

The ratio *L/D* is the equivalent length, in pipe diameters of straight pipe, which will cause the same pressure drop as the obstruction under the same flow conditions. Since the resistance coefficient *K* is constant for all conditions of flow, the value of *L/D* for any given valve or fitting must necessarily vary inversely with the change in friction factor (*f*) for different flow conditions.

Friction factor "*f* ", is derived from well-known Colebrook-White formula in order to be used for the rest of the calculations presented in this chapter;

$$f_{i+1} = \left[\frac{1}{-2.0 \times \log(\frac{e/D}{3.7} + \frac{2.51}{\mathrm{Re} \times f_i^{(0.5)}})} \right]^2 \quad \text{...... (Eq 4-1)}$$

It is obvious from equation 4-1 that iteration is needed to evaluate *f*. Miller [5] suggests that a single iteration will produce a result within 1% error if the initial estimate is calculated from;

$$f_0 = 0.25 \times \left[\log(\frac{e/D}{3.7} + \frac{5.74}{\mathrm{Re}^{(0.9)}}) \right]^{-2}$$ ...... (Eq 4-2)

Where;

e: surface roughness (m)

D: diameter of pipe (m)

Re: Reynolds Number

Reynolds number can be organized depending on the flowrate (*Q*) as follows: $\mathrm{Re} = \frac{V \cdot D \cdot \rho}{\mu}$, where "*V* " is the average velocity and "μ " is the absolute viscosity, is organized where it becomes

$$\mathrm{Re} = \frac{10 \cdot Q \cdot \rho}{9 \cdot \pi \cdot D \cdot \mu}$$ ...... (Eq 4-3)

Where;

Q: flowrate [m^3/h]

μ: Pa × s [$\frac{N \cdot s}{m^2}$]

D: Pipe diameter [m]

ρ: Density [kg/m^3]

Combination of Equations 4-1 and 4-3 provides an expression for "*f*" dependant on flowrate (*Q*) only in complete turbulent zone, where *e/D* ratio is constant for one type of pipe and through the flowrate range designated.

3.1.1 Assumptions

Here all the required assumptions are summarized used in the rest of calculations presented through this section in order to constitute the boundary conditions for further development of the numerical model of constructed educational setup.

3.1.2 Ambient Conditions and Physical Quantities (Assumptions)

Temperature is taken during the trial for the determination of nominal flowrate value of the pump which has been chosen for the construction of the pumping setup.

Water Temperature: 17 ^{o}C

Density: 1000 kg/m^3

Absolute Viscosity: μ = 0.85cP at 17 ^{o}C

Pipe Roughness for Steel Pipe: e = 47.5 μm (Commercial Steel Pipe) [4]

Reservoir Water Level: Constant

Flow Zone: Flow assumed to be in zone of *complete turbulence*.

3.1.3 Representative Resistance Coefficients (K) of Valves and Fittings

Empirical relations representing the resistance coefficients (*K*) for valves and fittings provided in this section are commonly used fittings which are used in the experimental setup.

3.1.4 Motor Operated, Wedge Disk Gate Valve

DC motor with reducing gearbox, position feedback equipment and assembly frame along with machined parts (adapters) between valve and motor shafts are custom made for the assembly of hand operated commercial wedge disc-gate valve. This valve is tagged as MOV01 in Figure 3.3.

Resistance coefficient (K) for this custom made valve is $K = 8f$, where $\beta = \frac{d_1}{d_2}$ =1 and $\theta = 0$ as indicated on the Figure 3.1 below.

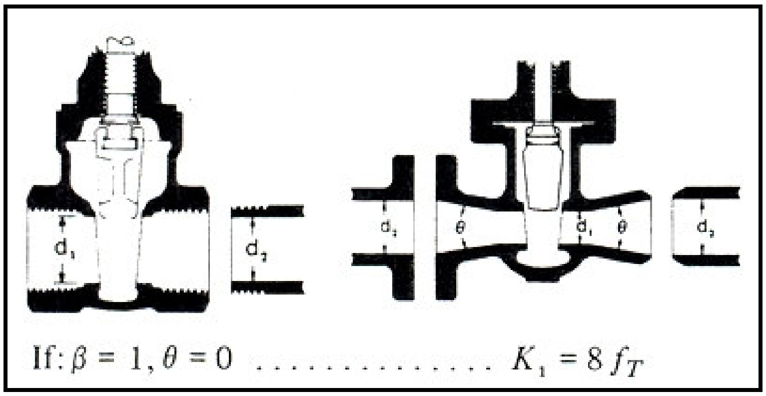

Fig 3.1: K Value for wedge disc gate valve

Rest of the fittings, which cause flow resistance, included in the experimental system and their resistance coefficients are provided in the Appendix.

3.1.5 Piping and Fittings

Experimental setup consists of commercial steel piping at three different elevations along with several fittings which cause flow restriction and hence result in flow resistance. Below there are the lists of piping and fittings of all three branches illustrated in the conceptual drawing of the educational setup in Fig 4.1.

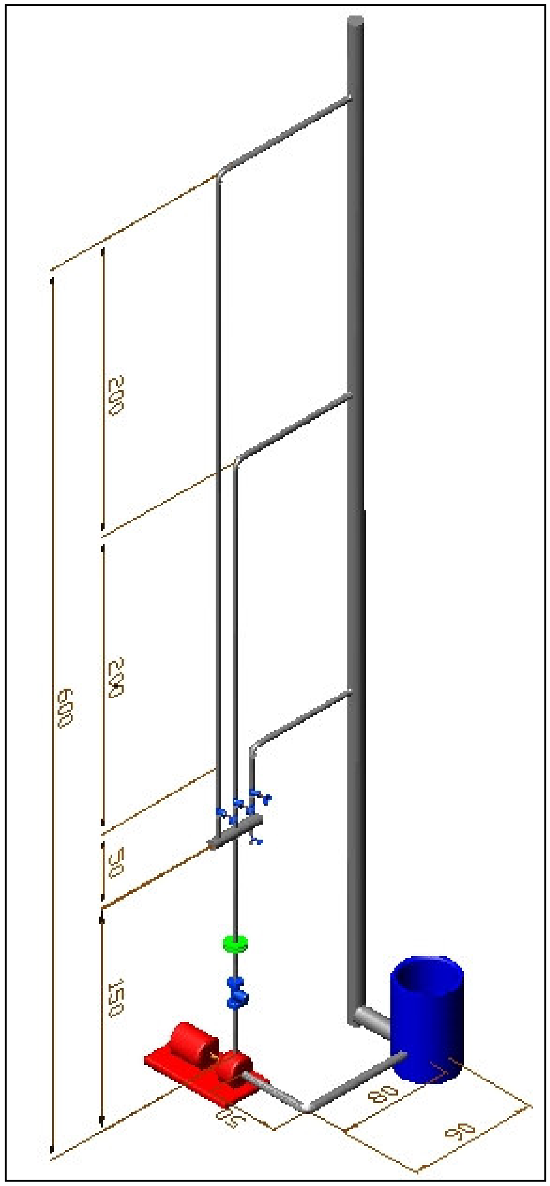

Fig 3.2: Conceptual General Arrangement

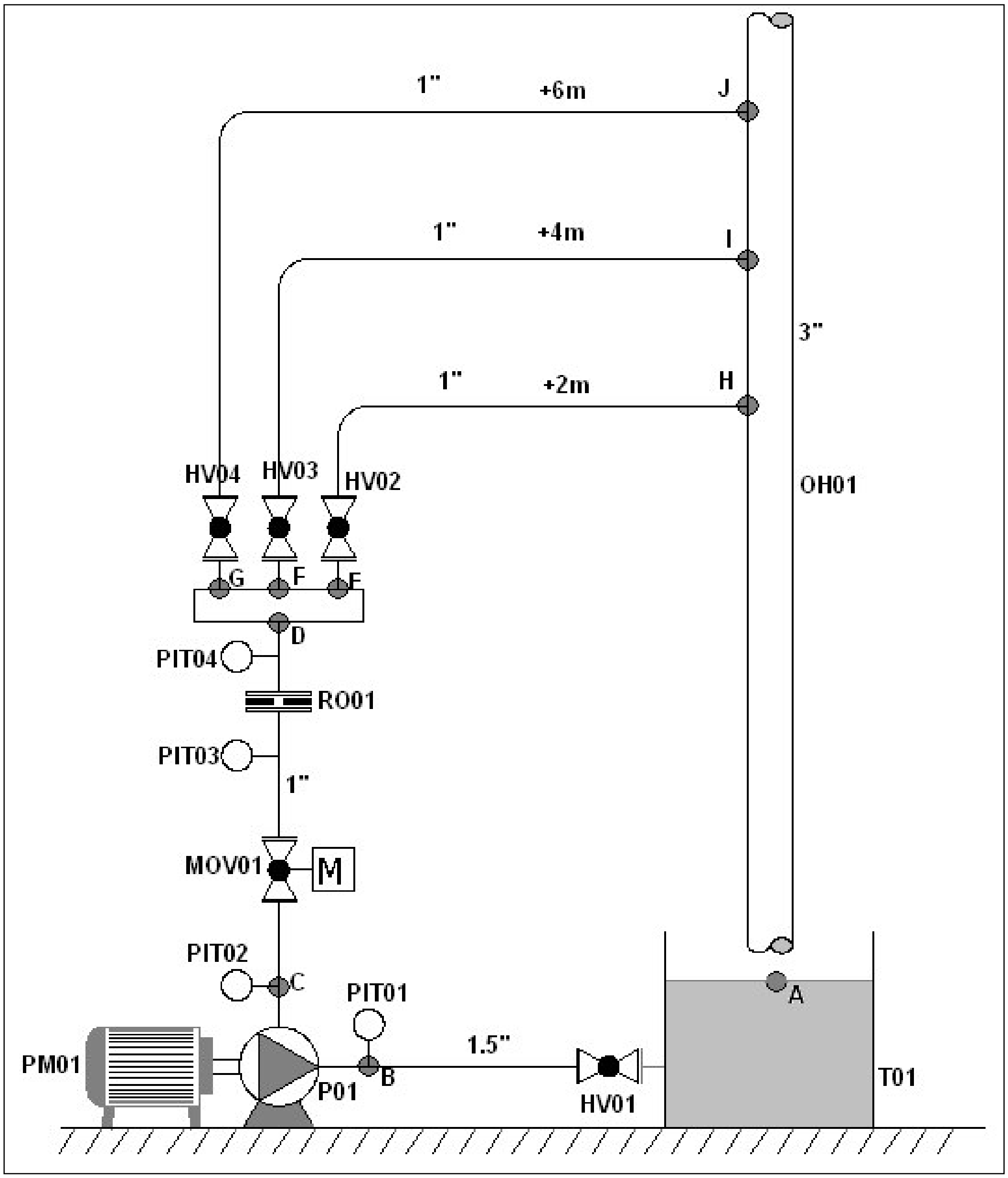

Fig 3.3: Schematic Representation of Experimental Setup

3.1.6 Resistance Coefficient *K*, Equivalent Length *L/D*

Pressure loss test data for a wide variety of valves and fittings are available in the literature [4]. (However, due to the time-consuming and costly nature of such testing, it is almost impossible, to obtain test data for every size and type of valve and fitting.)

3.2 Electrical Analogy

In order to define the system by means of Frey's graphical analysis, the elements contained in the overall system should be divided into corresponding resistance and potential components. In order to achieve this, an electricity analogy is constructed. This analogy is illustrated in Figure 3.4 for the actual pump bench, showing the piping and fittings of the system.

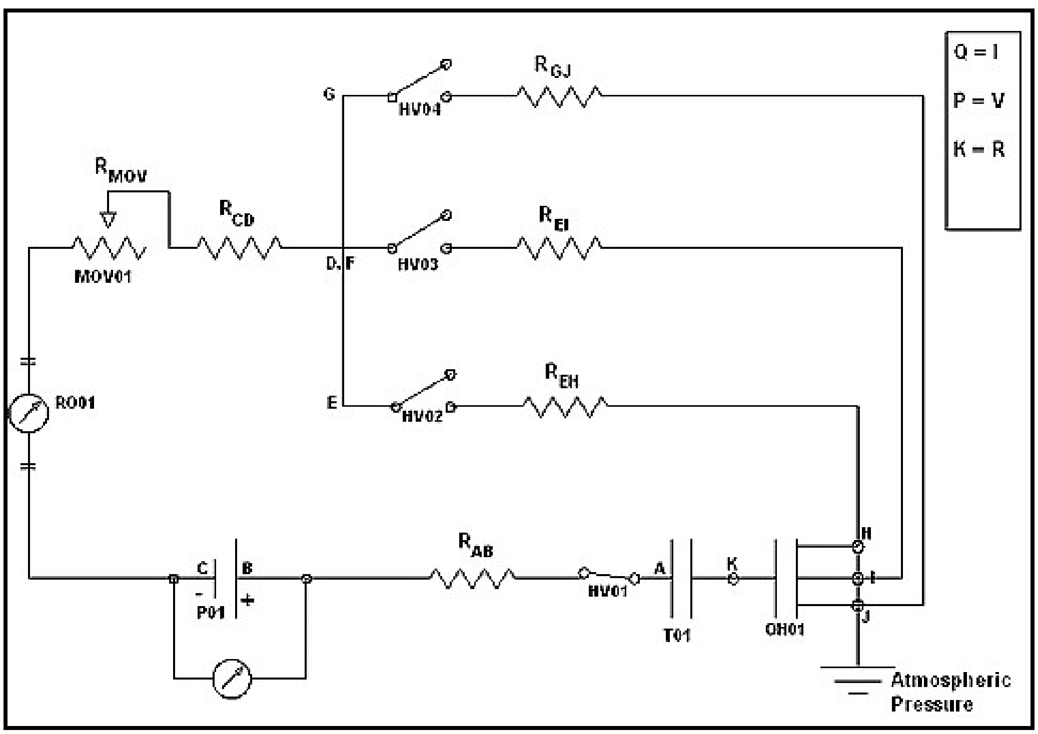

Fig 3.4: Electrical Analogy

There are 3 different branches in parallel at 3 different discharge elevations as seen in Figure 3.4. Resistances on these branches are designated as R_{GJ}, R_{EI}, R_{EH}.

These three resistances are directly connected to an open header (open to atmosphere), which is analogous with earthing point in an electrical circuit. This means that the points H, I and J have the same potential (atmospheric pressure in the open header) whereas the points D, E, F and G have different potentials due to differing resistances on each branch.

As it can be anticipated the pump serves as the power source in the circuit where suction side piping (1 ½") and fittings along with the valves are shown with the flow resistance R_{AB} just after the reservoir (T01) which resembles to a capacitor element in the electrical circuit. All hand operated ball valves (HV01 to HV04) are indicated as on/off switches which serve for diverting the flow into the branch desired.

Potential resistances created due to all elements assembled from the discharge side of the pump to the collector are considered in resistance R_{CD} excluding the motor operated throttling valve (MOV01).

Resistance created by the motor operated throttling valve (MOV01) is indicated as an adjustable resistance or as a trim-pot (R_{MOV}) on the circuit. If MOV01 is throttled during the system is operational, dynamic head loss increases at the discharge side of the pump whereas the flowrate decreases in the circuit, which corresponds to increasing voltage (head) and decreasing current (flow) in an electrical circuit.

Pressure transducers PIT01 and PIT02 in Figure 3.3 (connected to pump suction and discharge) serve as a voltmeter to read voltage output of the source, which corresponds to differential head (ΔP), created by the pump in the actual system.

Pressure transducers PIT03 and PIT04 in Figure 3.3 before and after the restriction orifice together serve like an ammeter, which reads the current on the main power line.

3.2.1 Flow Resistances

Flow resistances discussed in Section 3.2 are grouped in order to obtain common numerical expressions for each particular resistance group contained in the physical system. Pertinent fittings and resistances are shown in Table 3.1 below.

Fittings & Resistance	Pipe 1		Pipe 2		Elbow 90deg	Pipe Entrance	Hand Operated Valve	Orifice	Pipe Exit	∑K
	L [m]	Dia [in]	L [m]	Dia [in]						
AB	0,8	1,5	0,5	1,5	1	1	1	_	_	*40f+0,5*
CD	1,5	1	_	_	_	_	_	1	1	*1,0+$K_{orifice}$*
EH	0,5	1	0,77	1	1	1	1	_	1	*33f +1,78*
FI	2,5	1	0,9	1	1	1	1	_	1	*33f+1,78*
GJ	4,5	1	1,05	1	1	1	1	_	1	*33f+1,78*
MOV	_	_	_	_	_	_	_	_	_	*8f*

Table 3.1: Flow Resistances

3.2.1.1 Resistance between A - B (R_{AB})

For such a system with one size pipe and with a constant level reservoir as stated in section 4.4.1 at point A in Figure 3.3, expression of resistance through points A and B is derived from;

$$R_{AB} = (z_2 - z_1) + \frac{v^2}{2 \cdot g}\left(1 + \sum K + f\frac{L}{D}\right) \text{ [m]...... (Eq 4-4)}$$

If Equation 4-4 is organized as the function of flowrate;

$$R_{AB} = H_{geo} + \left(\frac{D + \sum K \times D + f \times \sum L}{1.62 \times 10^6 \times g \times \pi^2 \times D^5}\right) \times Q^2 \text{ [m]...... (Eq 4-5)}$$

Using the formulae in section 4.4.2 for *K* values of sharp edged pipe inlet, 90^o standard elbow and ball valve and with a neglected H_{geo} the Equation 4-5 becomes;

$$R_{AB} = 0 + \left(\frac{D + D \times (40f + 0.5) + f \times \sum L}{1.62 \times 10^6 \times g \times \pi^2 \times D^5}\right) \times Q^2 \text{ [m]}$$

and it is finally expressed with 1 ½" pipe diameter as ;

$$R_{AB} = \left(\frac{0.0381 + 0.0381 \times (40f + 0.5) + f \times 1.3}{1.62 \times 10^6 \times 9.81 \times \pi^2 \times (0.0381)^5}\right) \times Q^2 \text{ [m]...... (Eq 4-6)}$$

Using Equation 4-6 resistance characteristic of the line between points A and B is tabulated, representative curve for the tabulated data is illustrated in Appendix A-1.

A 2nd degree numerical expression is obtained for the corresponding flowrates using numerical results of flow resistances between points A and B in meters. Related polynomial regression analysis executed with *MathCAD 8.0* is presented in Appendix A-1.

As a result of numerical calculations provided in Appendix A-1, common flow - resistance expression for the subsystem between points A and B is identified as follows;

$$R_{AB} = -9.306268 \cdot 10^{-3} \cdot Q^2 - 3.750749 \cdot 10^{-3} \cdot Q + 1.224571 \cdot 10^{-3} \text{...... (Eq 4-7)}$$

3.2.1.2 Resistance between C - D (R_{CD})

One size straight pipe, motor operated wedge disc throttling valve and a restriction orifice for flow measurement exist on line C – D as illustrated in Figure 3.3. However motor operated valve is excluded from subsystem R_{CD} since it acts like an adjustable resistance as discussed in Section 4.5. In this regard expression of resistance through points C and D is derived using the relations presented in Section 4.4.2 as follows;

1 Sharp edged pipe exit has resistance coefficient of *K = 1.0*.
K resistance coefficient for custom made square edged restriction orifice having an opening area ratio of 60% is calculated using Equation 4-8.

$$K_{orifice} = \frac{1-\beta^2}{C^2 \cdot \beta^4} \text{...... (Eq 4-8)}$$

Where $\beta = \frac{d_1}{d_2}$ and "*c*" is the flow coefficient which may be obtained from *C-Re* Plots provided in Figures 3.5 and 3.6.

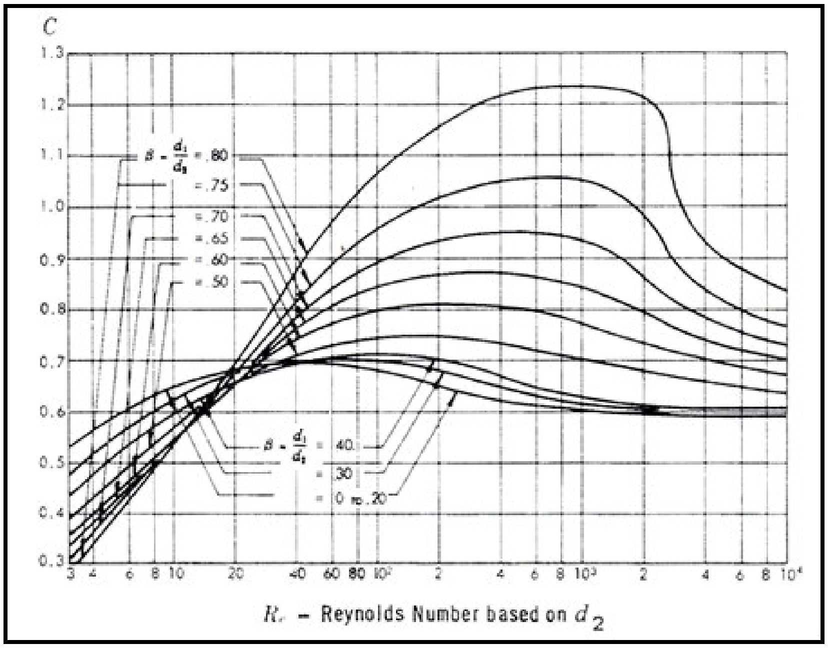

Fig 3.5: C-Re plot for Re range 3 to 10^4 [4]

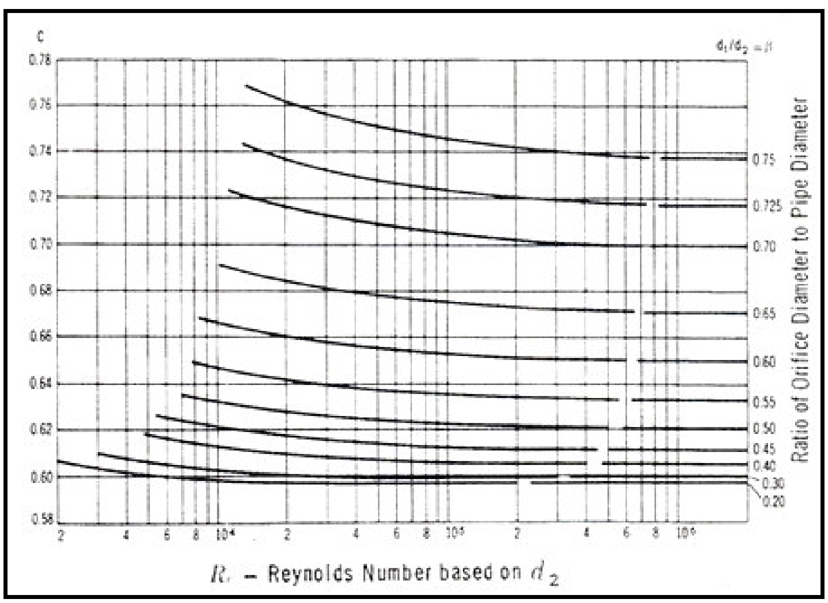

Fig 3.6: C-Re plot for Re range 10^6 to 10^4 [4]

In order to get a common expression for each flow coefficient C depending on corresponding Reynolds number a data set is constituted using the plots provided in Figures 3.5 and 3.6 by sampling enough number of coordinates of each point on the graphs. Tabulated data for *C-Re* within Reynolds number range of 100 to 500000 is provided in Table 3.2.

Since the Re-C graphs illustrated in Figures 3.5 and 3.6 are logarithmic plots, the dataset provided in Table 3.2 could not be used for polynomial regression as a whole through full range of Re values. Therefore the set of Re values is divided into four different set of ranges in order to obtain the best fit C(Re) functions which cover each of the related range of Reynolds values. In this regard, Range 1 - Re [100, 1000], Range 2 - Re [10^3,10^4], Range3 - Re [10^4, 10^5], Range 4 - Re [10^5, $5x10^5$] are indicated in Table 3.2.

Re - C Tabulation			
		Re *(Reynolds Number)*	C *(Flow Coefficient)*
1	**RANGE 1**	100	0,8
2		200	0,812971
3		400	0,806876
4		600	0,798281
5		800	0,785102
6	**RANGE 2**	1000	0,77307
7		1500	0,751869
8		2000	0,734952
9		4000	0,702865
10		6000	0,687394
11		8000	0,678227
12		9000	0,667458
13	**RANGE 3**	10000	0,666282
14		20000	0,660299
15		30000	0,657816
16		40000	0,656247
17		50000	0,655292
18		60000	0,654473
19		70000	0,653995
20		80000	0,653586
21		90000	0,653245
22	**RANGE 4**	100000	0,652835
23		200000	0,650993
24		300000	0,650515
25		400000	0,650379
26		500000	0,650311

Table 3.2: Re (Reynolds Number) – C (Flow Coefficient) Data Set, Prediction of “C” of Orifice Plate for Different “Re” Values

The polynomial regression analyses of “Re” over “C” in the above-mentioned ranges are executed on *MathCAD 8.0* and they are presented in Appendices A-2, A-3, A-4 and A-5. As a result of numerical calculations provided in Appendices A-2, A-3 and A-4, relationships between *Re* and *C* for 4 of the ranges indicated in Table 3.2 are provided in Appendix F.

Substituting Equations 4.9 through 4.12 into Equation 4-8 resistance coefficient *K* becomes

$$K_{orifice} = \frac{1-\beta^2}{C(\text{Re})_i^2 \cdot \beta^4} \text{ ...... (Eq 4-13)}$$

Expression of resistance through points C and D consists of combination of Darcy-Weisbach equation and the geometric head in the line and it is expressed as;

$$R_{CD} = H_{geo} + \frac{v^2}{2 \cdot g}\left(\sum K + f\frac{L}{D}\right) \text{ [m]...... (Eq 4-14)}$$

Organizing Equation 4-14 by means of the flowrate (Q);

$$R_{CD} = H_{geo} + \left[\frac{\sum K}{1.62\times10^6 \times \pi^2 \times g \times D^4}\right] \cdot Q^2 + \left[\frac{f \cdot L}{1.62\times10^6 \times \pi^2 \times g \times D^5}\right] \cdot Q^2 \text{ [m]}$$

Simplifying the above expression R_{CD} is found as;

$$R_{CD} = H_{geo} + \left[\frac{\left(D \times \sum K\right) + f \cdot L}{1.62\times10^6 \times \pi^2 \times g \times D^5}\right] \cdot Q^2 \text{ [m] ...... (Eq 4-15)}$$

Where;

Q: Flowrate [m^3/h]

D: Pipe diameter [m]

g: Gravitational acceleration [m/s^2]

$\sum K$ is found adding the sum of resistance coefficients in series *K = 1.0* for sharp edged pipe exit as defined in Section 4.4.2.4 and $K_{orifice}$ where it is expressed as $\sum K = 1.0 + K_{orifice}$.

Substituting the relevant values in Equation 4-15 final expression of resistance between C and D becomes;

$$R_{CD} = 1.5 + \left[\frac{(0.0254 \times (1 + K_{orifice})) + 1.5 \cdot f}{1.62 \times 10^6 \times \pi^2 \times 9.81 \times (0.0254)^5} \right] \cdot Q^2 \text{ ...... (Eq 4-16)}$$

Introducing Equation 4-20 for *resistance coefficient K* pertaining to the restriction orifice and Equation 4-5 for *friction factor f* in resistance expression presented with Equation 4-16 the resistance characteristic of the line between points C and D is tabulated and the representative curve for the tabulated data is illustrated in (Appendix A-6)

A 2nd degree numerical expression is obtained for corresponding flowrates depending on only the flowrate (Q) using numerical results of flow resistances between points C and D in meters. Related polynomial regression analysis executed on *MathCAD 8.0* is presented in Appendix A-6.

As a result of numerical calculations provided in Appendix A-6, common flow - resistance expression for the subsystem between points C and D is obtained as follows;

$$R_{CD} = -0.214512 \cdot Q^2 - 4.336151 \cdot 10^{-3} \cdot Q - 1.496213 \text{ ...... (Eq 4-17)}$$

3.2.1.3 Resistance of Wedge Disc Throttling Valve (R_{MOV})

As discussed in Section 4.6.2 motor operated valve is separately modeled between points C and D. *K* changes as the valve is throttled which would mean that the throttling characteristic (change of *K*) is a unique property for any motor operated valve depending on its throttling resolution. In this regard change in *K* depending on the valve position feedback is illustrated separately in the software as a part of the study and the valve is assumed as fully open throughout the Chapter.

Expression of resistance through the valve only depends on *K* and it is expressed in a similar fashion with the previous sections as;

$$R_{MOV} = \frac{v^2}{2 \cdot g}\left(\sum K\right) \text{...... (Eq 4-18)}$$

Substituting the resistance coefficient *K* = *8f* for *wedge disc gate valve* presented in Section 4.4.2.1 into Equation 4-18, the resistance of MOV01 is obtained as follows;

$$R_{MOV} = \left(\frac{8f}{1.62 \times 10^6 \times \pi^2 \times 9.81 \times D^4}\right) \cdot Q^2 \text{...... (Eq 4-19)}$$

Introducing 8*f* mentioned in Section 4.4.2.1 for the *resistance coefficient K* pertaining to the fully open wedge disc throttling valve and Equation 4-1 for *friction factor f* in resistance expression presented with Equation 4-18 the resistance characteristic of the line between points C and D is tabulated and the representative curve for the tabulated data is illustrated in Appendix A-7.

A 2nd degree numerical expression is obtained for the corresponding flowrates by means of the flowrate (Q) using numerical results of flow resistances between points C and D in meters. Related polynomial regression analysis executed on *MathCAD 8.0* is presented in Appendix A-7.

As a result of numerical calculations provided in Appendix A-7, common flow - resistance expression for the motor operated wedge disc throttling valve is obtained as follows;

$$R_{CD} = -2.841019 \cdot 10^{-3} \cdot Q^2 - 1.215187 \cdot 10^{-3} \cdot Q + 2.398201 \cdot 10^{-4} \text{...... (Eq 4-20)}$$

3.2.1.4 Resistance Expressions for R_{EH}, R_{FI} and R_{GJ}

Sub-systems between points E and H, F and I, G and J consists of one size pipe, one hand operated ball valve and a 90° standard elbow with certain amount of geometric head as stated in Section 4.6. All three resistance expressions are derived from the following expression;

$$R_{EH} = H_{geo} + \frac{v^2}{2 \cdot g}\left(\sum K + f\frac{\sum L}{D}\right) \text{...... (Eq 4-21)}$$

Σ_K is the sum of resistance coefficients, which are connected in series between points two consecutive points. Σ_K times ($v^2/2g$) represents the head loss within the system due to the fittings, valves and other flow obstructions other than the straight pipes. In this regard Σ_K is expressed as;

$$\sum K = K_{pipe-in} + K_{pipe-out} + K_{HV} + K_{elbow}$$

Where $K_{pipe-in}$ represents the resistance coefficient for inward projecting pipe inlet from the collector, $K_{pipe-out}$ represents the resistance coefficient of pipe exit at each of three different elevations into the open header, K_{HV} represents the resistance coefficient of hand operated ball valve, K_{Elbow} represents the resistance coefficient of 90° standard elbow at the elevation of discharge. Using the resistance values provided in Section 4.4 the expression for total resistance coefficient is obtained as follows;

$$\sum K = 0.78 + 1.00 + 30f + 3f$$

$$\sum K = 33f + 1.78 \text{...... (Eq 4-22)}$$

Organizing Equation 4-21 by means of the flowrate (Q) and applying the same steps for obtaining Equation 4-15 the general expression for resistance expression between two consecutive points is obtained as follows;

$$R_{EH} = H_{geo} + \left[\frac{\left(D \times \sum K\right) + f \cdot \sum L}{1.62 \times 10^{6} \times \pi^{2} \times g \times D^{5}} \right] \cdot Q^{2} \text{ ...... (Eq 4-23)}$$

Where;

Q: Flowrate [m^3/h]

D: Pipe diameter [m]

g: Gravitational acceleration [m/s^2]

Resistance expression presented with Equation 4-23 is used for three parallel branches and tabulated data for all three of these lines are presented in Appendix-8 and the representative curves for the tabulated data are also illustrated in Appendix-8 as well. 2^{nd} degree numerical expressions are similarly obtained by means of the flowrate (Q) using numerical results of flow resistances between couple of points in all three branches. Related polynomial regression analyses executed on *MathCAD 8.0* are presented in Appendix A-8.

As a result of numerical calculations provided in Appendix A-8, common flow - resistance expressions for flow resistances between points E and H, F and I, G and J, are respectively obtained as follows;

$$R_{EH} = -0.05674 \cdot Q^{2} - 0.012608 \cdot Q - 0.467512 \text{ ...... (Eq 4-24)}$$

$$R_{FI} = -0.086521 \cdot Q^{2} - 0.025346 \cdot Q - 2.494998 \text{ ...... (Eq 4-25)}$$

$$R_{GJ} = -0.116581 \cdot Q^{2} - 0.038203 \cdot 10^{-3} \cdot Q - 4.492461 \text{ ...... (Eq 4-26)}$$

3.3 Graphical Representation of Flow Resistances as per Frey's Convention

R_{AB}, R_{CD} and R_{MOV} always act as the flow resistance within the system during pump is operating. There are 3 hand-operated valves, which allow 4 possible parallel operation variations. Also single branch operation allows 3 more possibilities. Namely there are total of 7 alternatives that could be achieved in this educational pump setup.

As soon as the characteristic curve of any pump, which is connected to this setup, is known, the operating points of those pumps and operational variables at each discharge point can easily be predicted by using the methodology discussed in Chapter 3. Resistance cases given in Appendices A-9 to A-15 derived from the numerical expressions presented in this chapter are then used for the proper selection of piping and instrumentation to be implemented into the system.

