DESIGN AND SIMULATION OF A CONTROLLER SCHEME TO MITIGATE PROCESS FLOW ERRORS IN OIL AND GAS INDUSTRY.

BY

NWELE EMMANUEL ONYEKACHI

20214329818

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THE DEPARTMENT OF ELECTRICAL/ELECTRONIC ENGINEERING,
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DEDICATION

In loving memory of Ezinne Lolo **Ndulaka**, Josephine Comfort Okedu

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ABSTRACT

Flow in a process industry is characterized with issue of frictional force in the medium in which the fluid is being transported thereby creating pressure loss which leads to loss of time and output product. In this research, Direct Synthesis (DS) method is used, while the tools used include: Proteus version 7.6, MATLAB/Simulink software, LabVIEW Control Design and Simulation Module. A Proportional Integral Derivative (PID) and Distributed Control System (DCS) controllers are utilized in order to control the flow rate of the process fluids by controlling the loss in pressure due to frictional forces in the transport medium to ensure that the flow remains in laminar condition. Firstly, the PID was modeled, and the PID controller was designed and configured into the flow system, then it was simulated using MATLAB/Simulink and the result of the performance showed that when the PID was independently controlling the flow system, there was over shoot which was over come after some wasteful time before achieving steady or stability. Secondly, DCS was also used independently in the flow loop and it was simulated using Proteus software. The performance was observed in the software environment and it showed that when DCS was used independently, it had a good control efficiency but some percentage of transient and overshoot was noticed from the output result. Thirdly, the DCS and the PID were installed together and simulated using LabVIEW and the results obtained showed that the cascading of the two controllers cut down the time of attaining stability and the problems of drag and pressure loss were eliminated in a very short time. The research work achieved 99 percent of the results anticipated as all the specific objectives were achieved. The research was validated using Routh- Hurwitz stability criterion.

***Keywords*: Process Flow control, PID controller, DCS controller, Modelling, Direct synthesis method, Laminar .**

CHAPTER ONE

INTRODUCTION:

1.1 Background of Study

The ability to manipulate a flow field to effect a desired change is of immense practical importance. As a scientific discipline and a technological curiosity, flow control is more important in its pursuit to actualize optimum output and stability when fluid is being transported.

Flow means the given quantity of a substance either in terms of mass or volume that passes through a pipe per unit time. To measure the flow of any fluid, there is a need of a device or instrument, and the device used to measure the flow is known as a flow measurement device. Flow measurement proves crucial in various industries including petroleum and chemical industries. Most importantly, accurate flow measurements ensure the safety of the process and for those involved in its success.

Maintaining proper flow of fluids in a process system, is essential to maintain correct supply of raw materials to reactors, correct supply of water or steam for cooling or heating purpose etc, (www.pipingengineer.org, 2023). Flow control is a technique used to regulate data transfer between computers or other nodes in a network. Flow control ensures that the transmitting device does not send more data to the receiving device than it can handle, (www.techtarget.com, 2023). There are three fluid flow regimes: laminar, turbulent, and a transition region. The conditions that lead to each type of flow behavior are system-specific.

Process controls are necessary for designing safe and productive plants. A variety of process controls are used to manipulate processes, however the simplest and often most effective is the PID controller. The controller attempts to correct the error between a measured process variable and desired setpoint by calculating the difference and then performing a corrective action to adjust the process accordingly. A PID controller controls a process through three parameters: Proportional (P), Integral (I), and Derivative (D). These parameters can be weighted, or tuned, to adjust their effect on the process.

Much more practical than the typical on/off controller, PID controllers allow for much better adjustments to be made in the system. While this is true, there are some advantages of using an on/off controller, these include (1) relatively simple to design and execute and (2) generally more reliable and less expensive.

Although there are some advantages, there are large disadvantages of using an on/off controller scheme. They are (1) inefficient (using this control is like driving with full gas and full breaks), (2) can generate noise when seeking stability (can dramatically overshoot or undershoot a set-point), and (3) physically wearing on valves and switches (continuously turning valves/switches fully on and fully off causes them to become worn out much quicker).

The factors affecting flow measurement are Conductivity, temperature, pressure, and viscosity. How clean or dirty the fluid may be, could also impact on the type and style of meter, (www.mccrometer.com, 2023). In choosing a flow meter, one advice is to thoroughly understand the characteristics of the flow to be measured. Types of Flow Meters include Coriolis, DP Meters, Magnetic Meters, Multiphase Meters, Ultrasonic Meters, and Vortex Meters. (www.emerson.com, 2023)

The viscosity, density, and velocity of the fluid could change as a result of changes in the fluid temperature. It can also affect the length, inner diameter, and in the case of turbulent flow, the internal roughness of the pipe. A fluid's motion is affected by its speed, density, viscosity, and weight, as well as drag and lift. It can be compared to a pipe with different sized openings on either end to observe and quantify laminar flow of liquids.

The common measures of flow are: Obstruction type (differential pressure or variable area), Inferential (turbine type), Electromagnetic, Positive-displacement, flow meters, which accumulate a fixed volume of fluid and then count the number of times the volume is filled to measure flow. An area-velocity meter is an open channel flow meter that measures flow by making two separate measurements of depth and velocity. The depth is converted to cross sectional area using the geometry of the pipe or channel.

The dynamic behavior of industrial plants heavily depends on disturbances and in particular on changes in operating point, (Cam and İlhan, 2004). In many industrial processes, control of liquid flow or temperature control is required. Classic PID approaches as well as controllers are updated and expanded during the years, from the primary controllers on the basis of the relays as well as synchronous electric motors or pneumatic or hydraulic systems to current microprocessors, (Rasvarz et al, 2019). Currently, many techniques for the tuning as well as design of PI and PID controllers are proposed (Astrom and Wittenmark, 1990). The method proposed by Ziegler & Nichols, 1942 is the most widely utilized PID parameter tuning methodology in chemical industry and is considered as a conventional technique.

Process management instrumentality is meant to work the plants on a gentle state basis and management of the method needs thorough management data such as the behavior of the method parts, method details, and inter-relation at intervals for the sections of the method plant. Flow management encompasses a big selection of application in process industries. In 90% of flow management, applications have a tendency to manipulate the flow to get desired output. Flow is dynamic parameter and has totally different standardization strategies for standardization, (Rohit et al, 2020). The ratio and split range control take the place of cascade control. Ratio control is the technique in which it has two different values that are assigned a single set point respectively. The split range controls separate single set value into two independent set points. There are three tuning parameters for PID and it is also known as a three-term controller. The three parameters are proportional gain, integral gain and derivative gain. These three parameters affect in different ways the stability of system. So, the controller has to maintain the process variable close to desired set point, (Basilio et al, 2010). The various types of feedback control include Proportional (P) Controller, Proportional-Integral (PI) Controller, and Proportional-Integral-Derivative (PID) Controller. The Tuning of PID Controller includes Ziegler Nichols, Tyreus-Luyben Method, and Relay Auto-Tuning.

Nowadays, there is a special linear structure deployed with sensors on pipelines to monitor and regulate flow and pressure. They demonstrated multilayer communication schemes that ensure the effective routing of data among the sensors but there is no consideration of control valve and proper controllers among the sensor based remote communication networks which involves manual operation to achieve desired performance of pipeline transportation

(Priyanka et al, 2016). Basilio and Matos (2002) suggested a new method with less complexity in order to tune the parameters of PI controllers of the plant with monotonic step response, (Sina et al, 2019).

1.2 Problem Statement

Flow measurement in a process industry is characterized with errors. These errors are; under laminar, drags and turbulence. Most of these errors are traced to issue of frictional forces in the medium in which the fluid is being transported. When there is friction the flow pressure drops and it creates under laminar problem, also when the temperature is high, it increases the pressure above the set point which leads to turbulence, however, the latter occurs occasionally. Further, when there is pressure drop due to friction, this leads to drag, loss of time, decrease in output product and litigation between producers and distributors. It also causes rise in fluid temperature as a result of the mechanical energy being converted to thermal energy. This temperature rise due to frictional heating and pressure drop is usually a problem to the overall result of the quantity obtained at the outlet. Flow losses that are accounted for; by pressure losses and rise in temperature fall into two categories. Firstly, those associated with viscosity, the friction between the constriction walls and the flowing fluid, secondly, those associated with fittings, such as valves, elbows, tees, and so on. Changes in the fluid pressure and temperature due to friction in the flow line has always been a big concern to process industries. Researching on good controllers has been going on for decades to see if the problem could be curbed.

1.3 Objective of the Study

The main objective of the research work is Design and Simulation of a Controller Scheme to Mitigate Errors in Process Flow in Oil and Gas Industry. The specific objectives are to:

i. Model the process flow rate in pipeline using conservation of mass principle for flow rate.
ii. Formulate DCS-PID Control Scheme for the process flow rate model in (i).
iii. Simulate (i) and (ii) using MATLAB/Simulink and Proteus software.
iv. Validate stability of DCS-PID based process flow rate in pipelines by using Routh-Hurwitz stability criterion

1.4 Significance of the Study

In the recent decades, the market for the products of the industrial process industries
has changed greatly. The manufacture of mass products has shifted to locations where raw materials are available economically. Competitive pressures have forced a swing to specialization as well as to an ability to adapt to customers' desires. Flow control systems are designed so that the economic data, such as raw material properties, raw material costs, batch sizes, are quickly integrated into the processes. An important consideration is the assurance and improvement of product quality.
The operation of such systems requires a high degree of automation. With the assistance of process technology, flow control can be optimized and personnel requirements minimized. The process control technology assures that process cycles are documented so that the quality of the product is always traceable.

The goal of a PID controller is to produce a control signal that can dynamically minimize the difference between the output and the desired set point of a certain system. When error is minimized to certain degree of tolerance in process flow then the system has achieved the desired objectives. Process controls are necessary for designing safe and productive plants. A variety of process controls are used to manipulate processes

Flow control valves can be found in a variety of industries such as textile mills, water treatment plants, chemical plants, refineries, and power plants. These valves offer several benefits, including improved process efficiency, precise control, reduced energy consumption, and enhanced safety measures, (Google search, 2023).

The main purpose of flow control is to ensure that fluids move through pipes at the desired or intended rate in order to achieve optimal performance and efficiency. As with most applications, efficiency is key and flow control is vital to ensuring this efficiency. A lack of quality flow control can contribute to an increased risk and the consequences can be disastrous.

1.5 Scope of the Study

In this research work, the focus is on flow control of process liquids like gasoline diesel, kerosene and steam, modelling of the process flow rate in pipeline using conservation of mass principle for flow rate, formulation of DCS-PID Control Scheme for the process flow rate model which will be simulated at the end of the design using necessary software like Proteus, Lab-view and MATLAB/Simulink and the results compared and validated. The PID controller designed, will be cascaded with DCS for effective control measure.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview of Flow Control

2.1.1 Flow Control in terms of Computing

In computing point of view, flow control is a technique used to regulate data transfer between computers or other nodes in a network. Flow control ensures that the transmitting device does not send more data to the receiving device than it can handle. If a device receives more data than it can process or store in memory at any given time, the data will be lost and will need to be retransmitted.

The purpose of flow control is to throttle the amount of data transmitted to avoid overwhelming the receiver's resources. This is accomplished through a series of messages that the receiver transmits to the sender to acknowledge if frames have been received. The sender uses these messages to determine when to transmit more data. If the sender does not receive an acknowledgement (ACK), it concludes that there has been a problem with the transmission and retransmits the data.

Flow control is implemented in different ways, depending on how the sender and receiver handle messages and track data frames. There are two basic approaches to flow control: stop and wait and sliding window. The stop-and-wait approach is the simplest to implement, but it is not as efficient as sliding window, which delivers better network performance and utilizes network resources more effectively.

a. Stop-and-wait flow control

In the stop-and-wait approach, the sender segments the data into frames and then transmits one frame at a time to the receiver, which responds to each frame with an ACK message. This process occurs through the following steps:

i. The sender transmits a data frame to the receiver.
ii. The sender waits for the receiver to respond.
iii. Upon receiving the frame, the receiver transmits an ACK to the sender.
iv. Upon receiving the ACK, the sender sends the next frame to the receiver and waits for the next ACK. If the sender does not receive an ACK within a defined time limit, known as a *timeout*, the sender retransmits the same frame.
v. The process continues until the sender has finished transmitting all the data to the receiver, (www.techtarget.com, 2023).

b. Sliding window flow control

The sliding window approach addresses many of the issues that come with stop and wait because the sender can transmit multiple frames at once without having to wait for an ACK for each frame. However, this approach also comes with additional complexity.

When first connecting, the sender and receiver establish a window that determines the maximum number of frames the sender can transmit at a time. During the transmission, the sender and receiver must carefully track which frames have been sent and received to ensure that all the data reaches its destination and is reassembled in the correct order.

Sliding window flow control can be implemented using one of two approaches: Go-Back-N and Selective Repeat. With the Go-Back-N approach, the sender can send one or more frames but never more frames than the window allows. As the receiver acknowledges the frames, the sender moves to the next batch, or window, of frames that can now be sent. If there is a problem with a transmitted frame, the sender retransmits all the frames in the current window, (www.techtarget.com, 2023).

2.2 Flow Control in Process Industry

2.2.1 The Objectives of Control

A control system is required to perform the following;

(a) Maintain the process at the operational conditions and set points. Many processes should work at steady state conditions or in a state in which it satisfies all the benefits for a company such as budget, yield, safety, and other quality objectives. In many real-life situations, a process may not always remain static under these conditions and therefore can cause substantial losses to the process. One of the ways a process can wander away from these conditions is by the system becoming unstable, meaning process variables oscillate from its physical boundaries over a limited time span.

An example of this would be a water tank in a heating and cooling process without any drainage and is being constantly filled with water. The water level in the tank will continue to rise and eventually overflow. This uncontrolled system can be controlled simply by adding control valves and level sensors in the tank that can tell the engineer or technician the level of water in the tank. Another way a process can stray away from steady state conditions can be due to various changes in the environmental conditions, such as composition of a feed, temperature conditions, or flow rate.

(b) Transition the process from one operational condition to another.
In real-life situations, engineers may change the process operational conditions for a variety of different reasons, such as customer specifications or environment specifications. Although, transitioning a process from one operational condition to another can be detrimental to a process, it also can be beneficial depending on the company and consumer demands.

Examples of why a process may be moved from one operational set point to another are:

i. Economics
ii. Product specifications
iii. Operational constraints
iv. Environmental regulations
v. Consumer/Customer specifications

vi. Safety precautions

2.2.2 Definitions and Terminology

Variables: In controlling a process there exist two classes of variables.
i. **Input Variable** – This variable shows the effect of the surroundings on the process. It normally refers to those factors that influence the process. An example of this would be the flow rate of the steam through a heat exchanger that would change the amount of energy put into the process. There are effects of the surrounding that are controllable and some that are not. These are broken down into two types of inputs.
a. Manipulated inputs: variable in the surroundings that can be controlled by an operator or the control system in place.

b. Disturbances: inputs that cannot be controlled by an operator or control system. There exist both measurable and immeasurable disturbances.

ii. **Output variable**- Also known as the control variable, these are the variables that are process outputs that affect the surroundings. An example of this would be the amount of CO_2 gas that comes out of a combustion reaction. These variables may or may not be measured. In looking at controls problem, the two major control structures to be considered include:

a. Single Input-Single Output (SISO)- for one control(output) variable there exist one manipulate (input) variable that is used to affect the process
b. Multiple Input-Multiple Output (MIMO)- There are several control (output) variables that are affected by several manipulated (input) variables used in a given process.
Cascade: A control system with 2 or more controllers, a "Master" and "Slave" loop. The output of the "Master" controller is the setpoint for the "Slave" controller.

Dead Time: The amount of time it takes for a process to start changing after a disturbance in the system.

Derivative Control: The "D" part of a PID controller. With derivative action the
controller output is proportional to the rate of change of the process variable or error.

Error: In process controls, error is defined as: Error = setpoint - process variable.

Integral Control: The "I" part of a PID controller. With integral action the controller output is proportional to the amount and duration of the error signal.

2.2.3 Flow in Pipes

In fluid mechanics, flow in pipes is a type of fluid flow within a closed conduit, such as a pipe, duct or tube, (en.wikipedia.org, 2023). Fluid flow in circular and noncircular pipes is commonly encountered in practice. The hot and cold water used in our homes is pumped through pipes. Water in a city is distributed by extensive piping networks. Oil and natural gas are transported hundreds of miles by large pipelines. Blood is carried throughout our bodies by arteries and veins. The cooling water in an engine is transported by hoses to the pipes in the radiator where it is cooled as it flows. Thermal energy in a hydronic space heating system is transferred to the circulating water in the boiler, and then it is transported to the desired locations through pipes.

Fluid flow is classified as external and internal, depending on whether the fluid is forced to flow over a surface or in a conduit. Internal and external flows exhibit very different characteristics. In this chapter the internal flow is considered where the conduit is completely filled with the fluid, and flow is driven primarily by a pressure difference. This should not be confused with open-channel flow where the conduit is partially filled by the fluid and thus the flow is partially bounded by solid surfaces, as in an irrigation ditch, and flow is driven by gravity alone. This chapter is started with a general physical description of internal flow and the velocity boundary layer. The discussion proceeded with the dimensionless Reynolds number and its physical significance, then the characteristics of flow inside pipes are discussed, the pressure drop correlations associated with it for both laminar and turbulent flows are introduced, the minor losses are presented then the pressure drop and pumping power requirements for real-world piping systems are determined.

Liquid or gas flow through pipes or ducts is commonly used in heating and cooling applications and fluid distribution networks. The fluid in such applications is usually forced to flow by a fan or pump through a flow section. Priority is given to friction, which is directly related to the pressure drop and head loss during flow through pipes and ducts. The pressure drop is then used to determine the pumping power requirement. A typical piping system involves pipes of different diameters connected to each other by various fittings or elbows to route the fluid, valves to control the flow rate, and pumps to pressurize the fluid. The terms pipe, duct, and conduit are usually used interchangeably for flow sections.