3.4 Results of Pilot Tests

Pressure differential across the flow restriction orifice having an opening ratio of 60% is used for flow rate monitoring. Pressure transducers mounted on specially machined adapters are threaded on each flange. The following relationship between the flow rate and differential pressure across the orifice is valid for the case [6] and expressed as

$$Q = \sqrt{\frac{2(P_1 - P_2)}{\rho \cdot K}} \cdot A_2 \quad \text{...... (Eq 5-1)}$$

where;

Q = flowrate [m^3/h]

P_1 = orifice upstream pressure [Pa]

P_2 = orifice downstream pressure [Pa]

ρ = density of the fluid

A_2 = cross-sectional area of orifice opening [m^2]

K = Orifice constant (Constant of proportionality)

A set of 5 trials are executed for flowrate identification at +2m elevation branch of the setup In order to identify the value of "K" and to calibrate the orifice. 4 of these trials resulted in reasonable values where one of them provided ambiguous figures which are caused due to the measurement errors, therefore this measurement is neglected. During filling of a bucket elapsed time and P_1 and P_2 pressures are measured as follows:

1) Since the pressure transducers generate analogue current outputs between the range of 4 and 20 mA (miliamperes) which correspond to 0 to 2500mbar respectively, signal range is converted to analogue voltage output range of 4 to 20 V (volts) by connecting proper resistances to the measuring points (linear regression). Calculated scale for voltage - pressure conversion is 156.25 [mbarg / Volt]. Voltages are read by handheld multimeters where each one is assigned to only one transducer to achieve the same amount of error at each transducer and in each trial after calibrating all 4 at the same time.

Voltages observed at either side of the orifice are, V_{in} = 5.96 Volt (V) and V_{out} = 4.62 Volt (V) for +2m circuit during normal operation

These voltage levels corresponds to the following pressure values

P_1 = (5,96V – 4,00V) * 156.25 mbar/V

P_1 = 306.250 mbar

and

P_2 = (4.62V-4.00V) * 156.25 mbar/V

P_2 = 96.875 mbar

2) 5 measurements are taken and weight of each bucket of water is obtained by using a weight measuring device indicating the 1/1000'ths of 1 kg. Data set is obtained as follows where empty weight of bucket (tare) is recorded as 0.620kg:

	Weight [kg]			Elapsed Time [sec]	Flowrate [m^3/h]	Error [%]
	Gross	Tare	Net			
1st Trial	15,300	0,620	14,680	15,410	3,429	0,321
2nd Trial	14,400	0,620	13,780	14,420	3,440	1,250
3rd Trial	14,720	0,620	14,100	14,940	3,397	0,883
4th Trial	14,400	0,620	13,780	14,420	3,427	0,058
Arithmetic Mean	_	_	_	_	3,424	_

Table 3.3: Pilot Test Results for Flowrate Prediction

The largest deviation in the above-mentioned measurements is between the 2^{nd} and 3^{rd} trial. Amount of deviation is,

$$\varepsilon = \frac{3.440 - 3.397}{3.440} \times 100 \ \% \qquad \varepsilon = 1.25 \ \%$$

Arithmetic mean of 4 measurements are found as Q_{mean} = 3.424 [m^3/h]

This flowrate value is considered as the actual flowrate through the branch at +2m elevation where P_1 is found as 306.250 mbar and P_2 is found as

96.875 mbar across the orifice (flow is circulated through +2m elevated branch)

Going back to Equation 5-1, substituting the above-mentioned values and solving it for "K" (orifice constant). The value is found as K = 4.28

3) Similar to the procedure at the 1st step only the voltages are measured for +4m and +6m branches to identify and to examine the flow passing through those elevations using the "K" value found in Step 2. Following voltage levels are measured and flowrates are predicted via Equation 5-1:

	Reference Voltage [V]		Corresponding Pressure [mbar]		Measured Flowrate [m^3/h]	Calculated Flowrate [m^3/h]	% of Flow Through Branch at		Orifice Constant "*K*"
	In	Out	In	Out			+2m	+4m	
+2m	5,96	4,62	306,250	96,875	3,4240	_	_	_	4,28
+4m	7,00	5,92	468,750	300,000	_	3,0736	~ 90	_	
+6m	8,00	7,20	625,000	500,000	_	2,6453	~ 77	~ 86	

Table 3.4: Orifice Calibration Readings for Orifice Constant Prediction

In the light of the above pilot experiments and the obtained figures, the results are found satisfactory. Hence "K" (Orifice Constant) value is implemented into the software for flowrate prediction and monitoring purposes.

CHAPTER 4

DESIGN OF PROCESS CONTROL HARDWARE AND SOFTWARE

4.1 Introduction

As mentioned in Section 1.3, Variable Frequency Drives provide relatively more efficient operation while used in pumping systems by means of the pump speed control. There are several methods, which may be applied to any pumping system for flow control. Common methods of doing so are the valve throttling at a fixed pump speed, flow bypass and pump speed control.

The least efficient way of controlling the flow in a pumping system is the flow bypass and it shall be avoided if possible. Using a throttling valve with a fixed speed pump is the most common way of controlling the flow; however any obstacle ahead of the flow results in head loss, which is a sort of energy dissipation (wasted energy). From this point of view, obtaining the required discharge capacity by pump speed regulation is the most efficient way of controlling the flow if all the required parameters are appropriate to do so. This would mean that even pump speed control has some limitations and deficiencies based on requirements of different processes. In the light of the above this study introduced the demonstration of combination of two methods *pump speed control* and *valve throttling* for different operating conditions and requirements.

The experimental system consisted of mechanical (piping, fittings, custom made motor operated valve), electrical and instrumentation elements which are either controlled or governed by a supervisory software. The software provides an interface as well as a framework which analyses and processes the signals acquired from the instruments which are first converted into a digital format by the custom made circuitry.

There are 2 main modules of the software achieves both pump speed and valve-throttling control as explained in this chapter. The software also provides the means of visualization for the comparison of constant pump speed throttling control and variable speed pump control.

4.2 Design and Construction of Hardware

4.2.1 Pressure Transducers

In conjunction with the nominal flowrate value of Q = 5.04 [m^3/h] mentioned in section 4.4.1 and the case studies presented in Appendices A11 to A17 constituted the pressure transducer selection criteria. Mentioned cases indicated that the pressure levels encountered in the system would be between 0.9 barg and 1.25 barg at nominal flowrate. Looking at the said cases, even at 140% of the above-mentioned nominal flowrate value, the pressure levels encountered in the physical system are expected to be less than ~2.2 barg.

4.2.1.1 Design Requirements and Selection Criteria

In the light of the findings summarized in section 6.1 above, WIKA Eco-1 Transducers are selected from manufacturer’s catalogue out of a variety of pressure ranges. Pressure range of the selected transducers is 0 to 2.5 barg.

Minimum differential pressure which could be sensed by these transducers is 0,025m as per their datasheets however this value is considered as 0,030m where required. Selected transducers provide signal outputs within the range of 4 - 20 mA for 2-wire connection option which is also the applied as the connection option for the actual system studied. Also the analogue output signal ranging between 4 -20mA corresponds to 0 - 2.5 barg for this type of transducer. Schematic representation of above-mentioned 2-wire connection is illustrated in figure 4.1.

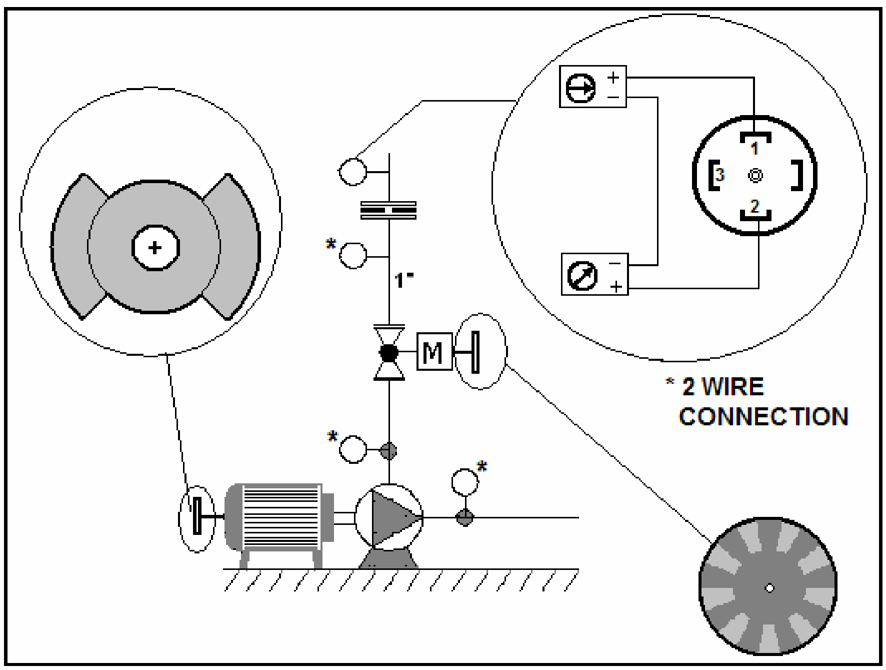

Fig 4.1: Transducer 2-Wire Connection & Encoder Discs

4.2.2 Orifice Plate

Flow restriction orifice is designed and machined with an opening area of 60% of the cross sectional area of the piping where it has been assembled in. Friction loss calculations are executed by taking this value into consideration where it is later used for the prediction of flowrate value as discussed in section 5.5.

4.2.2.1 Orifice Flanges and Adapters for Orifice Transducers

Orifice flanges are counter-bored and threaded (also drilled up to process line) where they are later assembled with the hexagon headed transducer adapters which are designed and machined specifically for ¼"NPT process connections of WIKA ECO-1 pressure transducers as seen in figure 4.2.

Fig 4.2: Orifice Flanges and Transducer Adapters

4.2.3 Motor Operated Throttling Valve

As a part of this thesis study, an operative DC motor actuated throttling valve is completely designed and constructed using a manually operated gate valve and a DC motor as the actuator which is furnished with a gearbox as well.

At the initial stage of the design of motor operated valve (MOV) several different design alternatives are examined. For example, a ball valve and a servo motor are considered for the design of the MOV as seen in figure 4.3. However this option introduced several problems where relatively high torque requirement of the ball valve has been in contradiction with the torque output of the servo motor. Later a gearbox is introduced into design in order to overcome the difficulty mentioned above. Consequently it is emerged that the angle being traced would be only 90° with a ball valve which would result in several throttling control pitfalls when considered in conjunction with the assembly difficulties (Fig. 6.4) and torque related problems of this alternative.

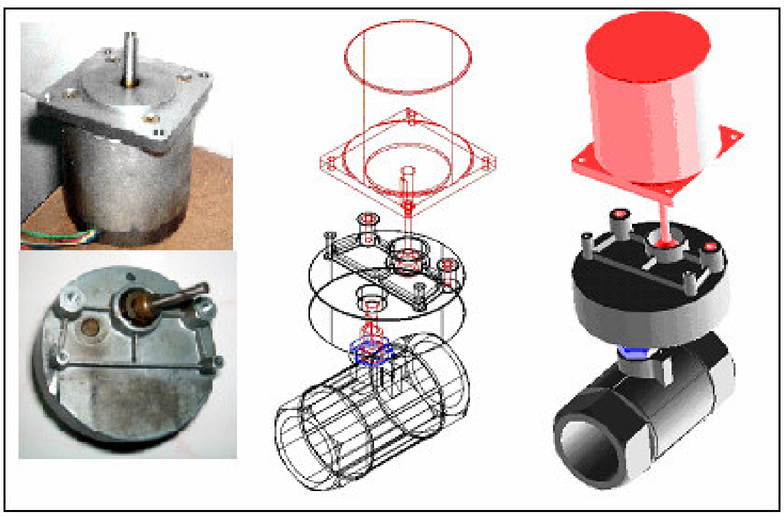

Fig 4.3: Servo Motor and Ball Valve Alternative

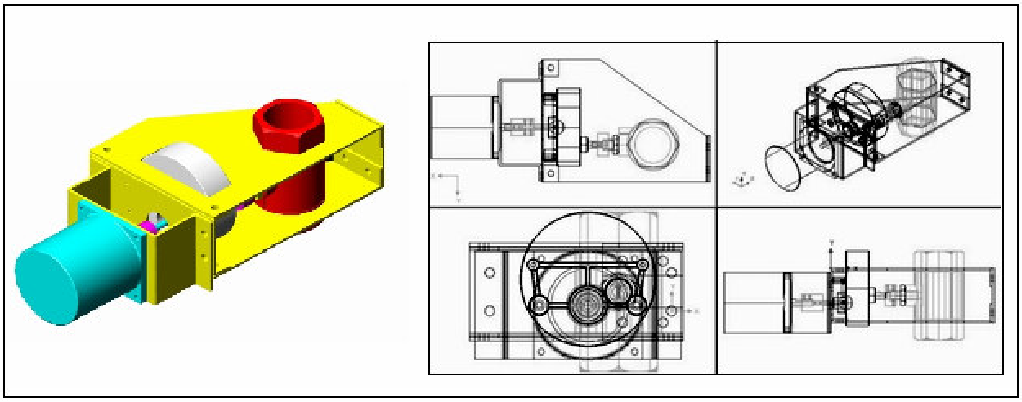

Fig 4.4: Assembly of Servo Motor, Gearbox and Ball Valve

4.2.3.1 DC Motor and Manually Operated Wedge Disc Throttling Valve

Although servo motors and stepper motors had good controllability and response characteristics for the position inputs, they are eliminated due to the reasons explained in section 6.2. Consequently a 24VDC e-motor having an integrated gearbox is used for the further construction of the MOV. Also a PN 16 wedge disc valve is preferred which has 6 complete revolutions (2160^o) along its stroke between closed and fully open positions instead of using a ball valve which only has a controllable angle of 90^o rotation between its fully closed state and fully open position. It is also noted that the torque needed to drive the mechanism of wedge disc valve is relatively low (where rotational movement is converted to linear movement of the disc) compared to the torque needed to move the mechanism of ball valve.

Also shaft coupler (assembly of valve shaft and driving end of DC motor) and 4mm stainless steel valve assembly frame (laser-cut, formed by a bending press) are specifically designed and fabricated to form the final valve assembly as seen in figure 4.5 below.

Fig 4.5: DC Motor Operated Wedge Disc Throttling Valve with Position Feedback

4.2.3.2 Valve Position Encoder

Ease of servo motor control comes from the use of ready to use subroutines which might have been facilitated in PIC algorithms. These subroutines allow the programmer to give the angle of servo motor rotation and the required time to finish the identified amount of rotation. However DC motors only may be driven by applying the required voltage to its poles. In order to reverse the direction of rotation the polarity should be reversed. Also the applied voltage needs to be cut-off if the rotational movement should be stopped.

As discussed above using a DC motor as the actuator came with the disadvantage of loosing the built-in valve position control feature which the servo motor might have brought as an advantage. Therefore an alternative encoder solution for the identification of valve position is introduced during the design of MOV constructed as a part of the thesis study.

In order to achieve valve position control, a disc made from printed circuit board (PCB) and an IR switch (transistor) are used for the valve position encoder. It is observed that most of the PCB's allow the infra red light to pass through the unprinted layers of PCB easily during the studies where PCB discs having different fin numbers is produced and tested in the MOV system as illustrated in figure 4.6. PCB encoder disc (9 fin version) is tightly mounted onto the valve shaft in order it to follow the valve rotation without slippage.

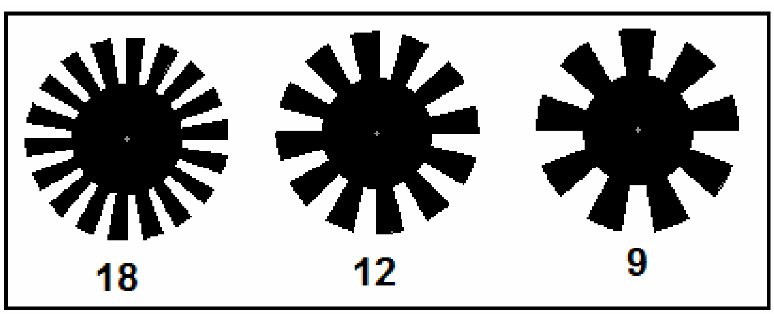

Fig 4.6: PCB Encoder Discs with Different Number of Copper Plated Fins

As the PBC encoder disc revolves together with the valve shaft each successive fin passes through the gap between the emitter (diode) and receiver (transistor) sides of the IR transistor. Each analogue signal generated by the movement of fins corresponds to logical 1 and 0 states. If the rotation starts algorithm in PIC, which is allocated for valve position control, checks the polarity of the motor by means of pin states of the PIC as illustrated in figure 4.7. Algorithm then decides upon whether the valve is being closed or opened and sets the direction variable as 1 or -1 depending on the direction of rotation. This variable is then processed by the valve control PIC to register the actual valve position in EEPROM of the PIC for further use.

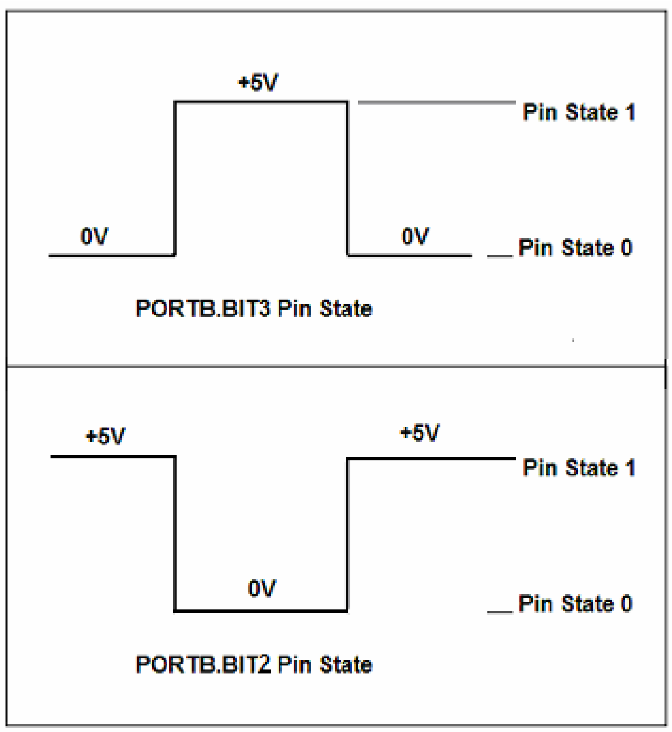

Fig 4.7: PortB.BIT3 and PortB.BIT2 Pin States of PIC16F628

Considering the 6 complete revolutions (360^o each) for the valve selected for this study and the 9-finned PCB encoder disc the total number of achievable valve positions corresponds to the multiplication of number of the revolutions with the number of printed copper fins on the PCB encoder disc. In this regard, 9 fins times 6 revolutions provided 54 different achievable valve (flow restriction disc) positions along the stroke of the motor operated valve where it is limited between 7 and 54 by means of the algorithms.

In order to be able to control the motor in both directions an H-Bridge is also used in the circuitry via use of 4 Metal Oxide Silicon Field Effect Transistors (MOSFET's) which are considered good for this service [10] (NPN Transistors and/or N-Channel MOSFETS).

One high side MOSFET driver which control the positive voltage to the motor (or sourcing current) and one low side MOSFET which sinks the current to the motor enables constituting a +18VDC bridge between (+) and (-) sides of the DC Motor which causes it to rotate forward. Similarly by the help of one high side MOSFET driver providing a +18VDC voltage to the (-) side of the motor and by one low side MOSFET which sinks the current to the DC motor from its (+) side cause the motor rotate backwards. By the help of the H-Bridge designed and built in the circuitry as explained above provided the bi-directional rotation feature for the throttling valve DC motor by means of reversed polarity.

Also the common block diagrams and PCB schematic drawings of the MCC circuitry as illustrated in figure 4.8 are generated using the shareware software package for the PCB Design & Layout Printing and Plotting which is called as CIRCAD-8. Also the subroutines included in the PIC Microcontrollers are generated in M-Basic language and complied via M-Basic Rev 5.2 compiler interface [12].

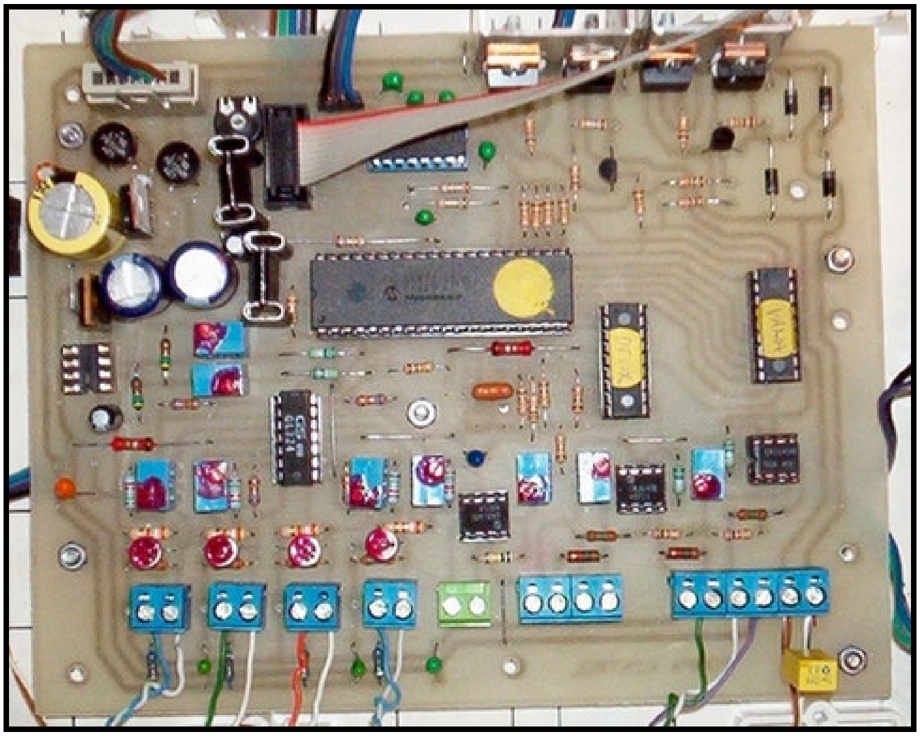

Fig 4.8: Plan View of Main Control Circuit (MCC) Board

4.3 Basics of Process Control Software

4.3.1 Throttling Control

Throttling control may be achieved by the use of control valves. For good controllability, the control valve is usually sized to pass the required flow with a pressure drop equal to the system head losses excluding the control valve. Varying the pressure drop across the valve controls the flow.

Bypass lines are not considered in the educational setup, therefore completely closed position of control valve is avoided by means of position feedback and position control. Also the range of the control valve and its control resolution are important parameters during the operation of physical setup. Thus, if the maximum flow required passing through the flow control valve is known then minimum controllable flow using the motor operated control valve can be predicted and used for further processing in decision making while the software is being developed further.

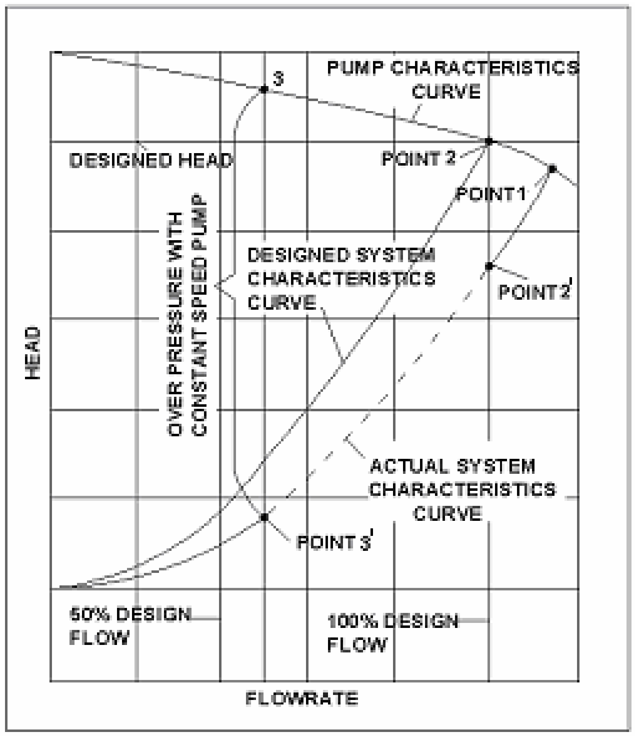

Fig 4.9: Pump operating points and valve throttling control

If the actual system curve turns out to have a lesser slope than what is assumed for the system curve in the design phase, the pump will end up operating at point 2' instead of at point 2 (Figure 4.9). In such a free-flowing system, the actual head will be lower and the actual flow will be higher than is designed. If the flow is controlled by throttling a control valve on the pump discharge, the pump will operate at point 2, and the differential head between point 2 and 2' will be dissipated in the form of pressure drop. If the system flow is reduced to 50%, the energy wasted in the form of valve pressure drop will increase to the differential head between points 3 and 3'.

In Figure 4.10, the useful pumping head is up to point 2', and the actual pumping head of the throttled system is the ordinate of point 2. The difference in between these points identifies the energy wasted through throttling. This is only part of the total loss of efficiency. As can also be seen in Figure 4.10, moving the operating point from 1 to 2 also reduces the pump efficiency to some extent.

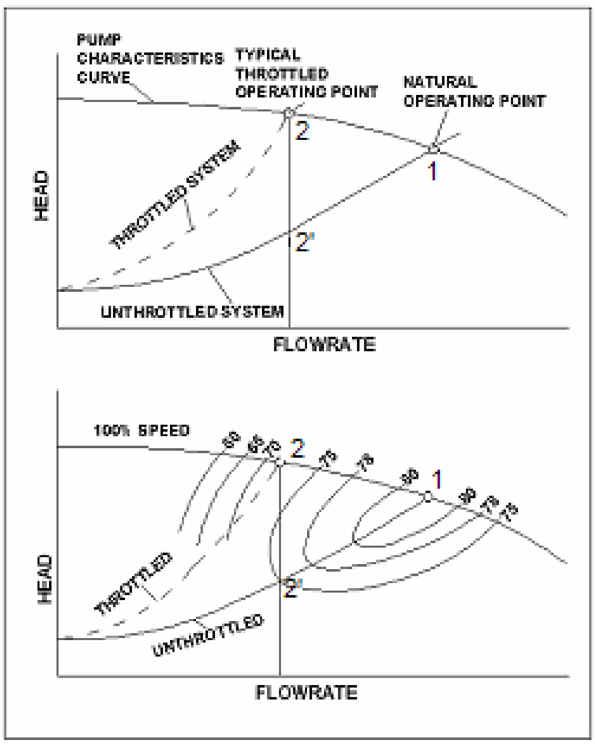

Fig 4.10: Efficiency change due to valve throttling control

4.3.2 Pump Speed Control

Flow control via speed control is less common than throttling with valves, because most of the AC electrical motors are constant-speed devices. In order to vary pump speeds with electric motors, it is generally necessary to use a variable-speed device in the power transmission line.

As shown in Figure 4.11, when the flow is reduced from Q_1 to Q_2, instead of wasting the excess pump head of (H_2 - H_1) in pressure drop through a valve, that pump head is not introduced in the first place. Therefore, speed throttling saves energy that valve throttling would have wasted.

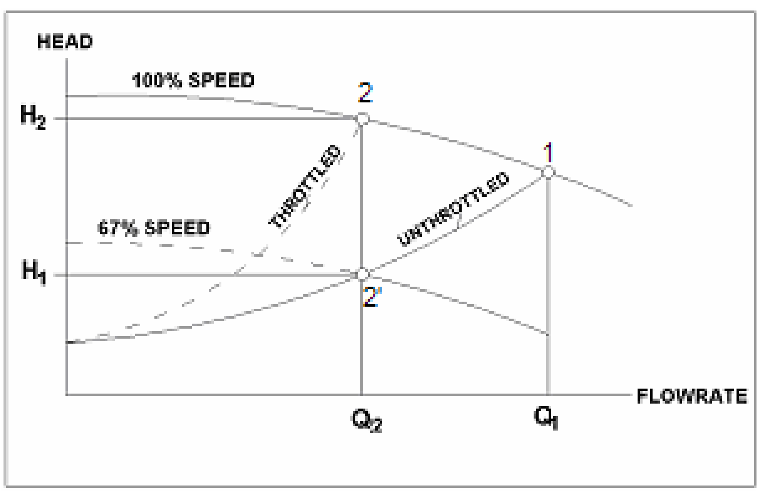

Fig 4.11: Energy Saving by Variable Speed Pump Operation

4.3.3 Switching between throttling and variable-speed operation

The shape of the system curve determines the saving potentials of variable-speed pumps. All system head curves are naturally parabolas, but they differ in the steepness and in the ratio of geometric head to frictional head drop. As shown in Figure 4.12, the value of variable-speed pumping increases as the system head curve becomes steeper.

In Figure 4.12 the shaded areas identify the energy-saving potentials of variable-speed pumps. The values of H_t and H_s are identified by determining their intersections with the pump and system curves. The larger the shaded areas in Figure 4.12, the higher the H_t/H_s ratio will be obtained and, therefore saving potentials will be increased.

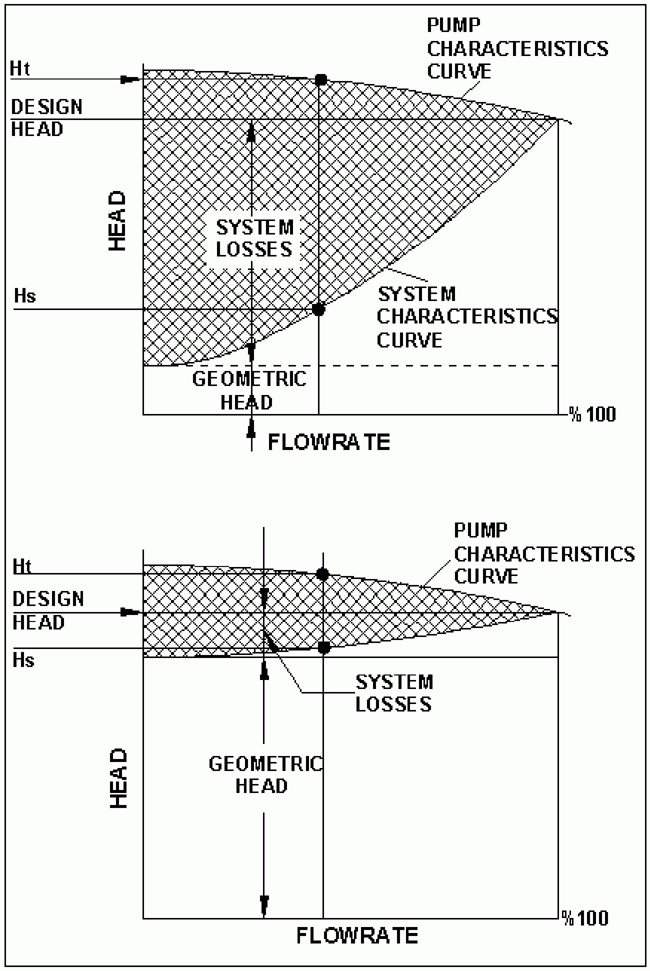

Fig 4.12: Ht / Hs ratio and variable speed operation

4.3.4 Modules of the Computer Program

Computer program provides an interface to control several parameters including flowrate, pump speed, valve position. As discussed through previous chapters variable frequency drive and motor operated gate valve provide the means of the said control in the physical system. Basics of the program are summarized throughout this section since the software is designed to be self explanatory by guiding the user in each step with clear and understandable set of instructions and via simple and user friendly interactive controls.

Any manipulation on the parameters discussed above using the software interface, results in various responses in the system (i.e. run at desired flowrate, throttle valve to desired position, change pump speed).

This program can be uploaded to a server which enables users to access the executable part of the software via worldwide web (www) and/or via local area network (LAN). However this system being the subject of study requires a Master PC with Control Program (PABLO: Pump Automation for Bench Level Operation) installed on it, to exist within the asynchronous data transmission distance limits of RS232 Serial Communication Circuitry (via DB9 serial cable connection between the MCC and PC). Hence, remote operation of the physical system via web may be a further step of another study introducing synchronous data transmission by the help of handshaking routines and protocols added to the source code during the code development and amendment of circuitry.

Above-mentioned introduction page guides the user through start-up options providing the necessary instructions prior to starting of the pump, plugging the MCC to power source and switching it on. This introduction page is illustrated in Figure 4.13 below.

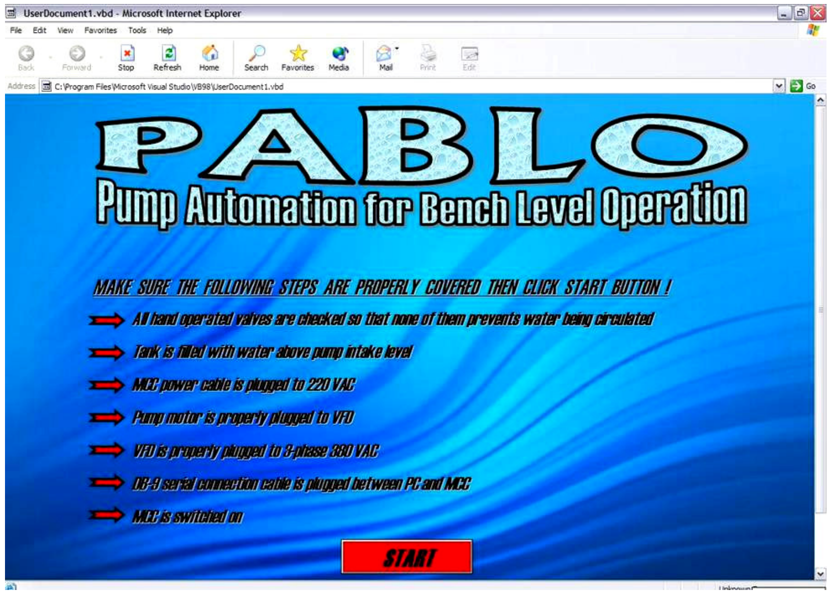

Fig 4.13: Introduction Page in Internet Explorer

Instructions to be followed prior to starting the program which are shown on Introduction Screen illustrated in figure 4.13 are as follows:

1) All hand operated valves are checked so that none of them prevents water being circulated
2) Tanks is filled with water above pump intake level
3) MCC power cable is plugged to 220 VAC source
4) Pump motor is properly plugged to VFD
5) VFD is properly plugged to 3-phase 380 VAC source
6) DB-9 serial connection cable is plugged between PC and MCC
7) MCC is switched on

4.3.5 Start-Up Options

There are two start-up options which can be accessed by the user. These two options allow users to start the system either via testing sequence step or using direct running module which may be called as *free run* mode. Mentioned interface screen is illustrated in Figure 4.14 below.

Fig 4.14: Start-Up Options Page

4.3.6 Free Run Module

Basically free run module allows users to make operational adjustments on several parameters such as valve position, pump speed and flowrate without monitoring the actual pump/system characteristics and change of operating point with time. Namely this module solely provides indication of operating point information (i.e flowrate, Q_i and pump head, H_i, pressure transducer readings, encoder readings etc.) at that instant using online instrumentation/encoder periphery. This enables the user to run the system and send commands to fully operational equipment through built-in controls without gathering pump and system characteristics first. Hence this module provides the means of checking functional performance of electrical and mechanical equipment without executing and passing through a data acquisition and numerical model building session.

Relevant commands are sent via button controls for valve position, pump speed and flowrate. Any change in the said parameters sent by the event of clicking a command button runs a subroutine which then sends the digital new value of relevant attribute to MCC and relevant PIC(s) accordingly via serial link established between the PC and RS232 integrated circuitry on the MCC. Digital bid received by the Master PIC is interpreted and converted to an equivalent analogue voltage signal which is later properly amplified (in-circuit amplification) and sent to the relevant equipment being targeted. Similarly analogue signals from instrumentation received by the MCC is converted to an equivalent digital value by its relevant PIC (speed and valve signals are processed in their own PIC's which are in fact slaves of the master PIC) and sent to Master PIC for further processing and transmission to PC for hydraulic calculations and for comparisons. A schematic representation of mechanical and electronical periphery of the whole system is illustrated in Figure 4.15. Relevant block diagrams of the above-mentioned in-circuit signal processing are provided in Appendix B.

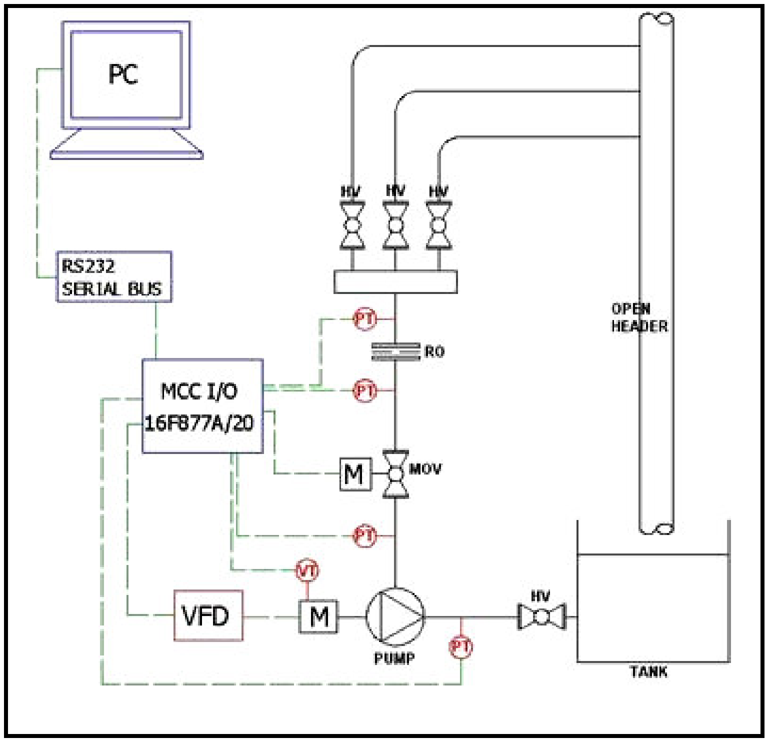

Fig 4.15: Schematic Representation of Complete Setup

4.3.7 Test Module

Test module of the software provides the means of adaptation of the *pump and system characteristics monitoring algorithms* to any system configuration regardless of changes in the geometric head, and the configuration changes in piping and fittings inventory (provided that the test sequence is restored after the case of the said changes).

Pump start and system testing sequences are represented in the following flow charts which summarize the basics of the program constituting the logic behind pump start and system test sequences.

Also the system limitation and optimization of operating conditions by means of the methodology discussed in Section 2.6.1 (fixed loss efficiency) is given as a recommendation for future work, further study and development of the software (add-on features), which has an open modular code structure.

After starting the pump, the system test sequence can be initiated using the built–in interface of the software. Basically the system test sequence calculates and stores the physical quantities needed to identify the operating points of the pumping system where they are later converted to common numerical formulae which are used for real-time monitoring of the operating point of the system. Test Sequence interface is illustrated in Figure 4.16.

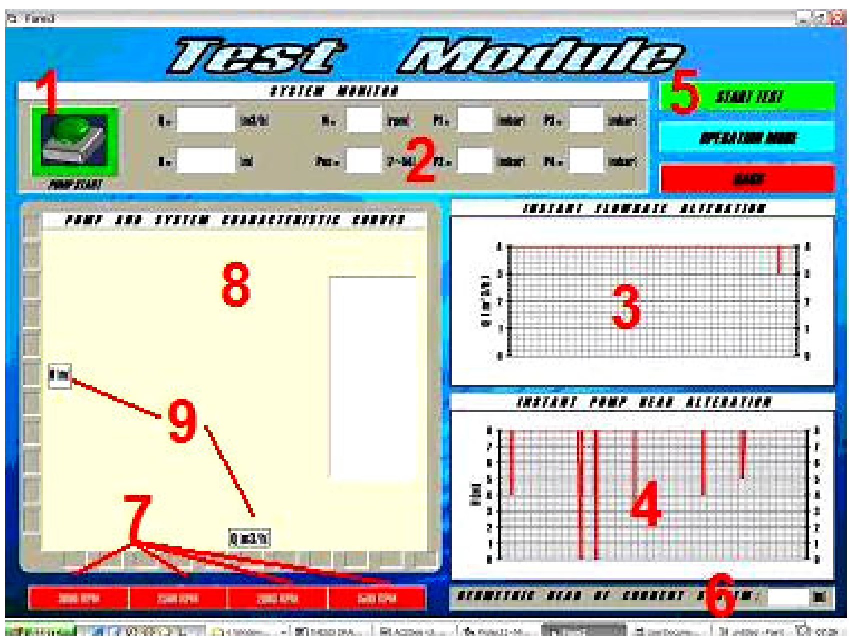

Fig 4.16: Test Sequence Screen

Accuracy of the transducers utilized in the system is ≤ 1.0 in % of span at limit point calibration (where range of measurement is 0 to 2500 mbar for WIKA Eco-1 Transducer as per the data sheet of the manufacturer). Therefore measurement resolution of the transducers corresponds to 0.025m where measuring range is 0 to 25m. Minimum differential of pressure which could be sensed by these transducers is taken as 0,030m to be on the safe side for limit point calibration.

Testing session of the operational system and the pump running at a preset speed by the initiation of "pump start" button is later controlled by the system test sequence algorithm (by clicking "*Start Test*" button). The necessary steps are illustrated in Figure 4.16. and summarized step by step as follows:

1) After initiating the test sequence screen the items 2, 3 and 4 which are the system monitor panel, real-time flowrate plotter and real-time head plotter respectively in figure 4.16 would stay still until the pump (e-motor) is started by clicking button control 1 in figure 4.16. Clicking button 1 which is tagged as "pump start" and colored green while pump is not running would turn into red and would be tagged as "pump stop" which provides the means of emergency stop utility as illustrated in figure 4.17 as item 1. Algorithm sets the MOV to fully open position (Position 54) and sets the pump speed to a preset value and makes sure that all the transducers indicate positive gage pressures (in order to take the geometric head measurement later). It also compares each successive transducer reading with the previous reading and waits until the reading differentials fit into the preset levels (pressure reading reliability achieved, system is filled and pump is primed).

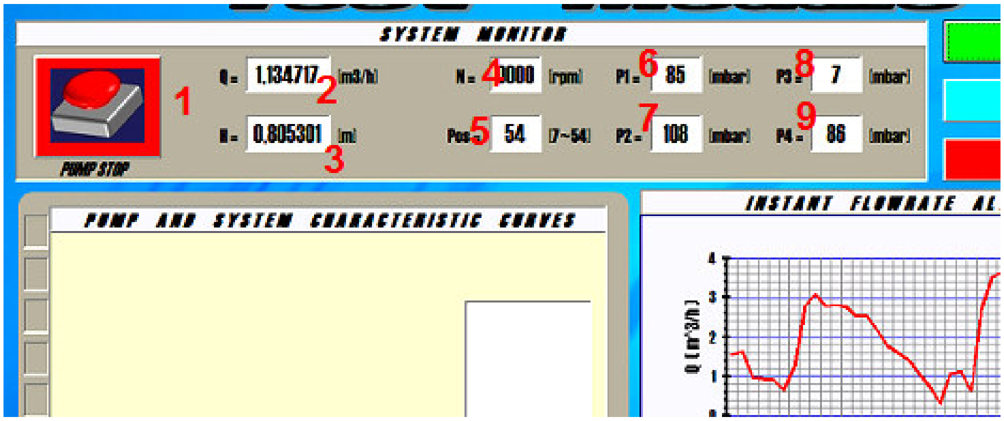

Fig 4.17: System Monitoring Panel

2) After pump starts running and water is being circulated in the loop, the system monitor panel illustrated in figure 4.17 starts monitoring the real-time operational data collected from the instrumentation. All pressure values which are converted to mbar (centimeters of water column) from the signals retrieved from 4 transducers are monitored in cells 6, 7, 8 and 9 as illustrated in figure 4.17. P1 in cell 6 corresponds to the inlet pressure of the orifice where P2 in cell 7 corresponds to the pressure at the outlet port of orifice. Similarly P3 indicated in cell 8 corresponds to the suction side pressure of the pump where the value indicated in cell 9 corresponds to the discharge side pressure of the pump. Instant value of flowrate in m^3/h is indicated in the cell numbered as 2 making use of the signals retrieved from the orifice transducer couple. At the same time, instant value of head delivered by the pump is indicated in cell 3 in meters of water column which is in fact defined as $\frac{N \times m}{N}$ (Amount of energy transferred to per unit weight of the fluid being pumped)

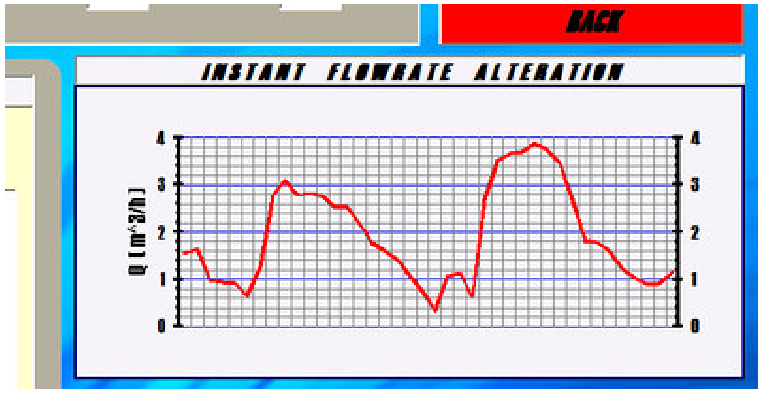

Fig 4.18: Real-time Flowrate Plotter

As the system monitor starts to indicate numerical values of real-time operational data in Fig.4.17, Instant Flowrate Alteration Screen in figure 4.18 and Instant Pump Head Alteration Screen in figure 4.19 start providing visual indication of changes in the values of flowrate and pump head.

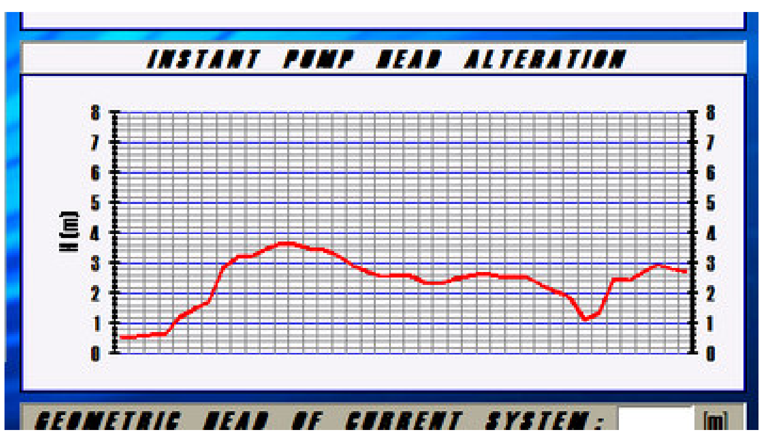

Fig 4.19: Real-time Pump Head Plotter

After step 2, pumped fluid reaches to a certain discharge height depending on which hand operated ball valve(s) is locked open initially (i.e. +2m, +4m or +6m). After filling the lines, clicking “start test” button control initiates the test sequence first by taking the geometric head value of the system (pump stops as the test starts). Algorithm compares each successive transducer reading with the previous reading and waits until the reading differentials across the orifice fit into the preset levels. Algorithm then takes the geometric pressure reading sensed by one of the transducers caused by the water column above it (by the help of non-return check valve at the discharge side of the pump) and decides upon the branch at which height is left open (or the highest branch during multiple branch operation). During this step the geometric head of the system (H_{geo}) is identified and first data point (zero flow) for the system characteristics curve is found which ends the first phase of the testing sequence. Then testing sequence is paused by the algorithm until the user starts the second phase by clicking the first of the 4 button controls in figure 4.16 (item 7) which are not enabled until the H_{geo} is identified successfully.

Each of these 4 buttons in Fig 4.16, (Item 7) starts an individual constant pump speed (i.e. 3000rpm, 2500rpm, 2000rpm, 1500rpm) valve throttling loop at certain valve positions (i.e. 54, 45, 35, 26, 16, 7) which are identical for each loop (each pump speed) as illustrated in figure 4.20 below.

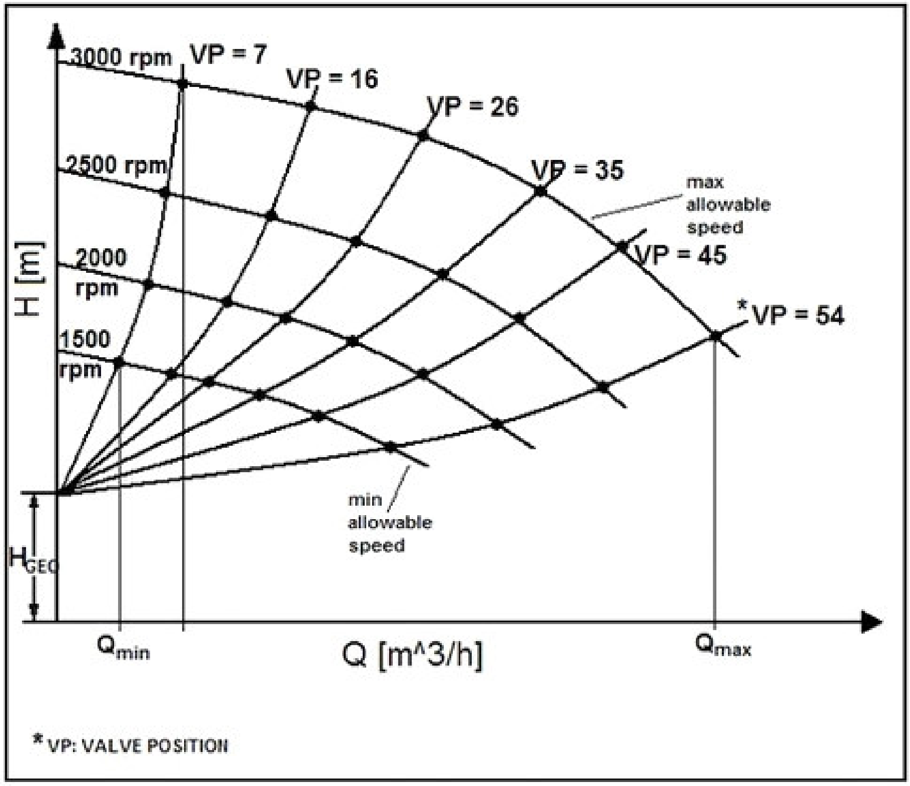

Fig 4.20: Data acquisition and system recognition

3) By clicking the button which initiates the first loop at highest speed (i.e. 3000 rpm) at fully open valve (valve position 54), the algorithm sets the speed to maximum allowable (Fig. 4.20) takes the measurements (pressure, speed, valve position) perform the calculations (flowrate, Q and head, H) and registers the results in database for further numerical analyses and curve fitting. Algorithm throttles the valve to the next preset valve position which is 45 as shown in figure 4.20 and performs the same operations as the ones done for the previous operating point. As the valve is throttled to position 7 and the last (6th) operating point is identified algorithm stays still until the next

constant speed valve throttling loop is initiated by the user by clicking the next button control in figure 4.16 (item 7).

4) Algorithm decreases the speed of the pump by a preset increment and takes the measurements which are similar to the ones in Step 3 and records the data points for further processing by initiating each individual loop using all 4 button controls shown in figure 4.16 (item 7).

5) Speed reduction, valve throttling and measurement loop is repeated until all of the 24 pump operating points are registered for further processing by means of the required hydraulic data.

6) Parsing through steps 3 to 5, the test sequence algorithm gathers all the necessary operational data for the development of numerical models and curves pertaining to the pump and system characteristics on Q - H plot area (limited by the allowable operational boundary values). Q - H plot area is illustrated in figure 4.16 (item 8) where flowrate and head value increments (item 9 in figure 4.16) are scaled by the program as per the operational data acquired during the test sequence.

7) Testing algorithm stops the pump and sets MOV to fully open position and waits for user input to proceed with the next mode which is called as the *pump operation module*.

4.3.8 Pump Operation Module

In contrary to *free run* module discussed in Section 5.5.2 *actual run* module monitors the actual pump/system characteristics and real-time change of operating point using the equations developed in *test sequence* module by the use of numerical methods adapted to programming subroutines, such as 3rd Order Curve Fitting and Gauss-Jordan method. Hence this module utilizes the means of decision making process between throttling and speed regulation to achieve a user-defined target operating point (prediction of head at a certain flowrate requested by the user). Namely this module allows user to observe and compare the predicted and actual values of parameters of any kind.

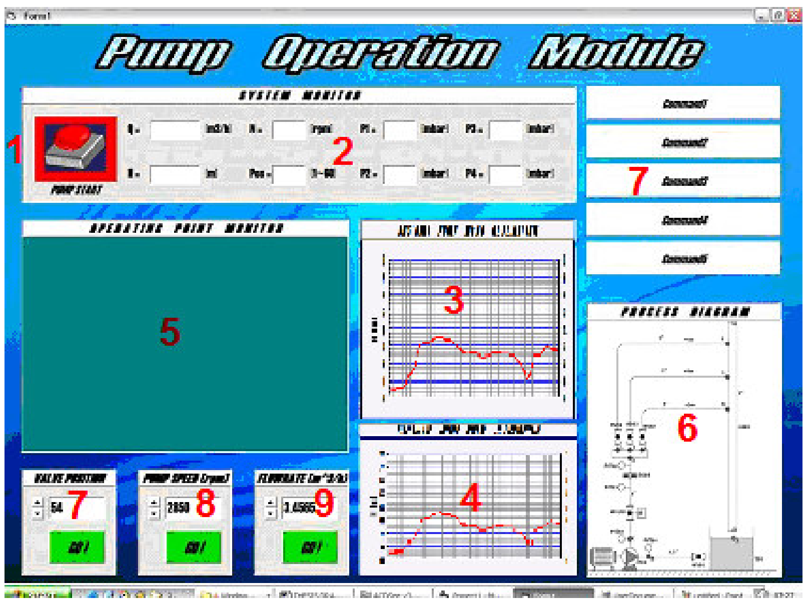

Fig 4.21: Pump Operation Module

Similar to *free run* module discussed in Section 5.5.2 *pump operation module* allows relevant commands being sent via button controls for valve throttling, pump speed and flowrate regulation and a similar hardwired signal flow is valid among the MCC and the PC in this module as well. This module also has some similar monitoring features like the test module discussed in section 5.5.3.

4.3.8.1 Common Monitors in Pump Operation Module

Operating point monitors integrated into pump operating module which are common with the previous modules are items 2, 3 and 4 in figure 4.21 and they are discussed in previous sections.

Nevertheless, operating point monitor (item 5 in figure 4.21) provides visual indication for the instant location of operating point (via use of flowrate, Q and pump head, H, pressure transducer readings, encoder readings etc.) at all times. Process diagram shown in figure 4.21 (item 6) is a schematic representation of the physical system where the process parameters are also monitored on pertinent sections of the diagram.

4.3.8.2 Common Controls in Pump Operation Module

Similar to the previously discussed modules, pump start and stop button control (item 1 in figure 4.21) exists in pump operation module as well.

Button controls grouped and illustrated as item7 in figure 4.21 are common controls providing the means of parsing through the screens (modules), terminating the session and/or program, recording and preparing the operational data for output, changing the attributes of the graph in operating point monitor (item 5 in figure 4.21) etc.

Common controls illustrated as items 7, 8 and 9 in figure 4.21 are valve position control, pump speed control and flowrate control panels respectively. Each of these controls have the indication of parameters which might be changed by the built-in “up-down” controls within the preset intervals and increments or steps (i.e 7 to 54 valve positions with 1 step increments for valve position control). As the user changes the value of each attribute the corresponding cell indicates that value which would be achieved by clicking the corresponding execution buttons tagged as “*GO*” in each panel.

4.4 Flowcharts of the Test Module

In order to visualize the programming logic of the test module relevant flowcharts are provided in the appendix whereas flowcharts for free-run and pump operation modules are excluded since they are designed as self explanatory modules running on a basis of distinct command and response chains.

CHAPTER 5

DISCUSSION, RECOMMENDATION FOR FUTURE WORK, AND CONCLUSION

5.1 Discussion

The aim which also formed the title of this study has been covered by most of the aspects of the design and construction of a pumping system including implementation of fully operational controls which would later be used for educational and practical purposes.

Since it is intended to visualize the basics of a pumping system as a part of this study as mentioned above, solely a minor part of the known and common information pertaining to the theory of hydraulic machines is discussed throughout the foregoing sections for clarity and integrity. In this regard the sum of efforts made for this study, which is required to achieve the identified aim, moved it to a multidisciplinary basis which is composed of the basics of the following disciplines:

- Hydraulics Theory
- Material Selection Criteria
- Manufacturing Processes (Traditional and Non-Traditional)
- Basics of Mechanisms
- Basic of Metrology
- Knowledge of Process Instrumentation
- Software Design
- Numerical Computing

- Knowledge of PIC Microcontrollers
- Basics of the Electronics
- Basics of Asynchronous Data Transfer

5.2 Conclusion

As mentioned previously the computer program provides an interface to control the several parameters including flowrate, pump speed and valve position easily depending on the process parameters. However much it sounds like a cliché the software in fact provides a clear set of feedbacks and outputs guiding the user in each step with understandable set of instructions via its simple and user friendly interface. From this point of view and in the light of the discussions summarized in section 7.1 the pump bench automation package as a whole would provide a handy tool for the intended practical purposes.

In addition to the foregoing the program can be uploaded to a server which would enable the users to access the executable part of the software via worldwide web (www) and/or via local area network (LAN). However this system requires a stationary Master PC with the executable Control Program (PABLO: Pump Automation for Bench Level Operation) nearby the asynchronous data transmission distance limits of RS232 Serial Data Transfer (via DB9 serial cable connection between the MCC and PC). Hence, remote operation of the physical system via web is recommended as a further study introducing synchronous data transmission by the help of handshaking routines and protocols added to the source code during the code development and amendment of circuitry.

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APPENDIX A1

POLYNOMIAL REGRESSION FOR FLOW RESISTANCE R_{AB}

REGRESSION OF FLOW RESISTANCE Rab

$$data := \begin{bmatrix} 0.25 & -0.000926626761670898 \\ 0.5 & -0.00325860793846393 \\ 0.75 & -0.00687675528714847 \\ 1 & -0.0117380704966496 \\ 1.25 & -0.017818654221764 \\ 1.5 & -0.0251031766869097 \\ 1.75 & -0.0335809935658784 \\ 2 & -0.0432443232062413 \\ 2.25 & -0.0540872646495167 \\ 2.5 & -0.0661052179681807 \\ 2.75 & -0.0792945188930386 \\ 3 & -0.0936521968037838 \\ 3.25 & -0.109175808069057 \\ 3.5 & -0.125863317611546 \\ 3.75 & -0.143713012530285 \\ 4 & -0.162723437712431 \\ 4.25 & -0.182893346933128 \\ 4.5 & -0.204221665113967 \\ 4.75 & -0.22670745877985 \\ 5 & -0.250349912643459 \\ 5.25 & -0.275148310839404 \\ 5.5 & -0.301102021734399 \\ 5.75 & -0.328210485521131 \\ 6 & -0.356473204002714 \\ 6.25 & -0.385889732118132 \\ 6.5 & -0.416459670863826 \\ 6.75 & -0.448182661344161 \\ 7 & -0.481058379741601 \\ 7.25 & -0.515086533041475 \\ 7.5 & -0.550266855379841 \\ 7.75 & -0.586599104909009 \\ 8 & -0.624083061095552 \end{bmatrix}$$

$X := data^{<0>}$ $Y := data^{<1>}$ $n := rows(data)$

$k := 2$

$n = ▮$

$z := \text{regress}(X, Y, k)$

$\text{fit}(x) := \text{interp}(z, X, Y, x)$

$\text{coeffs} := \text{submatrix}(z, 3, \text{length}(z) - 1, 0, 0)$

$$\text{coeffs}^T = \begin{bmatrix} 1.224571 \cdot 10^{-3} \\ -3.750749 \cdot 10^{-3} \\ -9.306268 \cdot 10^{-3} \end{bmatrix}$$

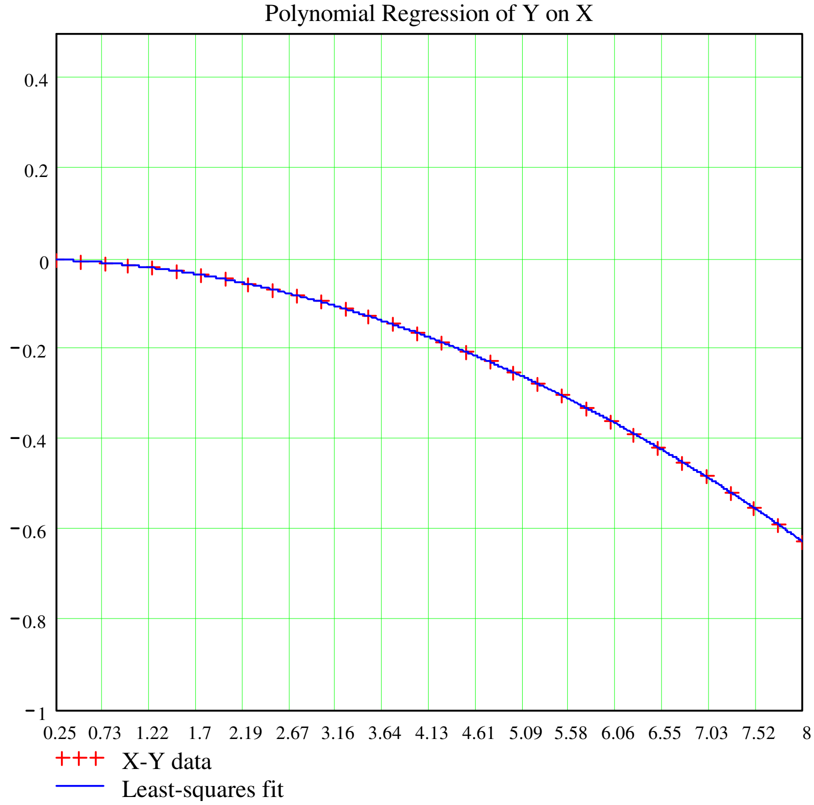
R^2:

$$\frac{\sum \overrightarrow{(\text{fit}(X) - \text{mean}(Y))^2}}{\sum \overrightarrow{(Y - \text{mean}(Y))^2}} = 0.999999$$

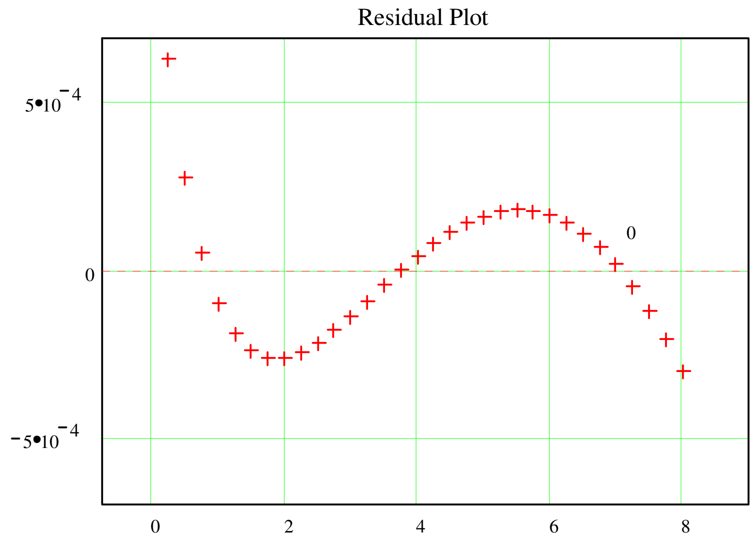
Degrees of freedom: $n - k - 1 = 29$

Plots

Polynomial Regression of Y on X



$scale := \max\left(\left|\overrightarrow{fit(X) - Y}\right|\right) \cdot 1.1$



APPENDIX A2

POLYNOMIAL REGRESSION OF RE OVER C FOR RANGE 1 (Re [100, 1000])

1st RANGE FOR POLYNOMIAL REGRESSION OF "Re" OVER "C"

Re = [100, 1000]

$$data := \begin{bmatrix} 100 & 0.8 \\ 200 & 0.812971 \\ 400 & 0.806876 \\ 600 & 0.798281 \\ 800 & 0.785102 \\ 1000 & 0.773070 \end{bmatrix}$$

$X := data^{\langle 0 \rangle}$ $\quad Y := data^{\langle 1 \rangle}$ $\quad n := rows(data)$

$k := 4$

$n = ▮$

$z := regress(X, Y, k)$

$fit(x) := interp(z, X, Y, x)$

$coeffs := submatrix(z, 3, length(z) - 1, 0, 0)$

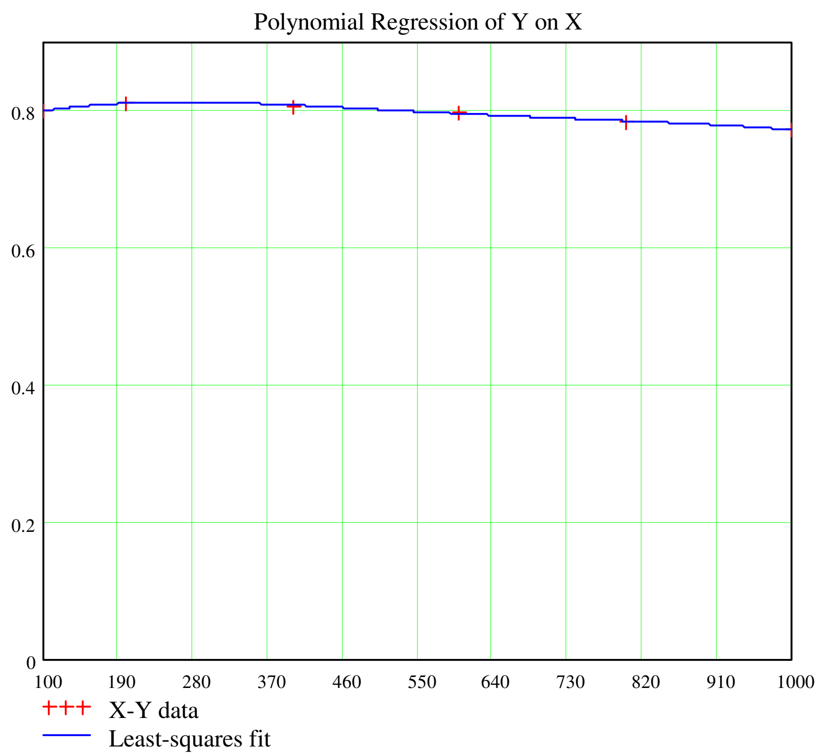
$coeffs^T = ▮$

R^2:

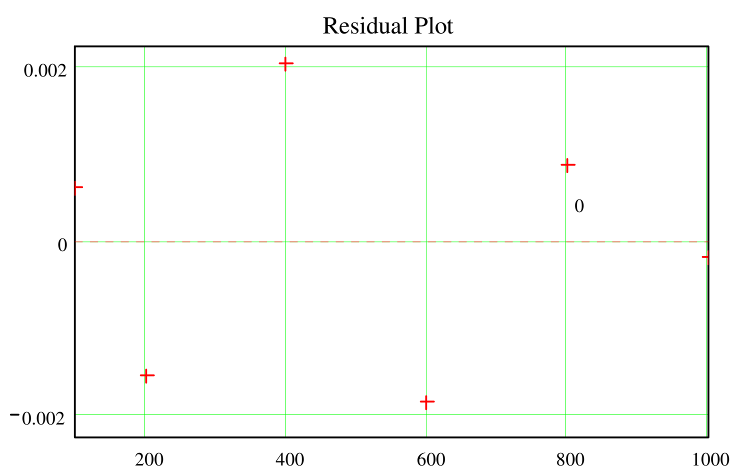
$$\frac{\sum \overrightarrow{(fit(X) - mean(Y))^2}}{\sum \overrightarrow{(Y - mean(Y))^2}} = ▮$$

Degrees of freedom: $n - k - 1 = ▮$

Plots



$$scale := \max\left(\overrightarrow{\left|fit(X) - Y\right|}\right) \cdot 1.1$$



APPENDIX A3

POLYNOMIAL REGRESSION OF RE OVER C FOR RANGE2 (Re[10^3,10^4])

2nd RANGE FOR POLYNOMIAL REGRESSION OF "Re" OVER "C"

Re = [1000, 10000]

$$data := \begin{bmatrix} 1000 & 0.773070 \\ 1500 & 0.751869 \\ 2000 & 0.734952 \\ 4000 & 0.702865 \\ 6000 & 0.687394 \\ 8000 & 0.678227 \\ 9000 & 0.667458 \\ 10000 & 0.666282 \end{bmatrix}$$