In general, flow sections of circular cross section are referred to as pipes (especially when the fluid is a liquid), while flow sections of noncircular cross section are referred to as ducts (especially when the fluid is a gas). Small diameter pipes are usually referred to as tubes. Considering the above stated, more descriptive phrases (such as a circular pipe or a rectangular duct) will be used whenever necessary to avoid any misunderstanding. It is generally known that most fluids, especially liquids, are transported in circular pipes. This is because pipes with a circular cross section can withstand large pressure differences between the inside and the outside without undergoing significant distortion. Noncircular pipes are usually used in applications such as the heating and cooling systems of buildings where the pressure difference is relatively small, the manufacturing and installation costs are lower, and the available space is limited for ductwork.

Although the theory of fluid flow is reasonably well understood, theoretical solutions are obtained only for a few simple cases such as fully developed laminar flow in a circular pipe. Therefore, reliance is on experimental results and empirical relations for most fluid flow problems rather than closed-form analytical solutions. Noting that the experimental results are obtained under carefully controlled laboratory conditions and that no two systems are exactly alike, one must not be so naive as to view the results obtained as “exact.”

The fluid velocity in a pipe changes from zero at the surface because of the no-slip condition to a maximum at the pipe center. In fluid flow, it is convenient to work with an average velocity Vavg, which remains constant in incompressible flow when the cross-sectional area of the pipe is constant. The average velocity in heating and cooling applications may change somewhat because of changes in density with temperature. But, in practice, the fluid properties are evaluated at some average temperature and treated as constants. The convenience of working with constant properties usually more justified than the slight loss in accuracy.

Also, the friction between the fluid particles in a pipe does cause a slight rise in fluid temperature as a result of the mechanical energy being converted to sensible thermal energy. But this temperature rise due to frictional heating is usually too small to warrant any consideration in calculations and thus is disregarded. For example, in the absence of any heat transfer, no noticeable difference can be detected between the inlet and outlet temperatures of water flowing in a pipe. The primary consequence of friction in fluid flow is pressure drop, and thus any significant temperature change in the fluid is due to heat transfer.

The value of the average velocity V_{avg} at some stream wise cross-section is determined from the requirement that the conservation of mass principle be satisfied.

2.2.3.1 Laminar and Turbulent Flows

If you have been around smokers, you probably have noticed that the cigarette smoke rises in a smooth plume for the first few centimeters and then starts fluctuating randomly in all directions as it continues its rise. But since it speeds up as it advances upwards, it will eventually reach a speed at which the flow develops to turbulent, (www.quora.com, 2023). Likewise, a careful inspection of flow in a pipe reveals that the fluid flow is streamlined at low velocities but turns chaotic as the velocity is increased above a critical value. The flow regime in the first case is said to be **laminar,** characterized by smooth streamlines and highly ordered motion, and **turbulent** in the second case, where it is characterized by velocity fluctuations and highly disordered motion. The **transition** from laminar to turbulent flow does not occur suddenly; rather, it occurs over some region in which the flow fluctuates between laminar and turbulent flows before it becomes fully turbulent. Most flows encountered in practice are turbulent. Laminar flow is encountered when highly viscous fluids such as oils flow in small pipes or narrow passages.

The existence of these laminar, transitional, and turbulent flow regimes can be verified by injecting some dye streaks into the flow in a glass pipe, as the British engineer Osborne Reynolds (1842–1912) did over a century ago. It is observed that the dye streak forms a straight and smooth line at low velocities when the flow is laminar (some blurring may be seen because of molecular diffusion), has bursts of fluctuations in the transitional regime, and zigzags rapidly and randomly when the flow becomes fully turbulent. These zigzags and the dispersion of the dye are indicative of the fluctuations in the main flow and the rapid mixing of fluid particles from adjacent layers. The intense mixing of the fluid in turbulent flow as a result of rapid fluctuations enhances momentum transfer between fluid particles, which increases the friction force on the surface and thus the required pumping power. The friction factor reaches a maximum when the flow becomes fully turbulent, (Woolf, 2009).

2.2.3.2 Reynolds Number

The transition from laminar to turbulent flow depends on the geometry, surface roughness, flow velocity, surface temperature, and type of fluid, among other things. After exhaustive experiments in the 1880s, Osborne Reynolds discovered that the flow regime depends mainly on the ratio of inertial forces to viscous forces in the fluid. This ratio is called the **Reynolds number** is expressed for internal flow in a circular pipe as:

$$R_e = \frac{\text{Inertial forces}}{\text{Viscous forces}} = \frac{V_{AVG}D}{v} = \frac{\rho V_{avg}D}{\mu}$$

(Osborne Reynolds, 1880) (2.1)

where:

V_{avg} is average flow velocity (m/s),

D is characteristic length of the geometry (diameter in this case, in m),

$v = \mu/\rho$ kinematic viscosity of the fluid (m^2/s).

At large Reynolds numbers, the inertial forces, which are proportional to the fluid density and the square of the fluid velocity, are large relative to the viscous forces, and thus the viscous forces cannot prevent the random and rapid fluctuations of the fluid. At small or moderate Reynolds numbers, however, the viscous forces are large enough to suppress these fluctuations and to keep the fluid "in line." Thus, the flow is turbulent in the first case and laminar in the second. The Reynolds number at which the flow becomes turbulent is called the **critical Reynolds number (**Recr.) The value of the critical Reynolds number is different for different geometries and flow conditions. For internal flow in a circular pipe, the generally accepted value of the critical Reynolds number is Recr 2300. For flow through noncircular pipes, the Reynolds number is based on the **hydraulic diameter** *Dh* defined as hydraulic diameter:

$$D_h = \frac{4A_C}{P}$$

(2.2)

where:

A_C and *p* are its wetted perimeter.

The hydraulic diameter is defined such that it reduces to ordinary diameter *D* for circular pipes,

$$D_h = \frac{4A_C}{P} = \frac{4(\frac{\pi D^2}{4})}{\pi D} = D$$

(2.3)

It is certainly desirable to have precise values of Reynolds numbers for laminar, transitional, and turbulent flows, but this is not the case in practice. It turns out that the transition from laminar to turbulent flow also depends on the degree of disturbance of the flow by *surface roughness, pipe vibrations,* and *fluctuations in the flow.* Under most practical conditions, the flow in a circular pipe is laminar for Re $\geq$ 2300, turbulent for Re $\geq$ 4000 and transitional in between. That is: $R_e =\leq 2300\ lamina\ flow$,

$2300 \leq R_e \leq 4000\ transitional\ flow$, $R_e \geq 4000\ turbulent\ flow$

In transitional flow, the flow switches between laminar and turbulent can be actualized randomly. It should be kept in mind that laminar flow can be maintained at much higher Reynolds numbers in very smooth pipes by avoiding flow disturbances and pipe vibrations. In such carefully controlled experiments, laminar flow has been maintained at Reynolds numbers of up to 100,000, (www.coursehero.com, 2023).

2.3 Physics of Flow Rate and Total Flow Measurements

2.3.1 Measured Variables

Measurement technology provides the tools for optimizing production processes and dosing operations. In addition to pressure and temperature, the flow rate is one of the most important measured variables. The quantitative determination of amount, volume, and flow rate allows production processes to be optimized through control and regulation. The most important basic values are mass and volume: Mass with the symbol m is measured in kg or g, Volume with the symbol V is measured in m^3, dm^3 or cm^3.

As a ratio of mass to volume, the density defines the relationship between both values:

$$Density = \frac{Mass}{Volume} = \rho = \frac{m}{v}\left[\frac{kg}{dm^3}, \frac{kg}{m^3}, \frac{g}{cm^3}\right]$$

(2.4)

Since the majority of production systems operate continuously, the measured values
must be representative of the instantaneous conditions or indicate the instantaneous
values. Using the two basic units, mass and volume, a distinction is made between the mass flow rate q_m and the volume flow rate q_v as expressed in equations 2.5 and 2.6:

$$Mass\ flow\ rate = \frac{Mass}{Time} : q_m = \frac{m}{t}\left[\frac{kg}{s} \frac{g}{s} \frac{kg}{\quad h}\right]$$

(2.5)

$$Volume\ \ flow\ rate = \frac{Volume}{Time} : q_v = \frac{v}{t}\left[\frac{m^3}{s}, \frac{1}{s}, \frac{m^3}{h}\right]$$

(2.6)

Mass flow rate is the ideal measurement value because it is independent of pressure
and temperature, although volume flow rate is usually technically more convenient to measure and, therefore, is preferred.

The volumes of the incompressible liquids are never affected by the pressure in the ranges normally encountered. Temperature changes, however, result in volume changes which in some cases require correction measures.

The flow rate, which is a time dependent value, furnishes information regarding the instantaneous conditions in the piping. It does not provide any information about the mass or volume delivered, i.e. the total quantity. In order to determine these values, an integration is required:

2.3.2 Volume Totalizers

Volume totalizers with moving measuring chambers driven by the measuring medium are also known as displacement meters. They are suitable for both gases and liquids. They are direct volume totalizers since they transport the measuring medium in chambers with defined, geometrically limited volumes. Among the direct volume totalizers are those with measuring vanes – also called turbine totalizers – and volume totalizers with forced flow changes. In this method a pulse total is generated which represents a specific – not geometrically bounded – volume, for example the quantity which produces one complete revolution of a rotary vane totalizer.

2.3.3 Oval Gear Totalizers

The measuring element of an oval gear totalizer consists of two oval gears. The driving liquid produces the required torque, which varies as a function of the gear position, to rotate the gears. For example, the torques on the lower gear in the left side cancel each other while the torque on the upper gear is one sided and actually causes the rotation. Around the upper gear a bounded crescent like volume exists which is pushed towards the outlet of the meter. Each rotation of the pair of oval gears transports a defined liquid volume. The number of rotations is therefore an exact measure of the quantity of liquid which has flowed through the meter. The precision teeth assure a good seal between the two gears. The clearance between the oval gears and the walls of the measuring chambers is so small that the leakage flow (gap loss) is negligible. The rotations of the pair of oval gears are transmitted without a stuffing box to an indicator either by a permanent magnet coupling or by a feedback-free magnetic field-controlled pulse transmitter.

The gears and bearings are subject to mechanical wear. Through selection of materials for the housing, oval gears, and bearings as well as by design consideration of expansions due to high temperatures, oval gear totalizers are suitable for almost all operating conditions.

2.4 Flow Sensors

2.4.1 Mechanism Flow Meter use to Measure Flow

Flow is defined as the rate (volume or area per unit time) at which a substance travels through a given cross section and is characterized at specific temperatures and pressures. The instruments used to measure flow are termed flow meters. The main components of a flow meter include the sensor, signal processor and transmitter. Flow sensors use acoustic waves and electromagnetic fields to measure the flow through a given area via physical quantities, such as acceleration, frequency, pressure and volume. As a result, many flow meters are named with respect to the physical property that helps to measure the flow. Flow measurement proves crucial in various industries including petroleum and chemical industries. Consequently, flow measurement is a major issue in the overall economic success or failure of any given process. Most importantly, accurate flow measurements ensure the safety of the process and for those involved in its success.

2.4.2 Common Types of Flow Meters.

The flow rate as determined by the flow sensor is derived from other physical properties. The relationship between the physical properties and the flow rate is derived from fundamental fluid flow principles, such as Bernoulli's equation.

2.4.2.1 Differential Pressure

These sensors work according to Bernoulli's principle which states that the pressure drop across the meter is proportional to the square of the flow rate.

$$-\Delta P \propto V^2$$

(2.7)

Using the pressure drop across a pipe's cross section is one of the most common manners to determine a flow measurement. As a result, this property has heavy implications for industrial applications. Flow meters characterized by differential pressure come in several different varieties and can be divided into two categories, laminar and turbulent.

Differential pressure sensors operate with respect to Bernoulli's principle. Bernoulli's principle states that the pressure drop across the meter is proportional to the square of the flow rate.

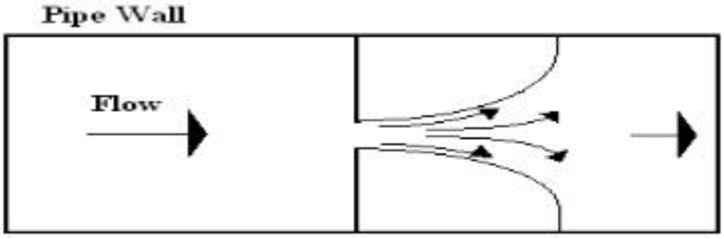
2.4.2.2 Orifice Meter

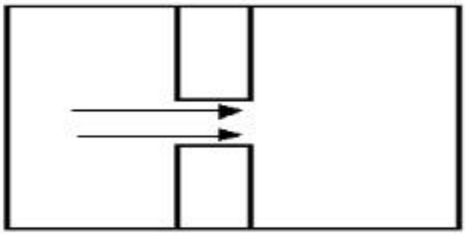
Orifice plates are installed in flow meters in order to calculate the material balances that will ultimately result in a fluid flow measurement on the sensor.

An orifice plate is placed in a pipe containing a fluid flow, which constricts the smooth flow of the fluid inside the pipe. By restricting the flow, the orifice meter causes a pressure drop across the plate. By measuring the difference between the two pressures across the plate, the orifice meter determines the flow rate through the pipe. The larger the pressure drop, the faster the flow rate would be. There are two types of orifice meters that are usually used in industry, they are the orifice-square edge and the orifice-conic edge. The orifice-square edge has insignificant friction at the interface between the fluid and the orifice plate. These types of orifice plates are recommended for smooth fluid flows, particularly clean liquids and gases such as steam. Generally, drain holes are incorporated in the design so that liquids and gases do not accumulate inside the pipes. Multi-phase fluids are not recommended for the orifice-squared edge because clogging becomes a significant problem as time progresses. The orifice-conic edge is similar to the orifice-square edge, the primary difference being that the orifice-conic edge has a gradually expanding cross sectional area, and this cross-sectional area is circular in shape. A conic-edge design is often a better choice for low velocity, high viscosity flows. Both types operate best under comparable temperature and pressure conditions, pipe sizes and provide similar accuracies.

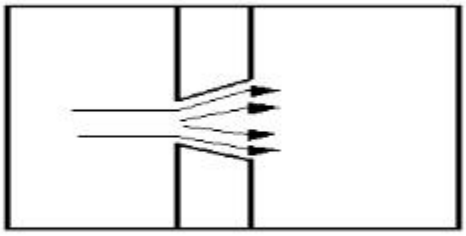
Orifice meters used in conjunction with DP (Differential Pressure) cells are one of the most common forms of flow measurement. In addition, an orifice meter can be used to measure flows when there is a significant difference in pressure in the pipe, like between the upstream and downstream sides of a partially obstructed pipe, which is exactly what the orifice meter does on its own. The plate offers a precisely measured obstruction that essentially shrinks the pipe and forces the flowing substance to constrict. A DP cell allows the comparison of pressure on the upstream (unobstructed) side and the downstream (constricted) side. A greater rate of fluid flow would usually result in a larger pressure drop, since the size of the orifice remains constant and the fluid is held longer, building potential energy on the upstream side of the orifice. Some of the other types of orifice plates include concentric, eccentric and segmental plates, each having different shapes and placements for measuring different processes. These plates are available in varied shapes so that the meter has the optimum structure for different applications. Moreover, the density and viscosity of the fluid, and the shape and width of the pipe also influences the choice of plate shape to be used.

Figure 2.1 shows the description of flow through Orifice medium while Figure 2.2 shows flow in pipe through orifice meter.