$X := data^{<0>}$ $\quad$ $Y := data^{<1>}$ $\quad$ $n := rows(data)$

$k := 3$

$n = ▮$

$z := regress(X, Y, k)$

$fit(x) := interp(z, X, Y, x)$

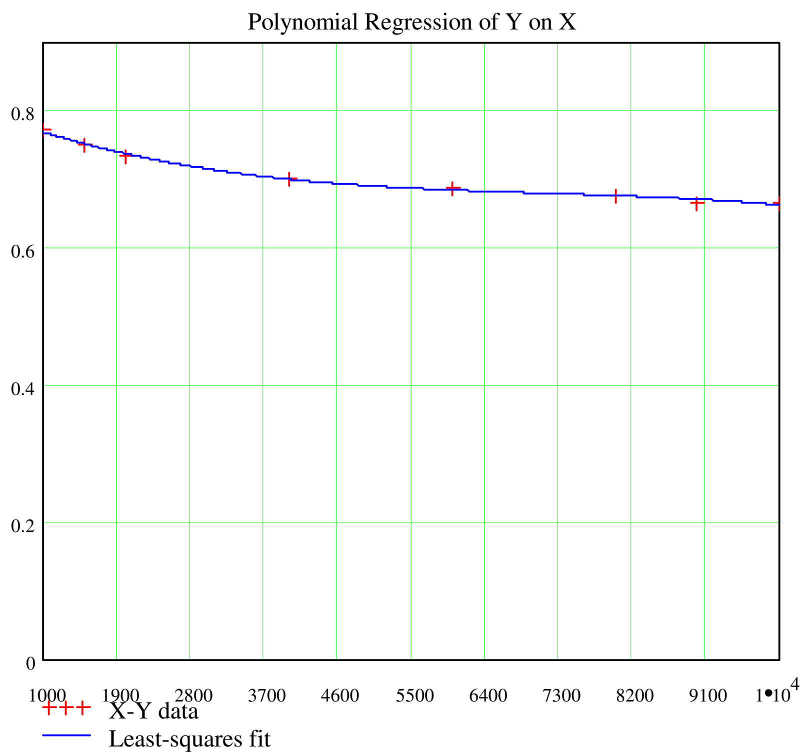
$coeffs := submatrix(z, 3, length(z) - 1, 0, 0)$

$coeffs^T = ▮$

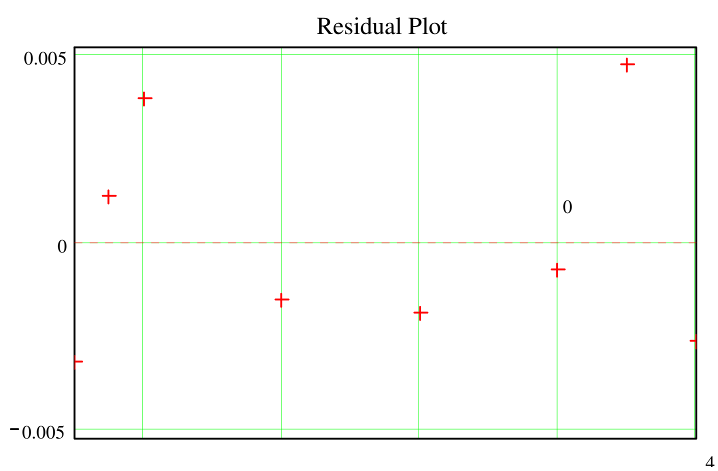
R^2: $$\frac{\sum \overrightarrow{(fit(X) - mean(Y))^2}}{\sum \overrightarrow{(Y - mean(Y))^2}} = ▮$$

Degrees of freedom: $n - k - 1 = ▮$

Plots



$$scale := \max\left(\overrightarrow{\left|fit(X) - Y\right|}\right)\cdot 1.1$$



APPENDIX A4

POLYNOMIAL REGRESSION OF RE OVER C FOR RANGE3 (Re[10^4,10^5])

3rd RANGE FOR POLYNOMIAL REGRESSION OF "Re" OVER "C"

Re = [10000, 100000]

$$data := \begin{bmatrix} 10000 & 0.666282 \\ 20000 & 0.660299 \\ 30000 & 0.657816 \\ 40000 & 0.656247 \\ 50000 & 0.655292 \\ 60000 & 0.654473 \\ 70000 & 0.653995 \\ 80000 & 0.653586 \\ 90000 & 0.653245 \\ 100000 & 0.652835 \end{bmatrix}$$

$X := data^{<0>}$ $\quad$ $Y := data^{<1>}$ $\quad$ $n := rows(data)$

$k := 2$

$n = ▮$

$z := regress(X, Y, k)$

$fit(x) := interp(z, X, Y, x)$

$coeffs := submatrix(z, 3, length(z) - 1, 0, 0)$

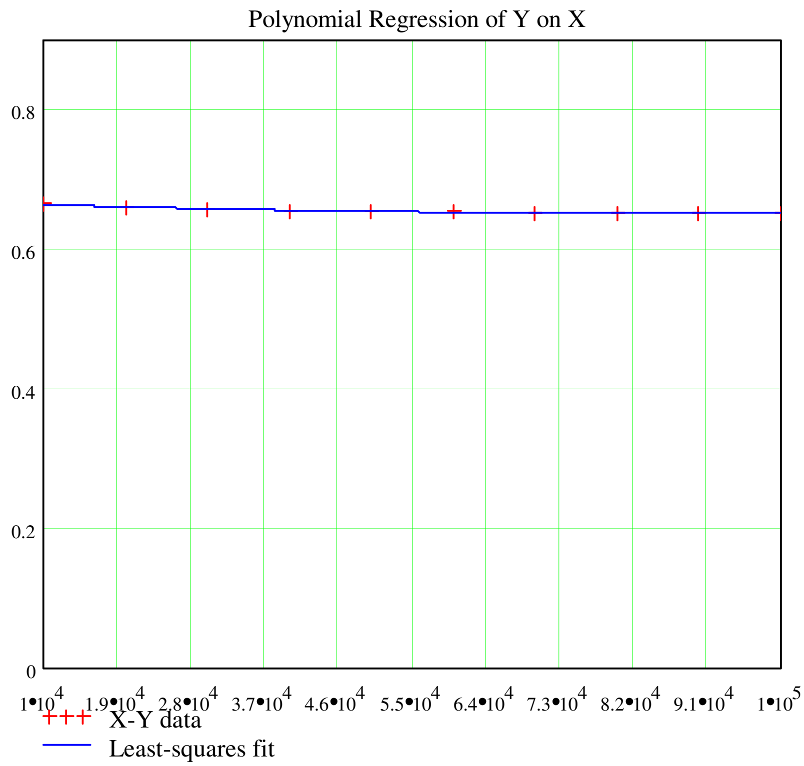
$coeffs^T = ▮$

R^2:

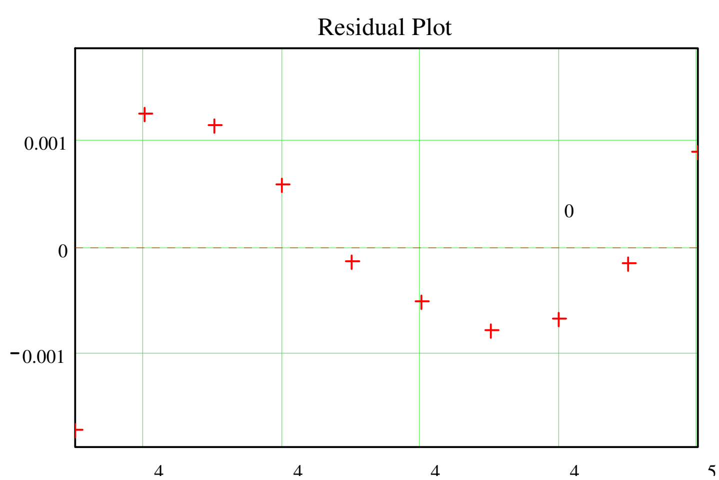
$$\frac{\sum \overrightarrow{(fit(X) - mean(Y))^2}}{\sum \overrightarrow{(Y - mean(Y))^2}} = ▮$$

Degrees of freedom: $\quad n - k - 1 = ▮$

Plots



$$\text{scale} := \max\left(\left|\overrightarrow{\text{fit}(X) - Y}\right|\right)\cdot 1.1$$



APPENDIX A5
POLYNOMIAL REGRESSION OF RE OVER C FOR RANGE 4
(Re[10^5,5X10^5])

4th RANGE FOR POLYNOMIAL REGRESSION OF "Re" OVER "C"

Re = [100000, 500000]

$$data := \begin{bmatrix} 100000 & 0.652835 \\ 200000 & 0.650993 \\ 300000 & 0.650515 \\ 400000 & 0.650379 \\ 500000 & 0.650311 \end{bmatrix}$$

$X := data^{<0>}$ $\quad$ $Y := data^{<1>}$ $\quad$ $n := rows(data)$

$k := 2$

$n = ▮$

$z := regress(X, Y, k)$

$fit(x) := interp(z, X, Y, x)$

$coeffs := submatrix(z, 3, length(z) - 1, 0, 0)$

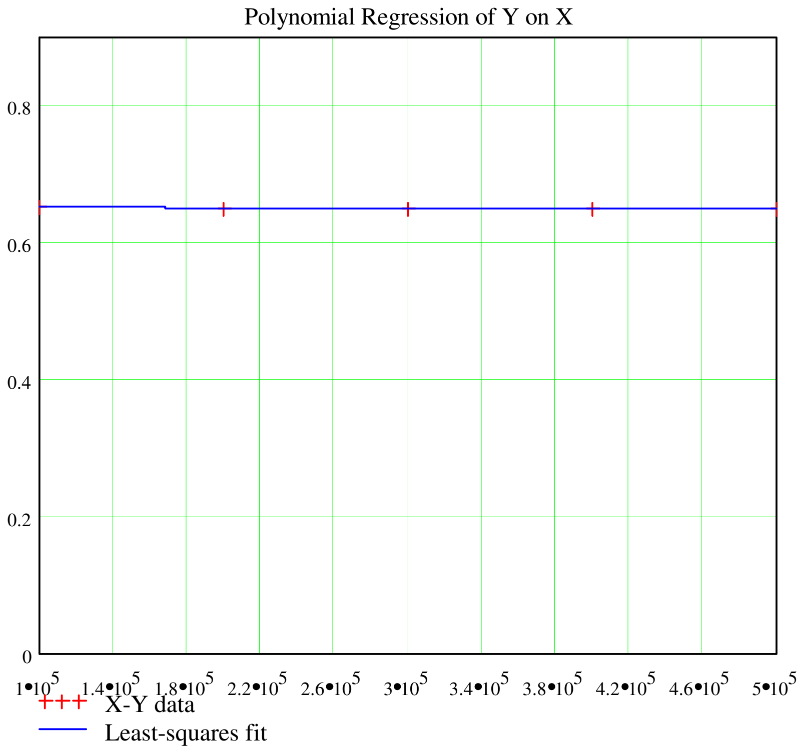
$coeffs^T = ▮$

R^2:

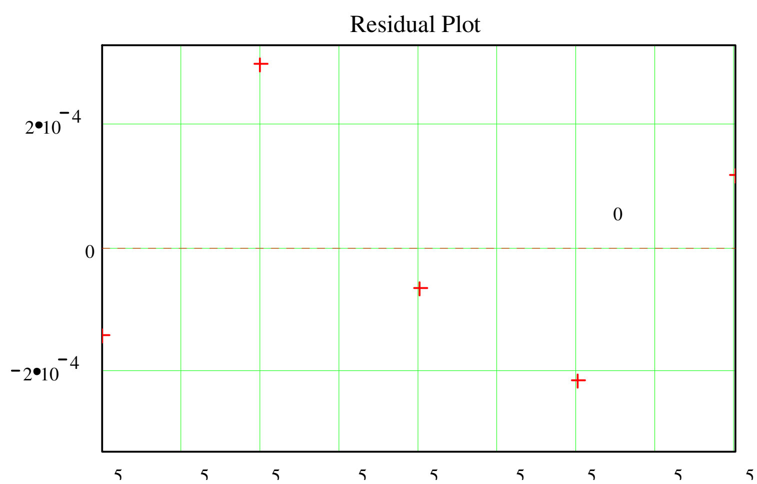
$$\frac{\sum \overrightarrow{(fit(X) - mean(Y))^2}}{\sum \overrightarrow{(Y - mean(Y))^2}} = ▮$$

Degrees of freedom: $\quad n - k - 1 = ▮$

Plots



$$scale := max\left(\left|\overrightarrow{fit(X) - Y}\right|\right) \cdot 1.1$$



APPENDIX A6

POLYNOMIAL REGRESSION FOR FLOW RESISTANCE R_{CD}

REGRESSION OF FLOW RESISTANCE Rcd

data :=

0	-1.5
0.25	-1.51293240486383
0.5	-1.55300043513954
0.75	-1.62159681402572
1	-1.715310408069
1.25	-1.83579451395269
1.5	-1.98318452554787
1.75	-2.15759829197394
2	-2.35913043161866
2.25	-2.58784920356804
2.5	-2.84379459305491
2.75	-3.12697705491839
3	-3.43737665634393
3.25	-3.77494248779588
3.5	-4.1395922712481
3.75	-4.5312121252915
4	-4.94965646298643
4.25	-5.39474800739942
4.5	-5.86627791496433
4.75	-6.36400599983847
5	-6.88057639440025
5.25	-7.43096836701395
5.5	-8.00822739933148
5.75	-8.61236349145127
6	-9.24338633964994
6.25	-9.90130532437011
6.5	-10.5861295003827
6.75	-11.2978675886604
7	-12.0365279696099
7.25	-12.8021186773912
7.5	-13.5946473951148
7.75	-14.4141214507518
8	-15.2605478136278

$X := data^{<0>}$ $\quad Y := data^{<1>}$ $\quad n := rows(data)$

$k := 2$

$n = ▮$

$z := regress(X, Y, k)$

$fit(x) := interp(z, X, Y, x)$

$coeffs := submatrix(z, 3, length(z) - 1, 0, 0)$

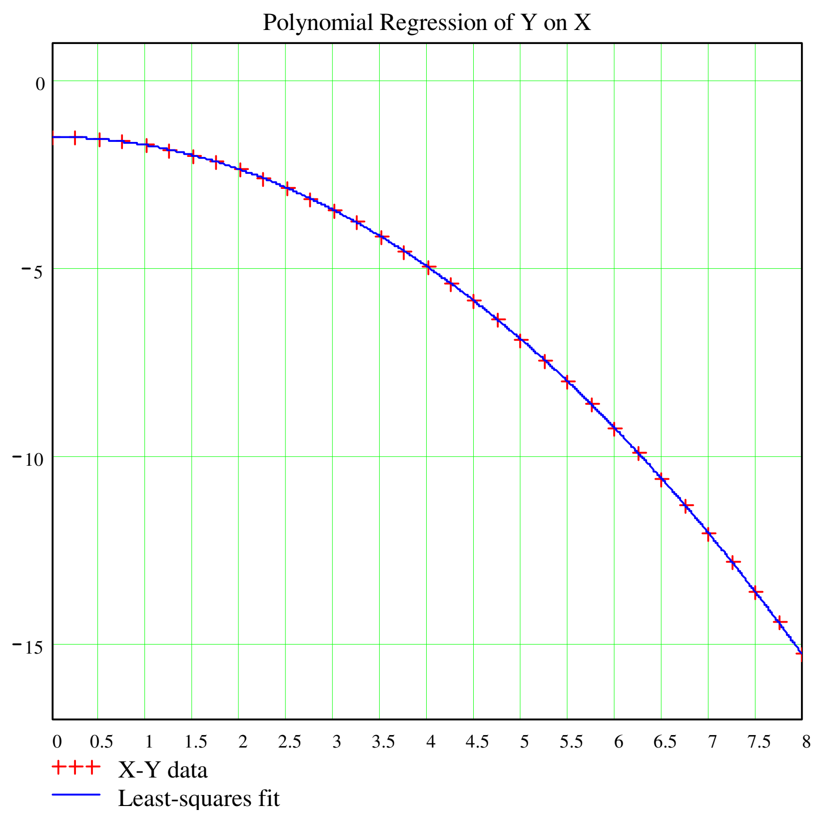
$$coeffs^T = \begin{bmatrix} -1.496213 \\ -4.336151 \cdot 10^{-3} \\ -0.214512 \end{bmatrix}$$

R^2:

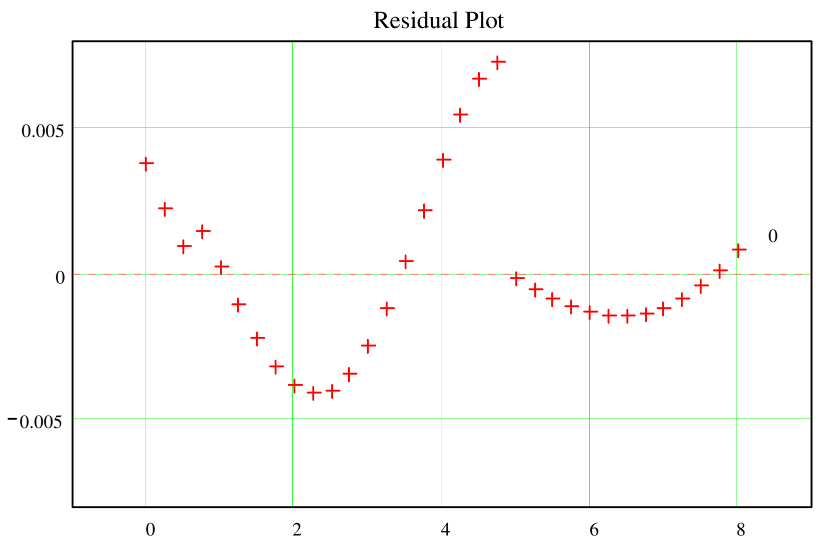
$$\frac{\sum \overrightarrow{(fit(X) - mean(Y))^2}}{\sum \overrightarrow{(Y - mean(Y))^2}} = 1$$

Degrees of freedom: $n - k - 1 = 30$

Plots



$$scale := \max\left(\left|\overrightarrow{fit(X) - Y}\right|\right)\cdot 1.1$$



APPENDIX A7

POLYNOMIAL REGRESSION FOR FLOW RESISTANCE R_{MOV}

REGRESSION OF FLOW RESISTANCE Rmov

data :=

0	0
0.25	-0.000317878456387718
0.5	-0.00107487004919837
0.75	-0.00222274152319251
1	-0.00374633956106987
1.25	-0.00563808884505301
1.5	-0.00789355904736684
1.75	-0.0105099172642138
2	-0.0134852409367129
2.25	-0.0168181675680412
2.5	-0.0205076988681966
2.75	-0.0245530836603991
3	-0.028953744195309
3.25	-0.0337092278536515
3.5	-0.0388191744172127
3.75	-0.044283293263133
4	-0.0501013470913238
4.25	-0.0562731400731108
4.5	-0.0627985090638644
4.75	-0.069677316983578
5	-0.0769094477597693
5.25	-0.0844948024147809
5.5	-0.0924332960037158
5.75	-0.100724855193061
6	-0.109369416327702
6.25	-0.118366923874325
6.5	-0.127717329157845
6.75	-0.137420589328043
7	-0.14747666650866
7.25	-0.157885527092215
7.5	-0.168647141152108
7.75	-0.179761481949731
8	-0.191228525519084

$X := data^{\langle 0 \rangle}$ $Y := data^{\langle 1 \rangle}$ $n := rows(data)$

$k := 2$

$n = \blacksquare$

$z := regress(X, Y, k)$

$\text{fit}(x) := \text{interp}(z, X, Y, x)$

$\text{coeffs} := \text{submatrix}(z, 3, \text{length}(z) - 1, 0, 0)$

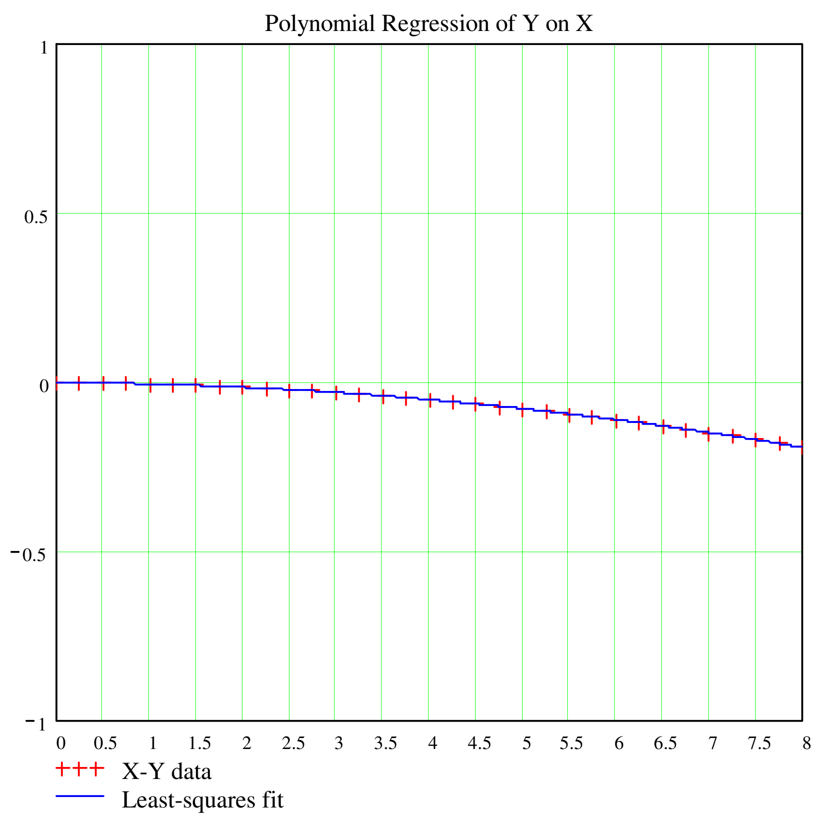
$$\text{coeffs}^T = \begin{bmatrix} 2.398201 \cdot 10^{-4} \\ -1.215187 \cdot 10^{-3} \\ -2.841019 \cdot 10^{-3} \end{bmatrix}$$

R^2:

$$\frac{\sum \overrightarrow{(\text{fit}(X) - \text{mean}(Y))^2}}{\sum \overrightarrow{(Y - \text{mean}(Y))^2}} = 0.999999$$

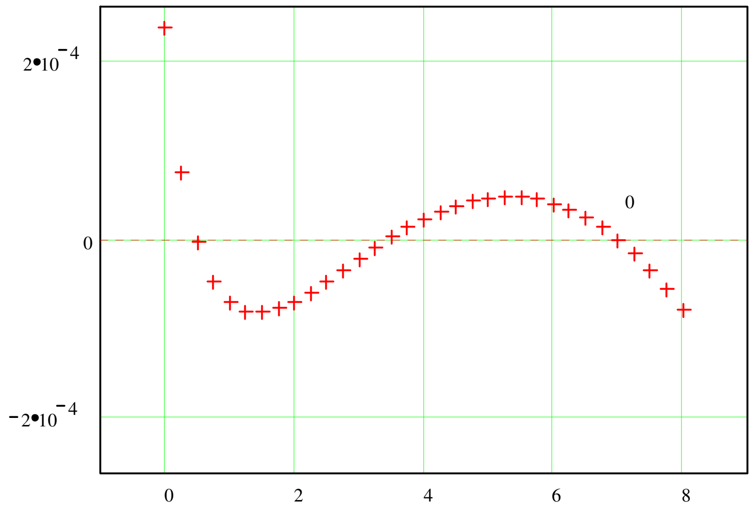
Degrees of freedom: $n - k - 1 = 30$

Plots



$$scale := \max\left(\overrightarrow{\left|fit(X) - Y\right|}\right) \cdot 1.1$$

Residual Plot



APPENDIX A8

POLYNOMIAL REGRESSION FOR FLOW RESISTANCE R_{EH}

REGRESSION OF FLOW RESISTANCE Reh

data :=

0	-0.5
0.25	-0.505002035266266
0.5	-0.517967961885406
0.75	-0.538397359834311
1	-0.566133013445992
1.25	-0.601096328798506
1.5	-0.643241341241187
1.75	-0.692538659397137
2	-0.748968336717963
2.25	-0.812516237299129
2.5	-0.883172003881862
2.75	-0.960927843007071
3	-1.04577776052536
3.25	-1.13771706051174
3.5	-1.23674200570225
3.75	-1.34284958088473
4	-1.45603732407075
4.25	-1.57630320353782
4.5	-1.7036455266604
4.75	-1.83806287123343
5	-1.9795540330049
5.25	-2.12811798508161
5.5	-2.28375384616027
5.75	-2.44646085540568
6	-2.616238352396
6.25	-2.79308576097314
6.5	-2.97700257613307
6.75	-3.16798835330476
7	-3.36604269952204
7.25	-3.57116526610729
7.5	-3.78335574257203
7.75	-4.00261385150321
8	-4.22893934425356

$X := data^{<0>}$ $\quad Y := data^{<1>}$ $\quad n := rows(data)$

$k := 2$

$n = ▮$

$z := regress(X, Y, k)$

$\text{fit}(x) := \text{interp}(z, X, Y, x)$

$\text{coeffs} := \text{submatrix}(z, 3, \text{length}(z) - 1, 0, 0)$

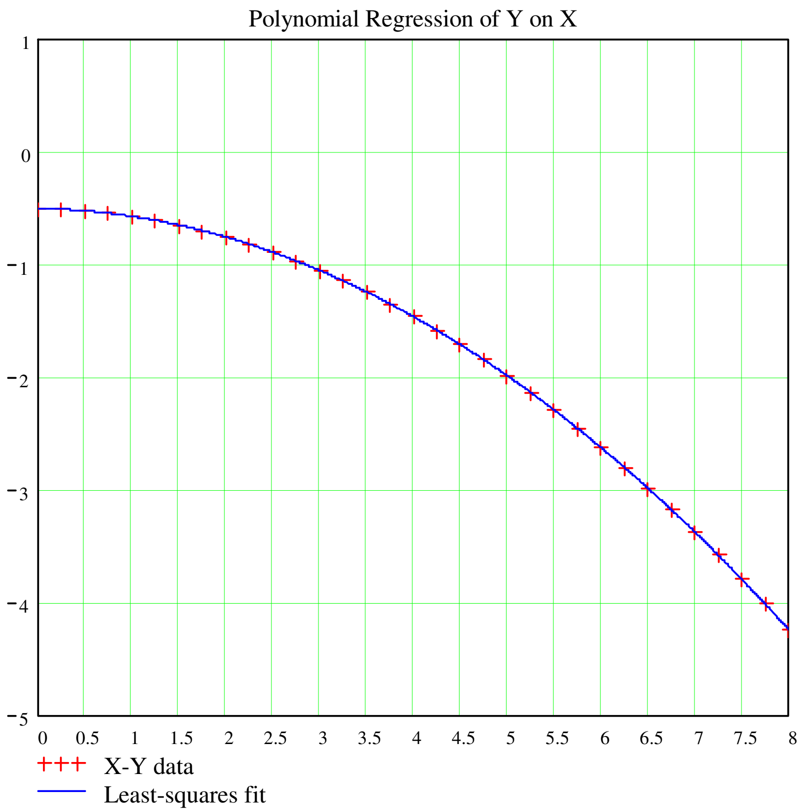
$$\text{coeffs}^T = \begin{bmatrix} -0.497512 \\ -0.012608 \\ -0.05674 \end{bmatrix}$$

R^2:

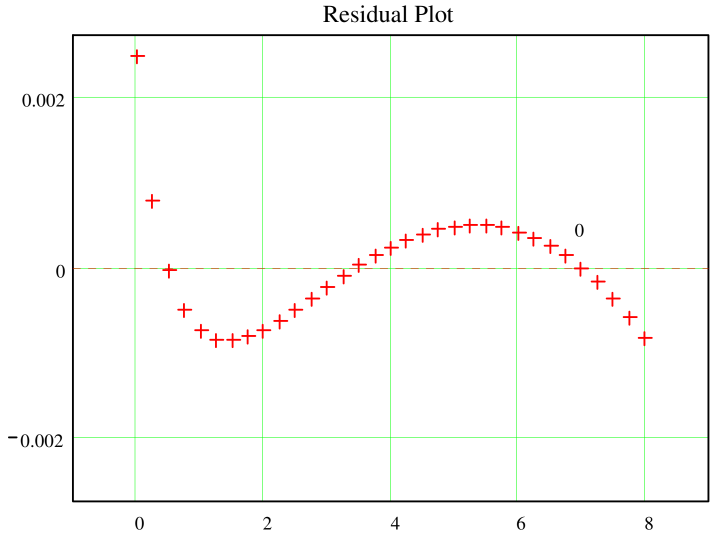
$$\frac{\sum \overrightarrow{(\text{fit}(X) - \text{mean}(Y))^2}}{\sum \overrightarrow{(Y - \text{mean}(Y))^2}} = 1$$

Degrees of freedom: $n - k - 1 = 30$

Plots



$$\text{scale} := \max\left(\overrightarrow{\left|\text{fit}(X) - Y\right|}\right)\cdot 1.1$$



APPENDIX A9

POLYNOMIAL REGRESSION FOR FLOW RESISTANCE R_{Fl}

REGRESSION OF FLOW RESISTANCE Reh

data :=

0	-2.5
0.25	-2.5083341273534
0.5	-2.52923505442868
0.75	-2.56169676654888
1	-2.60540320667965
1.25	-2.66019637427076
1.5	-2.72598386471998
1.75	-2.80270659134977
2	-2.89032445480457
2.25	-2.98880903710192
2.5	-3.09813951662428
2.75	-3.2183002258646
3	-3.34927911454114
3.25	-3.49106674224539
3.5	-3.64365559580394
3.75	-3.80703961361344
4	-3.98121384623866
4.25	-4.16617420922545
4.5	-4.36191729982
4.75	-4.56844025890578
5	-4.7857406655261
5.25	-5.01381645527592
5.5	-5.25266585643544
5.75	-5.5022873394668
6	-5.76267957669721
6.25	-6.03384140985263
6.5	-6.315771823703
6.75	-6.60846992450916
7	-6.91193492227521
7.25	-7.22616611604045
7.5	-7.55116288161725
7.75	-7.88692466131092
8	-8.23345095525577

$X := data^{\langle 0 \rangle}$ $\quad$ $Y := data^{\langle 1 \rangle}$ $\quad$ $n := rows(data)$

$k := 2$

n = ▮

$z := regress(X, Y, k)$

fit(x) := interp(z, X, Y, x)

coeffs := submatrix(z, 3, length(z) − 1, 0, 0)

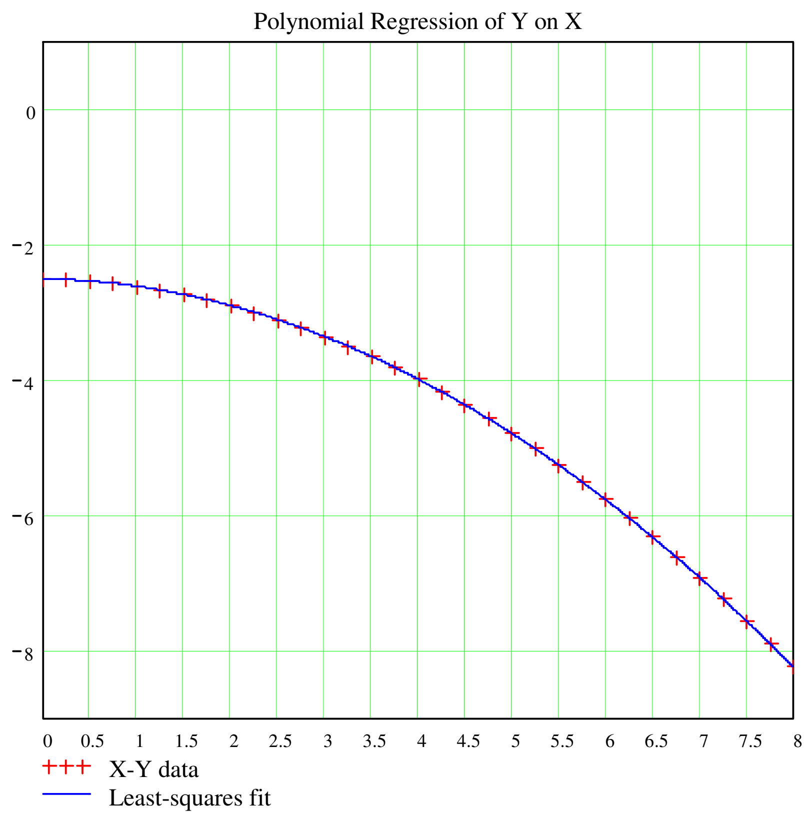
$$\text{coeffs}^T = \begin{bmatrix} -2.494998 \\ -0.025346 \\ -0.086521 \end{bmatrix}$$

R^2:

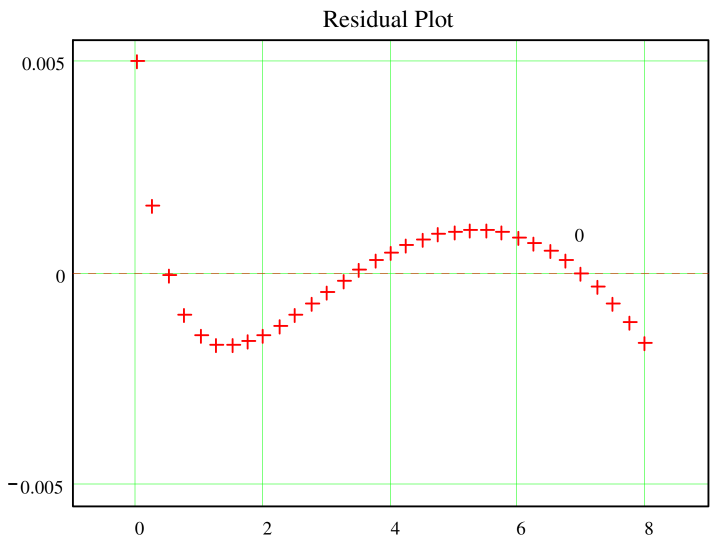
$$\frac{\sum \overrightarrow{(\text{fit}(X) - \text{mean}(Y))^2}}{\sum \overrightarrow{(Y - \text{mean}(Y))^2}} = 0.999999$$

Degrees of freedom: $n - k - 1 = 30$

Plots



$$scale := \max\left(\overrightarrow{\left|fit(X) - Y\right|}\right) \cdot 1.1$$



APPENDIX A10

POLYNOMIAL REGRESSION FOR FLOW RESISTANCE R_{GJ}

REGRESSION OF FLOW RESISTANCE Rgj

data :=

0	-4.5
0.25	-4.51169750669018
0.5	-4.54060794126813
0.75	-4.58521494703541
1	-4.64504213412207
1.25	-4.71985134974746
1.5	-4.80950331330187
1.75	-4.91390896397802
2	-5.03300786038495
2.25	-5.16675716835826
2.5	-5.31512550366474
2.75	-5.47808925081469
3	-5.65563024652891
3.25	-5.84773426136621
3.5	-6.05438997078922
3.75	-6.27558823819875
4	-6.51132160335651
4.25	-6.76158390980216
4.5	-7.02637002859613
4.75	-7.30567565021824
5	-7.59949712558272
5.25	-7.90783134303074
5.5	-8.23067563206531
5.75	-8.56802768722803
6	-8.91988550732988
6.25	-9.28624734651503
6.5	-9.6671116745365
6.75	-10.0624771442695
7	-10.4723425649603
7.25	-10.8967068800575
7.5	-11.3355691487286
7.75	-11.7889285303657
8	-12.2567842715256

$X := data^{<0>}$ $\quad$ $Y := data^{<1>}$ $\quad$ $n := rows(data)$

$k := 2$

n = ▮

$z := regress(X, Y, k)$

fit(x) := interp(z, X, Y, x)

coeffs := submatrix(z, 3, length(z) − 1, 0, 0)

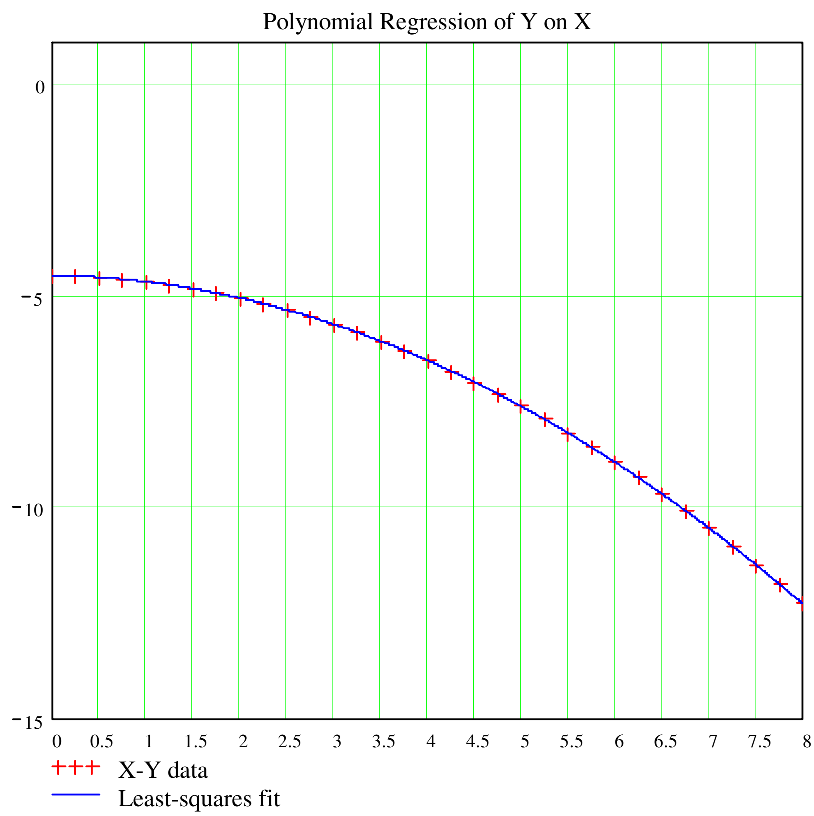
$$\text{coeffs}^T = \begin{bmatrix} -4.492461 \\ -0.038203 \\ -0.116581 \end{bmatrix}$$

R^2:

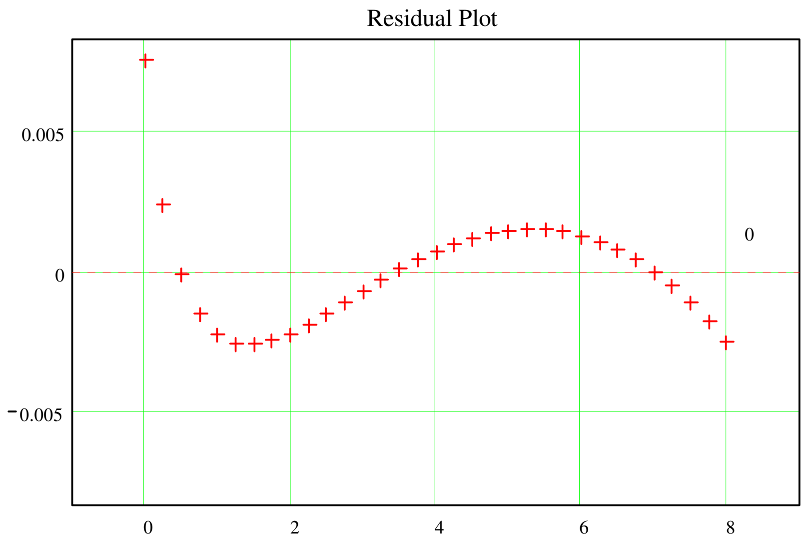
$$\frac{\sum \overrightarrow{(\text{fit}(X) - \text{mean}(Y))^2}}{\sum \overrightarrow{(Y - \text{mean}(Y))^2}} = 0.999999$$

Degrees of freedom: n − k − 1 = 30

Plots



$$scale := \max\left(\overrightarrow{\left| fit(X) - Y \right|}\right) \cdot 1.1$$



APPENDIX A11
FLOW RESISTANCE - CASE1 – R_{EH} (+2m)

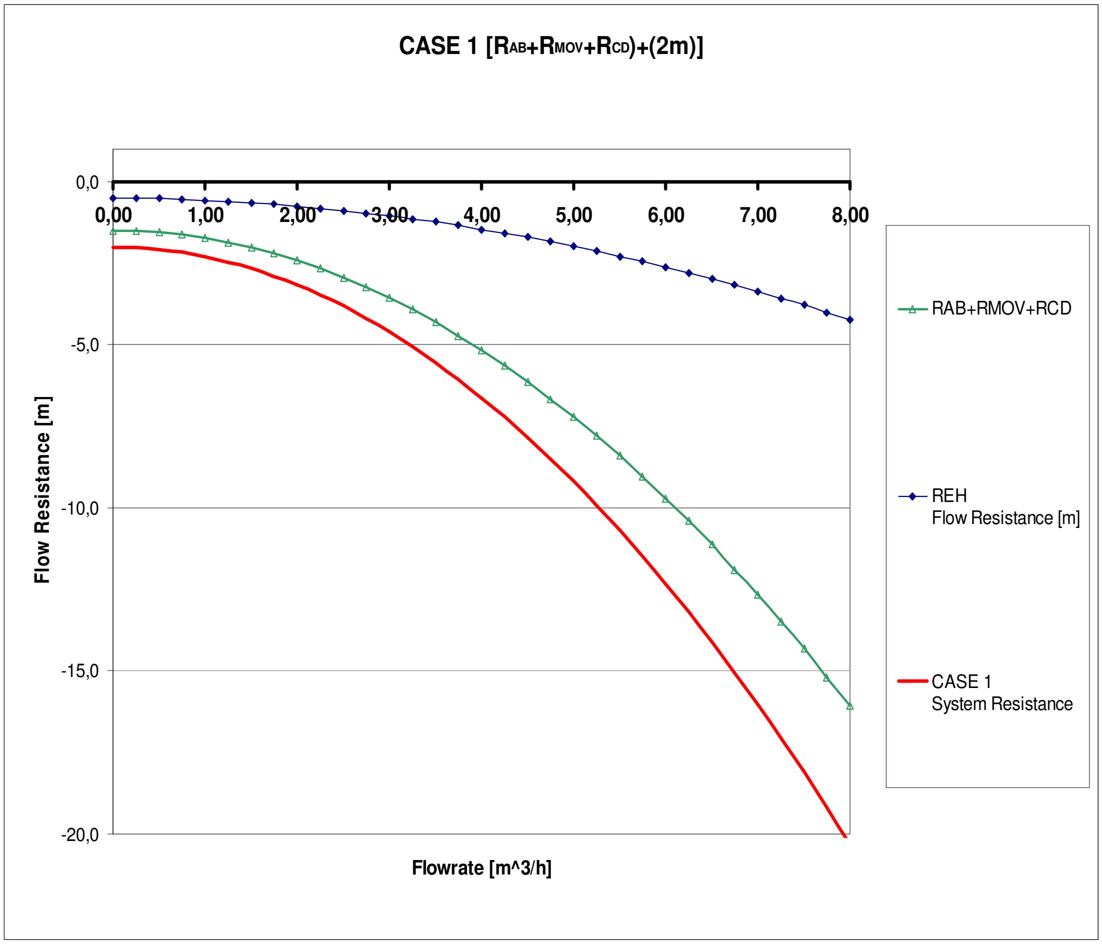


Fig A11: Case 1

APPENDIX A12

FLOW RESISTANCE – CASE2 - R_{FI} (+4m)

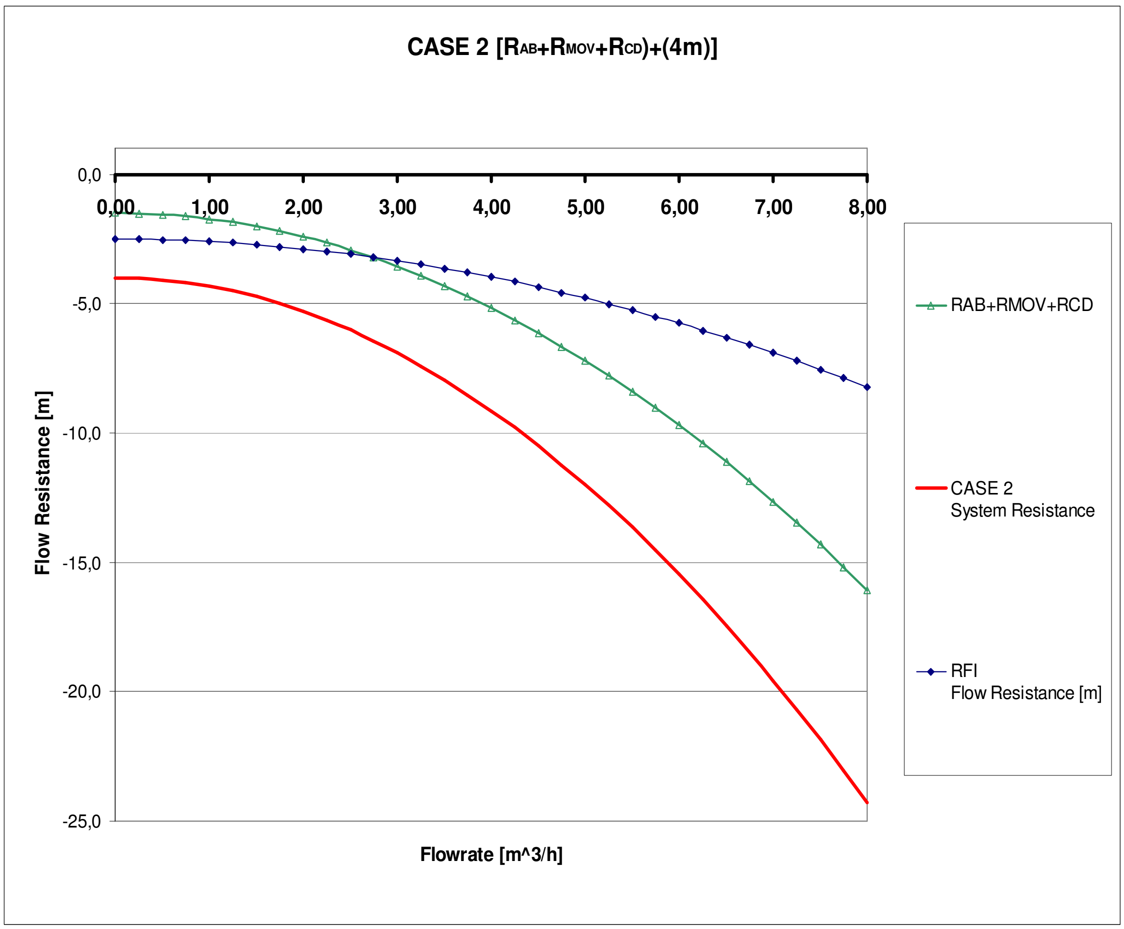


Fig A12: Case 2

APPENDIX A13

FLOW RESISTANCE – CASE3 - R_{GJ} (+6m)

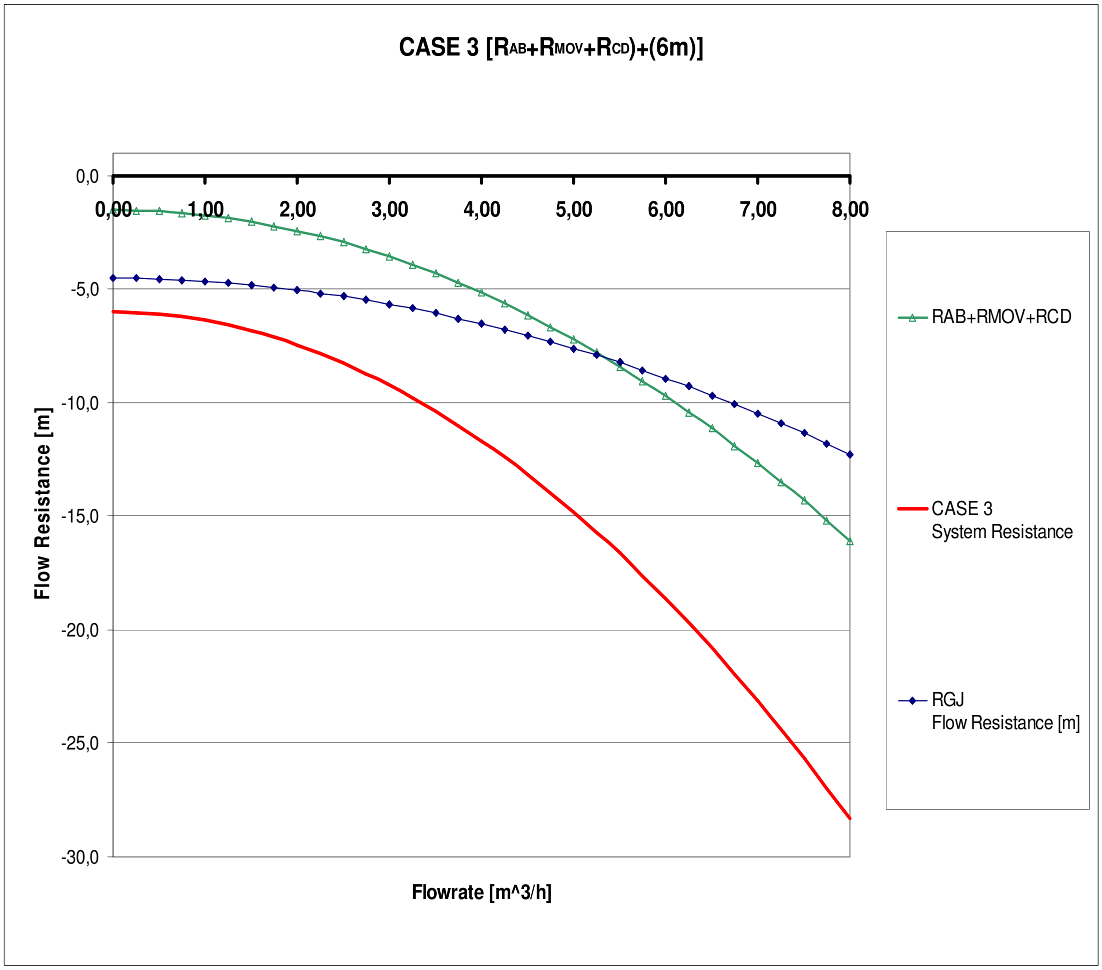


Fig A13: Case 3

APPENDIX A14

FLOW RESISTANCE – CASE4 - R_{EH} // R_{FI} (+2m // +4m)

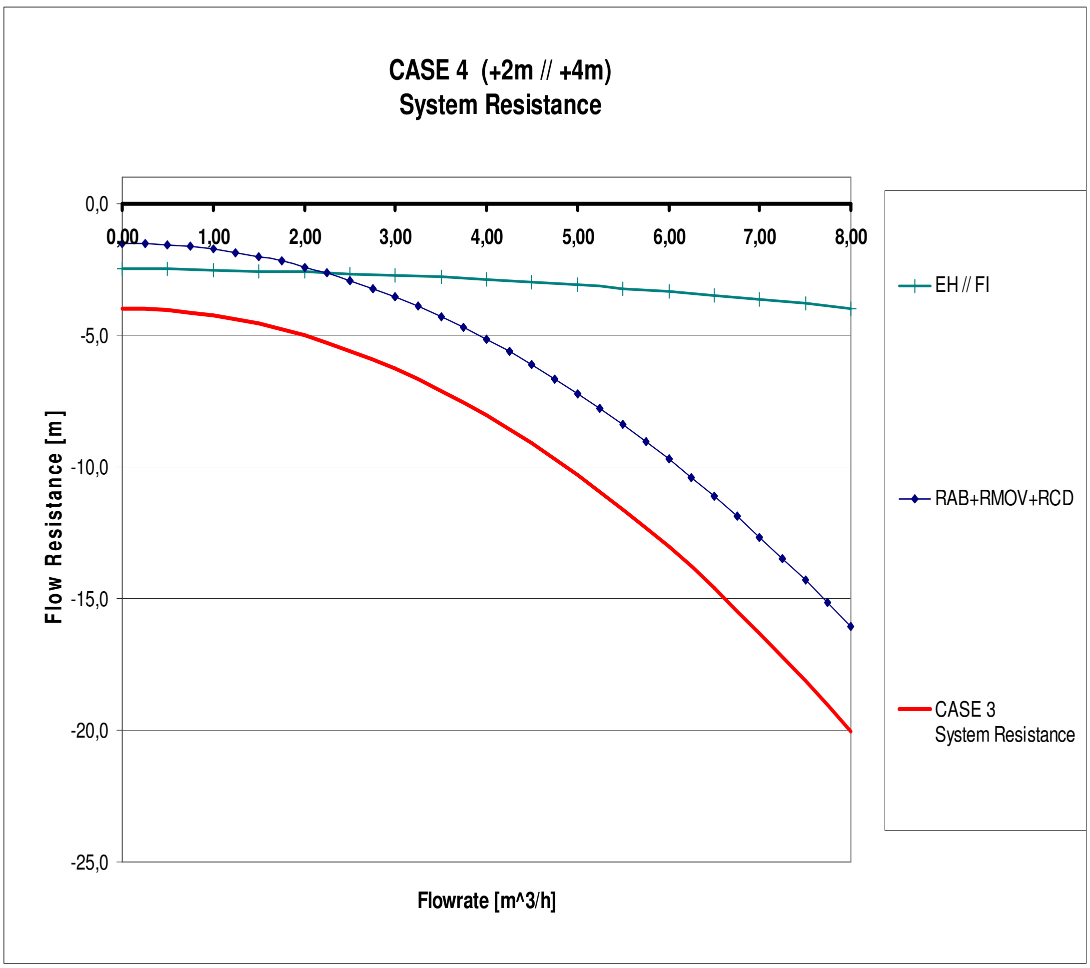


Fig A14: Case 4

APPENDIX A15

FLOW RESISTANCE – CASE5 - R_{EH} // R_{GJ} (+2m // +6m)

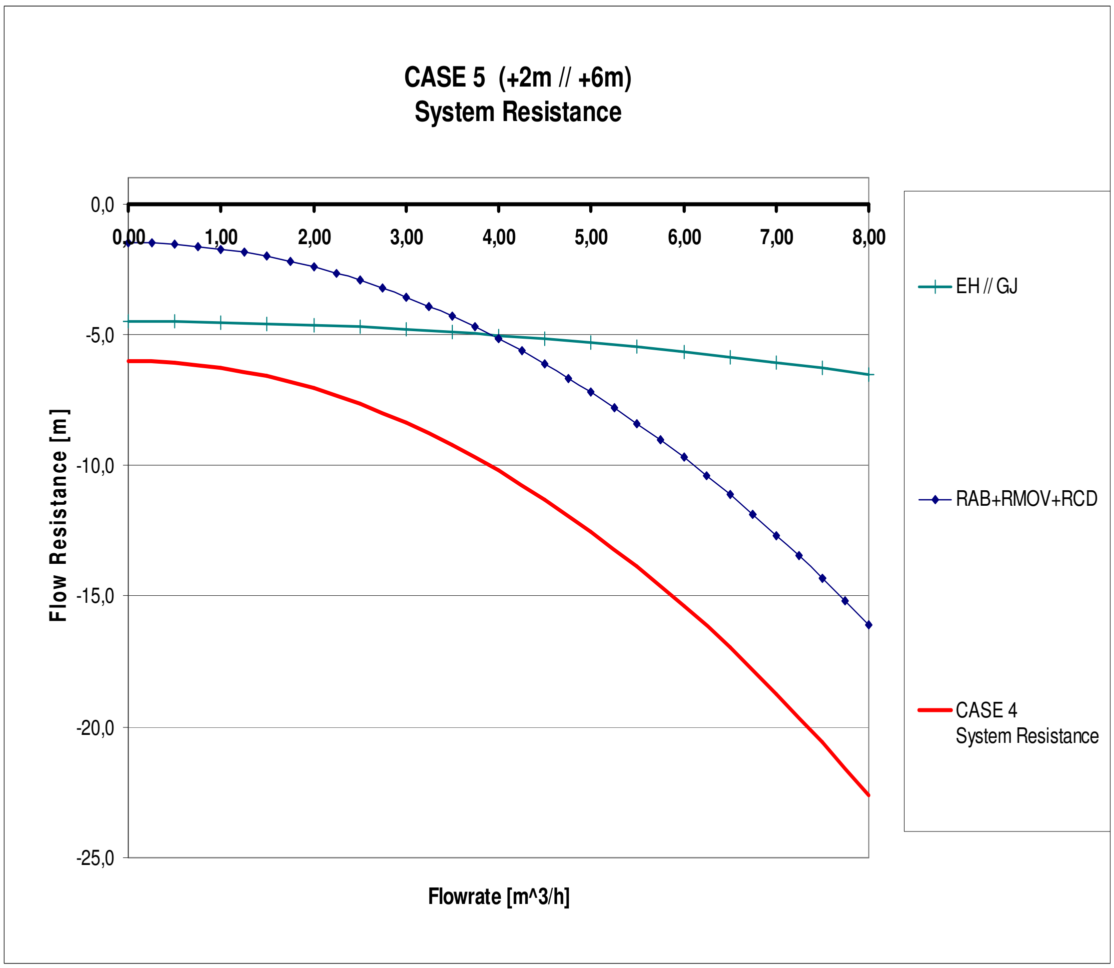


Fig A15: Case 5

APPENDIX A16

FLOW RESISTANCE – CASE6 - R_{FI} // R_{GJ} (+4m // +6m)

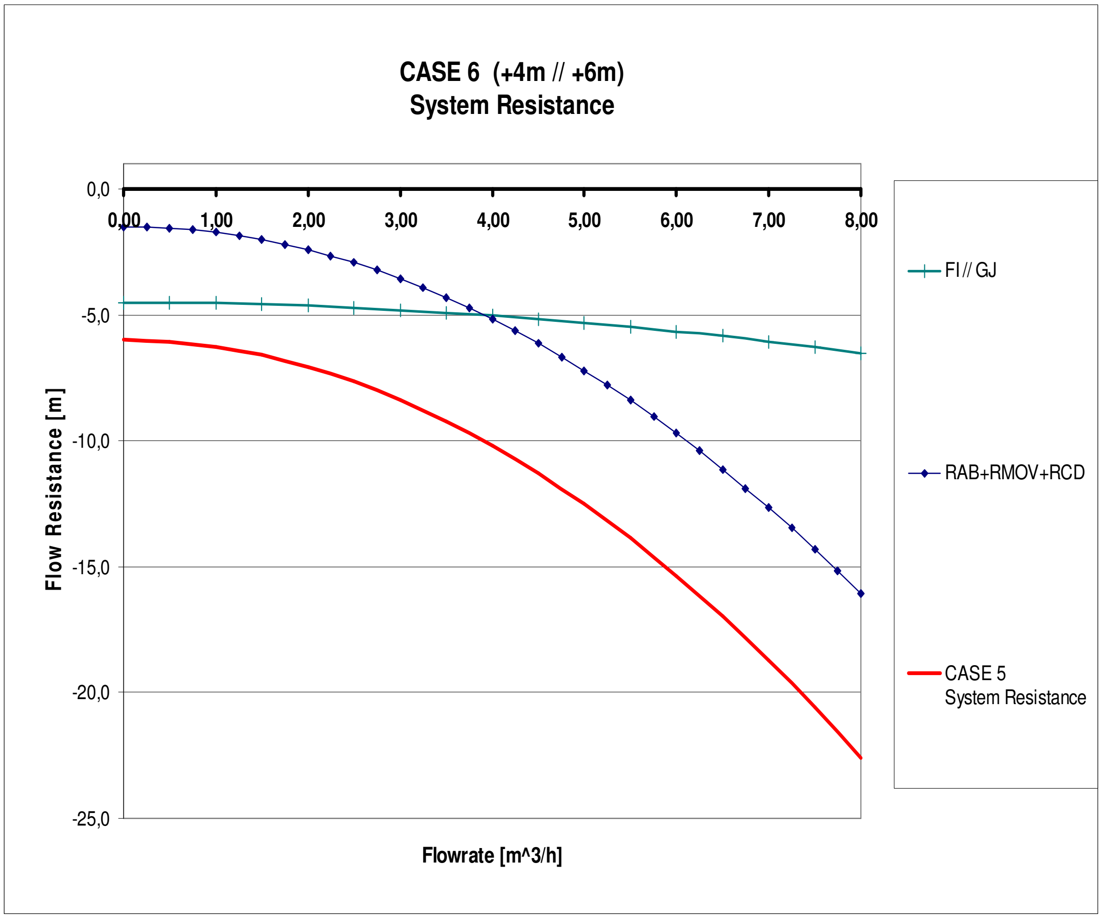


Fig A16: Case 6

APPENDIX A17

FLOW RESISTANCE – CASE7 - R_{EH} // // R_{FI} // R_{GJ} (+2m // +4m // +6m)

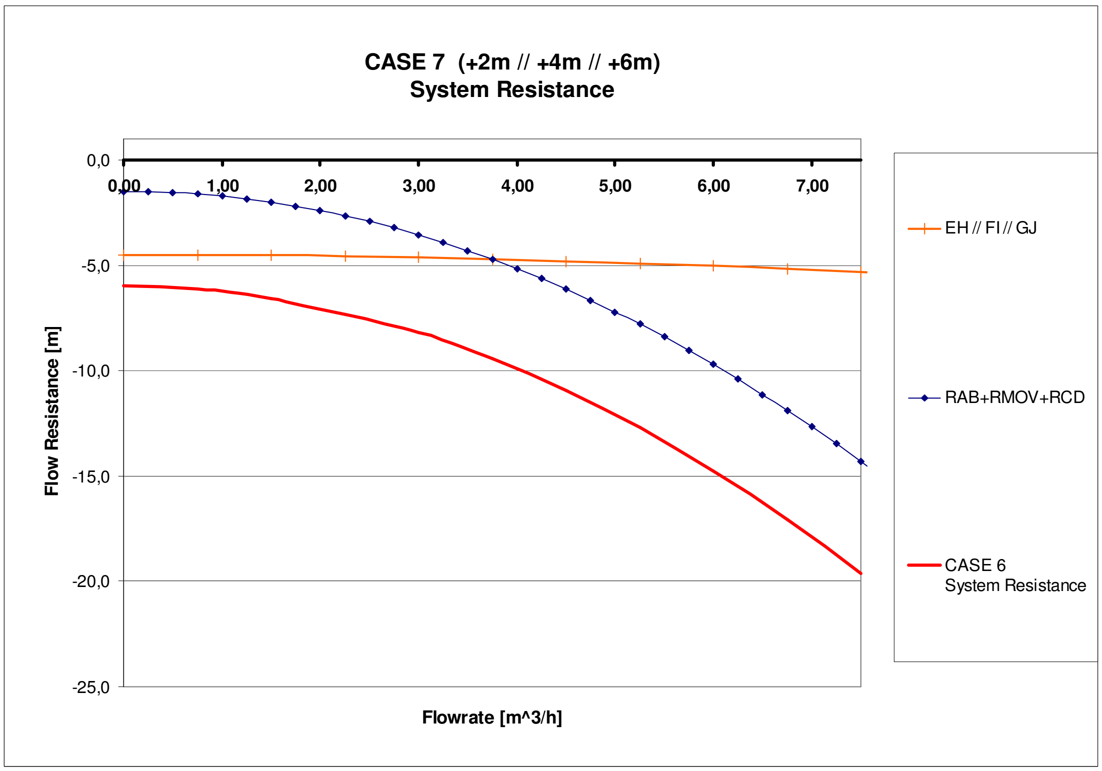


Fig A17: Case 7

APPENDIX B1

PIC SUBROUTINE FOR RPM CONTROL

```
CPU = 16F628
MHZ = 4
CONFIG 16225

'RPM MONITORING RPM_CONTROL2.BAS- AND SERIAL 2X16 FOR LCD

TRISA=%00010111
TRISB=%11111111
PORTA=%00000000
PORTB=%00000000

      Periyot                VAR         long
      Devir1                 VAR         word
      DEVIR            VAR         WORD
      PULS_0                 VAR         long
      PULS_1                 VAR         long
      XX                     var         NIB
      ORNEK            VAR         NIB   ;NUMBER   OF   SAMPLING   IN   EACH
MEASUREMENT

                  DEVIR=0
                  DEVIR1=0
                  ORNEK=6
BASLA:
;***********************


      SetExtInt Ext_H2L
      OnInterrupt ExtInt,Ser_Out

;***********************

;RPM SAMPLES ARE BEING READ AND SPEED IS COMPUTED
      Enable ExtInt
MAIN :
            PERIYOT=0
      FOR XX=1 TO ORNEK
            PULSIN B5,0,PULS_0
                  ; "0" PERIOD IS BEING READ (uSec)
            Pause 1
            PULSIN B5,1,PULS_1
            PERIYOT=PERIYOT+PULS_0+PULS_1
            PAUSE 1
      NEXT
; "1" PERIOD OF THE NEXT STEP IS BEING READ
            PERIYOT=(2*PERIYOT)/ORNEK
                        ;READ 1 VE 0 VALUES ARE COLLECTED
            DEVIR1=(60*1000000)/(PERIYOT)


            IF DEVIR1>6000 or DEVIR1<800 THEN
                  DEVIR1=0
            ENDIF
```

```
            DEVIR=DEVIR1
GOTO MAIN

;********************
DISABLE
Ser_Out
            PAUSE 5
            SEROUT A3,N2400,5,[Devir.BYTE0,DEVIR.BYTE1]
            DEBUG [DEC DEVIR,10,13,13]

RESUME

END
```

APPENDIX B2

PIC SUBROUTINE FOR VALVE POSITION AND DC MOTOR CONTROL

```
CPU = 16F628
MHZ = 4
CONFIG 16225

;   VALVE_CONTROL2_628.BAS  (VALVE POSITION READOUT AND DC MOTOR CONTROL)
161 BYTES FREE

      TRISA=%00010000
      TRISB=%11111101
            ;SET I/O PORT DIRECTION
      PORTA=%00000000
      PORTB=%00000000
            ;SET ALL I/O PORT OUTPUTS LOW

;  DECLARE VARIABLES

      POZ               VAR         WORD
            ;VANA POZISYONU
      FLAG        VAR         BIT
      YON               VAR         SWORD
      XX                VAR         WORD

                  DATA @0,0,0
                                                                        ;SET
VALVE POSITION TO FULLY CLOSED AT THE BEGINNING
                  CMCON =7
                  SetExtInt Ext_H2L
                  OnInterrupt ExtInt,Ser_Out

                  CLEAR

;TURN THE COMPARATOR OFF
                  READDM 0,[POZ.BYTE0,POZ.BYTE1]
                        ;READ THE LAST VALVE POSITION INFORMATION

;           IF POZ>0 THEN
;                 poz=poz-1
;           ENDIF
                  LOW A0
      ;OUTPUT PIN 1
                  LOW A1
      ;OUTPUT PIN 2
                  LOW A2      ;  IF  B0=1   A  WARNING  IS  BEING  SENT  TO
MASTER
                  LOW B1      ; IF B1=1 A WARNING IS BEING SENT TO MASTER
                  FLAG=0
                  YON=0
                  PAUSE 10000

                  Enable EXTINT


      MAIN:

;                 PORTA.BIT0=PORTB.BIT2
```

```
;                 PORTA.BIT1=PORTB.BIT3

            IF PORTB.BIT3=1 AND PORTB.BIT2=0 THEN
                        YON=1
                        LOW A0
      ;AC
                        HIGH A1
            ENDIF

            IF PORTB.BIT3=0 AND PORTB.BIT2=1 THEN
                        YON=-1
      ;kapa
                        LOW A1
                        HIGH A0
            ENDIF
            IF PORTB.BIT3=0 AND PORTB.BIT2=0 THEN
                        YON=0
                        LOW A0
                        low A1
            ENDIF
      ATLA0:

      POZ_SAY:
FOR XX=0 TO 6
;***********************************************************************
            IF POZ<7  THEN
                  HIGH A2
            ELSEIF POZ>53
                  HIGH B1
            ELSEIF POZ>6 AND POZ<54
                  LOW A2
                  LOW B1

                        IF PORTB.BIT2=1 AND PORTB.BIT3=0 THEN
                              YON=-1
                              LOW  A1
      ;kapa
                              HIGH A0
                        ENDIF
                        IF PORTB.BIT2=0 AND PORTB.BIT3=1 THEN
                              YON=1
                              LOW A0                                    ;ac
                              HIGH A1
                        ENDIF
                        IF    (PORTB.BIT2=0    AND    PORTB.BIT3=0)    OR
(PORTB.BIT2=1 AND PORTB.BIT3=1) THEN
                              YON=0
                              LOW A0




                              LOW A1
                        ENDIF
            ENDIF
; *************************************************************************

                                    IF FLAG=0 THEN
                                          IF  PORTB.BIT5=0 THEN
                                                PAUSE 5
                                                GOTO ATLA1
                                          ENDIF
```

```
                              ENDIF
            IF  FLAG=1 THEN
                  IF PORTB.BIT5=1 THEN
                        PAUSE 5
                        FLAG=0
                  ENDIF
            ENDIF
NEXT
                              GOTO ATLA2
      ATLA1:
                              FLAG=1
                              POZ=POZ+YON
                              WRITEDM 0,[POZ.BYTE0,0]

      ATLA2:

                              DEBUG["POZ=",DEC     POZ,"         OUT=",DEC
PORTA.BIT1,DEC PORTA.BIT0,13,10]
      GOTO MAIN


      DISABLE
      SER_OUT:
;                             LOW A0
;                             LOW A1
                              PAUSE 5

                              SEROUT A3,N2400,1,[POZ.BYTE0,0]
                              ; SENDING TO MASTER
      RESUME


END
```