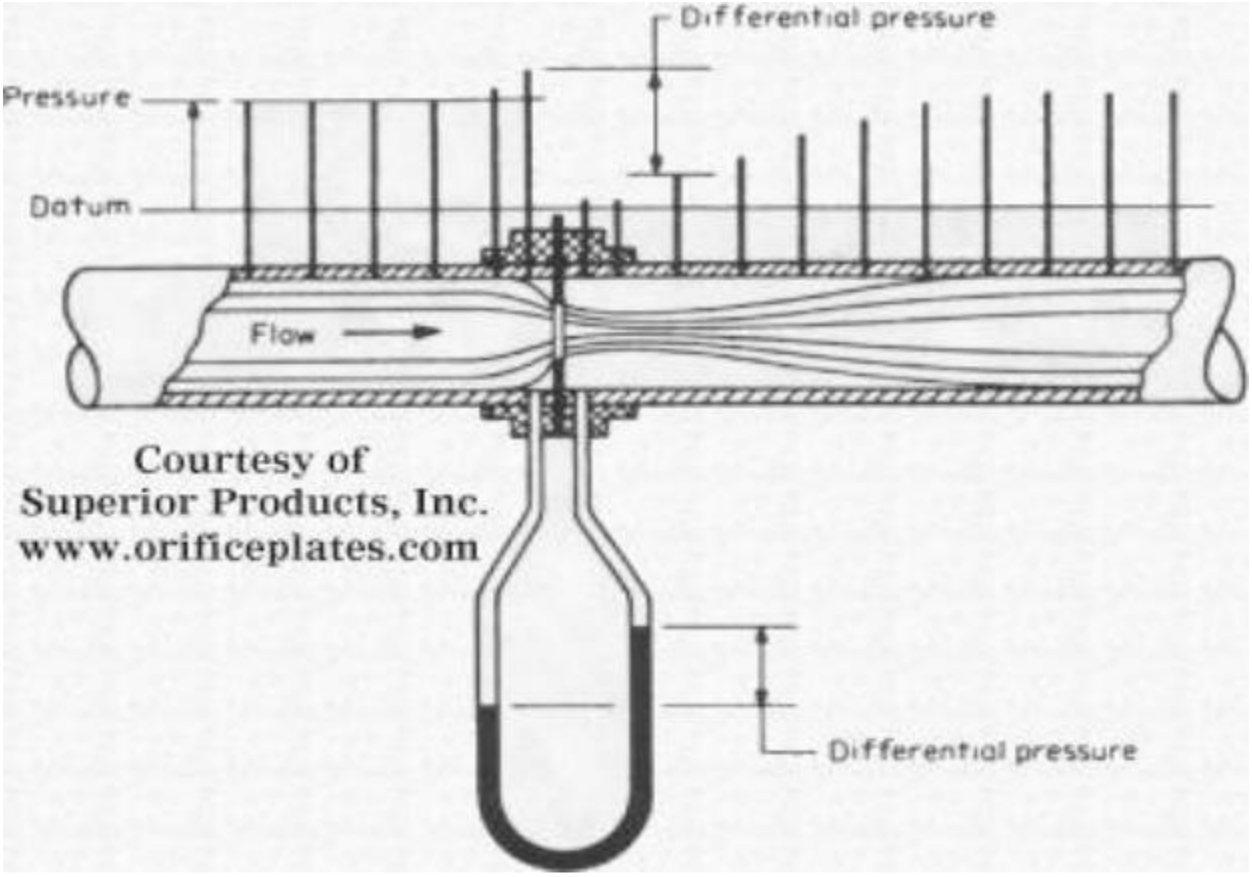


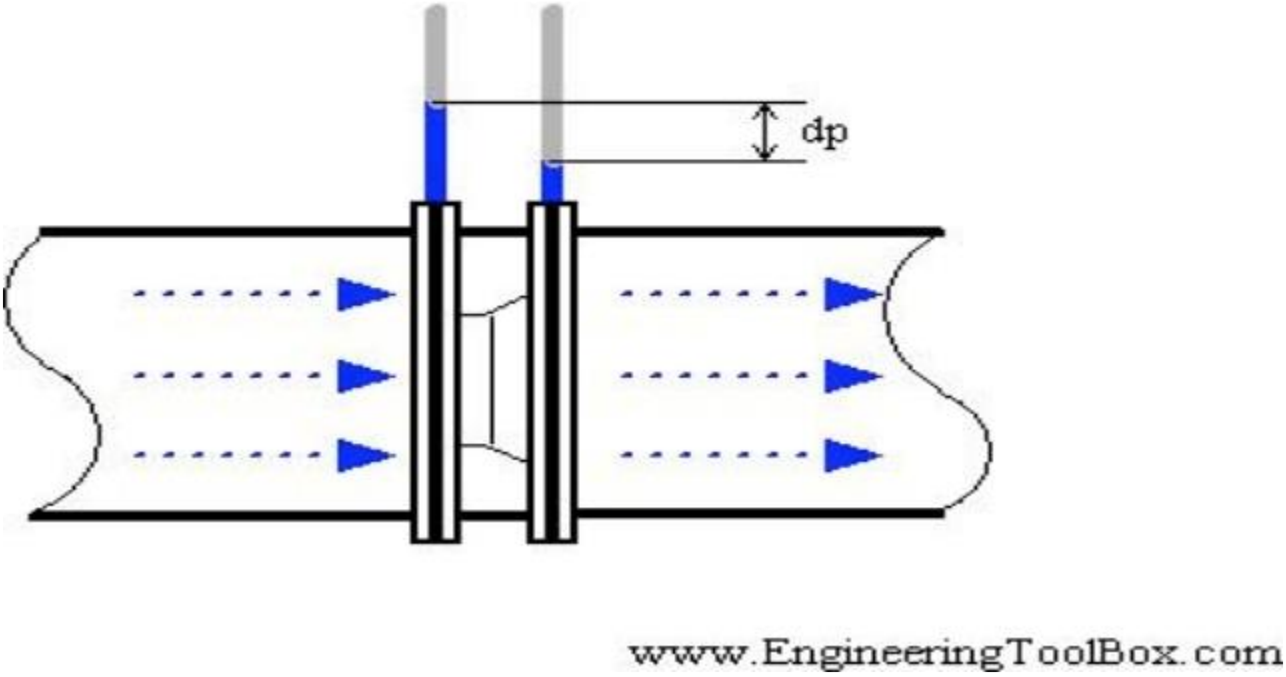
Orifice-Square Edge



Orifice-Conic Edge

Fig. 2.1: Flow description through Orifice Medium (www.engineeringtoolbox.com)





www.EngineeringToolBox.com

Fig. 2.2: Flow in a pipe through orifice meter (www.engineeringtoolbox.com)

Such a pressure drop across the plate is then related to the flow rate using basic fluid mechanics principles that incorporate parameters such as density of the fluid and size of the pipe. The flow rate Q, given by the orifice meter, is usually modeled with the following equation:

$$Q = \frac{C_d A_2}{\sqrt{1-\left(\frac{A_2}{A_1}\right)^2}} \sqrt{\frac{2(P_1-P_2)}{\rho}} \tag{2.8}$$

where:

P_1 - P_2 is the pressure drop across the plate,

ρ is the fluid density,

A_1 is the pipe cross-sectional area,

A_2 is the orifice cross-sectional area, and

C_d is the discharge coefficient (usually about 0.6).

C_d is used to account for energy losses within the system. The orifice meter is one of the most commonly used flow meters, since it is inexpensive to install and operate, it is uncomplicated and easy to construct, and it is highly robust and long lasting. Orifice meters are not only simple and cheap, they can also be delivered for almost any application and be made of any material. This simplicity of its design and function is one of its paramount advantages, with the meter essentially consisting of just a modified plate. This not only reduces its initial price but also shrinks its operating costs, maintenance expenses, and spare parts expenditure and availability. Lower flow rates reduce their accuracy, whereas higher flow rates combined with high quality, unworn orifice plates increase it. The orifice plate is best when a sharp edge is present towards the upstream side of the meter. Wear reduces the accuracy of orifice plates. The turn down rate of orifice plates is generally less than 5:1.

2.5 Review of Related Works on Flow

Keshav, (2017), *A Control-Theoretic Approach to Flow Control*: In his paper, he presented a control-theoretic approach to reactive flow control in networks that do not reserve bandwidth. He assumed a round-robin-like queue service discipline in the output queues of the network's switches, and propose deterministic and stochastic models for a single conversation in a network of such switches. These models motivate the Packet-Pair rate probing technique, and a provably stable rate-based flow control scheme. A Kalman state estimator is derived from discrete-time state space analysis, but there are difficulties in using the estimator in practice. These difficulties are overcome by a novel estimation scheme based on fuzzy logic. The author then presented a technique to extract and use additional information from the system to develop a continuous-time system model. This was used to design a variant of the control law that was also provably stable, and, in addition, took control action as rapidly as possible. Finally, practical issues such as correcting parameter drift and co-ordination with window flow control were described.

Sanket et al (2016), *A Review on Active and Passive Flow Control Techniques:* Flow control technique is an important research field of aerodynamics. Flow control implies a small change of a configuration serving an ideally large engineering benefit. The aim of this paper was to study various flow control techniques. In this paper the author went through the developments in the flow control technology over last few decades and then studied some modern flow control techniques gave us a whole new viewpoint on the science of flow control. A new classification of the techniques was introduced and major contributions under them were shown in this paper. A comparative study on active and passive flow control technologies was done and theoretical drag reduction possible using these techniques. It was concluded that active flow control technology has obvious advantages over passive control but passive control is easy to implement and practically used.

In their conclusion, they inferred that the above content emphasizes on flow control, its need and extensive review on the flow control methods. It also included the evolution of flow control techniques over past few decades. Simulating multi-physical medium model is difficult and hence researchers have come up with unique models like Penalization method to solve such problems.

The authors stated that active methods will yield much better results in drag reduction and control than the passive. But active flow control has its limitations because of complications in sensor technology and algorithm development. Passive techniques are easy to implement and free from any kind of external energy requirement.

Millán, (2020), *An Algorithm for Flow Control in Computer Networks Based in Discrete Control Theory*: Worked on Developing an effective flow control algorithm to avoid congestion and this is a hot topic in computer network society. This document gives a mathematical model for general network at the beginning, and then discrete control theory is proposed as a key tool to design a new flow control algorithm to avoid congestion in the high-speed computer network, the proposed algorithm ensures stability of network system. The results of the simulation show that the proposed method can adjust the sending speed and the queue level in the buffer quickly and effectively. In addition, the method is easy to implement and apply to high-speed computer network.

In their conclusion, they concluded that to realize a healthy and efficient production process in the chemical process industry, all parameters must be kept under control. It is necessary to choose the optimum algorithm compatible with the system for this control. In the study, the PID control algorithm, frequently used in industrial applications, has been implemented in the COMSOL program. The concentration level and velocity flow of the model consisting of two inputs and one output were controlled. The flow rate of the fluids can be changed with the PID controller to achieve the desired concentration. As a result of the simulation with different PID coefficients, the best response was obtained when the high proportional gain coefficient was applied. High overshoot and steady-state error occurred at low gain values in the system response. It has been determined that the best process response in both concentration and velocity data is achieved when $k_\mathrm{p} =$

–1 $m^4/(mol \cdot s)$. This application can be integrated into a system where the concentration in the combustion chamber is adjusted. As a result of mixing the two gases in the combustion chamber, the concentration is measured, and ignition takes place. The flow rate of the gases can be changed with the PID controller to obtain the desired concentration.

Raheleh et al, (2019), *Control of Flow Rate in Pipeline Using PID Controller:* Worked on Control of Flow Rate in Pipeline Using PID Controller. In their paper, a PID controller was utilized in order to control the flow rate of the heavy-oil in pipelines by controlling the vibration in motor-pump. A torsional actuator is placed on the motor-pump in order to control the vibration on motor and consequently controlling the flow rates in pipelines. The necessary conditions for asymptotic stability of the proposed controller is validated by implementing the Lyapunov stability theorem. The theoretical concepts are validated utilizing numerical simulations and analysis, which proves the effectiveness of the PID controller in the control of flow rates in pipeline.

In their conclusion, a novel active control strategy for the attenuation of motor vibration was proposed which consequently controls the flow rate in heavy-oil pipelines. The important theoretical contribution associated with the stability analysis for the PID controller is developed. The required stability conditions are obtained for the purpose of tuning the PID gains. By utilizing Lyapunov stability analysis, the sufficient conditions for the minimum amounts of the proportional, integrator as well as the derivative gains are obtained. The numerical simulation and analysis validates the effectiveness of PID controllers in the minimization of motor vibration to control the flow rate in pipelines. The main contributions of this paper are:

1) In the work, the stability of PID controller was validated which has not been given importance in earlier researches considering the flow rate control.

2) The technique of using torsional actuator on the motor pump arrangement is entirely a new concept. Future work is intended towards the development of the experimental setup for further investigation and the improvement of the controller by fuzzy methods.

Robert et al (2021), *Efficient Reconciliation and Flow Control for Anti-Entropy Protocols*: Worked on Anti-entropy, or gossip, as an attractive way of replicating state that does not have strong consistency requirements. With few limitations, updates spread in expected time that grows logarithmic in the number of participating hosts, even in the face of host failures and message loss. The behavior of update propagation is easily modeled with well-known epidemic analysis techniques. As a result, many distributed applications use gossip to contain various inconsistencies. In spite of its popularity, little study has been done into how gossip protocols behave under high update load. Gossip protocols purport to deliver messages within a certain configurable number of rounds with high probability, and thus provide synchronous guarantees. Like any other synchronous communication channel, gossip has capacity that is limited by available bandwidth for transporting gossip data and CPU cycles for generating and processing the gossip messages. Under high update load, a gossip protocol may not be able to send all updates required to reconcile differences between peers. Updates would take arbitrary time to propagate as the gossip channel gets backed up. Gossip protocols are designed to be non-invasive and have predictable performance, and for this a designer has to fix not only the gossip rate per participant but also the maximum size of gossip messages (e.g., maximum UDP packet size). While this avoids network and CPU overload, it also limits the capacity of the gossip channel.

This paper makes two contributions. First, it presents a new state reconciliation mechanism that is designed both for minimal CPU overhead and for situations in which only limited bandwidth is available. Secondly, it proposes and analyzes a flow control scheme for gossip.

In their conclusion, they concluded that Anti-entropy has a limited capacity given a certain budget of network bandwidth and CPU cycles. The authors demonstrated
that if too much data is gossiped, anti-entropy protocols lose their objective of predictable performance. The paper presents two complementary techniques. The first technique is a new reconciliation mechanism that, in the face of overload, aggressively selects updates that have not been made obsolete by later updates, but without starving updates that are not yet obsolete. The second technique is a flow control mechanism for anti-entropy protocols. In this mechanism, each participant locally adapts its rate of updates. The protocol assures fairness by dividing the available network capacity among the participants that are actively gossiping new updates. While each technique is useful by itself, the combination appears particularly effective. The authors believed that both techniques are amenable to further improvements, such as giving differentiated performance for classes of updates, and accommodating heterogeneous participants, for example in environments where not all participants have equal network access.

Kuma et al, (2014), *Enhancement of PID Controller Performance for a Quadruple Tank Process with Minimum and Non-Minimum Phase Behaviors:* Worked on Enhancement of PID Controller Performance for a Quadruple Tank Process with Minimum and Non-Minimum Phase Behaviors

The paper analyses the Proportional-Integral-Derivative (PID) controller’s performance for quadruple tank process. The selection of controlling the flow ratios in quadruple tank process act as Minimum and Non-minimum phase system. Its performance could be affected when system is shifted from minimum to non-minimum phase configuration and vice versa. This paper mainly focuses on searching the optimal controller structure by increasing the controllers' performance criteria. A comparative study on different controllers' structures responses are in the presence of peak overshoot. A simulation study of PID controller and Modified PID controller structures have been designed and to analyzed the different controllers' performance for the minimum and non-minimum phase system. The simulation results show that the PI-PD controller structure is provides enhanced performance for the set point tracking with nonappearance of peak overshoot.

In their conclusion, they inferred that they designed different modified PID controllers and applied to the four tank system with minimum phase and non-minimum phase system. MATLAB simulations showed that PI-PD controller results in a quicker response with a no overshoot than the conventional PID, PI-D and I-PD controllers. It has a strong ability to adapt to the significant change of controlling flow ratio in quadruple tank level process. To summarize, the PI-PD controller has been proved to be an effective method in the level control in both minimum and non-minimum phase system.

Dennis & Isreal, (2020), *Flow Control Applications*: worked on Flow Control Applications. In their work, they attributed that Flow control subsumes all types of technical flow control including laminar flow control, mixing enhancement, separated flow control, vortex control, turbulence control, heat transfer control, favorable wave interference, designer fluids and much more. Also included is the vast preponderance of extant industrial flow control technology which involves valves and fluidics, for which there is immense literature and technology including active control. The vision for designer fluid mechanics includes, for example, the enablement of improved high lift, vectored thrust, drag reduction (e.g. viscous, form, drag-due-to-lift), signature reduction, enhanced combustion, reduced noise and pollution, improved flight/engine controls, reduced buffet, flutter and fatigue, heat transfer control and a host of manufacturing, process and application specific benefits.

Ricardo et al, (2022), *Flow Control in Wings and Discovery of Novel Approaches via Deep Reinforcement Learning:* In this paper, they summarize existing trends of flow control used to improve the aerodynamic efficiency of wings. They first discuss active methods to control turbulence, starting with flat-plate geometries and building towards the more complicated flow around wings. Then, the authors discussed active approaches to control separation, a crucial aspect towards achieving a high aerodynamic efficiency. Furthermore, the authors highlighted methods relying on turbulence simulation, and discuss various levels of modeling. Finally, they thoroughly revised data-driven methods and their application to flow control, and focus on deep reinforcement learning (DRL). The authors concluded that this methodology has the potential to discover novel control strategies in complex turbulent flows of aerodynamic relevance.

In their conclusion, the demonstrated that Machine-learning-based control methods are an exciting set of techniques that are receiving considerable attention recently for performing active flow control. This spike in interest follows both increases in computational power and the development of effective algorithms that can learn effectively through direct interaction with black-box, complex systems. These ML methods follow a completely different approach compared with how flow control strategies have usually been designed. Instead of performing a local analysis of the flow properties by considering the flow equations and using advanced mathematical and analytical tools to find optimal perturbations, ML techniques discover a control strategy through a trial-and-error approach. There are a number of promising methods that belong to the ML family of control algorithms, including, for example, genetic programming (GP) and deep reinforcement learning (DRL). In this review, the authors focused on DRL methods in particular, and they discussed how recent works indicate that they can be efficiently used for controlling large, complex, non-linear systems arising from control tasks in fluid mechanics. The efficiency of DRL has been demonstrated in a number of active flow control situations so far, and the fluid mechanics community is progressively tackling more and more complex flow configurations. In particular, recent works are pushing the use of DRL for flow control into intermediate Re values, leading to more non-linear and more complex flows, so far successfully. The next steps will be to demonstrate the DRL control of complex 3D CFD simulations and to further increase Re to reach fully turbulent conditions. While this will pose new challenges to the DRL method due to the inherent increase in complexity compared with the configurations studied so far, a number of preliminary works indicate that DRL is well adapted to controlling complex systems with a large number of control locations, and that the inherent parallelism present in the DRL experience sampling process can offer large speed-ups on complex dynamical systems.

This push to more complex systems represents not only a scientific, but also a technical endeavor. Indeed, applying DRL to 3D flow control at moderate to high Re will pose a number of technical challenges regarding the amount of CFD computational power required, the ability to handle large amounts of data, and the coupling of CFD and DRL codes that were designed independently of each other at a time when the ability to couple them was not yet foreseen. All these aspects put tough requirements on the level of both expert knowledge (few people are experts in both DRL and large scale CFD) and general technical expertise (combining several different complex software stacks into a single system, and deploying this in HPC environments). In our opinion, these technical challenges, rather than fundamental issues, are presently the main limiting factor for applying ML control to active flow control. A possible way out of this challenge is to follow the example set by the ML community and to adopt a resolute open source release policy of codes, scripts, tutorials, and trained networks to reduce the barrier to entry for new groups joining in this research direction.