APPENDIX B3

MAIN CONTROL SUBROUTINE FOR MASTER PIC

```
CPU = 16F877
MHZ = 4
CONFIG 16241

;     SETUP PORTS
      TRISA=%11111111
      TRISB=%00001111
      TRISC=%10100000
      TRISD=%00001110
      TRISE=%00000111

      PORTA=%00000000
      PORTB=%00000000
      PORTC=%00000000
      PORTD=%00000000
      PORTE=%00000000

;     SETUP ANALOG INPUTS
      CLK                          CON   2 ;CLK OPTION IS BASED ON 1/16
OF EXTERNAL OSCILLATOR SPEED
      ADSETUP                      CON   %10000010   ;SETS   UP   ADCON1
REGISTER, A0,A1,A2,A3,AND A5 IS NOW ANALOG

;     DECLARE VARIABLES

      I                                  VAR         BYTE
      XX                                 VAR         BYTE
      ZZ                                 VAR         WORD
      ADIM                               VAR         SBYTE
      ANDI                               VAR         WORD(5)
      ANA                                VAR         WORD(5)
      PumpInputPres                      VAR         WORD
      PumpOutputPres                     VAR         WORD
      OrificeInputPres                   VAR         WORD
      OrificeOutputPres                  VAR         WORD
      OrificePressureDrop                VAR         WORD
      OrificeDeltaP                      VAR         WORD

      DEVIR                              VAR         WORD
      DEVIR_NEW                          VAR         WORD
      DEVIR_OLD                          VAR         WORD
      DUTY1                              VAR         WORD
      POZ1                               VAR         BYTE
      POZ                                VAR         WORD
      POZ_NEW                            VAR         WORD
      POZ_OLD                            VAR         WORD
      SF                                 VAR         BYTE
      ;DIFF. AMP. GAIN FACTOR*10
      YON                                VAR         SBYTE
      STR0                               VAR         BYTE(2)
      STR1                         VAR         BYTE(4)
      STR2                         VAR         BYTE(2)
      STR3                         VAR         BYTE(4)
;     SETUP LCD
                        PAUSE 500
```

```
                        LCDWRITE
D6\D7,PORTB.HIGHNIB,[INITLCD1,INITLCD2,TWOLINE,CLEAR,HOME,SCR]

                        CLEAR
      SETHSERIAL H9600
                        SF=5
                        DEVIR_NEW=0
                        DUTY1=0
                        LOW D4
                        LOW D5
                        LOW C4
                        LOW C3
                        LCDWRITE     D6\D7,PORTB.NIB1,[CLEAR,HOME,"*POMPA
KONTROL*"]
                        LCDWRITE          D6\D7,PORTB.NIB1,[SCRRAM+$40,"*
PROGRAMI ! *"]
                        PAUSE 3000
      ATLA100:
                        HIGH C4
                        PAUSE 2
                        LOW C4

                        SERIN D3,N2400,20,ATLA110,[POZ.BYTE0,POZ.BYTE1]
                        GOTO ATLA120
      ATLA110:
      POZ=POZ_OLD
                        LCDWRITE      D6\D7,PORTB.NIB1,[CLEAR,HOME,"*VANA
POZiSYONU*"]
                        LCDWRITE      D6\D7,PORTB.NIB1,[SCRRAM+$40,"*
OKUNAMIYOR! *"]
PAUSE 1000
      ATLA120:
                        HIGH C3
                        PAUSE 2
                        LOW C3
                        SERIN
D1,N2400,20,ATLA130,[DEVIR.BYTE0,DEVIR.BYTE1]
                        GOTO ATLA139
      ATLA130:
      DEVIR=0

                        LCDWRITE   D6\D7,PORTB.NIB1,[CLEAR,HOME,"*   POMPA
DEVRi *"]
                        LCDWRITE          D6\D7,PORTB.NIB1,[SCRRAM+$40,"*
OKUNAMIYOR ! *"]

PAUSE 2000

      ATLA139:
                        PAUSE 1
;                       HSERIN
ATLA140,40,[DEVIR_NEW.LOWBYTE,DEVIR_NEW.HIGHBYTE,POZ_NEW.LOWBYTE,POZ_NEW.
HIGHBYTE]
                        HSERIN ATLA140,40,[STR STR0\2,STR STR1\4]
                              IF STR0(0)="8" AND STR0(1)="8" THEN
                                    DEVIR_NEW=((STR1(0)-
48)*1000)+((STR1(1)-48)*100)+((STR1(2)-48)*10)+(STR1(3)-48)
                                    GOTO ATLA141
                              else
                                    goto atla140
                              ENDIF
      ATLA140:
                        DEVIR_NEW=0
PAUSE 2000
```

```
      ATLA141:
                        HSERIN ATLA142,40,[STR STR2\2,STR STR3\4]
                              IF STR2(0)="9" AND STR2(1)="9" THEN
                                    POZ_NEW=((STR3(0)-
48)*1000)+((STR3(1)-48)*100)+((STR3(2)-48)*10)+(STR3(3)-48)
                                    goto atla150
                              else
                                    goto atla142
                              ENDIF
      ATLA142:
                        POZ_NEW=40
                        goto atla151
      ATLA150:

                        GOTO BASLA
      ATLA151:

                        LCDWRITE  D6\D7,PORTB.NIB1,[CLEAR,HOME,"*  PC'DEN
BiLGi *"]
                        LCDWRITE          D6\D7,PORTB.NIB1,[SCRRAM+$40,"*
ALINAMIYOR !*"]
                        PAUSE 1000
;                       GOTO ATLA140
BASLA:
                        LCDWRITE         D6\D7,PORTB.NIB1,[SCRRAM+$4,DEC4
DEVIR\4]
                        LCDWRITE D6\D7,PORTB.NIB1,[SCRRAM+$C,DEC2 POZ\2,"
"]
                        GOSUB F_LCD
                        LCDWRITE          D6\D7,PORTB.NIB1,[SCRRAM+$4,DEC
DEVIR\4,SCRRAM+$C,DEC                                POZ\2,SCRRAM+$44,DEC
PumpOutputPres\4,SCRRAM+$4C,DEC OrificePressureDrop\4]
;***********************************************
;***********************************************

BASLA1:
                        GOSUB F_ANALOG
                        GOSUB F_RPM
                        GOSUB F_VALVEOKU
                        GOSUB F_HSERIAL
                        GOSUB F_VALVEOKU
                        GOSUB F_VALVEYAZ
                        GOSUB F_PWM
GOTO BASLA1

;***********************************************
;***********************************************

F_ANALOG:

            FOR XX=0 TO 4
                        ANA(XX)=0
                        ANDI(XX)=0
            NEXT


                  FOR I=0 TO 9
                              ADIN A0,CLK,ADSETUP,ANDI(0)
                        ;  LOADS   THE  VARIABLE  PUMP_INP_PRESS  WITH  THE
SAMPLE
                                    ANDI(0)=ANDI(0) MIN 205
                              ADIN A1,CLK,ADSETUP,ANDI(1)
                        ; 2,5 bar=1024 COUNTS
                                    ANDI(1)=ANDI(1) MIN 205
```

```
                        ADIN A2,CLK,ADSETUP,ANDI(2)
                              ANDI(2)=ANDI(2) MIN 205
                        ADIN A3,CLK,ADSETUP,ANDI(3)
                              ANDI(3)=ANDI(3) MIN 205
                        ADIN A5,CLK,ADSETUP,ANDI(4)
                              ANDI(4)=ANDI(4) MIN 0
                                          ANA(0)=ANA(0)+ANDI(0)
                                          ANA(1)=ANA(1)+ANDI(1)
                                          ANA(2)=ANA(2)+ANDI(2)
                                          ANA(3)=ANA(3)+ANDI(3)
                                          ANA(4)=ANA(4)+ANDI(4)
            NEXT
                  PumpInputPres=(((ANA(0)-2048)*2500)/8182 )
            ; PUMP INPUT PRESSURE IN mbar
                  PumpOutputPres=(((ANA(1)-2048)*2500)/8182 )
            ; PUMP OUTPUT PRESSURE IN mbar
                  OrificeInputPres=(((ANA(2)-2048)*2500)/8182)
            ; ORIFICE INPUT PRESSURE IN mbar
                  OrificeOutputPres=(((ANA(3)-2048)*2500)/8182)
            ; ORIFICE OUTPUT PRESSURE IN mbar
                  OrificePressureDrop=((ANA(4)*2500)/(10230*SF))
            ; ORIFICE PRESSURE DROP IN mbar
            OrificeDeltaP =((OrificeInputPres-OrificeOutputPres)) MIN 0


                  LCDWRITE        D6\D7,PORTB.NIB1,[SCRRAM+$44,DEC4
PumpOutputPres\4,SCRRAM+$4C,DEC4 OrificeDeltaP\4 ]

RETURN


F_RPM:
FOR I=0 TO 2
                  DEVIR_OLD=DEVIR

                  HIGH C3
                  PAUSE 2
                  LOW C3

                  SERIN
D1,N2400,20,ATLA200,[DEVIR.BYTE0,DEVIR.BYTE1]  ;RPM IS READ FROM SLAVE
                  GOTO ATLA210
      ATLA200:
      DEVIR=DEVIR_OLD
                  LCDWRITE D6\D7,PORTB.NIB1,[SCRRAM+$4,"!!  "]
NEXT
                  DEVIR=DEVIR_OLD
                  GOTO ATLA211
      ATLA210:
;                 DEVIR=DEVIR MAX 4000
                  LCDWRITE         D6\D7,PORTB.NIB1,[SCRRAM+$4,DEC4
DEVIR\4]
      ATLA211:
RETURN



F_HSERIAL:
                  DEVIR_OLD=DEVIR_NEW
                  POZ_OLD=POZ_NEW
                  HSEROUT      [DEC      DEVIR\5,DEC      POZ\5,DEC
PumpInputPres\5,DEC      PumpOUTputPres\5,DEC      OrificeInputPres\5,DEC
OrificeOutputPres\5,DEC OrificePressureDrop\5] ;C6
```

```
;                       PAUSE 30
;                       HSEROUT  [DEC  DEVIR\5,DEC  POZ\5,DEC  ANA(0)\5,DEC
ANA(1)\5,DEC ANA(2)\5,DEC ANA(3)\5,DEC ANA(4)\5]
;C6

                        PAUSE 3

;                       HSERIN
ATLA240,40,[DEVIR_NEW.LOWBYTE,DEVIR_NEW.HIGHBYTE,POZ_NEW.LOWBYTE,POZ_NEW.
HIGHBYTE]
                        HSERIN   ATLA240,40,[STR   STR0\2,STR   STR1\4,STR
STR2\2,STR STR3\4]
                              IF   (STR0(0)="H"   AND   STR0(1)="Z")   and
(STR2(0)="V" AND STR2(1)="P") THEN

                                    DEVIR_NEW=((STR1(0)-
48)*1000)+((STR1(1)-48)*100)+((STR1(2)-48)*10)+(STR1(3)-48)
                                    IF DEVIR_NEW>3999 THEN
                                    DEVIR_NEW=DEVIR_OLD
                                    ENDIF
                                    POZ_NEW=((STR3(0)-
48)*1000)+((STR3(1)-48)*100)+((STR3(2)-48)*10)+(STR3(3)-48)
                              ELSE
                                    GOTO ATLA240
                              ENDIF
                              GOTO atla250 ;ATLA241
      ATLA240:
                        DEVIR_NEW=DEVIR_OLD
                        POZ_NEW=POZ_OLD
;     ATLA241:
;                       HSERIN ATLA242,40,[STR STR2\2,STR STR3\4]
;                             IF STR2(0)="9" AND STR2(1)="9" THEN
;                                   POZ_NEW=((STR3(0)-
48)*1000)+((STR3(1)-48)*100)+((STR3(2)-48)*10)+(STR3(3)-48)
;                             ELSE
;                                   GOTO ATLA242
;                             ENDIF
;                       GOTO ATLA250
;     ATLA242:
;                       POZ_NEW=POZ_OLD
      ATLA250:
                        LCDWRITE         D6\D7,PORTB.NIB1,[SCRRAM+$4,DEC4
DEVIR\4]
                        LCDWRITE D6\D7,PORTB.NIB1,[SCRRAM+$C,DEC2 POZ\2,"
"]
RETURN


F_PWM:
;DEVIR_NEW=1000
IF DEVIR_NEW<100 THEN
TRISC.BIT1=1
ELSE
```

```
TRISC.BIT1=0
ENDIF
IF DEVIR_NEW>3999  THEN
      DEVIR_NEW=DEVIR_OLD
ENDIF

                        DUTY1=DEVIR_NEW   ;MAX 3999
;           Period=4000  CORRESPONDS TO 4OOO REVS
                        HPWM 1, 10000, DUTY1
                        IF DUTY1<100 THEN
                              TRISC.BIT1=0
                              PORTC.BIT1=0
                        ENDIF

RETURN

F_LCD:
                        LCDWRITE
D6\D7,PORTB.NIB1,[CLEAR,HOME,"RPM=",SCRRAM+$9,"Vp="]
                        LCDWRITE         D6\D7,PORTB.NIB1,[SCRRAM+$40,"Po
=",SCRRAM+$49,"Or="] ; LCD
RETURN

F_VALVEOKU:
                        POZ_OLD=POZ
FOR I=0 TO 2

                        HIGH C4
                        PAUSE 2
                        LOW C4

                        SERIN D3,N2400,20,ATLA260,[POZ.BYTE0,POZ.BYTE1]

; OLD POS. IS BEING READ

                        GOTO ATLA270

      ATLA260:
;     POZ=POZ_OLD
                        LCDWRITE D6\D7,PORTB.NIB1,[SCRRAM+$C,"!1  "]
NEXT
                        POZ=POZ_OLD
;                       GOTO ATLA271

      ATLA270:
                        LCDWRITE D6\D7,PORTB.NIB1,[SCRRAM+$C,DEC2 POZ\2,"
"]
      ;                 LCDWRITE         D6\D7,PORTB.NIB1,[SCRRAM+$C,DEC2
POZ_NEW\2,"  "]
      ATLA271:
```

```
RETURN

F_VALVEYAZ:

      ATLA290:

            IF POZ<7 AND (PORTD.BIT2=1 AND PORTC.BIT5=0) THEN
                        POZ_NEW=7
            ENDIF

            IF POZ>54 AND (PORTC.BIT5=1 AND PORTD.BIT2=0)THEN

                        POZ_NEW=54
            ENDIF

            IF POZ_NEW>POZ THEN
                        YON=1
                        HIGH D5           ;DIRECTION OF ROTATION=1
                        LOW D4
            ENDIF
            IF POZ_NEW<POZ THEN
                        YON=-1
                        LOW D5            ; DIRECTION OF ROTATION=-1
                        HIGH D4
            ENDIF
            IF POZ_NEW=POZ THEN
                        YON=0
                        LOW D5            ; DIRECTION OF ROTATION=0
                        LOW D4
            ENDIF
RETURN

END
```

APPENDIX C1

VALVE AND DC MOTOR CONTROL DIAGRAM

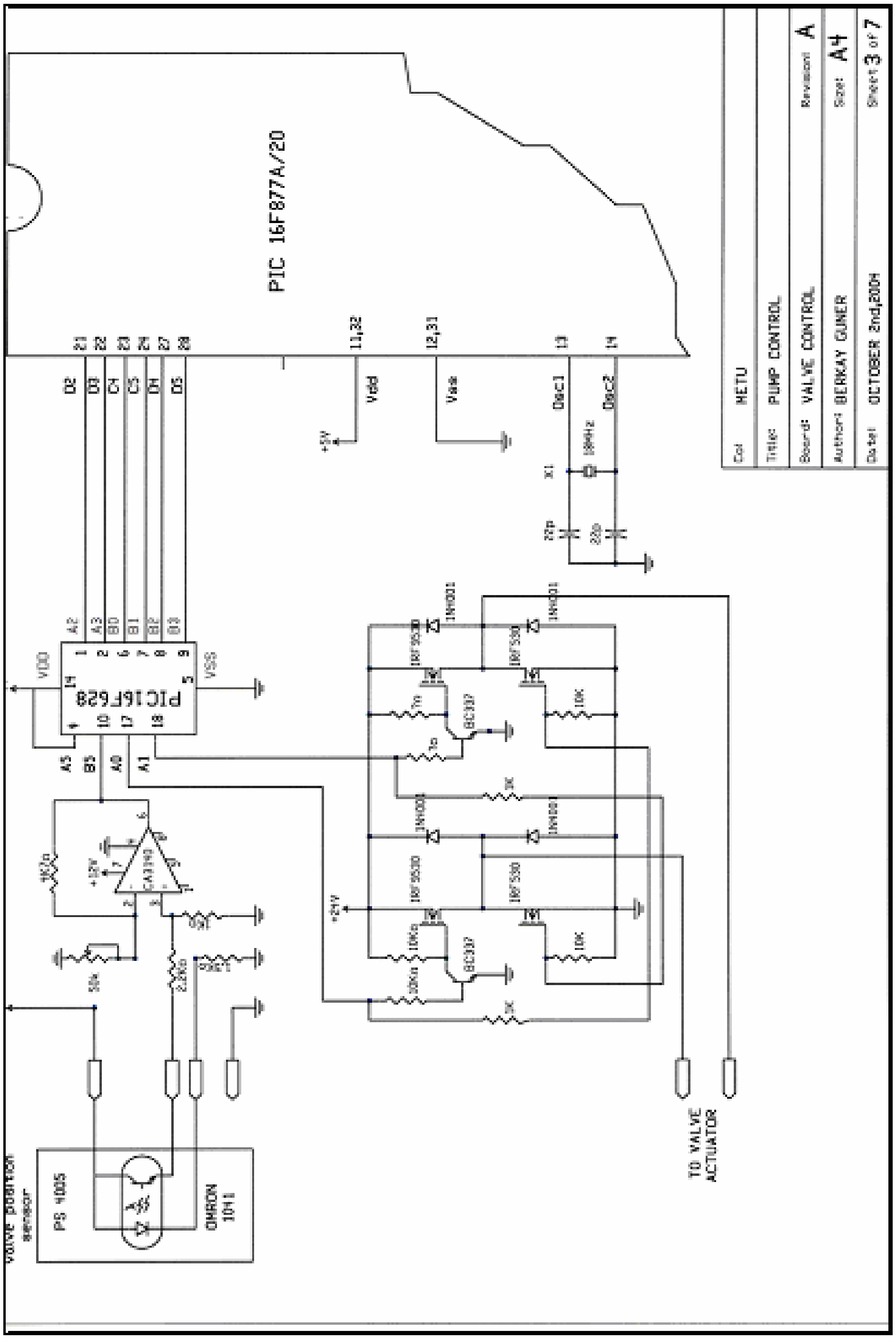


Fig C1: Valve and DC Motor Control Diagram

APPENDIX C2

PUMP RPM AND PWM CONTROL DIAGRAM

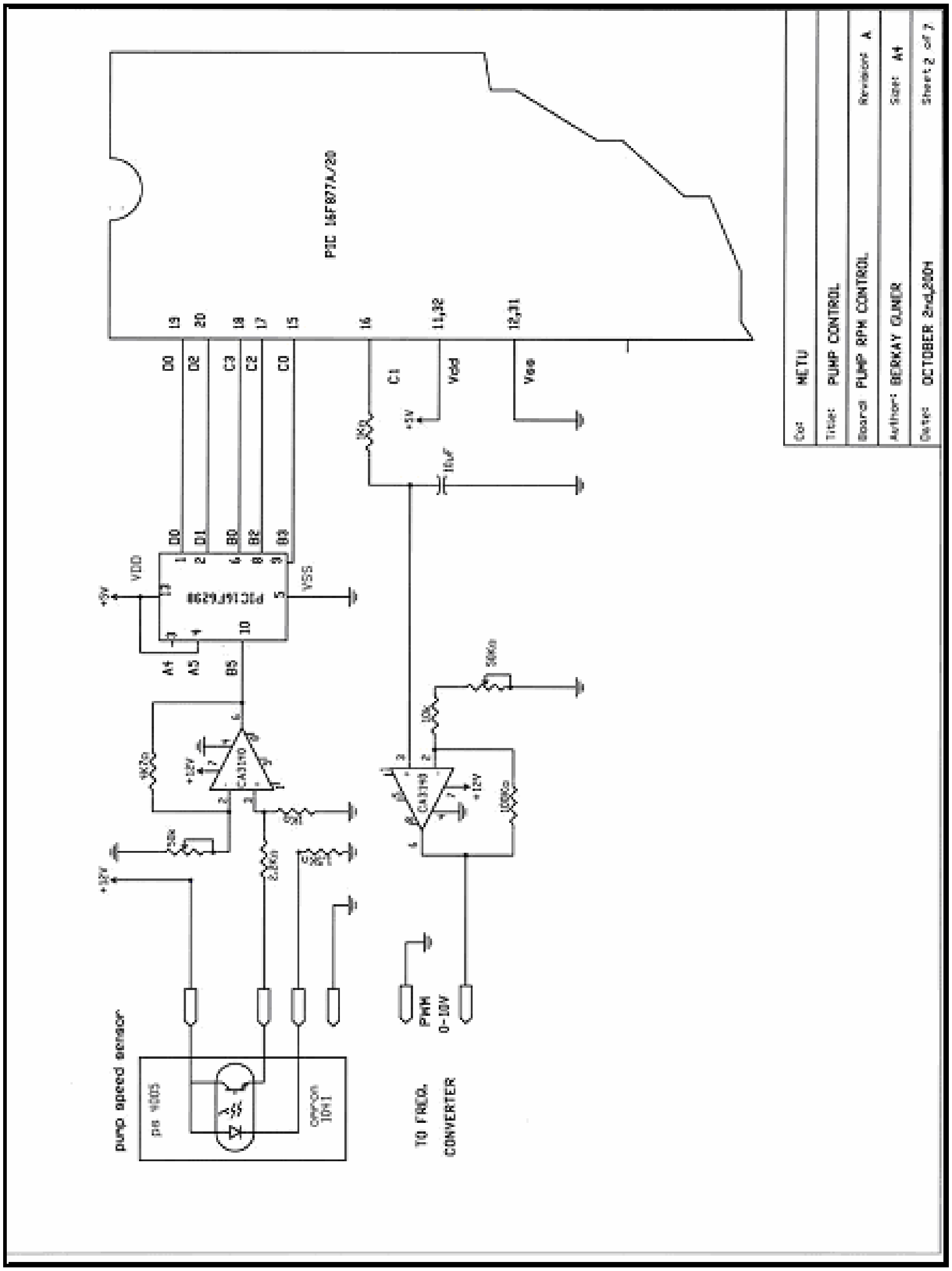


Fig C2: Pump RPM and PWM Control Diagram

APPENDIX C3

ANALOGUE PRESSURE INPUT DIAGRAM

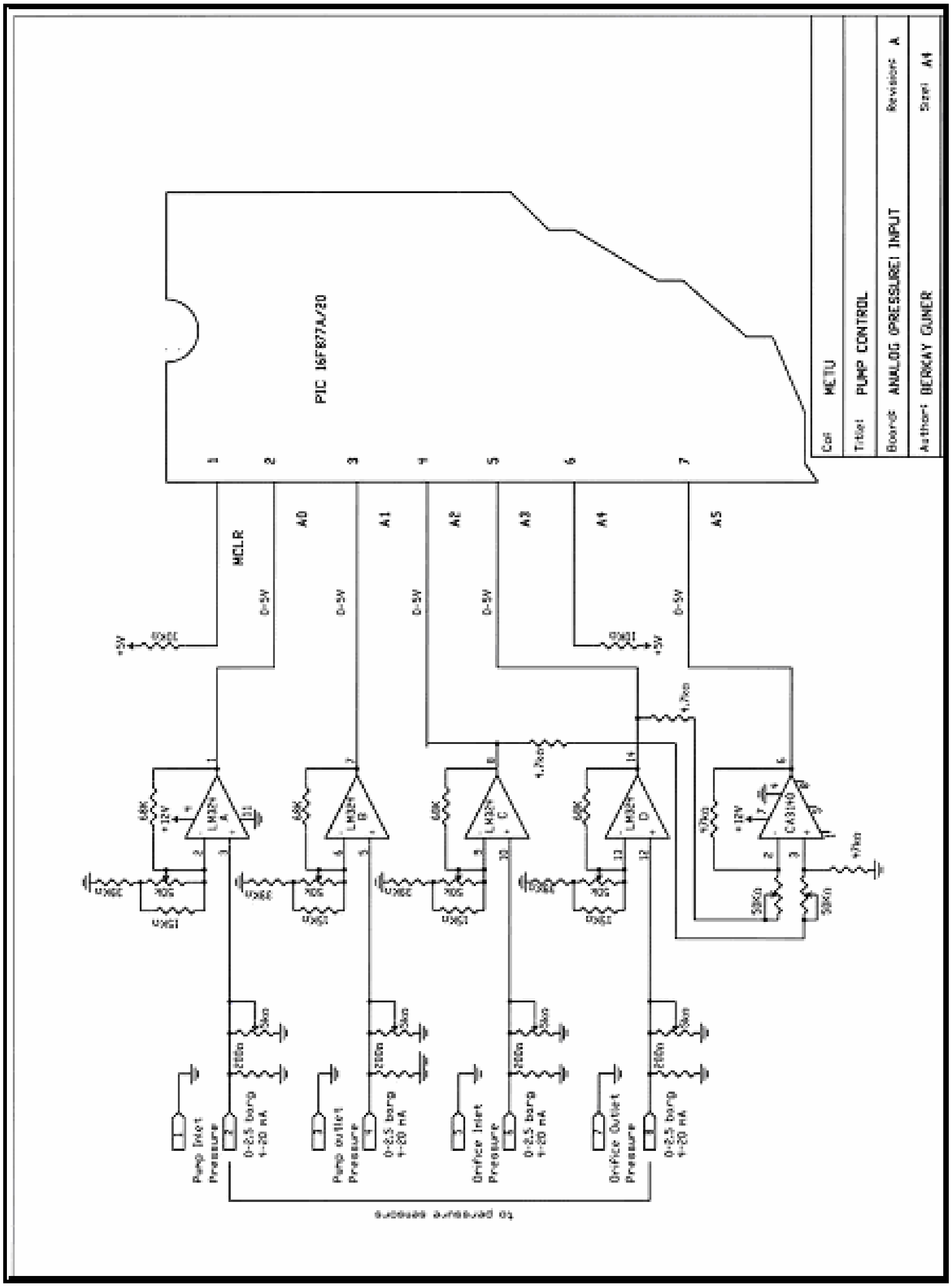


Fig C3: Analogue Pressure Input Diagram

APPENDIX C4

RS-232 AND LCD CONTROL DIAGRAM

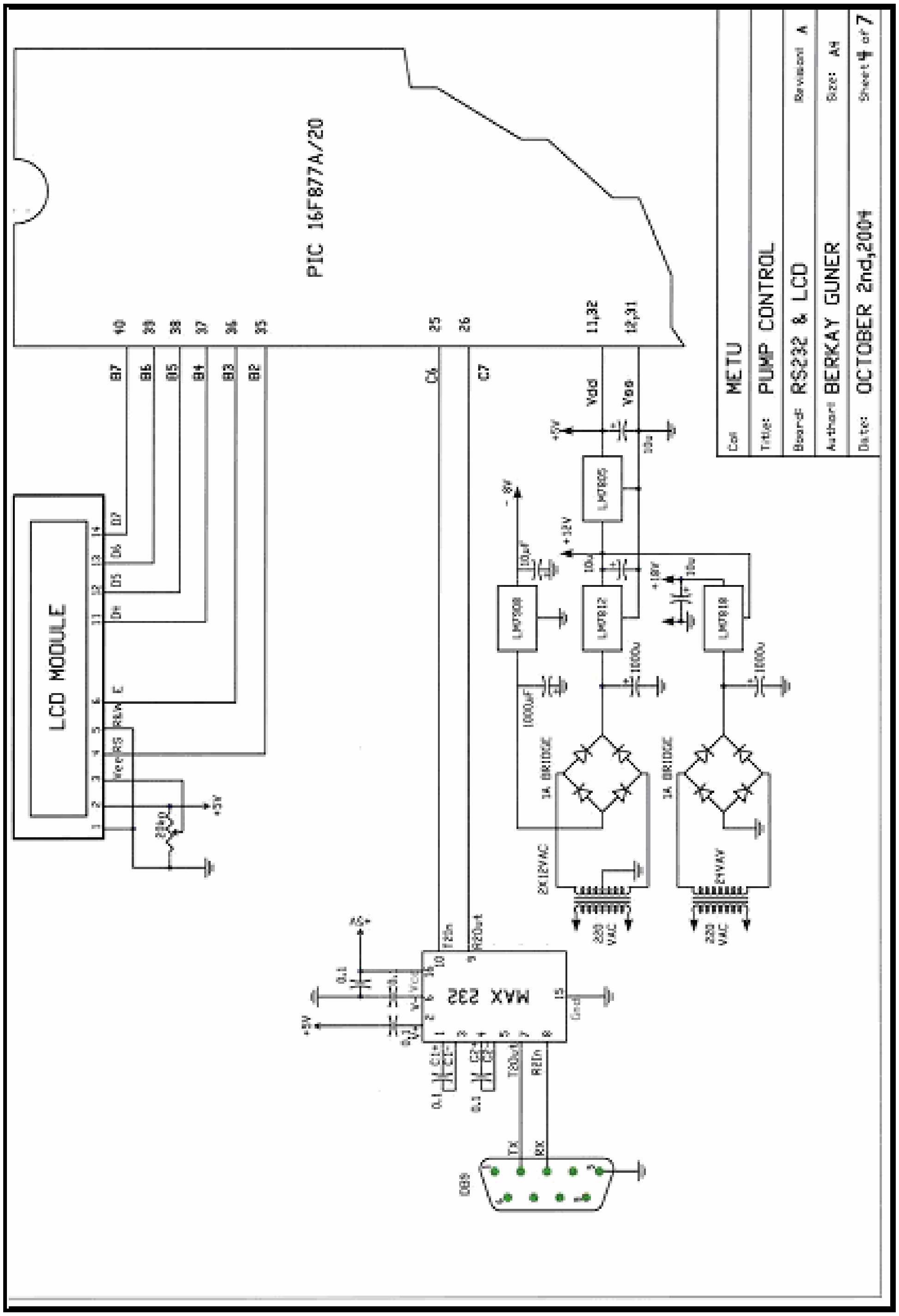


Fig C4: RS-232 and LCD Control Diagram

APPENDIX C5

PUMP CONTROL PCB DIAGRAM

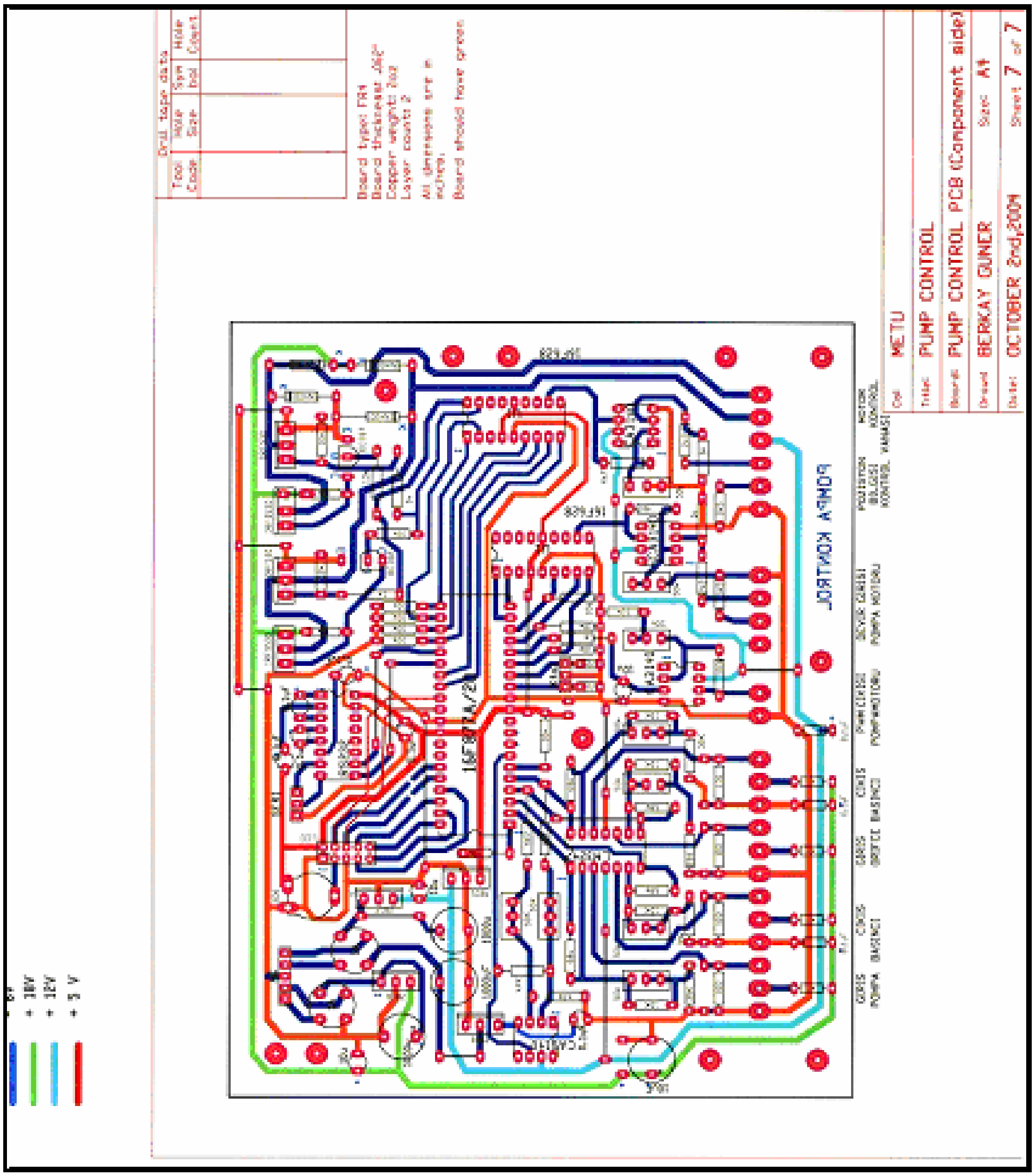


Fig C5: Pump Control PCB Diagram

APPENDIX C6

WIRING DIAGRAM

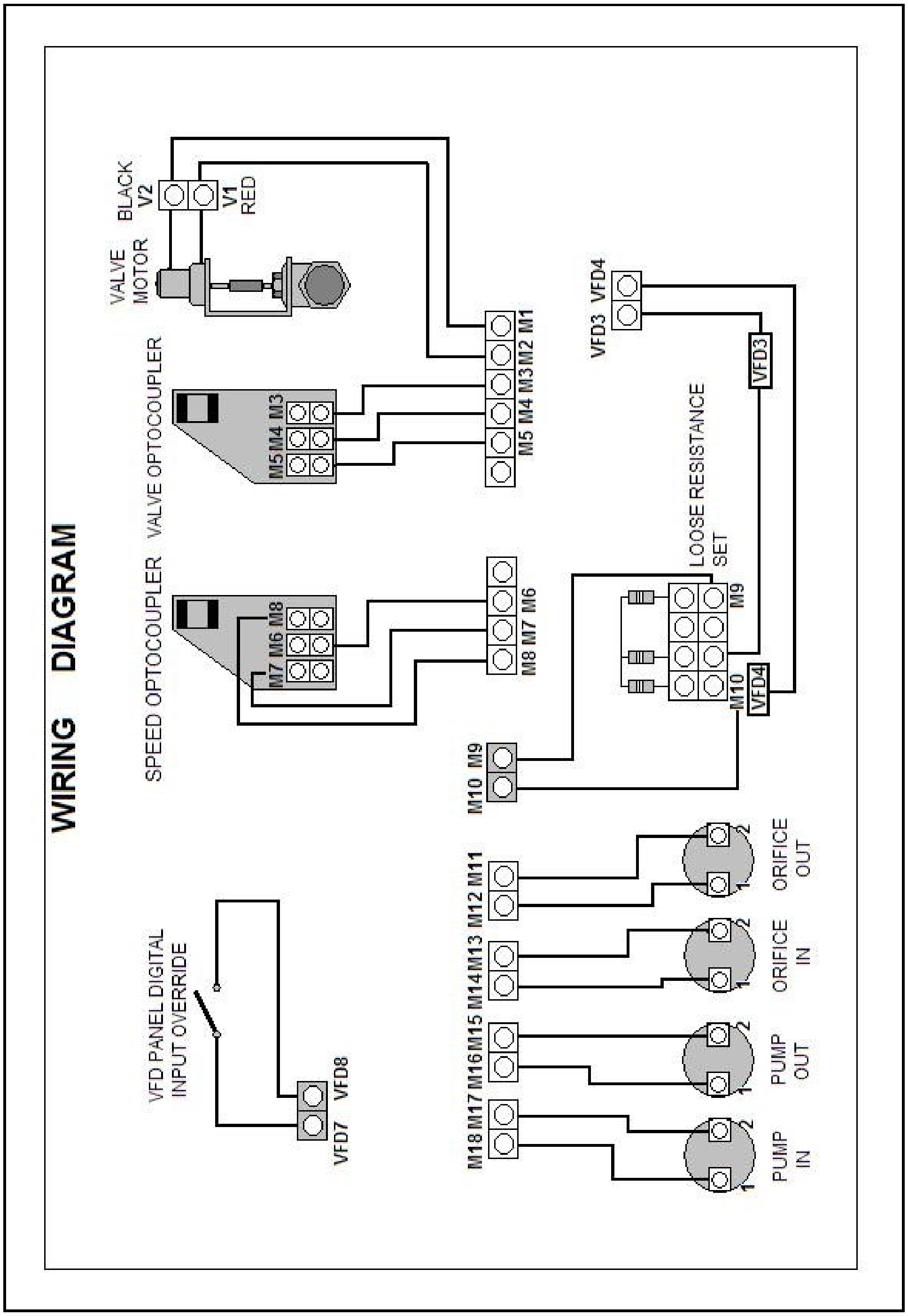


Fig C6: Wiring Diagram

APPENDIX D
K VALUES OF FITTINGS

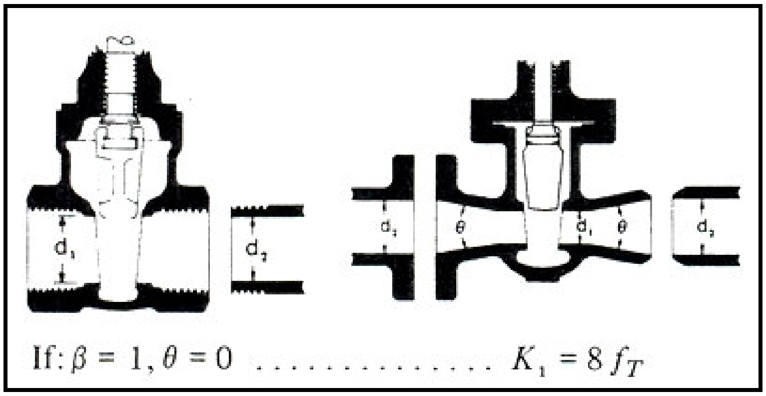


Fig D1: K Value for wedge disc gate valve

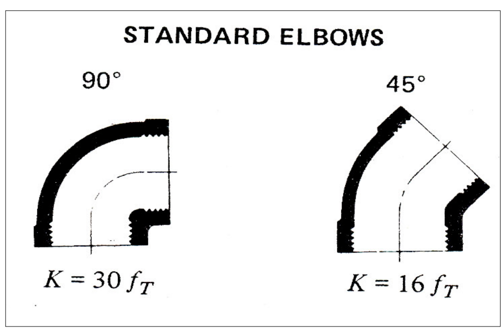


Fig D2: K Value for standard elbows

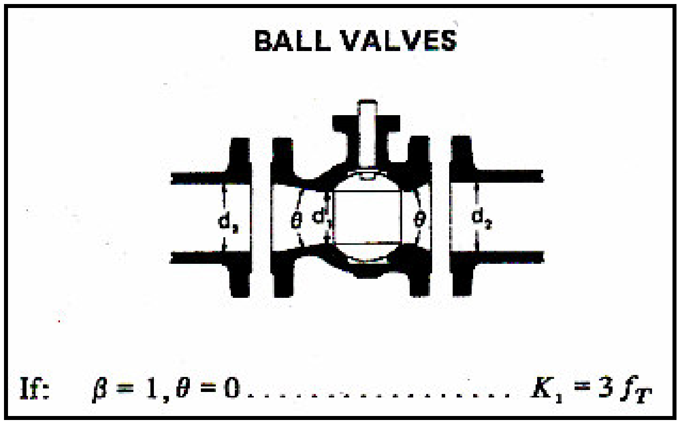


Fig D3: K Value for ball valves

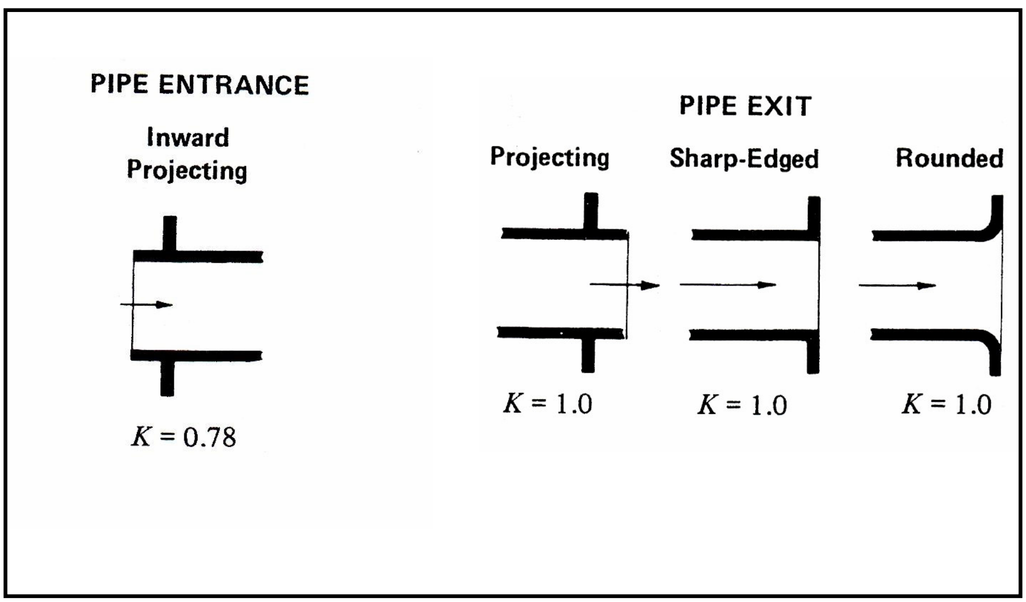


Fig D4: K Value for pipe entrance and pipe exit

APPENDIX E1

PIPING AND FITTING INVENTORY AT +6M ELEVATION

Upstream Side:

- 1 x Sharp Edge Pipe Inlet (From Reservoir)
- 0.8m 1 ½” Pipe
- 0.5m 1 ½” Pipe
- 1 x 90^{o} Standard Elbow

Downstream Side:

- 1.5 m 1” Pipe
- 1 x Motor Operated Throttling Valve (Wedge Disc Gate Valve) 1”
- 1 x Restriction Orifice (Opening Ratio %60)
- 1 x Pipe Exit (to collector)
- 1 x Pipe Inlet (from collector)
- 1 x Hand Operated Ball Valve
- 4.5m 1” Pipe
- 1.05m 1” Pipe
- 1 x 90^{o} Standard Elbow
- 1 Pipe Exit (to 3” open discharge header)

APPENDIX E2

PIPING AND FITTING INVENTORY AT +4M ELEVATION

Upstream Side:

- 1 x Sharp Edge Pipe Inlet (From Reservoir)
- 0.8m 1 ½” Pipe
- 0.5m 1 ½” Pipe
- 1 x 90^{o} Standard Elbow

Downstream Side:

- 1.5 m 1” Pipe
- 1 x Motor Operated Throttling Valve (Wedge Disc Gate Valve) 1”
- 1 x Restriction Orifice (Opening Ratio %60)
- 1 x Pipe Exit (to collector)
- 1 x Pipe Inlet (from collector)
- 1 x Hand Operated Ball Valve
- 2.5m 1” Pipe
- 0.9m 1” Pipe
- 1 x 90^{o} Standard Elbow
- 1 Pipe Exit (to 3” open discharge header)

APPENDIX E3

PIPING AND FITTING INVENTORY AT +2M ELEVATION

Upstream Side:

- 1 x Sharp Edge Pipe Inlet (From Reservoir)
- 0.8m 1 ½" Pipe
- 0.5m 1 ½" Pipe
- 1 x 90^{o} Standard Elbow

Downstream Side:

- 1.5 m 1" Pipe
- 1 x Motor Operated Throttling Valve (Wedge Disc Gate Valve) 1"
- 1 x Restriction Orifice (Opening Ratio %60)
- 1 x Pipe Exit (to collector)
- 1 x Pipe Inlet (from collector)
- 1 x Hand Operated Ball Valve
- 2.5m 1" Pipe
- 0.9m 1" Pipe
- 1 x 90^{o} Standard Elbow
- 1 Pipe Exit (to 3" open discharge header)

APPENDIX F

C ~ Re RELATIONSHIP

Range 1 for Re [100, 1000]:

$$C(\mathrm{Re})_1 = -4.344 \cdot 10^{-13} \cdot \mathrm{Re}^4 + 1.119 \cdot 10^{-9} \cdot \mathrm{Re}^3 - 1.034 \cdot 10^{-6} \cdot \mathrm{Re}^2 + 3.463 \cdot 10^{-4} \cdot \mathrm{Re} + 0.775$$

Range 2:

$$C(\mathrm{Re})_2 = -2.859 \cdot 10^{-13} \cdot \mathrm{Re}^3 + 6.129 \cdot 10^{-9} \cdot \mathrm{Re}^2 - 4.748 \cdot 10^{-5} \cdot \mathrm{Re} + 0.812$$

For Re [10^3,10^4]

Range 3:

$$C(\mathrm{Re})_3 = 2.296 \cdot 10^{-12} \cdot \mathrm{Re}^2 - 3.732 \cdot 10^{-7} \cdot \mathrm{Re} + 0.668$$

For Re [10^4, 10^5]

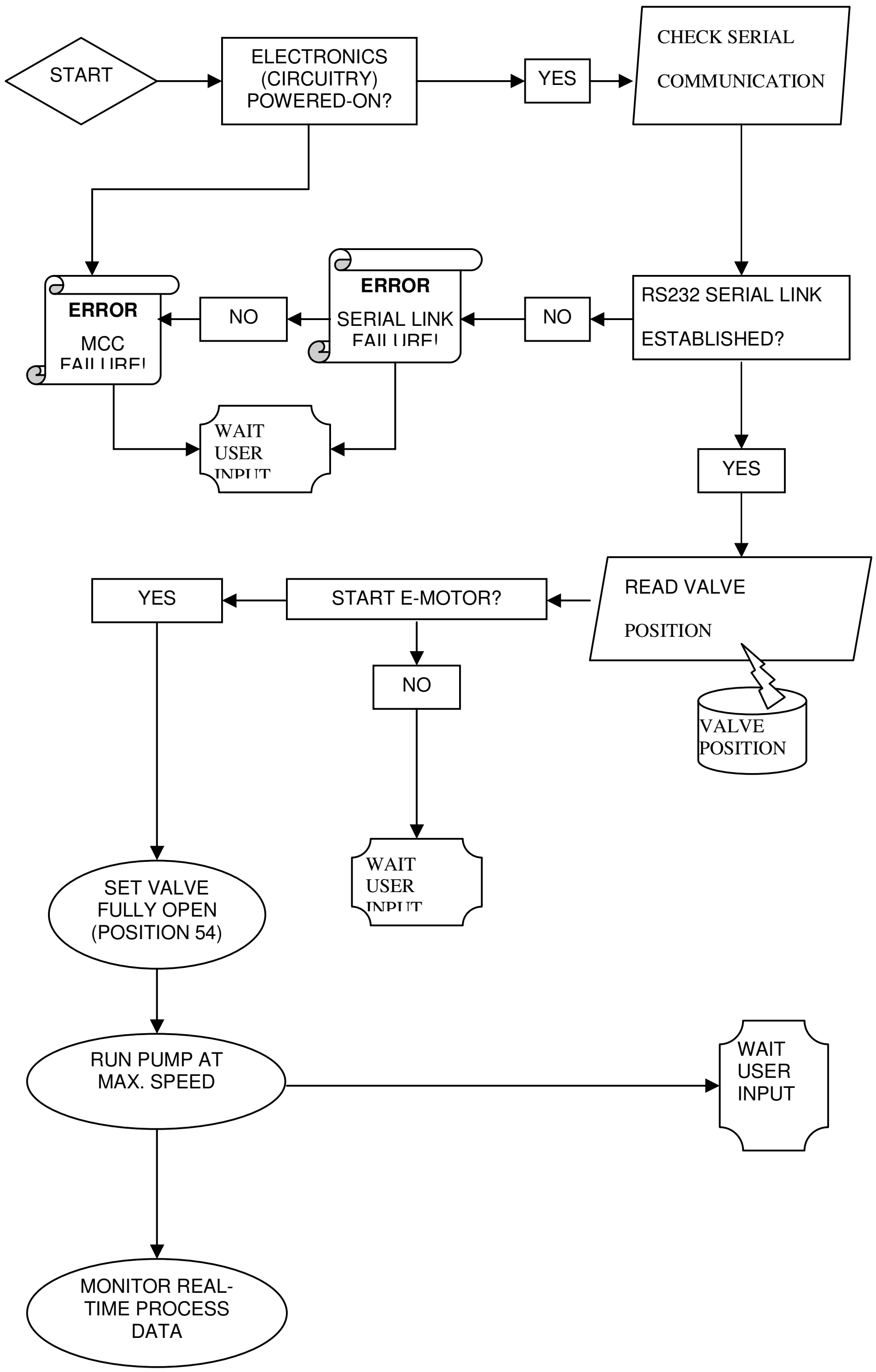
Range 4:

$$C(\mathrm{Re})_4 = 2.779 \cdot 10^{-14} \cdot \mathrm{Re}^2 - 2.233 \cdot 10^{-8} \cdot \mathrm{Re} + 0.655$$

For Re [10^5, 5x10^5]

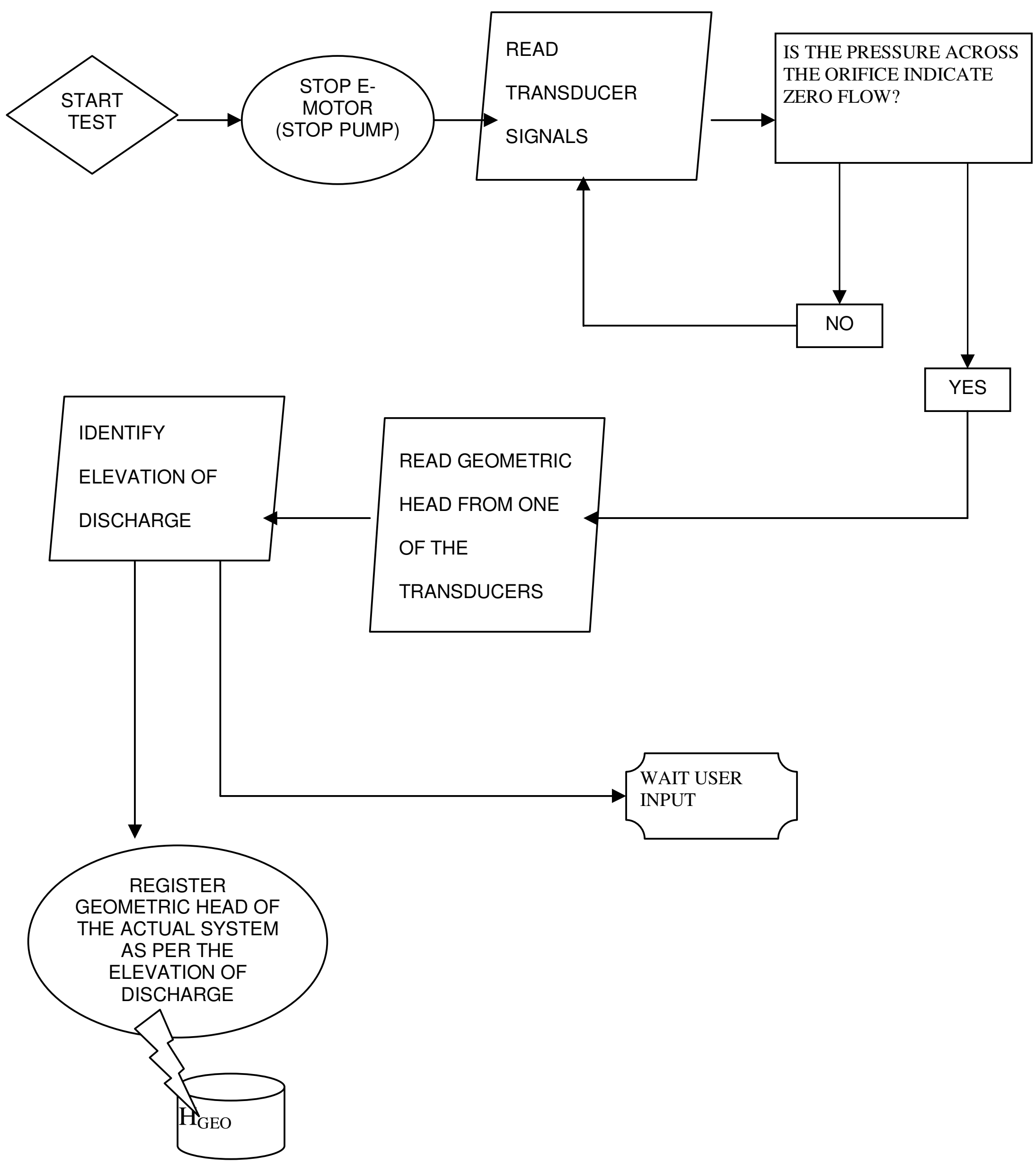
APPENDIX G1

FLOWCHART FOR PUMP START SEQUENCE IN TEST MODULE



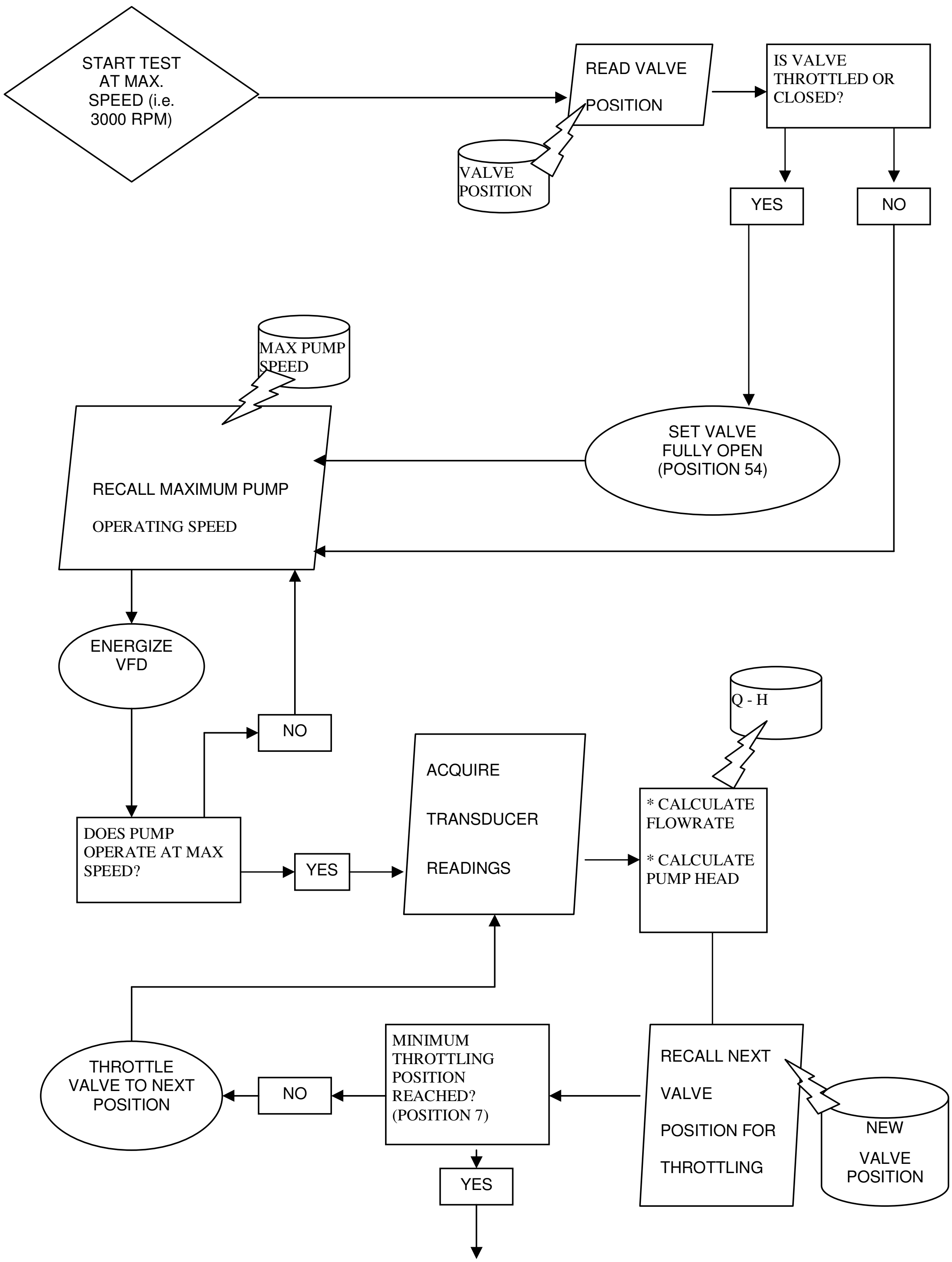
APPENDIX G2

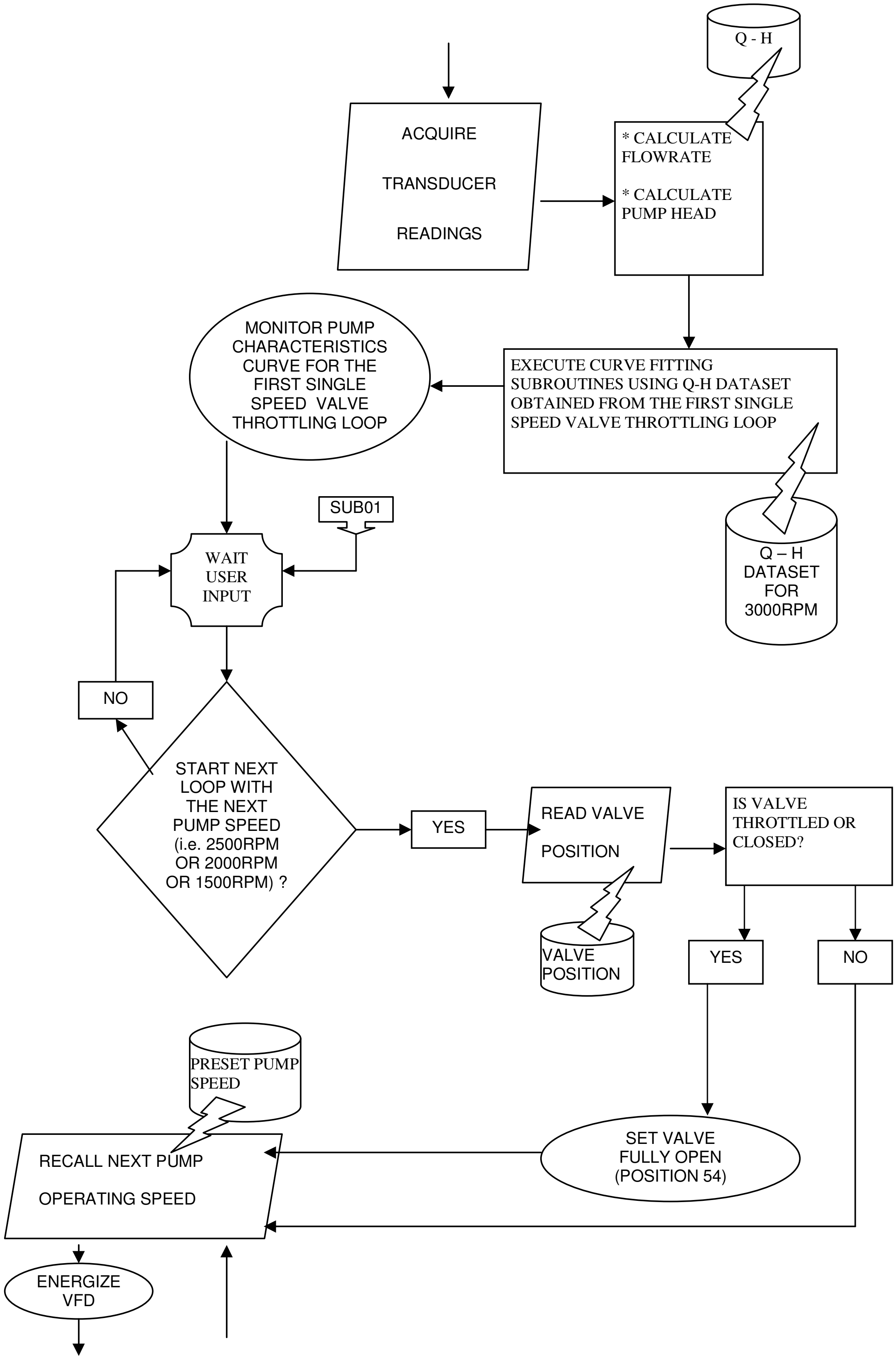
FLOWCHART OF IDENTIFICATION OF GEOMETRIC HEAD OF SYSTEM (H_{GEO}) IN TEST MODULE

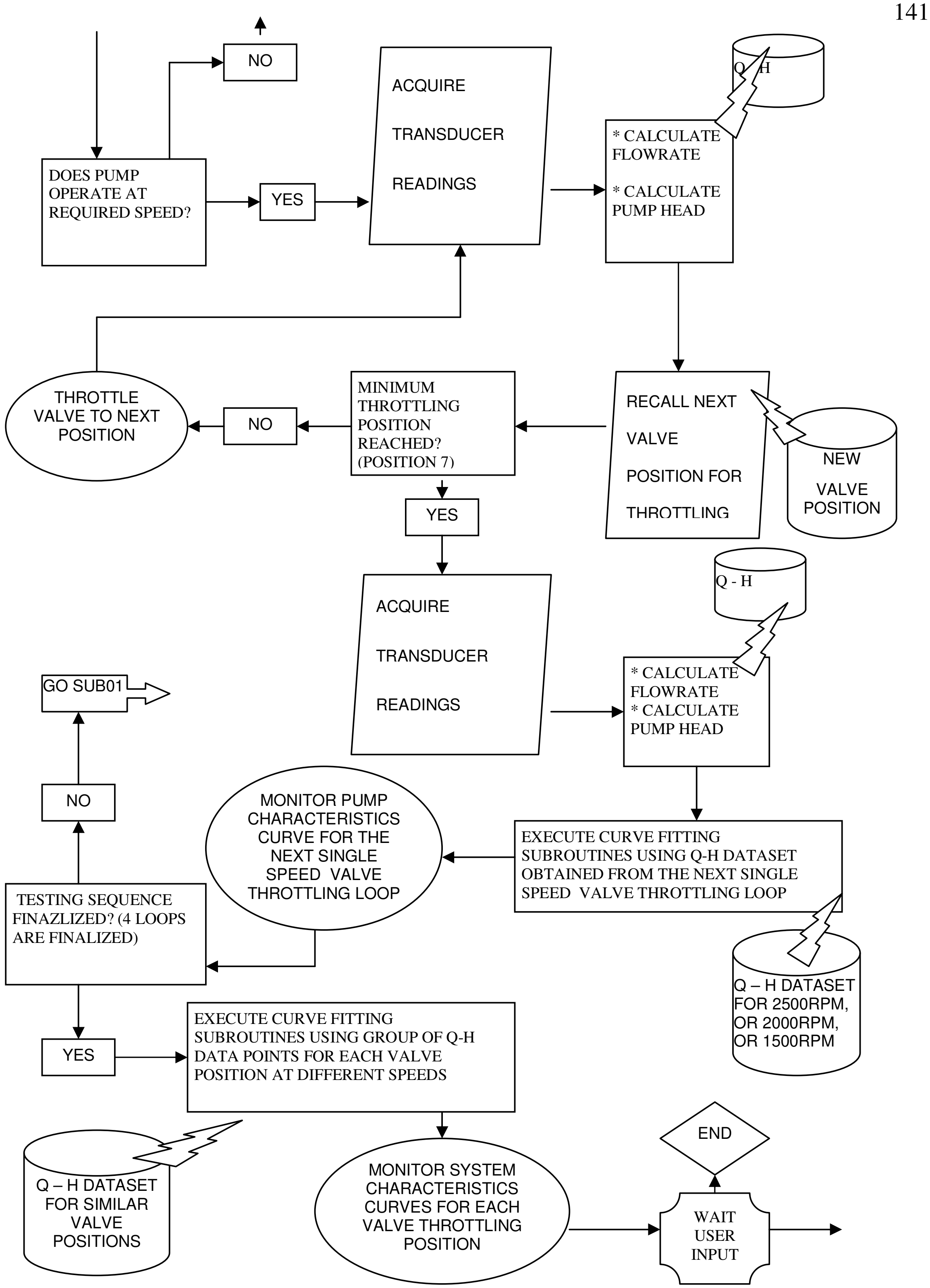


APPENDIX G3

SINGLE SPEED VALVE THROTTLING LOOPS IN TEST MODULE




Q - H
ACQUIRE
TRANSDUCER
READINGS
* CALCULATE FLOWRATE
* CALCULATE PUMP HEAD
EXECUTE CURVE FITTING SUBROUTINES USING Q-H DATASET OBTAINED FROM THE FIRST SINGLE SPEED VALVE THROTTLING LOOP
MONITOR PUMP CHARACTERISTICS CURVE FOR THE FIRST SINGLE SPEED VALVE THROTTLING LOOP
Q – H DATASET FOR 3000RPM
SUB01
WAIT USER INPUT
NO
START NEXT LOOP WITH THE NEXT PUMP SPEED (i.e. 2500RPM OR 2000RPM OR 1500RPM) ?
YES
READ VALVE
POSITION
IS VALVE THROTTLED OR CLOSED?
VALVE POSITION
YES
NO
PRESET PUMP SPEED
RECALL NEXT PUMP
OPERATING SPEED
SET VALVE FULLY OPEN (POSITION 54)
ENERGIZE VFD


NO
DOES PUMP OPERATE AT REQUIRED SPEED?
YES
ACQUIRE TRANSDUCER READINGS
Q - H
* CALCULATE FLOWRATE
* CALCULATE PUMP HEAD
THROTTLE VALVE TO NEXT POSITION
NO
MINIMUM THROTTLING POSITION REACHED? (POSITION 7)
RECALL NEXT VALVE POSITION FOR THROTTLING
NEW VALVE POSITION
YES
ACQUIRE TRANSDUCER READINGS
Q - H
* CALCULATE FLOWRATE
* CALCULATE PUMP HEAD
GO SUB01
NO
MONITOR PUMP CHARACTERISTICS CURVE FOR THE NEXT SINGLE SPEED VALVE THROTTLING LOOP
EXECUTE CURVE FITTING SUBROUTINES USING Q-H DATASET OBTAINED FROM THE NEXT SINGLE SPEED VALVE THROTTLING LOOP
TESTING SEQUENCE FINAZLIZED? (4 LOOPS ARE FINALIZED)
Q – H DATASET FOR 2500RPM, OR 2000RPM, OR 1500RPM
YES
EXECUTE CURVE FITTING SUBROUTINES USING GROUP OF Q-H DATA POINTS FOR EACH VALVE POSITION AT DIFFERENT SPEEDS
END
Q – H DATASET FOR SIMILAR VALVE POSITIONS
MONITOR SYSTEM CHARACTERISTICS CURVES FOR EACH VALVE THROTTLING POSITION
WAIT USER INPUT

APPENDIX H
PROPOSED EXPERIMENTAL PROCEDURE AND OPERATION DETAILS

ME

EXPERIMENT

IDENTIFICATION OF PUMP, SYSTEM CHARACTERISTICS AND COMPARISON OF THROTTLING CONTROL AND PUMP SPEED CONTROL

1.1 OBJECTIVE

In this experiment the pump characteristics at different pump speeds are identified by using an automated (computer controlled) pump bench and its auxiliaries. Pump and system characteristics data obtained and stored by the help of pump control software. Later the differences between pump speed control and valve throttling control are demonstrated, identified and commented accordingly.