Sina et al, (2019), *Flow Control of Fluid in Pipelines Using PID Controller*: In this paper, a PID controller was utilized in order to control the flow rate of the heavy oil in pipelines by controlling the vibration in a motor pump. A torsional actuator is placed on the motor pump in order to control the vibration on a motor and consequently controlling the flow rates in pipelines. The necessary conditions for the asymptotic stability of the proposed controller are validated by implementing the Lyapunov stability theorem. The theoretical concepts are validated utilizing numerical simulations and analysis, which proves the effectiveness of the PID controller in the control of flow rates in pipelines.

In conclusion, the paper, reviewed that a novel active control strategy for the attenuation of motor vibration is proposed which consequently controls the flow rate in heavy-oil pipelines. The important theoretical contribution associated with the stability analysis for the PID controller is developed. The required stability conditions are obtained for the purpose of tuning the PID gains. By utilizing Lyapunov stability analysis, the sufficient conditions for the minimum amounts of the proportional, integrator as well as the derivative gains are obtained. The numerical simulation and analysis validates the effectiveness of PID controllers in the minimization of motor vibration to control the flow rate in pipelines.

Yair et al, (2016), *Global Flow Control for Wide Area Overlay Networks: A Cost-Benefit Approach*: This paper presented a flow control protocol for multi sender multi-group multicast and unicast in wide area overlay networks. The protocol is analytically grounded and achieves real world goals, such as simplicity, fairness and minimal resource usage. Flows are regulated based on the “opportunity” costs of network resources used and the benefit provided by the flow. In contrast to existing window based flow control schemes, we avoid end-to-end per sender or per group feedback by looking only at the state of the virtual links between participating nodes. This produces control traffic proportional only to the number of overlay network links and independent of the number of groups, senders or receivers. The authors showed the effectiveness of the resulting protocol through simulations and validate the simulations with live Internet experiments.

The paper concluded that they presented a new global flow control approach for wide-area overlay networks based on sound theoretical foundations. Our Cost-Benefit framework provides a simple and flexible way to optimize flow control to achieve several desirable properties such as near optimal network throughput and automatic adjustment to dynamic link capacities. The resulting algorithm provides fairness between equal cost internal flows and is fair with outside traffic, such as TCP. The authors implemented the framework in the ns2 simulator and showed results similar to those predicted by theory. They then implemented the framework in the Spread group communication system and conducted live experiments on the CAIRN network to validate the simulations and show the real-world performance of the framework.

Yuqi et al, (2021), *Investigation on the Characteristics of a Combination Microflow Control Valve*: Their study is based on combination of microflow control valves (CMCVs) which are widely used in high-pressure and low-flow-rate hydraulic systems, such as the helicopter brake system, flow and dynamic characteristics of the valve have a significant impact on the hydraulic system’s performance. Typically, the working pressure of the hydraulic system varies suddenly, which may cause instability of the system and components. Therefore, the CMCV with rapid response and stable performance is the key component, which largely determines the stability and performance of the entire hydraulic system.

Saket et al, (2021), *Review on Flow Control Methods*: In their work, they attempt to mention all the possible methods that can be used to control the flow and the applications of DCS in industrial sector. They suggested that amongst all the control systems, Distributed Control System is widely being used and is more popular in modern industrial processes. Distributed Control System is nothing but a computer controlled software application which is designed to work on the computer to complete the desired process by providing it with all necessary devices. Distributed Control System has plethora of advantages as compared to any other control system. Some of the advantages are, it helps to reduce the time required by the process to complete, as it can be automatically handled, it can reduce the labor cost, it also gives the ease to control and monitor real time condition. The flow control in pipeline is shown and also the process of bottle filling using distributed control system is mentioned. In most industries, flow management encompasses a big selection of application. Distributed Control System provides advanced management ways to regulate the method parameters.

They concluded that there are various advantages of DCS which allocate flexibility, simplicity by allowing central control, scalability, possible to control through dynamic graphic and monitoring and reporting of individual components and processes. Though there are some limitations of DCS like, failure of one controller effects more than one loop and requirement of skilled operator. The various extension or future scope of DCS is to make the DCS system more secure, so there will not be any cyber security attacks.

Rohit et al, (2020), *Tuning of flow control loop using DeltaV DCS and MATLAB*; in their research paper elucidates about the tuning of stream control utilizing
DeltaV DCS and MATLAB. The complete focus is on the three tuning strategies, for example, internal model control, PID tuner and the trial-and-error method. The paper gives definite data about the block diagram of the system which is used to control flow utilizing Delta V. The flow from the pneumatic control valve is given to the turbine flow transmitter which changes over the input flow into 4-20ma signal. This 4-20ma signal is then given to the DCS that includes a PID controller functional block which deals with making the controlled variable closer to the set point value.
It does as such by computing the values for proportional gain, reset and rate parameters by setting the method of the controller in the auto state. DCS ensure that the flow (controlled variable) arrives at nearer to the set point value.
The output of DCS goes as an input to the current to pressure converter which considered liable for closing or opening of the control valve. Predominant flow exploitation alludes that DCS is the best combination. DCS provides very advanced approaches to control the method parameters. Thus, the authors had a tendency to square measure attending to interface flow management loop with DCS, study its behavior for a step input modification, verify its transfer and operate on their model
victimization advanced DCS management functions. The comparative studies show that the simulations results vary from real time implementation results.

Neha et al. **(2016)**, *LabVIEW Based System for PID Tuning and Implementation for a Flow Control Loop:* They mentioned about the three tuning parameters for PID which are also known as a three-term controller. The three parameters are proportional gain, integral gain and derivative gain. These three parameters effect in different way to the stability of system. So, the controller has to maintain the process variable close to desired set point. The three tuning methods that are Ziegler Nichols, Cohen-Coon and Chein Hrones-Reswick was depend on percent overshoot, settling time, rise time and integral absolute error. The ZN and CHR gave good results than CC method. MATLAB is a tool used to map out mathematical methods from real time data. Thus, transfer function model is obtained using system identification tool. In Lab View the real time execution of the tuning methods is done using the PID gains that are measured using formula.

Anandrao et al, (2015), *Modeling, Simulation and Control of Flow Tank System:* In their paper focus is on the Process Control. This is a fusion between the enumeration and engineering discipline that offer the mechanism, architecture, algorithm for manipulating a process. Determined by how the supervised outputs and controlled inputs present in a process involving chemical reactions. The chemical processes can be differentiated by the control layout as Single Input Single Output (SISO) Systems and Multiple Input Multiple Output (MIMO). The MIMO Systems slightly differ from SISO due to maximum number of variables as the name suggests nevertheless rather very important is linkage between input and output variables. The methods utilized for Tuning of PID Control are based on ultimate parameters like ultimate gain and ultimate period for a real time system operation. It is observed that out of controller design for the single tank system although three methods Relay Auto Tuning gives the most accurate response for designing of single tank system.

Payam et al (2012), *Simulation Study of Flow Control Based on PID ANFIS Controller for Non-Linear Process Plants:* This paper deals with the basic concepts, mathematical parameters and design aspects of the Neuro-Fuzzy logic based controller for Non-Linear process plant to control flow rate of a system. Many techniques such as conventional PID and also fuzzy controllers have been proposed to control the flow rate. In this paper a new control approach is composed which is called PID ANFIS controller. Finally, the operation features of the three methods have been compared in terms of system overall performance. The designing of the scheme and the corresponding results have been tested by employing MATLAB-Simulink. It will be shown that the composed ANFIS based controller is more versatile in comparison with those two others, for Non-Linear process plants. In addition, there is a considerable comparison between the three controllers in the presence of disturbance and environmental noise.

The use of conveyor transport systems is especially widespread in the mining industry, where the operation of transport conveyor systems is associated with a number of unique features and restrictions. The first of the features that should be noted is that the rock flow entering the transport conveyor system is non-stationary. The non-stationarity and stochasticity of the material flow are directly related to rock mining technology. The non-uniform flow of material entering the transport system is the reason for the non-uniform distribution of material along the transport route. It results in the accumulation of material in some places of the transport route on the conveyor belt, but other places on the conveyor belt remain unfilled to the required level.

2.6 Summary of Related Works Done

Keshav, (2017), *A Control-Theoretic Approach to Flow Control*:

The author’s work is based on computer and telecom network flow of signal packets. No emphasis was placed on fluids flow in process industry.

Sanket et al (2016), *A Review on Active and Passive Flow Control Techniques:*

The author’s focus was purely on flow mechanism in aerodynamics in passive and active circumstances no special interest on the area of differential pressure that is usually encountered in process industry.

Millán, (2020), *An Algorithm for Flow Control in Computer Networks Based in Discrete Control Theory*:

The author worked on flow control of computer network based on discrete signals to ensure that there is no traffic congestion within the network of interest. No comment was made about flow in pipelines or in a process industry.

Raheleh et al, (2019), *Control of Flow Rate in Pipeline Using PID Controller:*

The author actually worked on the process flow control but emphasis was on vibration in the pipe which could be harmful or alter the stability of the system. No attention was given to other numerous problems associated with flow of a process system.

Robert et al (2021), *Efficient Reconciliation and Flow Control for Anti-Entropy Protocols*:

The authors worked on the propagation of flow of information in while propagating in telecommunication systems errors due to pressure or atmospheric conditions were not looked into.

Kuma et al, (2014), *Enhancement of PID Controller Performance for a Quadruple Tank Process with Minimum and Non-Minimum Phase Behaviors:*

From the conclusion and analysis of the authors, they actually worked on using PID to control flow in multiple tank staking. Emphasis on how different errors were articulated was not shown. Mitigation of disturbances that comes from different dimensions could be a difficult one.

Dennis & Isreal, (2020), *Flow Control Applications*:

In their work, they attributed that Flow control subsumes all types of technical flow control including laminar flow control, mixing enhancement, separated flow control, vortex control, turbulence control, heat transfer control, favorable wave interference, designer fluids and much more. Their work was generic in approach, in process flow control there are specific errors that need to be eradicated to have robust flow void of losses.

Ricardo et al, (2022), *Flow Control in Wings and Discovery of Novel Approaches via Deep Reinforcement Learning:*

From their work it could be deduced that they worked on flow and how it affects planes and drones and how to control turbulence when there is disturbance in the environment.

Sina et al, (2019), *Flow Control of Fluid in Pipelines Using PID Controller*:

In their paper emphasis was placed on how a good flow rate by applying a torsional actuator to ensure that specific error did not emanate during transportation or metering but specific errors were not identified.

Rohit et al, (2020), *Tuning of flow control loop using DeltaV DCS and MATLAB*:

Their work basically depicts using DCS AND MATLAB to actualize the set objective. Even when DCS is used in the control system agitations are bound to be there due to errors emanating due to disturbance from the system flow is a complex issue.

Anandrao et al, (2015), *Modeling, Simulation and Control of Flow Tank System:*

In their work, it was not streamline to a particular area of process. Process flow has so many dimensions either flow in pipes, tunnels, tanks, bottles, cylinders etc. There was no particular emphasis to know where the mitigation approach is channeled to.

2.7 Gap Covered

In all the papers reviewed, there was no place the peculiar problem like particular friction, which is directly related to the pressure drop and head loss during flow through pipes and ducts and other problems like turbulent flow, shear rate, pressure loss and fluid velocity were mentioned as being mitigated with controllers.

In particular, there was no cascaded technology of two distinct controllers used to mitigate the errors in process fluid in all the literatures reviewed

In many serious situations, problem emanates between two clients especially when they are metering their products which occurs mainly in oil and gas and electricity sectors through flow. This research intends to cover these gaps through hybrid control mechanism of different controllers.

CHAPTER THREE

MATERIALS AND METHOD

3.1 Materials

i. Proteus version 7.6 tool
ii. MATLAB and Simulink software tool
iii. LabVIEW Control Design and Simulation Module

3.2 Method

In this research work, the result that would be obtained is crucial to process industries and as a result, validation of stability is required. Routh Hurwitz stability criterion was used to validate the design. Hence it is necessary to note certain conditions of stability thus:

Conditions for Stability of any System are:

a. When all the characteristics equations are found in the left half of the s-plane, the system responses due to initial conditions will decrease to zero as time approaches infinity.

b. If one or more pairs of simple roots are located on the imaginary axis of the s-plane, but there are no roots in the right half of the s-plane, the response due to initial condition will be undamped sinusoidal oscillations.
c. If one or more roots are found in the right hand of the s-plane, the response will increase as time increases.
d. When all the roots are found in the left s-plane
e. When there is no sign change in the array of the characteristic equation

Note: Conditions (b) and (c) are classified as **unstable** conditions

Condition (a), (d) and (e) are the **stability** condition.

In Routh- Hurwitz criterion which is one of the criteria for stability test, an array is usually formed from the characteristic equation obtained.

3.2.1 Modeling of Process Flow Rate in Pipeline

In considering flow rate in pipeline, the average velocity of the medium has to be known. The value of the average velocity V_{avg} at some stream wise cross-section is determined from the requirements of the conservation of mass principle. Equation (3.1) shows the expression for the mass flow rate, according to (Woolf, 2009).

$$\dot{m} = \rho V_{avg} A_C = \int_{A_C} \rho U(r) d\, A_C \quad (3.1)$$

where:

$\dot{m}$ = Mass flow rate

ρ = Density of the fluid

A_C = Cross Sectional Area

$U(r)$ = Velocity Profile

The average velocity for flow in a circular pipe of radius *R* according to Woolf, 2009 can be expressed as:

$$V_{avg} = \frac{\int_{A_C} \rho U(r) d A_C}{\rho A_c} = \frac{\int_0^R \rho U(r) 2\pi r d r}{\rho \pi R^2} = \frac{2}{R^2} \int_0^R U(r) r dr \qquad (3.2)$$

Therefore, when we know the flow rate or the velocity profile, the average velocity can be determined easily.

3.2.1.1 Orifice plate as Flow Measuring Device

This flow device is created by inserting an obstructing plate, usually with a round hole in the middle, into the pipe and measuring the pressure on each side of the orifice. These plates are generally installed by trapping it between two pipe flanges. Pressure taps on each flange allow you to easily measure the pressure differential across the plate. This pressure differential, along with the dimensions of the plates are combined with certain fluid properties to determine the flow through the pipe.

Figure 3.1 shows samples of the several types of orifice plate used for flow measurement.

Fig. 3.1: Samples of several types of orifice plate (www.emerson.com)

$$\Delta P = \frac{1}{2}\rho V_2^2 - \rho V_1^2$$

(3.3)

Equation (3.3) is the calculation for incompressible liquid flow described by Bernoulli equation. To obtain the flow rate, equation (3.4) is applied

$$Q = C_d \sqrt{\frac{2(P_1 - P_2)}{\rho} \times \frac{A_2}{\sqrt{1-\left(\frac{A_2}{A_1}\right)^2}}}$$

(3.4)

where:

Q = Flow rate

P_1 = Upstream pressure

P_2 = Downstream pressure

C_d = Discharge coefficient (This is the point at which the flow turns turbulent in the medium)

C_f = Flow profile coefficient

A_1 = Area of the orifice at upstream

A_2 = Area of the orifice at downstream

Determination of flow profile in the downstream is cumbersome therefore substitution of C_d and the area with C_f becomes necessary. Thus:

$$Q = C_f A_0 \sqrt{\frac{2\Delta P}{\rho}}$$

(3.5)

For Compressible Flow,

$$Q_m = \frac{g C_0 Z \sqrt{2\rho\Delta P}}{\sqrt{1-\propto^4}}$$

(3.6)

$$Q_0 = \frac{Q_m}{\rho}$$

(3.7)

$$Q_1 = Q_0 \frac{P_1 \theta_{std}}{P_A \theta}$$

(3.8)

$$\rho = \frac{P_1}{G_C}$$

(3.9)

$$g = 1 - (0.41 + 0.35\propto^4)\frac{\Delta P}{G_{Is} P_1}$$

(3.10)

$$\alpha = \frac{D_{Th}}{D}$$

(3.11)

$$R_{SND} = \frac{V_G D}{G_{KV}}$$

(3.12)

$$R_N = \frac{G_V d}{G_{KV}}$$

(3.13)

$$G_{KV} = \frac{\mu}{\rho}$$

(3.14)

$$W = \frac{\sqrt{1-\propto^4} - C\propto^2}{\sqrt{1-\propto^4} - C\propto^2}\Delta P$$

(3.15)

$$M_L = \frac{2W}{\rho {V_G}^2}$$

(3.16)

$$M_L = \frac{Q_0}{P_A}$$

(3.17)

$$G_V = \frac{Q_0}{Z}$$

(3.18)

$$P_A = \frac{\pi}{4} D^2$$

(3.19)

$$T_A = \frac{\pi}{4} d^2$$

(3.20)

Coefficient of Discharge:

$$C_0 = 0.5961 + 0.0261\propto^2 + 0.216\propto^8 + 0.000521\left(\frac{10^6\propto}{R_N D}\right)^{0.7} + \left(0.0188 + 0.0063\left(\frac{19000\propto}{R_{ND}}\right)^{0.8}\right)\left(\frac{10^6}{R_{ND}}\right)^{0.3}\propto^{3.5} + \left(0.043 + 0.08g^{-10L_1} - 0.123g^{-7L_1}\right)\left(1 - 0.11\left(\frac{18000\alpha}{R_N}\right)^{0.9}\right)\frac{\alpha^A}{1-\alpha^A}$$

$$- \quad 0.0032\left(\frac{2L_2^1}{1-\propto} - \quad 0.8\left(\frac{2L_2^1}{1-\propto}\right)^{1.1}\right)\propto^{1.3}$$

(3.21)

where:

k_R = Equivalent roughness of pipe material in meters (L)

G_{Is} = Gas isentropic exponent

M_f = Mass flowrate (M/T)

P_A = Standard absolute pressure (1.016×10^5 N/M^2)

G_c = Gas constant

R_N = Reynolds number based on D_{Th}

V_G = Gas velocity in pipe (L/T)

Sp = Static pressure loss (F/L^2)

G_{KV} = Gas kinematic viscosity (L^2/T)

θ_{std} = Standard absolute temperature

P_A = Pipe area (L^2)

D_{th} = Throat diameter (L)

T_A = Throat area (L^2)

D = Pipe diameter (L)

Co = Discharge coefficient

M_L = Minor loss coefficient

P^2 = Downstream absolute pressure (F/L^2)

P1 = Upstream absolute pressure (F/L^2)

g = Gas Expansivity

$\propto$ = Ratio d/D

ρ = Gas density (M/L^3)

Q_O = Actual volumetric flow rate

Q1 = Volumetric flow rate in standard pressure and temperature (L^3/T)

θ = Gas Temperature

Gv = Gas velocity in throat (L/T)

W = Molecular weight of gas (gram/mole)

μ = Gas dynamic viscousity (F-T/L^2)

NOTE: Dimensions; F=Force, L=Length, M=Mass, T=Time

Outlet losses. The flow rate Q from the continuity equation

$$Q = VA \tag{3.22}$$

where:

Q = flow rate
V = average velocity
A = cross-sectional area of the pipe

To account for the outlet loss, equation (3.22) is modified to equation (3.23)

$$Q = CDVA \tag{3.23}$$

where *CD* is the discharge coefficient that is dependent on the shape and size of the orifice. *The discharge coefficients can be found in flow data handbooks*.

Frictional losses. They are losses from liquid flow in a pipe due to friction between the flowing liquid and the restraining walls of the container. These frictional losses are given by:

$$h_L = \frac{fLV^2}{2Dg}$$

(3.24)

where:

h_L = head loss

f = friction factor

L = length of pipe

D = diameter of pipe

V = average fluid velocity

g = gravitation constant

The frictional factor f depends on the Reynolds number for the flow and the roughness of the pipe walls

To take into account losses due to friction and fittings, the Bernoulli equation could be modified as follows:

$$\frac{P_A}{\gamma_A} + \frac{V_A^2}{2g} + Z_A = \frac{P_B}{\gamma_B} + \frac{V_B^2}{2g} + Z_B + h_{Lfriction} + h_{Lfittings}$$

(3.25)

Form drag is the impact force exerted on devices protruding into a pipe due to fluid flow. The force depends on the shape of the insert and can be calculated from

$$F = C_D \gamma \frac{AV^2}{2g}$$

(3.26)

where:

F = force on the object

C_D = drag coefficient

g = specific weight

g = acceleration due to gravity

A = cross-sectional area of obstruction

V = average fluid velocity

3.2.2 Modelling of Flow Controllers

The methodology of internal mode principle, being a control structure that ensures closed-loop stability and output regulation, is utilized in order to extract the gains of PID and PI controllers. Exhaustive investigation from literatures revealed that the outcomes of P control are very sensitive to the sensing location as well as the quantity of phase shift. By suitable selections of these variables, the P control can be completely efficient in annihilating the vortex shedding or minimizing its strength.

In order to implement the control law, the primary step is to determine a desired output response of a particular system to an arbitrary input over a time interval that can be carried out by system identification. Generally, it is feasible to generate a model on the basis of a complete physical illustration of the system.

3.2.2.1 Modelling of PID Controller for Heavy Oil or Fluid

i. To give an approximate indication of the use of PID controllers for different
types of loops, the following are general rules that should be followed: Pressure control requires proportional and integral; derivative is normally not required.

ii. Level control uses proportional and sometimes integral, derivative is not normally required.
iii. Flow control requires proportional and integral; derivative is not normally required.
iv. Temperature control uses proportional, integral, and derivative usually with integral set for a long time period.

3.2.2.2 PID electronic controller

In any electronic setup, there are two basic blocks which are analogue and digital. Digital systems are built on the basis and foundation of analogue blocks. So first we consider the analogue.

Figure 3.2 shows the block diagram of an analogue PID controller. The measured variable from the sensor is compared to the set point in the first unity gain comparator; its output is the difference between the two signals or the error signal. This signal is fed to the integrator via an inverting unity gain buffer and to the proportional amplifier and differentiator via a second inverting unity gain comparator, which compares the error signal to the integrator output. Initially, with no error signal the output of the integrator is zero so that the zero-error signal is also present at the output of the second comparator.

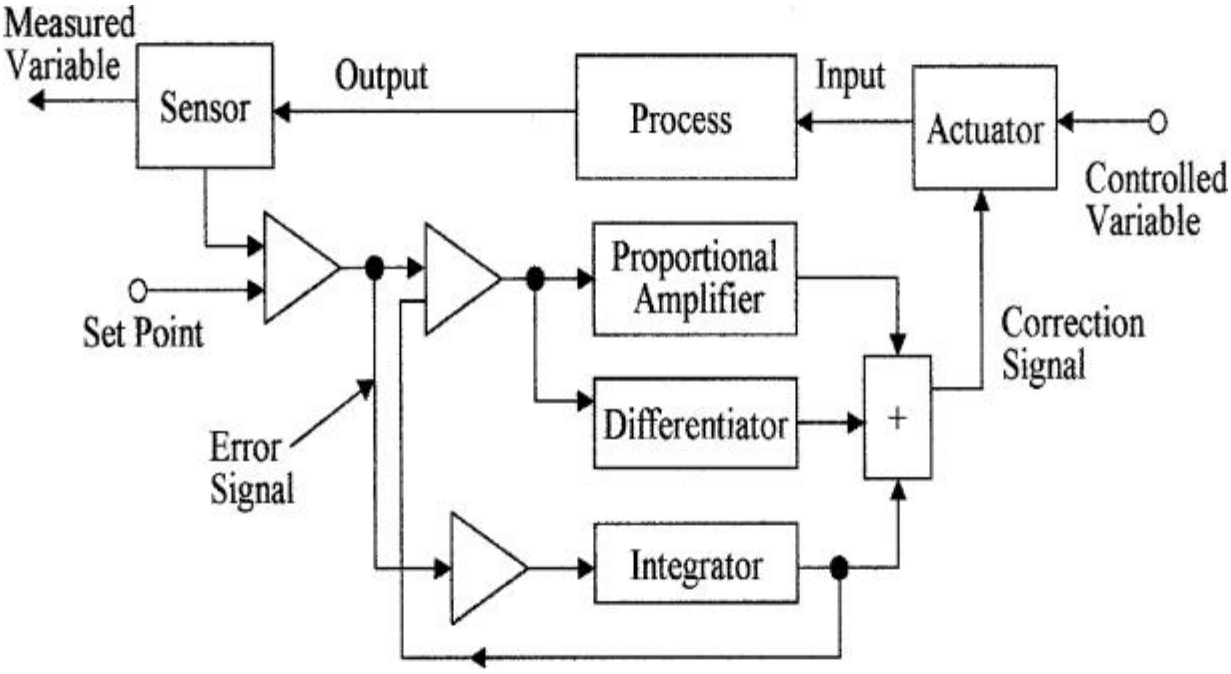


Fig. 3.2: Block diagram of a PID analogue electronic controller.

When there is a change in the measured variable, the error signal is passed through the second comparator to the proportional amplifier and the differentiator where it is amplified in the proportional amplifier, added to the differential signal in a summing circuit, and fed to the actuator to change the input variable. Although the integrator sees the error signal, it is slow to react and so its output does not change immediately, but starts to integrate the error signal. If the error signal is present for an extended period of time, the integrator will supply the correction signal via the summing circuit to the actuator and input the correction signal to the second comparator.

This will reduce the effective error signal to the proportional amplifier to zero, when the integrator is supplying the full correction signal to the actuator. Any new change in the error signal will still be passed through the second comparator as the integrator is only supplying an offset to correct for the first long-term error signal. The proportional and differential amplifiers can then correct for any new changes in the error signal.

The circuit implementation of the PID controller is shown in Figure 3.3. This is a complex circuit because all the amplifier blocks are shown doing a single function to give a direct comparison to the block diagram and is only used as an example. In practice there are a large number of circuit component combinations that can be used to produce PID action.

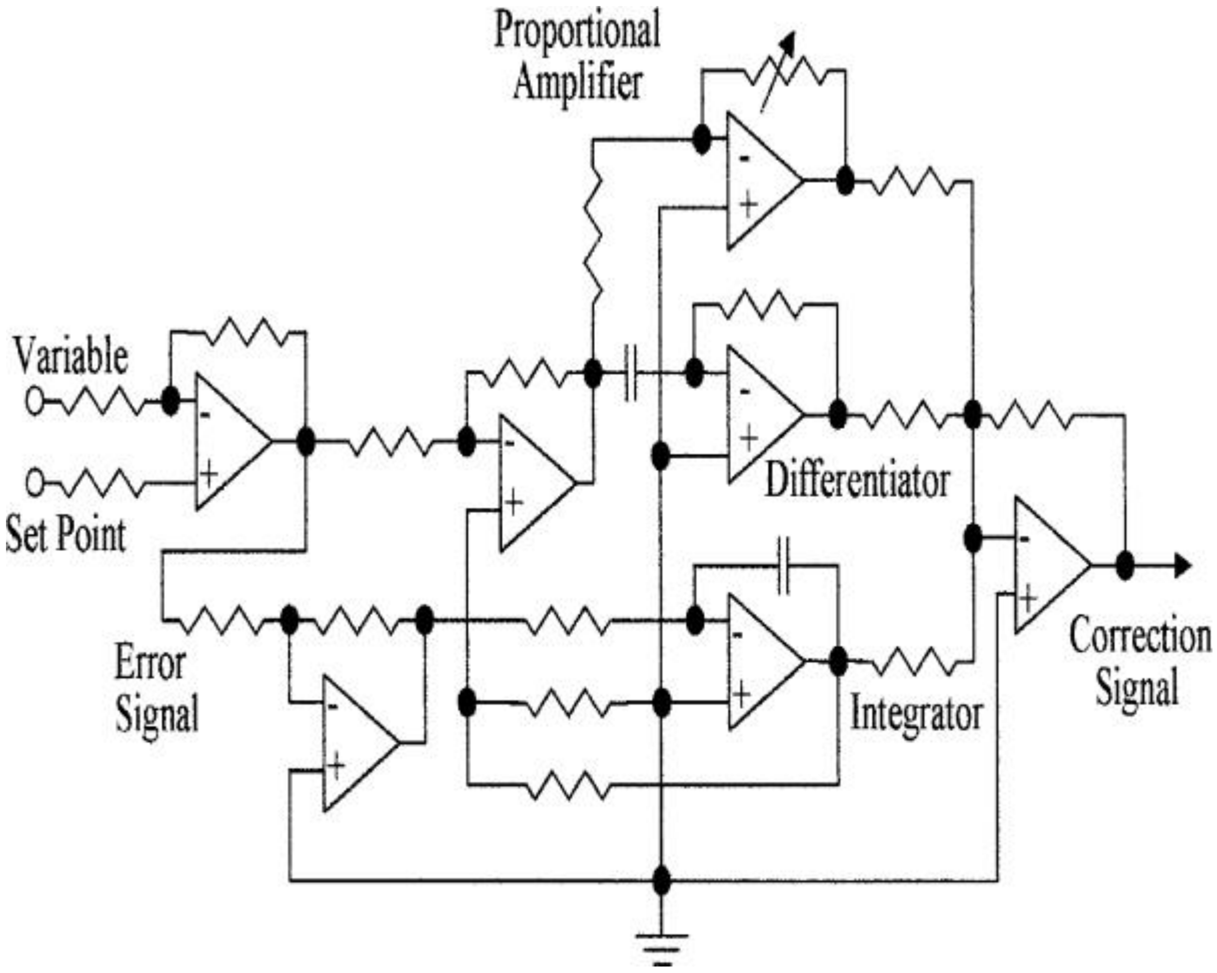

Proportional
Amplifier
Variable
Set Point
Differentiator
Error
Signal
Integrator
Correction
Signal

Fig. 3.3: Circuit of a PID action electronic controller.

A single amplifier can also be used to perform several functions which would greatly reduce the circuit complexity. Such a circuit is shown in Figure. 3.4 where feedback from the actuator position is used as the proportional band adjustment.

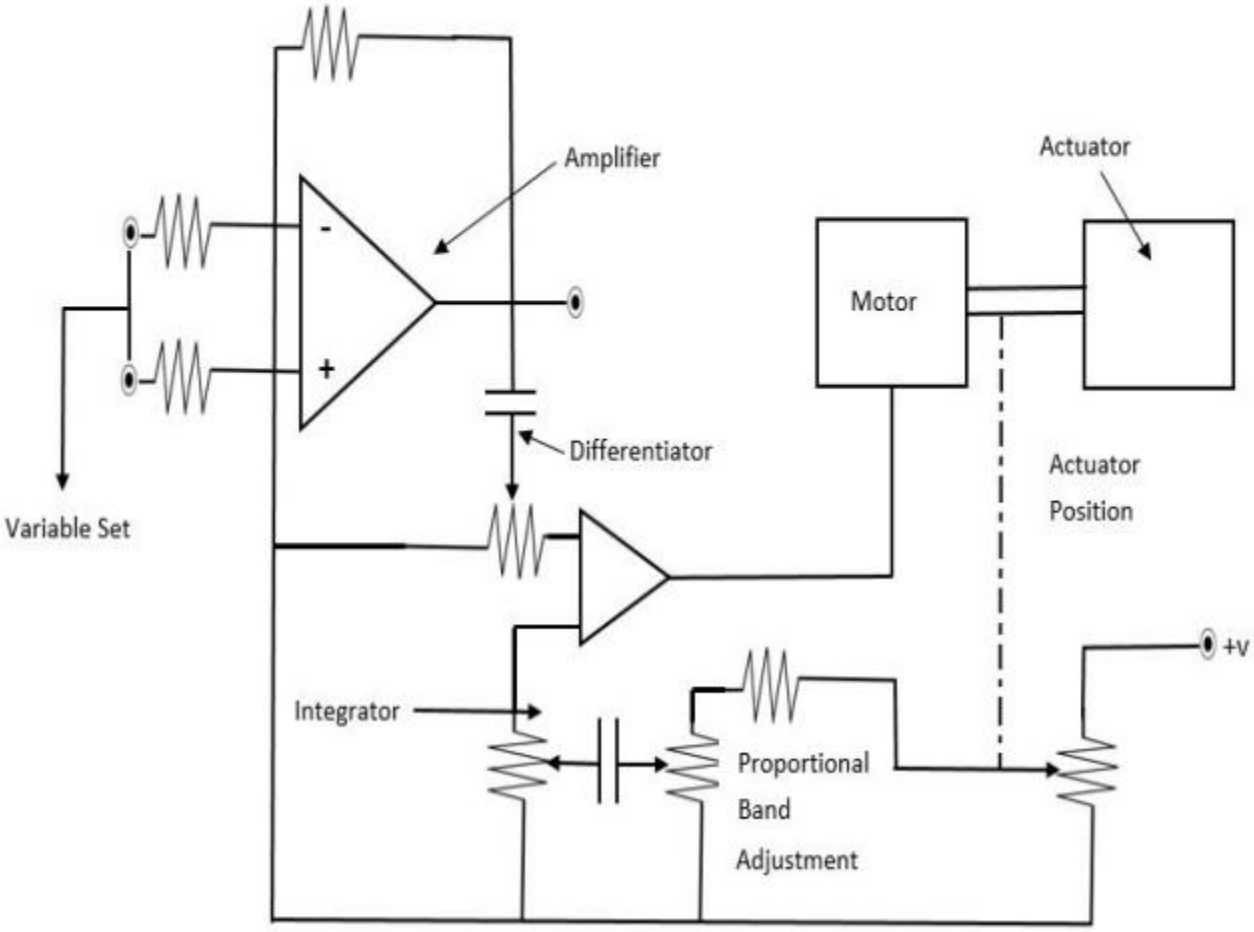


Fig. 3.4: Circuit of a PID electronic controller with feedback from the actuator position

The major key component of the proposed process is the *proportional-integral-derivative* controller (PID controller) control loop mechanism, which is widely used in industrial control systems, to mitigate faults by adjusting the process control inputs. Examples of such systems are the ones where the temperature, pressure, or the flow rate, need to be controlled. In such scenarios, the PID controller aims at detecting the possibility of a fault far enough in advance so that an action can be performed to prevent it from happening.

Figure 3.5 shows the general PID control system loop. The *set point* is the desired or command value for the process variable. The control system algorithm uses the difference between the output (process variable) and the *setpoint* to determine the desired actuator input to drive the system.