1.2 INTRODUCTION

The adjustment of the flowrate to actual requirements using speed regulation is particularly useful if the system characteristics curve is steep (i.e. if the dynamic pump head is considerably greater than the geometric head) (Figure 1a). In this case, the pump's efficiency is only altered slightly because the alteration of the operating point is effected approximately along a parabola.

For relatively flat system characteristics curves (geometric head H_{geo} is considerably greater than the dynamic head loss), the useful range of adjustment is small due to the fact that the small changes in speed results in sudden alteration of operating point as a result the efficiency of the pump also alters suddenly. Thus, economic operation must be reviewed for such applications. Throttling may possibly be more economical in the case of a flat system characteristics curve than speed control due to relatively higher initial investment costs.

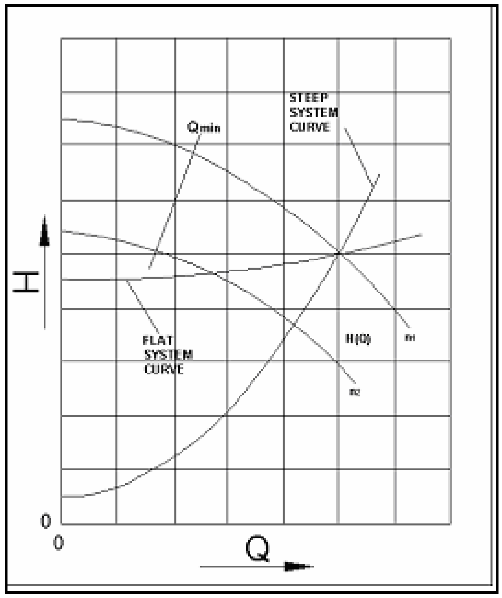


Fig 1a

System characteristics of pumping systems change due to wear, aging of piping, and accumulation of deposits in the system and/or due to configuration changes. This may put any sort of controlling algorithm into a state where they become unsuitable for that particular case. The said mismatch between the physical system and software controlling the process may cause inefficient operation of the pump which may even lead to total system failures.

As shown in Figure 1b, when the flow is reduced from Q_1 to Q_2 instead of wasting the excess pump head of (H_2 - H_1) in pressure drop through a valve (by throttling), reducing pump speed saves energy that the valve throttling would have wasted.

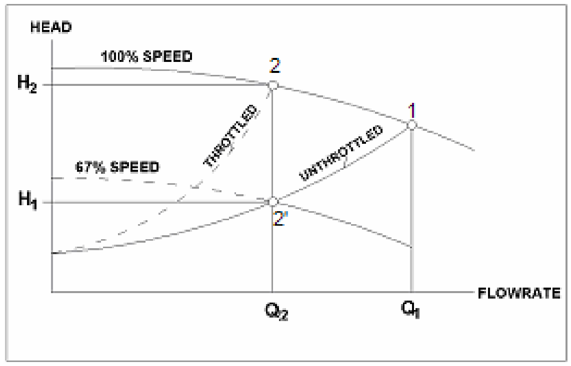


Figure 1b

1.3 EXPERIMENTAL SETUP

CENTRIFUGAL PUMP

Single stage Alem-Bertola centrifugal pump with 2-pole e-motor having a nominal speed of 2850rpm will be used in this experiment which is available in the Fluid Mechanics Laboratory.

Piping Arrangement

Pipes located at three different discharge elevations exist in the experimental setup. Conceptual general arrangement of the piping arrangement is seen in Figure 2 below.

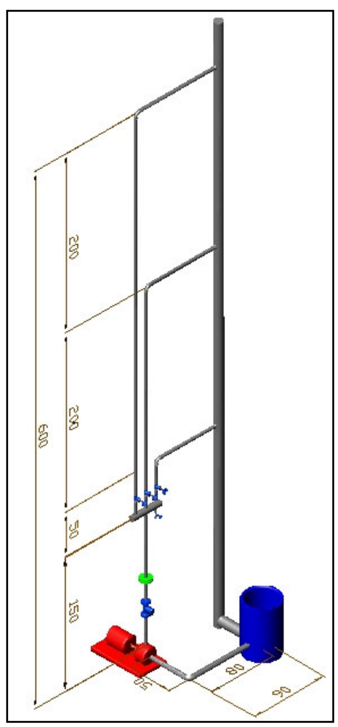


Figure 2

PRESSURE TRANSDUCERS AND ENCODERS

WIKA Eco-1 Transducers are used as pressure sensing elements. Pressure range of the transducers is 0 to 2.5 bar gage. Minimum differential pressure which is sensed by the transducers is 0,025m as per manufacturer's data. These transducers provide signal outputs within the range of 4 - 20 mA for 2-wire connection option seen in figure 3. Also the analogue output signal ranging between 4 - 20mA corresponds to 0 - 2.5 barg for this type of transducer. Schematic representation of above-mentioned 2-wire connection is illustrated in figure 3.

Valve position and pump speed data are read by the use of encoder discs seen in figure 3. Different types of encoder discs having different number of fins (copper plated circuit board) are seen in figure 4. Default fin numbers for valve position and pump speed encoder discs are 9 and 2 respectively.

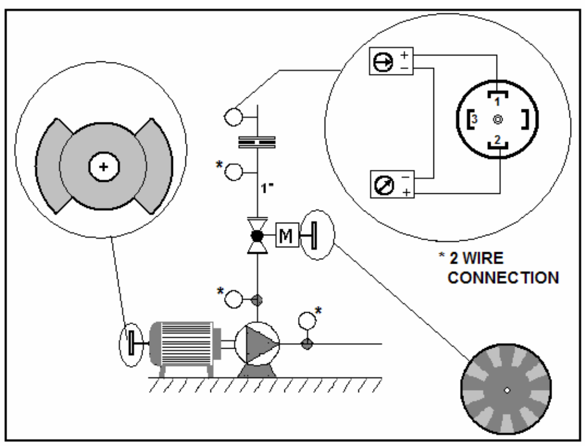


Figure 3

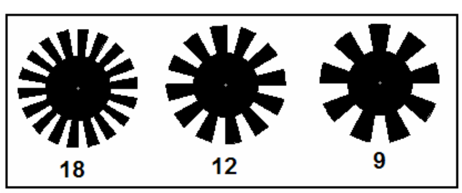


Figure 4

MOTOR OPERATED THROTTLING VALVE WITH POSITION FEEDBACK (MOV)

MOV is made of a 24VDC electrical motor with an integrated gearbox assembled to a PN 16 wedge disc valve. The motor operated valve which has 6 complete revolutions along its stroke between closed and fully open positions will be used for throttling control.

1.4 PROCEDURES

Instructions to be followed prior to starting the program are as follows:

8) All hand operated valves are checked so that none of them obstruct water circulation
9) Tank is filled with water above pump intake level
10) MCC power cable is plugged to 220 VAC source
11) Pump motor is properly plugged to VFD
12) VFD is properly plugged to 3-phase 380 VAC source
13) Digital input override switch is ON
14) DB-9 serial connection cable is plugged between PC and MCC
15) MCC is switched on

1.4.1 Testing Module

SETTINGS

Before proceeding to the testing module make sure that the correct settings are done. Click settings button (figure 5) and check whether the following default adjustments are done properly or not:

- Transducer Signal Lower Level = 4 [mA]
- Transducer Signal Upper Level = 20 [mA]
- Pressure Lower Level = 0 [mbar]
- Pressure Upper Level = 2500 [mbar]
- Pump speed encoder fin configuration = 2 fins
- Valve position encoder fin configuration = 9 fins

After making the adjustments, just click OK button.

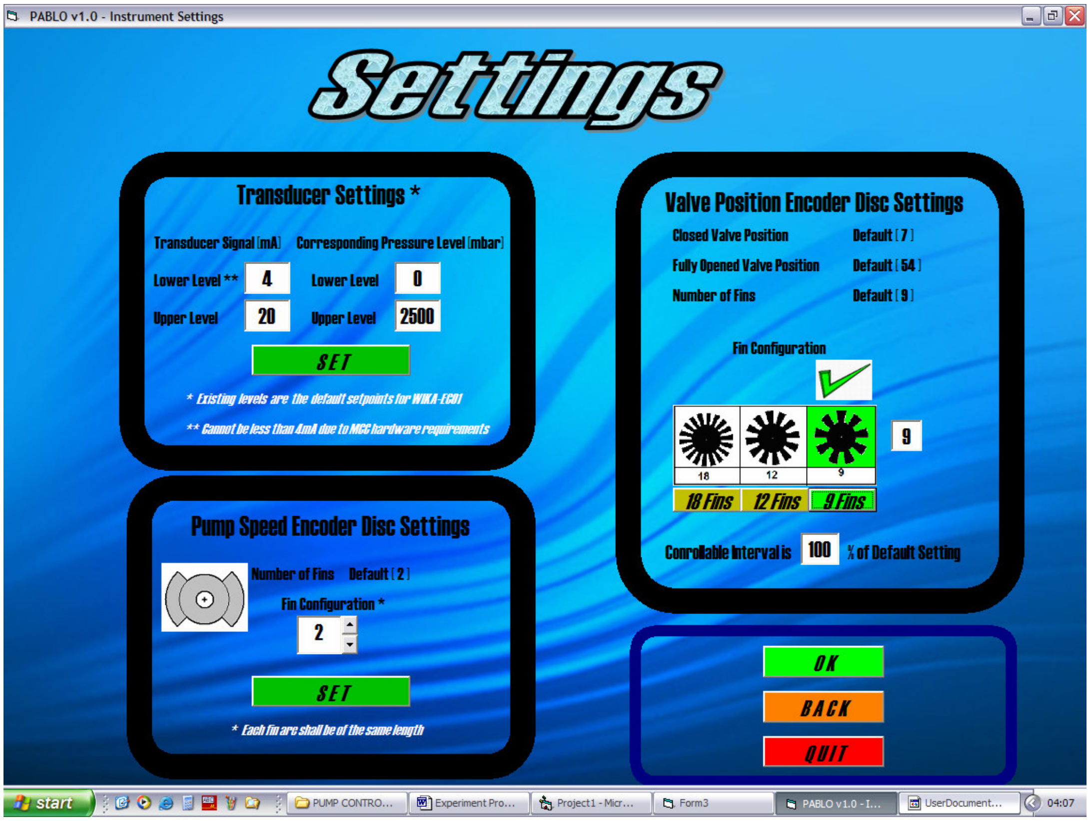


Figure 5

TEST SEQUENCE

Important Note!: ***In any case if the valve position does not change or proceed to the required position the valve disc might have reached to its mechanical limits at either end (mechanical backlash failure and actual valve position loss). In such a case immediately turn of the MCC in order to protect the valve motor. For resetting the valve position and for the corrective actions see the instructions at the end of the procedures section***

1) Leave only one of the ball valves open (i.e. +2m or +4m or +6m)
2) Click pump start button which is initially green.
3) Wait until water comes out of the PVC return header.

4) Wait until the pump head variation curve and flowrate variation curve are stabilized (turn into horizontal line with reasonable amount of fluctuation)
5) Click start test button. The following reactions shall be observed:
    a. Pump stops or it tends to slow down
    b. Geometric head of system is monitored at the bottom right-hand side of the screen. (record geometric head into your datasheet)
    c. Pump starts or it tends to speed-up after geometric head is indicated successfully
    d. 3000RPM button turns into green (at the bottom left hand side of screen)

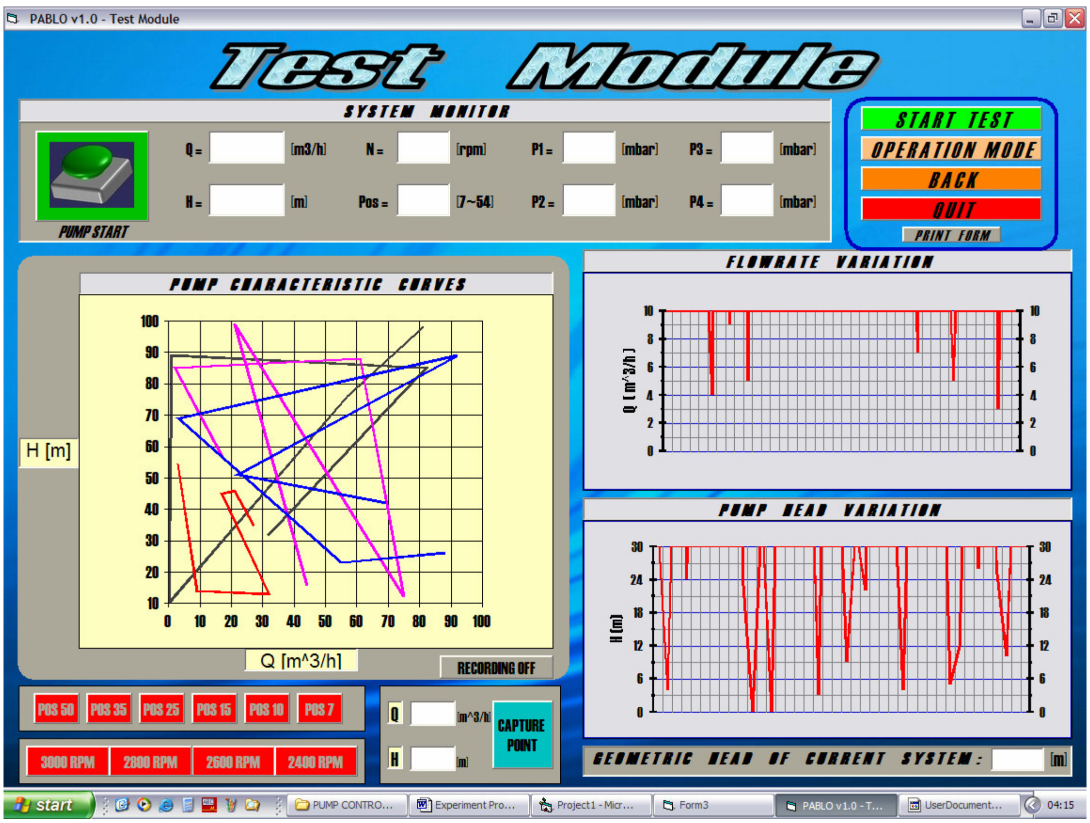


Figure 6

6) Click 3000RPM button. The following reaction shall be observed:
    a. POS 50 button turns into green

7) Click RECORDING OFF button where it turns into green and caption changes to RECORDING ON (by this step the test data are recorded and kept in distinct files for reporting purposes)
8) Click POS 50 button and wait until the valve position indicator shows position 50 in the system monitor panel located at the top of the screen.
9) Click Capture Point button to record first set of Flowrate and Head data. Record flowrate and head values on attached datasheets. Afterwards POS 35 button turns into green for the next throttling step.
10) Click POS 35 button and wait until the valve position indicator shows position 35 in the system monitor panel located at the top of the screen.
11) Repeat step 9 for data acquisition and recording until POS 7. (Follow Q and H values carefully at each throttling step, if there is no significant change in these values at that valve position, manually operated ball valve may be throttled to some extent for the sake of continuity of testing sequence)

12) 2800RPM button turns into green (at the bottom left hand side of screen) where 3000RPM button is disabled automatically.
13) Click 2800RPM button. The following reaction shall be observed:
    a. POS 50 button turns into green or it is enabled
14) Follow the same procedure mentioned in steps 6, 8, 9, 10, 11, 12 respectively until all four speeds are tested ("*Test Sequence Finished*" message appears in the end). Observe four different *Pump Characteristics Curve*s on the screen.

15) If a printer is installed and connected to the PC click print form button to get a hardcopy output of the existing screen for reporting purposes.

NOTE: Procedure may be repeated for different discharge elevations

1.4.2 Operation Module

SETTINGS

If settings were checked and adjusted before using testing module just click operation mode button at the top on the right hand side of the screen in figure 6. If settings need to be checked for some reason, proceed with the following:

Before proceeding to the operation module make sure that the correct settings are done in case no adjustment was done prior to using testing module. Click settings button (figure 5) and check whether the following default adjustments are done properly or not:

- Transducer Signal Lower Level = 4 [mA]
- Transducer Signal Upper Level = 20 [mA]
- Pressure Lower Level = 0 [mbar]
- Pressure Upper Level = 2500 [mbar]
- Pump speed encoder fin configuration = 2 fins
- Valve position encoder fin configuration = 9 fins

After making adjustments just click OK button. Then click Operation Mode button. This would run Pump Operation module seen in Figure 7.

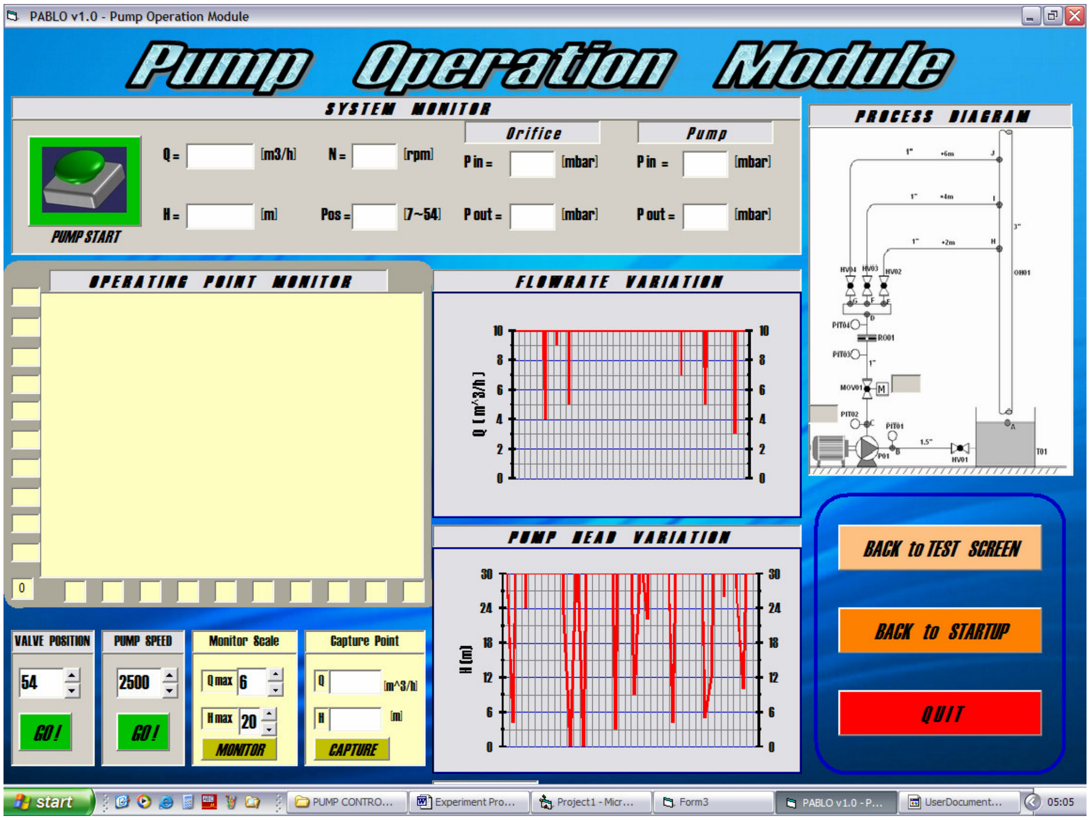


Figure 7

PUMP OPERATION MODULE

1) Leave only one of the ball valves open (i.e. +2m or +4m or +6m)
2) Click pump start button which is initially green.
3) Wait until water comes out of the PVC return header.
4) Wait until the pump head variation curve and flowrate variation curve are stabilized (turn into horizontal line with reasonable amount of fluctuation)
5) In order to send valve position and pump speed commands at any instance, use the up-down controls at the bottom on the le ft hand side of the screen in Figure 7 to adjust required valve position and/or pump speed. After the adjustment click corresponding GO button to send the command.
6) In order to activate the real-time operating point monitor, adjust flowrate and head scales using corresponding up-down controls and then click the *monitor* button.

a. Above-mentioned actions would result in activation of operating point monitor where a crosshair shows the actual point of pump operation on H-Q plot area. Each time the crosshair moves, it leaves a trace (dot) at the previous point of operation.

7) Identify a single flowrate value (i.e. $2m^3/h$) which will be later achieved by both throttling and pump speed adjustment. Record this flowrate into your datasheet.
8) Throttle valve (as explained in Step 5) until the desired flowrate (identified in Step 7) is achieved. Use capture button to get a snapshot of head and flowrate values in textboxes of Capture Point frame. Record Head and Flowrate

9) Open the valve to its original position and similar to the previous step now try to reduce the speed until the same flowrate value identified in Step 7 is achieved. Use capture button to get a snapshot of head and flowrate values in textboxes of Capture Point frame. Record Head and Flowrate.

NOTE: Procedure may be repeated for different discharge elevations

1.5 CALCULATIONS

- Power delivered to the fluid during throttling and speed reduction in section 1.4.2
  $P_{FLUID} = \rho[kg/m^3] \cdot g\ [m/s^2] \cdot H_{pump}[m] \cdot Q\ [m^3/s]$

- Open the following automatically saved files in MS-Word and save them into the diskette and draw pump and system characteristics in MS-Excel (Smooth X-Y Scatter). Draw *power delivered to fluid* vs. *valve position* and *power delivered to fluid* vs. *pump speed graphs* using the data contained in these files: *Pumpgraph, SystemGraph1, SystemGraph2, SystemGraph3, SystemGraph4, SystemGraph5, SystemGraph6.*

1.6 DISCUSSION & CONCLUSION

Discuss the results obtained in the experiment. Compare throttling control and pump speed control by commenting on the data obtained during actual test runs. Identify advantages and disadvantages of both methods. In addition to this, give the possible amount of error occurred during the experimental procedure and calculations.

2 REPORT FORMAT

You are required to prepare your laboratory reports in the following format:

1. Title Page: This page shall include course number and title, title of the experiment date, names of group members and supervisor.
2. Abstract: One paragraph describing general terms, the objective of the experiment, experiment procedure, results and considerable conclusions and comments. This part shall serve as an executive summary.
3. Nomenclature: A list of symbols used as well as the acronyms referred shall be presented in this part
4. Objective: Brief and clear explanations pertaining to the objective and goal of the experiment shall be provided.
5. Introduction: Any sort of background information and an overview of the report shall be presented through this part
6. Theory and Experimental Procedure: The basic theory and concepts constituting the basis of the experiment shall be summarized. A schematic drawing and/or block diagram of the experimental setup shall be provided. Description of the method used to gather the data shall be presented and any special measures taken to ascertain the reliable results shall be mentioned as well
7. Data and Results: This section must include all data and results of the experiment regardless of the degree of error. Any tabulated data and/or graphs with regard to the actual experiment shall be presented. A discussion with regard to the results shall be included where this part shall also emphasize the trends of measured data. In addition to the foregoing comparison between the measured data and theoretical predictions shall be presented if applicable.
8. Sample Calculations: Complete calculations for at least one set of data shall be presented
9. Discussion and Conclusions: Each conclusion shall be supported by specific references to the tabulations and curves. An analysis of accuracy is always in order, indicating effects of :
    - Probable errors in observed quantities
    - Duration of runs
    - Frequency of readings
    - Methods of calculation and analysis ,

shall be presented. Constructive criticism of apparatus, instruments, and test methods shall be included besides the positive suggestions for improvements.

10. References:

A list of resources and reference material which have been applied to shall be presented. Each item in this list shall be referred accordingly throughout the report.

11. Appendices: Any additional information, illustration, photograph, schematic drawings etc. shall be presented in this part of the report.

ME
Experiment
DATA SHEET

Ambient Temperature		C
Ambient Pressure		m Water Column

NAME , SURNAME	
DATE	

Data	Valve	Speed 3000rpm		Data	Valve	Speed 2800rpm		Data	Valve	Speed 2600rpm		Data	Valve	Speed 2400rpm	
#	Pos	Q	H	#	Pos	Q	H	#	Pos	Q	H	#	Pos	Q	H
1	50			1	50			1	50			1	50		
2	35			2	35			2	35			2	35		
3	25			3	25			3	25			3	25		
4	15			4	15			4	15			4	15		
5	10			5	10			5	10			5	10		
6	7			6	7			6	7			6	7		

APPENDIX I1

FUNCTIONAL TEST RESULTS (PUMP CHARACTERISTICS)

**** GRAPH 1, Pump Characteristics Data at 3000 RPM ****

Q1=	3,79186039653923	H1=	5,11722731906218
Q2=	3,75652805922547	H2=	5,26673462453279
Q3=	3,6057238434531	H3=	5,12402310567448
Q4=	3,37080076792811	H4=	6,78899082568807
Q5=	2,01142334756584	H5=	9,85049269452939
Q6=	1,6228206907644	H6=	11,8008834522596

**** GRAPH 2, Pump Characteristics Data at 2800 RPM ****

Q1=	3,81455726424397	H1=	4,76724430852871
Q2=	3,78981276633663	H2=	4,86578321440707
Q3=	3,49046936149016	H3=	5,04247366632688
Q4=	3,27516510358509	H4=	5,86816173972137
Q5=	3,07069050930504	H5=	7,41080530071356
Q6=	2,58949785918914	H6=	8,48453958545702

**** GRAPH 3, Pump Characteristics Data at 2600 RPM ****

Q1=	3,50779782677164	H1=	4,37988447162759
Q2=	3,37805917925896	H2=	4,43425076452599
Q3=	3,3251265016733	H3=	4,47162759089365
Q4=	3,30024223216698	H4=	5,03567787971458
Q5=	2,96941060880903	H5=	5,63710499490316
Q6=	2,64422081396912	H6=	5,71185864763846

**** GRAPH 4, Pump Characteristics Data at 2400 RPM ****

Q1=	3,24635878674963	H1=	4,06727828746177
Q2=	3,09595194124939	H2=	4,47842337750595
Q3=	2,95833491011073	H3=	4,67889908256881
Q4=	2,64039564090731	H4=	5,01868841318383
Q5=	2,52915286655841	H5=	5,70506286102616
Q6=	2,52896589705845	H6=	6,63608562691132

APPENDIX I2

FUNCTIONAL TEST RESULTS (SYSTEM CHARACTERISTICS)

```
**** GRAPH 1, System Characteristics Data (Valve Pos.50) ****

Q5=           3,79186039653923          H5=           5,11722731906218

Q4=           3,81455726424397          H4=           4,76724430852871
Q3=           3,50779782677164          H3=           4,43425076452599
Q2=           3,24635878674963          H2=           4,06727828746177
Q1=           0            H1=           2

**** GRAPH 2, System Characteristics Data (Valve Pos.35) ****

Q5=           3,75652805922547          H5=           5,26673462453279

Q4=           3,78981276633663          H4=           4,86578321440707
Q3=           3,37805917925896          H3=           4,37988447162759
Q2=           3,09595194124939          H2=           4,47842337750595
Q1=           0            H1=           2

**** GRAPH 3, System Characteristics Data (Valve Pos.25) ****

Q5=           3,6057238434531           H5=           5,12402310567448

Q4=           3,49046936149016          H4=           5,04247366632688
Q3=           3,30024223216698          H3=           4,47162759089365
Q2=           2,95833491011073          H2=           4,67889908256881
Q1=           0            H1=           2

**** GRAPH 4, System Characteristics Data (Valve Pos.15) ****

Q5=           3,37080076792811          H5=           6,78899082568807

Q4=           3,27516510358509          H4=           5,86816173972137
Q3=           3,3251265016733           H3=           5,03567787971458
Q2=           2,64039564090731          H2=           5,01868841318383
Q1=           0            H1=           2

**** GRAPH 5, System Characteristics Data (Valve Pos.10) ****

Q5=           2,01142334756584          H5=           9,85049269452939

Q4=           3,07069050930504          H4=           7,41080530071356
Q3=           2,96941060880903          H3=           5,63710499490316
Q2=           2,52915286655841          H2=           5,70506286102616
Q1=           0            H1=           2
```

**** GRAPH 6, System Characteristics Data (Valve Pos.7) ****

```
Q5=           1,6228206907644            H5=           11,8008834522596

Q4=           2,58949785918914           H4=           8,48453958545702
Q3=           2,64422081396912           H3=           5,71185864763846
Q2=           2,52896589705845           H2=           6,63608562691132
Q1=           0            H1=            2
```

APPENDIX I3

FUNCTIONAL TEST RESULTS (TEST MODULE OUTPUT)

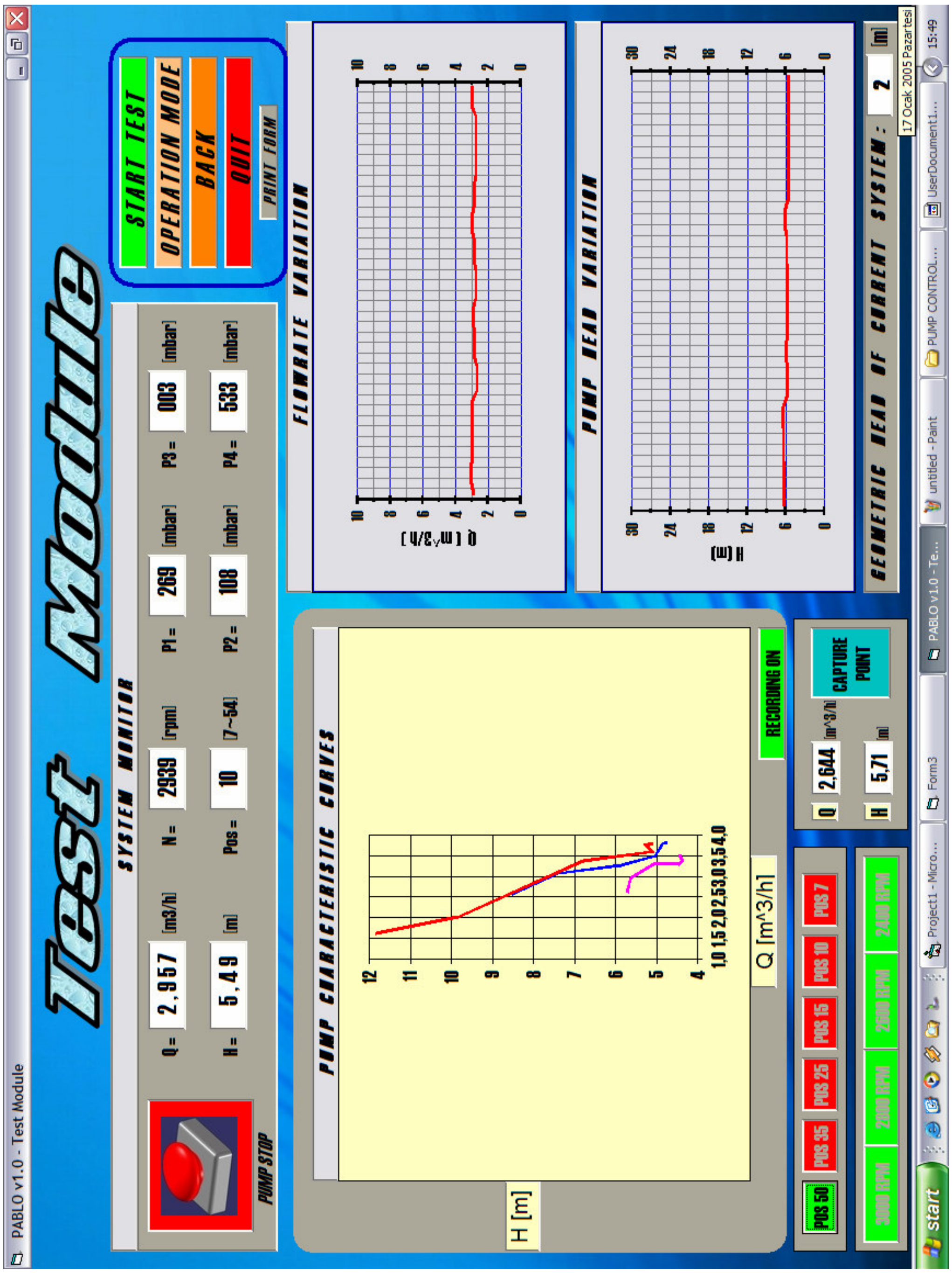


Fig I3: Test Module Output Screen