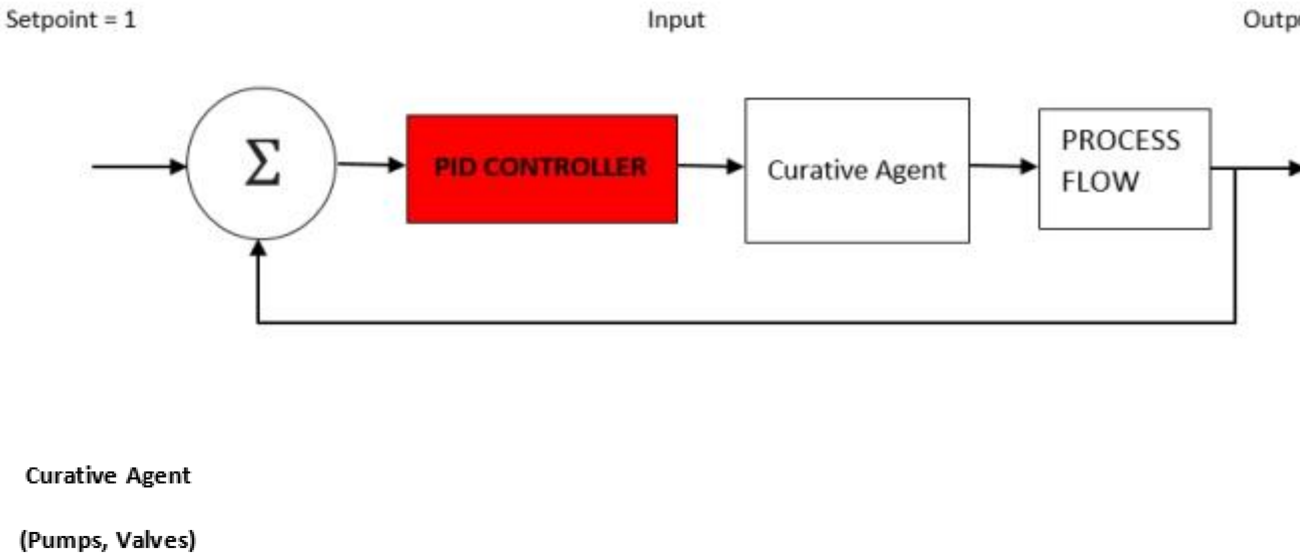


Fig. 3.5: PID control system loop

3.2.2.3 Inter Phase Friction Coefficient:

In modeling the PID, certain variables need to be considered. The first is the interface fiction coefficient. The two phases, gas and liquid, slip with respect to each other resulting in the inter phase-friction force, as stated in equation (3.27)

$$F = D_C \rho B_P V_{slip}$$

(3.27)

where;

ρ = Density of the gas phase

D_C = Drag coefficient

V_{slip} = The resultant slip velocity

B_P = The total projected droplet area in the cell given by

$$B_P = \left(1.5\frac{V}{d}\right) R_e$$

(3.28)

where d is the droplet diameter, V is the volume of the cell, and R_e is the particle Reynolds number given by

$$R_e = d\frac{V_{SLIP}}{\beta_i}$$

(3.29)

where:

β_i is the laminar viscosity of the gas, the drag coefficient D_c is evaluated as follows;

$$D_c = max\left[0.42\frac{24}{R_e}(1 + 0.15R_e^{0.68}) + \frac{0.42}{1+(4.25\times10^4)R_e^{-1.16}}\right]$$

(3.30)

3.2.2.4 Mass Transfer Coefficient for Fluid Inter Phase: As cooling of heated areas deals with evaporating fluids due to friction, the loss of mass of the fluid droplets which is the second variable needs to be calculated, see equation (3.31).

$$\dot{M} = \frac{A\sigma}{C_pD}ln\left(1 + C_p\frac{T_g-T_s}{L}\right)$$

(3.31)

where:

C_p= The specific heat capacity, which is assumed to be constant for both phases

D = The initial droplet diameter

σ = The thermal conductivity of the fluid droplets

L = The latent heat of evaporation

T_g = The temperature of the gas

T_s = The temperature at the surface of the droplet.

A = The interface surface area per cell given by

$$A = \frac{6R_2V}{d}$$

(3.32)

where R_2 is the liquid volume fraction, V is the cell volume, and d is the droplet diameter.

3.2.2.5 PID Models

Figure 3.6 shows the PID control system loop for a PID Model

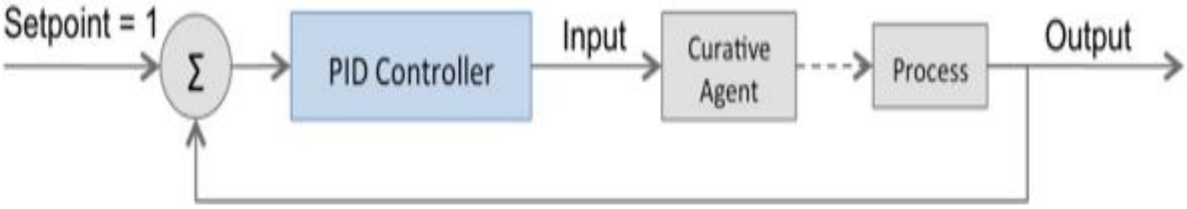


Fig. 3.6: PID control system loop (PID Model)

The control signal *u*(*t*) (output) is defined as follows:

$$u(t) = K_p e(t) + K_i \int_0^i e(t)\, dt + K_d \frac{de(t)}{dt} \qquad (3.33)$$

where K_p is the proportional gain constant, K_i is the integral gain constant, K_d is the derivative gain constant, and *e* is the error defined as the difference between the *setpoint* and the process variable value.

For a process fluid, consider the loop in Figure 3.7, where each variable is the Laplace transform of a deviation variable. To simplify the notation, the primes and s dependence have been omitted; thus, *Y* is used rather than Y'(s). Because the final control element is often a control valve, its transfer function is denoted by G_v. Note that the process transfer function G_p indicates the effect of the manipulated variable on the controlled variable. The disturbance transfer function G_d represents the effect of the disturbance variable on the controlled variable for the flow channel.

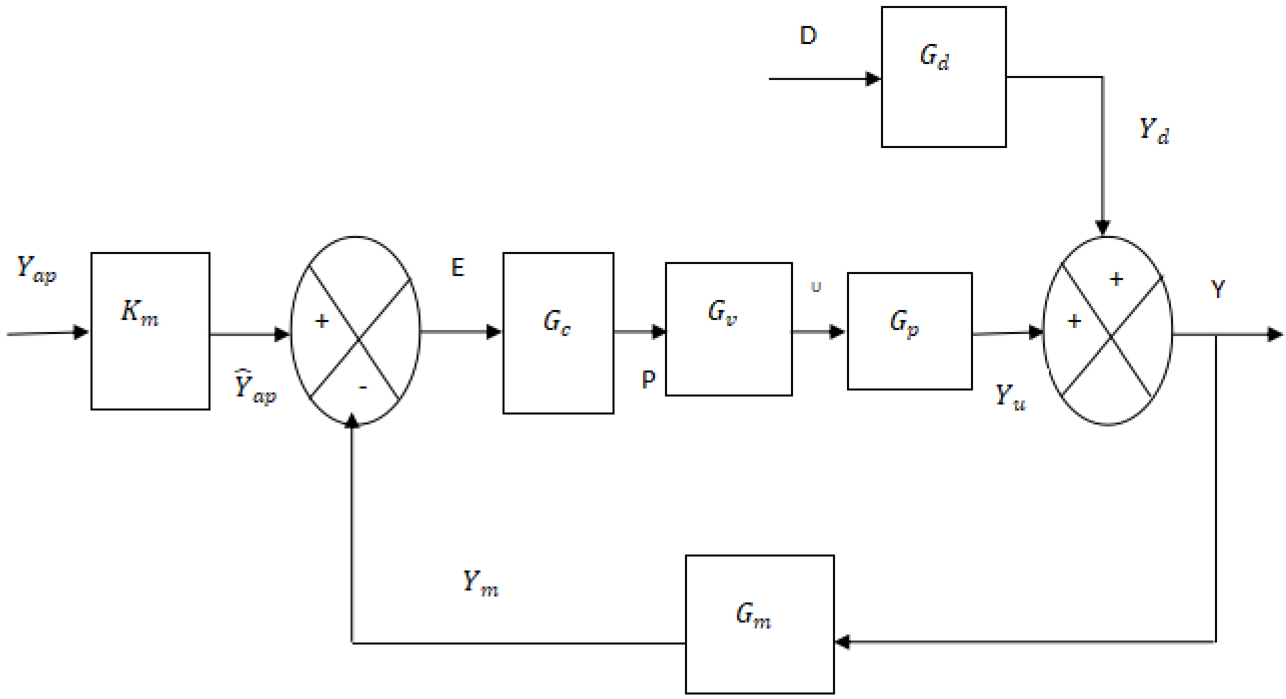


Fig. 3.7: Block diagram for a process fluid feedback control system. Based on Direct Synthesis (DS) method

The block diagrams considered so far have been specifically developed for the fluid storage system in a process plant.

Y = controlled variable

U = manipulated variable

D = disturbance variable (also referred to as the *load variable)*

P = controller output

E = error signal

Y_m = measured value of Y

Y_{sp} = set point p

$\mathbf{Y}_{\mathbf{sp}}$ = internal set point (used by the controller)

Y_u = change in Y due to U

Y_a = change in Y due to D

G_c = controller transfer function

G_v = transfer function for the final control element

G_P = process transfer function

G_d = disturbance transfer function

G_m = transfer function for sensor add transmitter

Km = steady-state gain for Gm

From figure 3.6, assuming that no disturbance change occurred, it can now be said that D = 0, this follows that:

$$Y = Y_d + Y_u$$

(3.34)

$$Y_d = G_d D = 0 \ (because\ D = 0)$$

(3.35)

$$Y_u = G_p U$$

(3.36)

Combining gives

$$Y = G_p U$$

(3.37)

$$U = G_v P$$

(3.38)

$$P = G_c E$$

(3.39)

$$E = \widehat{Y}_{SP} - Y_m$$

(3.40)

$$\widehat{Y}_{sp} = K_m Y_{sp}$$

(3.41)

$$Y_m = G_m Y$$

(3.42)

Combining the above equations gives

$$Y = G_p G_v P = G_p G_v G_c E = G_p G_v G_c \left(\widehat{Y}_{sp} - Y_m\right) = G_p G_v G_c \left(K_m Y_{sp} - G_m Y\right)$$

(3.43)

Rearranging gives the desired closed-loop transfer function,

$$\frac{Y}{Y_{sp}} = \frac{K_m G_c G_v G_p}{1 + G_c G_v G_p G_m}$$

(3.44)

In both the numerator and denominator of Equation. (3.44) the transfer functions have been rearranged to follow the order in which they are encountered in the feedback control loop. This convention makes it easy to determine which transfer functions are present or missing in analyzing subsequent problems.

3.2.3 Formulation of DCS-PID Control Scheme for the Process Flow Rate Model

3.2.3.1 Design of the Flow Controller PID using direct synthesis method

In the Direct Synthesis (DS) method, the controller design is based on a process model and a desired closed loop transfer function. The DS approach provides valuable insight into the relationship between the process model and the resulting controller.

As a starting point for the analysis, consider the block diagram of a feedback control system in Figure. 3.6 The closed-loop transfer function for set-point changes was derived in equation (3.44).

Let $G \triangleq G_v G_p G_m$ and assume that

$$G_m = k_m$$

(3.45)

Then equation (3.44) becomes:

$$\frac{Y}{Y_{sp}} = \frac{G_c G}{1+G_c G}$$

(3.46)

Rearranging and solving for G_c gives an expression for the ideal feedback controller:

$$G_c = \frac{1}{G}\left(\frac{\frac{y}{Y_{sp}}}{1-\frac{Y}{Y_{sp}}}\right)$$

(3.47)

Desired Closed-Loop Transfer Function

The performance of the DS controller in Equation (3.48) strongly depends on the specification of the desired closed-loop transfer function, A practical design equation can be derived by replacing the unknown G by G, and Y/Y_{sp} by a desired closed-loop transfer function, $(Y/Y_{sp})_d$: $(Y/Y_{sp})_d$· Ideally, $(Y/Y_{sp})_d = 1$

so that the controlled variable tracks set-point changes instantaneously without any error

$$G_c = \frac{1}{\tilde{G}}\left(\frac{\left(\frac{Y}{Y_{sp}}\right)_d}{1-\left(\frac{Y}{Y_{sp}}\right)_d}\right)$$

(3.48)

$$\left(\frac{Y}{Y_{sp}}\right)_d = \frac{1}{\tau_c s+1}$$

(3.49)

Where τ_c is the desired closed-loop time constant.

By substituting equation (3.49) into equation (3.48), and solving for G_c, the controller design equation becomes

$$G_c = \frac{1}{\tilde{G}}\frac{1}{\tau_c s}$$

(3.50)

The $\frac{1}{\tau_c s}$ term provides integral control action and thus eliminates offset. Design parameter τ_c provides a convenient controller tuning parameter that can be used to make the controller more aggressive (small τ_c) or less aggressive (large). τ_c

3.2.3.2 PID Hybridized with Distributed Control System (DCS) Controller

Figure 3.8 illustrates the flow control action when PID is used as a controller

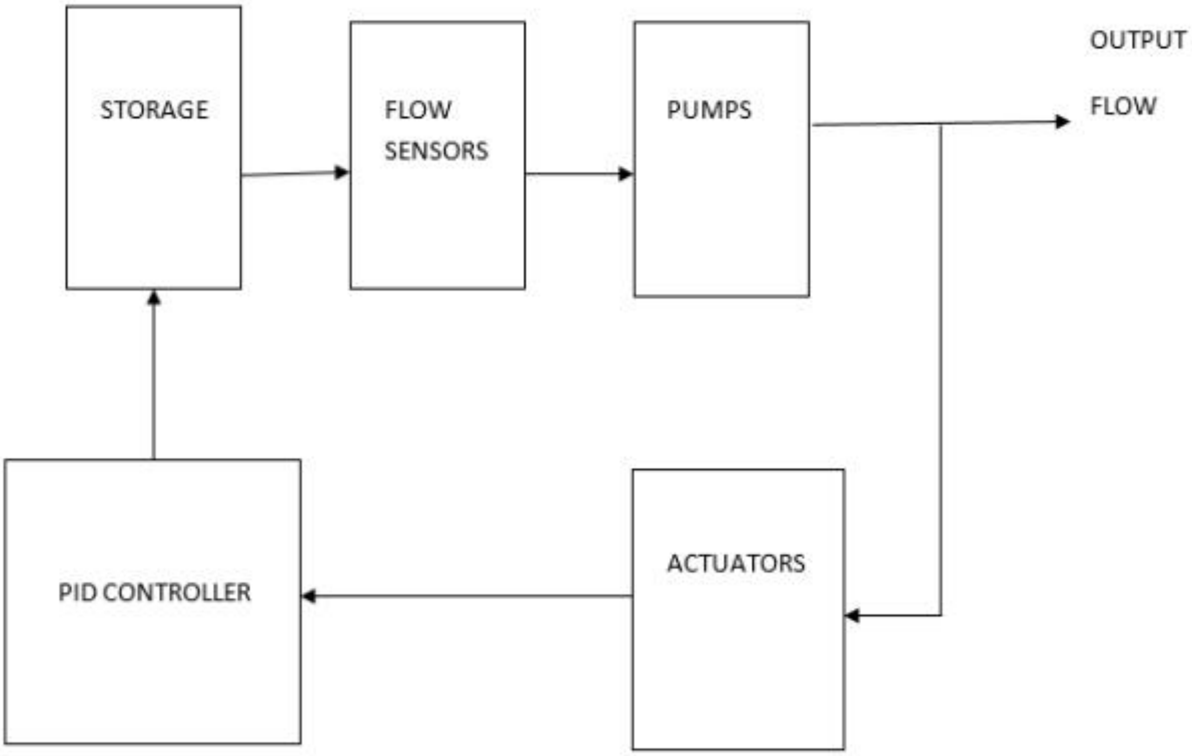


Fig. 3.8: Flow control action when PID is used as a controller

For simulation and comparison, the flow system, actuator, valve, flow sensors are mathematically modeled and another experimental data is added. The experimental process data are as follows:

Process response to the fluid flow gain -40^{0}C/Kg/Sec

Time constants -25 sec

Actuator response to variation of process fluid flow gain -2.5^{0}C/Kg/Sec

Sensors response to variation of process pressure Control valve capacity for fluid flow -1.8 Kg/Sec

Time constant of control valve - 3 Sec

Time constant of flow sensor -25 Sec

From the experimental data, the characteristic equation and the gains are obtained as shown in equation (3.51):

$$G(S) = S^3 + 20S^2 + 30S + 50k$$

(3.51)

Figure 3.9 shows the flow control action when PID is cascaded with DCS as a controller

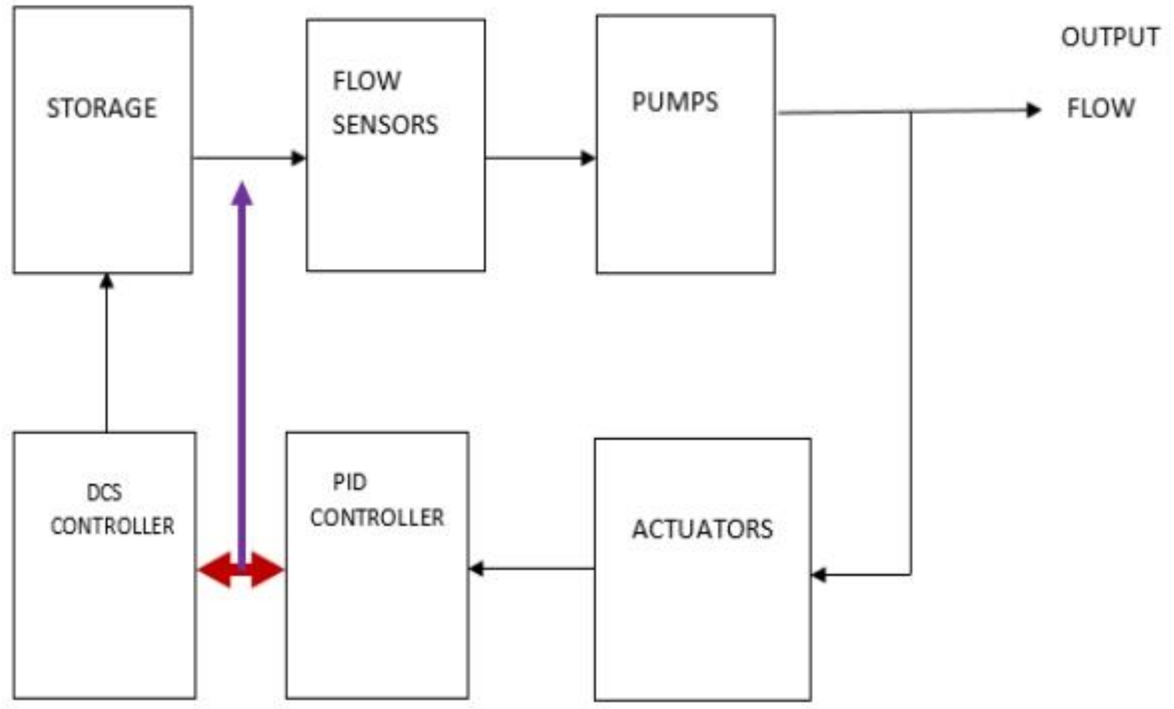


Fig. 3.9: Flow control action when PID is cascaded with DCS as a controller

Distributed control system, is a computerized control system for a process or plant usually with many control loop, in which autonomous controllers are distributed

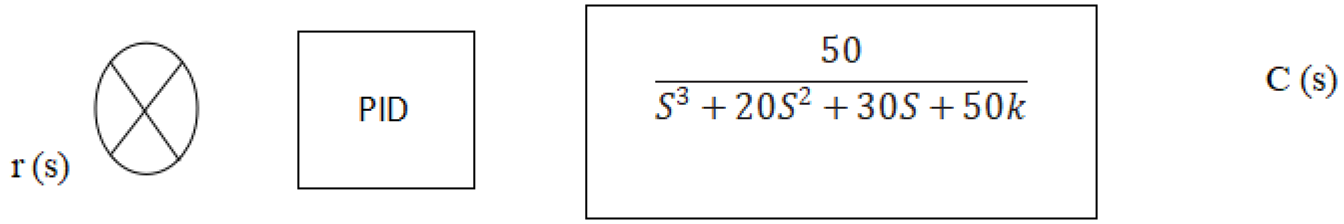
throughout the system, but there is no central operator supervisory control. This is in contrast to systems that use centralized controllers. Discrete controllers are located at central control room or within a central computer. The DCS concept increases the reliability and reduces the installation cost by localizing the control functions near the process plant, with remote monitoring and supervision

3.2.4 Simulation of the Designed Controllers

Simulation of the PID controller was done using MATLAB/Simulink software. This was done using the designed control variables and the models shown in sections 3.2.1, 3.2.2 and 3.2.3. The results are shown in Chapter Four.

Lab-view software and Proteus software were used when the PID and DCS were cascaded to see the best or better performance in the Internal Model control method used for the flow control. The results obtained are also shown in chapter four.

3.2.4.1 PID Controller and Tuning



If the block diagram of Figure 3.8 is reduced to simple PID control loop, it become as shown in Figure 3.10 for ease of tuning and simulation. This becomes:

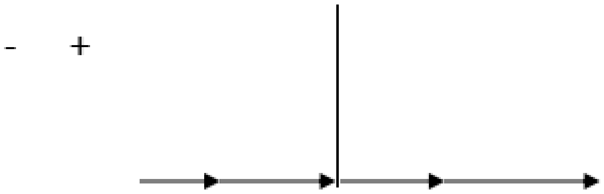


Fig. 3.10: PID block diagram for tuning

Figure 3.11 illustrates a Simulink representation of a feedback control system

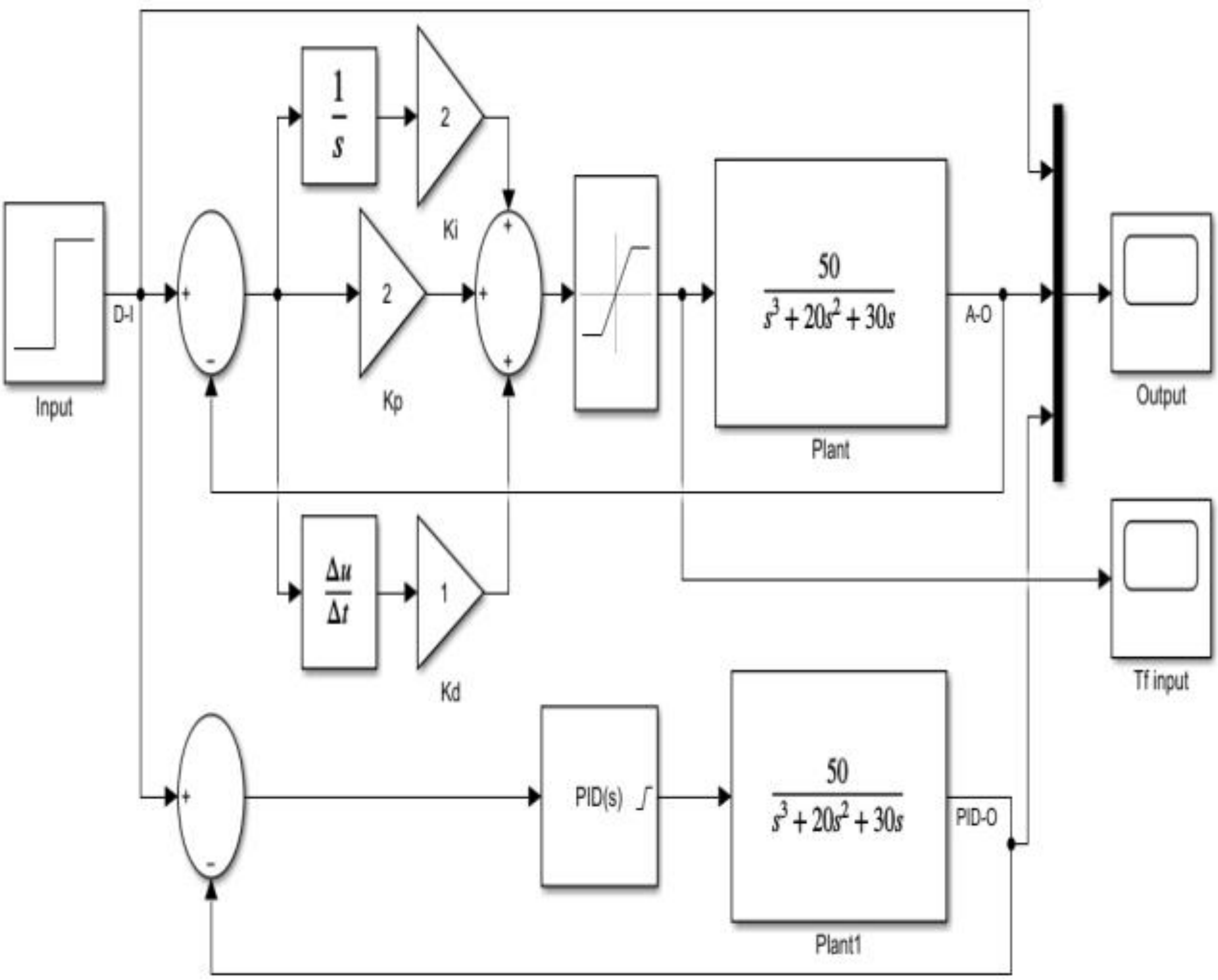


Fig 3.11: Simulink representation of feedback control system

3.2.4.2 Test for Stability of the Control System for Validation

Applying Routh- Hurwitz criterion to equation (3.51), the characteristic equation was obtained as:

$$S^3 + 20S^2 + 30S + 50k = 0 \tag{3.52}$$

In Routh- Hurwitz criterion which is one of the criteria for stability test, an array is usually formed from the characteristic equation obtained. Some of the fundamental rules for example, if we are considering sixth order-characteristics equation, are shown in Table 4.1

From equation (3.52), we form the Routh Hurwitz array as

s^3	1	30

$$\begin{array}{lll} s^2 & 20 & 50K \\ s^1 & \frac{(20)(30)-50K}{20} & 0 \\ s^0 & 50K & \end{array}$$

For the system to be stable, or for all the roots of equation (3.51) to be in the left- half of the s-plane, all the coefficient in the first column of the Routh–Hurwitz tabulation as shown in Table 4.1 must have the same sign.

This leads to the following conditions:

$\frac{(20)(30)-50K}{20} = \frac{600-50k}{20} > 0$, and $50k > 0$

Solving for value of K, let

$$\frac{600-50k}{20} = 0$$

Therefore,

$$600 - 50K = 0$$

$$K = \frac{600}{50} = 12$$

$$But\ K > 0$$

If we let K = 12,

We will have to find the roots from the auxiliary equation taken from s^2 row of Routh- Hurwitz tabulation in Table 4.1

Thus,

$A(s) = 20s^2 + 50k = 0$

$20s^2 + 50x12 = 0$

$20s^2 + 600 = 0$

$20s^2 \quad = -600$

$s^2 = \frac{-600}{20} \qquad s = -\left(\pm\sqrt{30}\right) = \pm\ 5.5$

$s = \pm\ j5.5$

The corresponding value of K at the points of s above is the critical value for stability.

Thus, the system is said to be stable.

CHAPTER FOUR

RESULT AND DISCUSION

4.1 Results of Simulations

Figure 4.1 shows the simulated result when the pressure of the fluid was noticed to have dropped due to friction in the medium in which it is being transported.

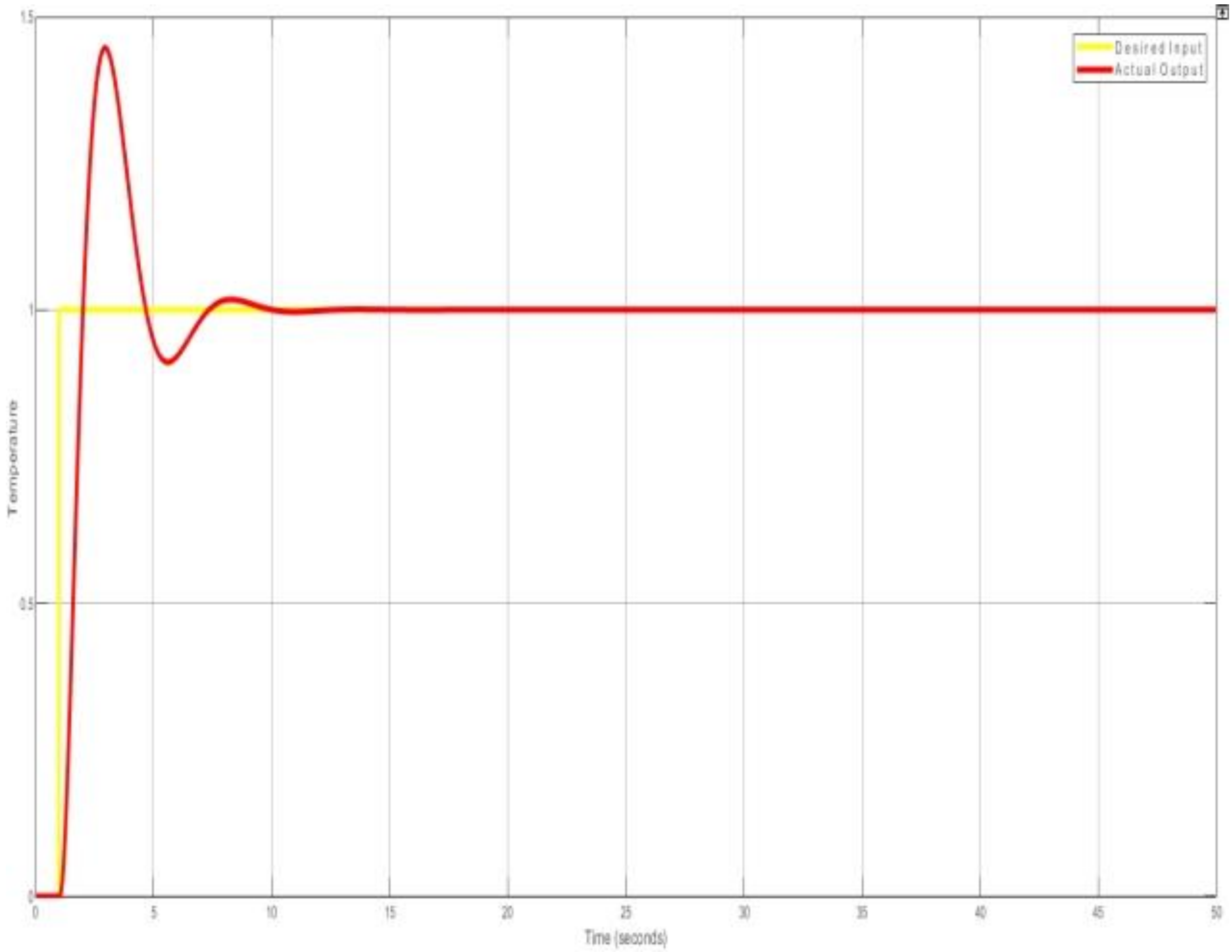


Fig. 4.1: Simulation results of flow when there was no controller and pressure error occurred.

Figure 4.2 shows the response of the flow when PID controller was in place

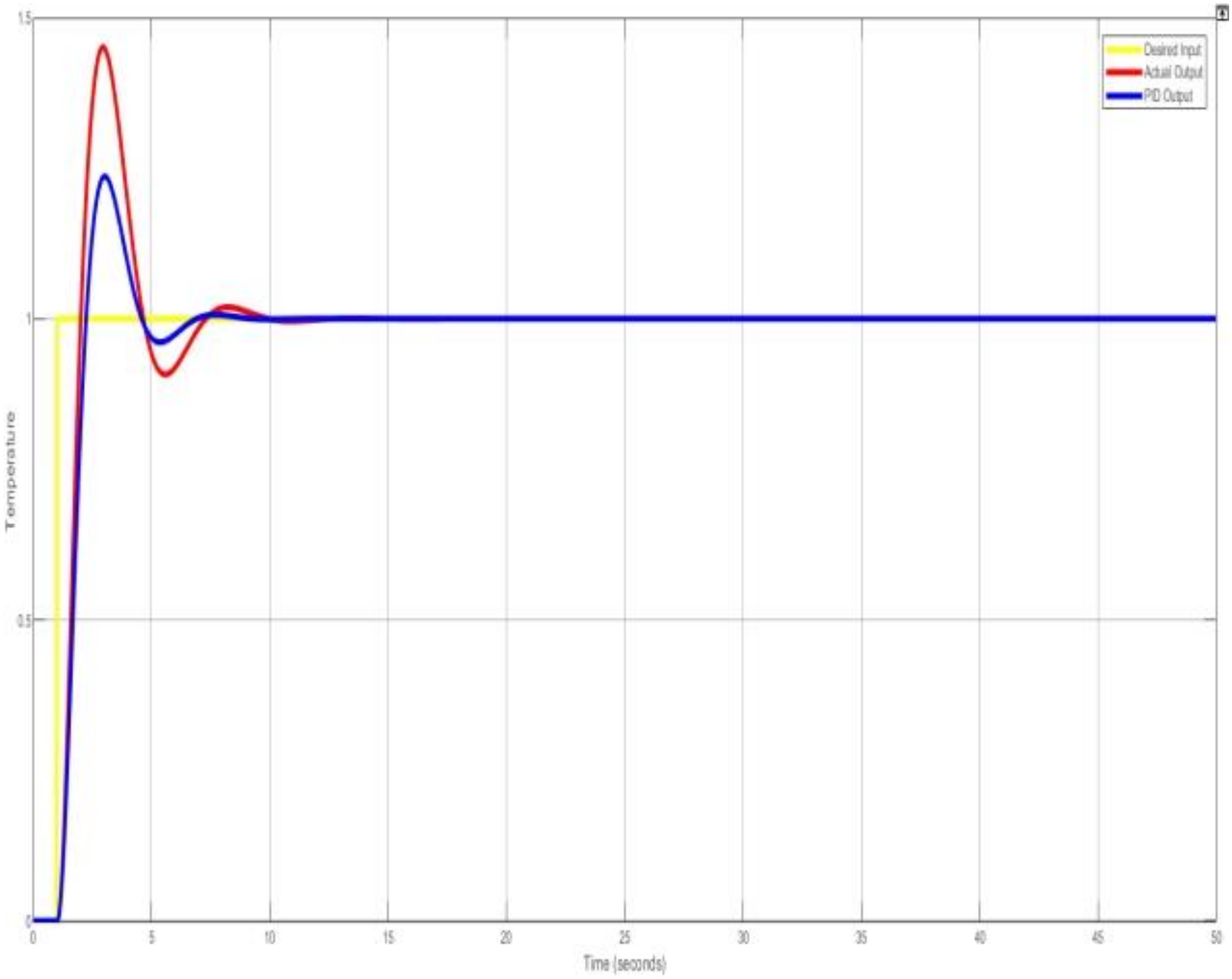


Fig. 4.2: Simulation results of flow when PID controller was integrated

Figure 4.3 shows the simulation result of flow condition for PID controller when there was drag in the flow condition due to frictional issues and system begin to change from its laminar state.

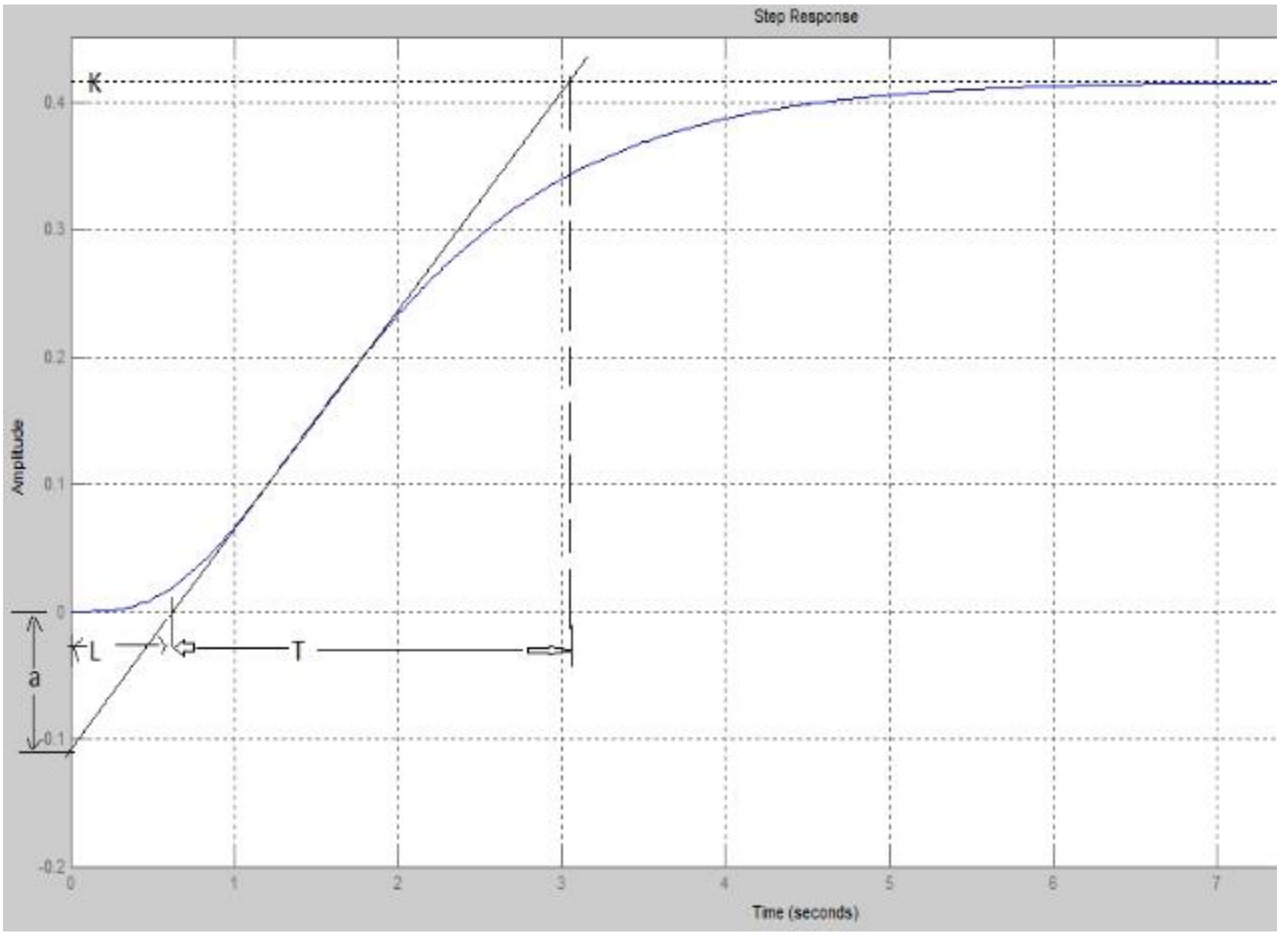


Fig. 4.3: Simulation result from Proteus software when Drag was noticed in the fluid flow (Designed PID controller was in place. (Drag error))

Figure 4.4 shows the simulation result of the PID controller when the system observed turbulence at the initial stage when the pumps tried to adjust the pressure to set point for better output result. Proteus was used for the simulation.

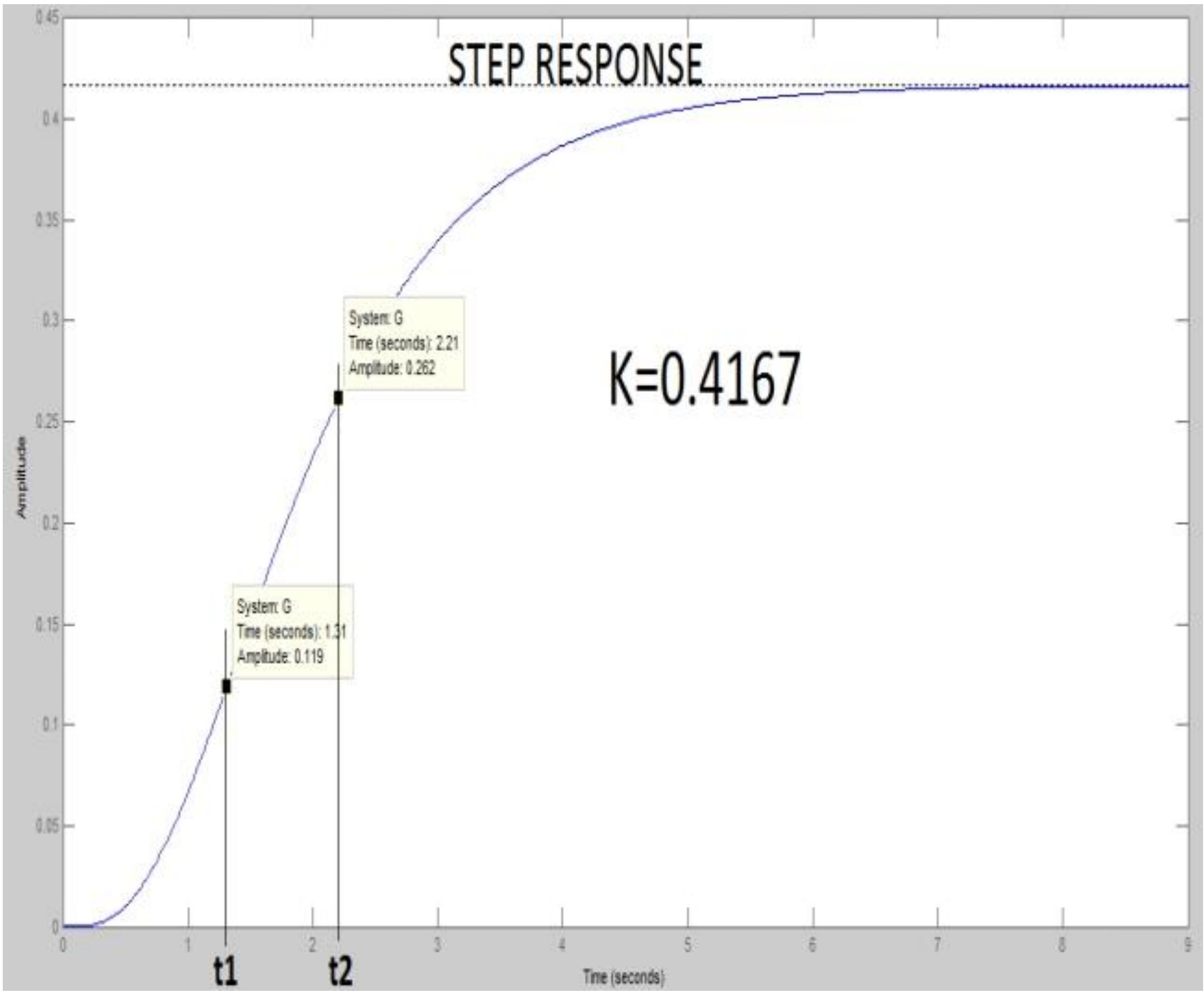


Fig. 4.4: PID controller result when system was turbulent at initial stage before stabilization was achieved. This was due to temperature rise (turbulent error).

Figure 4.5 shows the tuning result when the system tried to adjust the valves, pumps and tuned the controller for quick stability to be restored. The initial result was manipulated through the tuning processes to achieve a stable condition.

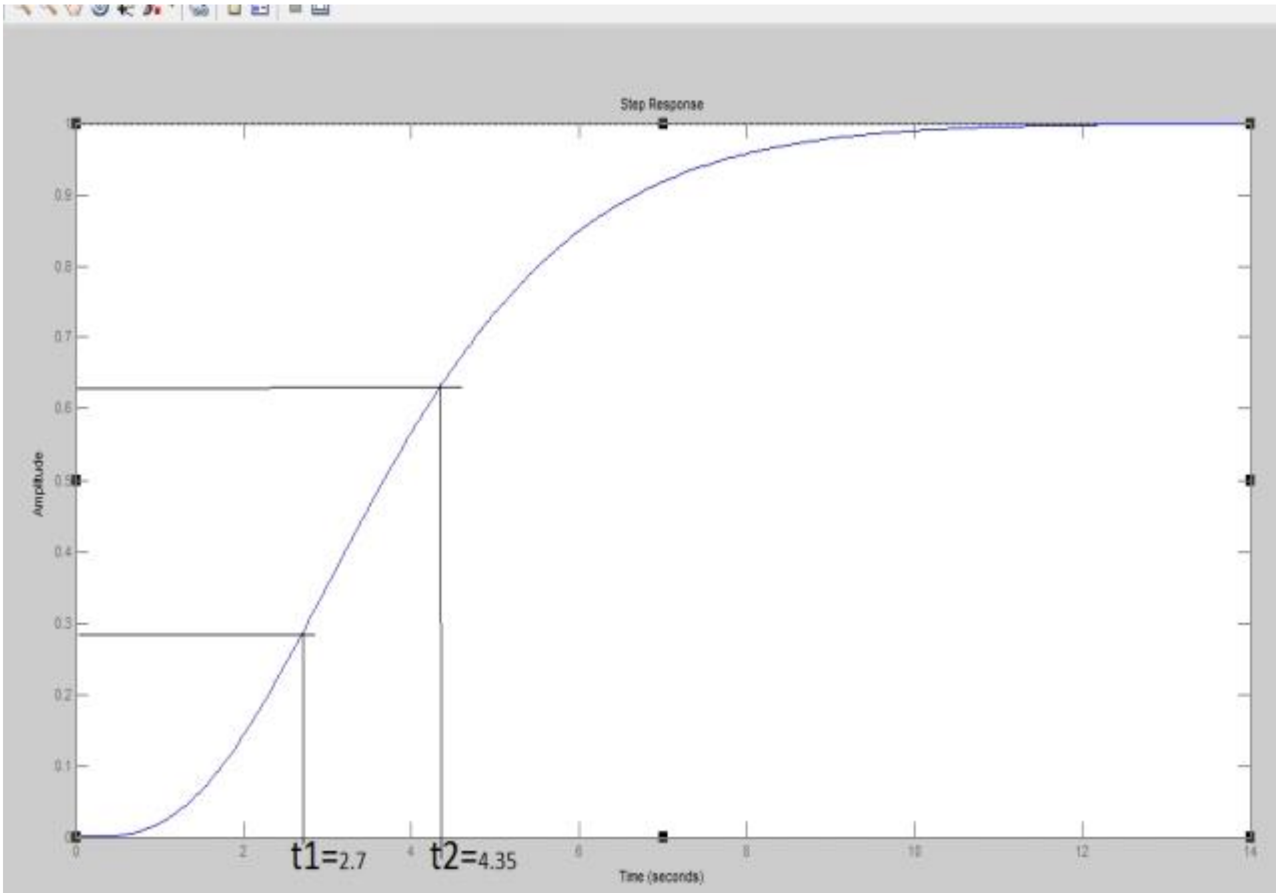


Fig. 4.5: Auto tune of the control system using Ziegler- Nichole tuning method to overcome drag error.

The table in Appendix C, contains a near to real time situation used to simulate at different scenario of disturbance event during flow operations using PID independently, DCS independently and combination of the two controllers to see how fast stability/best performance could be achieved. Detailed discussions of all simulation results are in the section termed discussion in chapter 4.2

Figure 4.6 is a simulation result showing when the two controllers were used independently and when they were cascaded to see how fast they could overcome disturbance and achieve stability that could eliminate abnormal output of the flow rate.

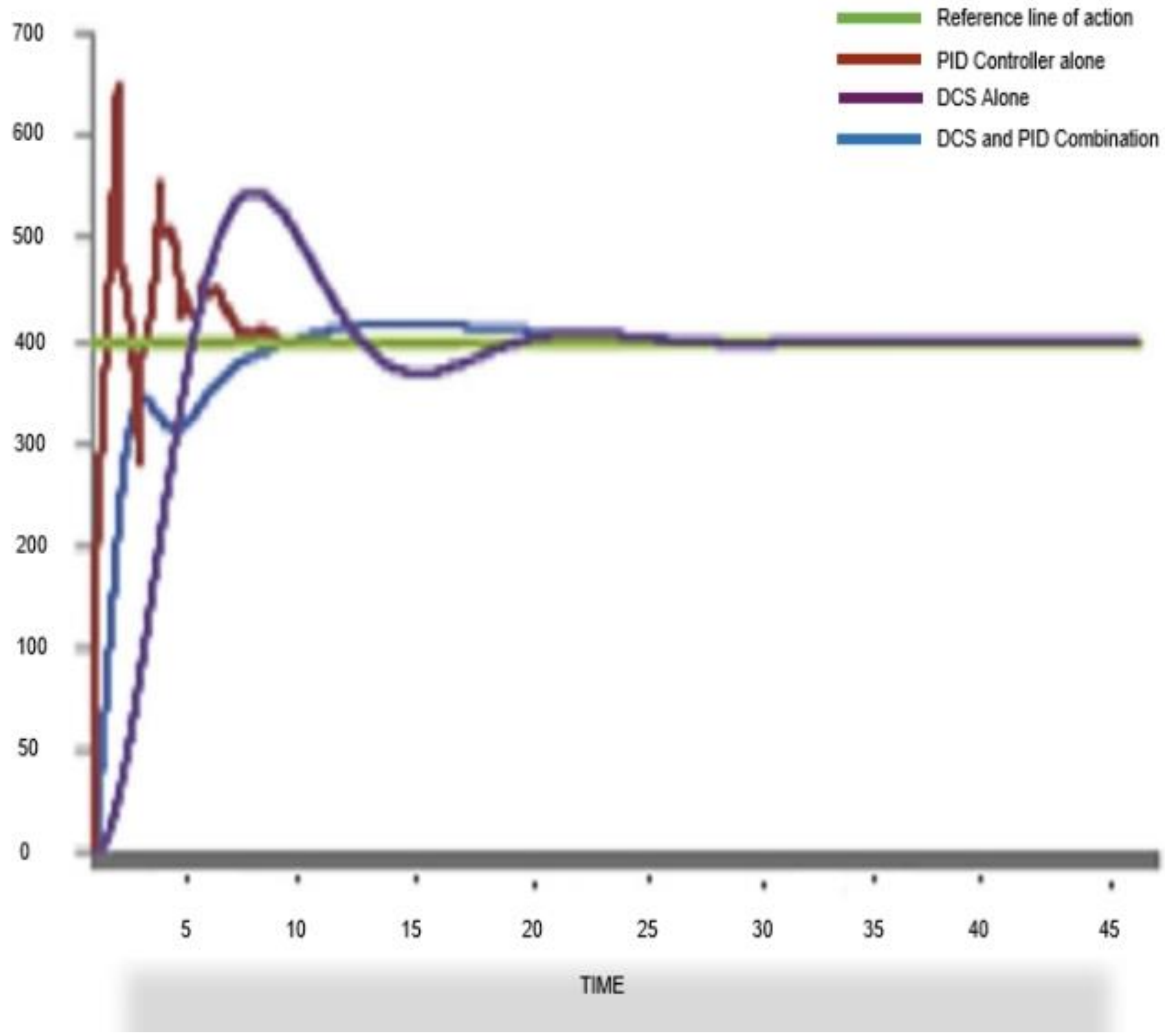


Fig. 4.6: Performance analysis of the two controllers in different scenarios.

4.2 Discussions

4.2.1 General Overview

In process industry, four major variables have always been a problem militating against the robustness of control of products. These are Flow, Temperature, Level and Pressure. Researchers have been going through a lot of advancement to see how to curb these negative issues associated with these fundamental variables.

In this research work, one of the problems which is errors associated with flow in process industries was picked to see how they can or could be mitigated to achieve robust and optimal stability.

In flow phenomenon, the desired objective is to have the flow in the designed laminar condition so that time and profit could be maximized and the estimated quantity of the product achieved at the end of the production exercise. In real time, this is not achievable due to certain errors like drag, under laminar, turbulence etc.

These errors are due to frictional forces that occurs in the medium in which the fluid is being transmitted. When frictional forces occur in the medium in which the fluid is being transmitted drag error will emanate, pressure value will drop and the fluid will get stalled in the medium moving sluggishly and this usually elongate the time needed to receive the product, it will further reduce the quantity expected at the output end and this is termed under laminar status. It could also create drags where the transmitter will not get signal on time to initiate a control action

Flow losses are accounted for; by pressure losses and rise in temperature and fall into two categories. Firstly, those associated with viscosity, the friction between the constriction walls and the flowing fluid, secondly, those associated with fittings, such as valves, elbows, tees, and so forth.

The phenomenon of flow control system is basically a feedback control system. The flow from the control valve is given to the flow transmitter which converts the input flow into 4-20mA signal. This 4-20mA signal is then given to the PID and DCS system. The DCS and the PID controllers functional block takes care of making the controlled variable closer to the set point value. It does so by calculating the values for proportional gain, reset and PI parameters by setting the mode of the controller in the auto state. The values for proportional gain, PI and reset are calculated using tuning functionality of Ziegler Nichols tuning method. The DCS and PID ensured that the controlled variable which in this case is flow reaches closer to the set point value and overcome all disturbances and restrictions that could hamper or turn the flow from laminar to turbulence. Direct synthesis (DS) method of control were also considered. The output of DCS and PID during their combination, activate the pumps to increase the pressure immediately the pressure is reduced due to friction in the transporting medium. This will send signal to a converter whose duty is to close or open the control valve depending upon the output of the PID and the DCS. With this, the flow is said to be controlled according to the setpoint value.

4.2.2 Discussion of Simulation Results

From Figure 4.1, it could be seen that the overshoot was very high when the issue of pressure drop occurred and there was no controller in the system in as much as there are sensors and actuators. Also, it could be seen from the simulation result that there were issues of transients after the overshoot. Stability or steady state was achieved after several times were wasted and required output lost. The essence of control is to immediately bring the disturbance under control without much time lost.

In Figures 4.2, 4.3, 4.4, the PID controller was used to mitigate the errors of drag, under laminar and turbulent errors as a result of frictional forces and it tried to reduce the overshoot so that the system could be stabilized or reach a steady state but the set point was not achieved as required. Figure 4.5 shows when the PID as the only controller was tuned using Ziegler Nichols' method to ensure that stability was achieved without combination of DCS controller. This brought significant improvement but it could be seen that there was drag from the beginning of the simulation.

In Figure 4.6, the simulation study shows the performance of two controllers which are used for virtual buildup of control activity of flow. The controllers DCS and PID were used independently to see their performance in terms of control activity. When they are used independently, it can be seen from Figure 4.6 that the PID controller has a high over shoot and rise time before overcoming the disturbance to attain stability. Also observing Figure 4.6, it can be seen that the DCS also has a high overshoot when used alone to control the flow before attaining stability.

When the two controllers were incorporated in the loop, the result became fantastic as the overshoot was reduced to minimum level and stability was achieved with a very short time. It also gives faster disturbance rejection with the time duration of few seconds and smaller overshoot. This was achieved by also using Ziegler Nichol to tune the two controllers for a quick steady or robust stability. This improvement brought a new window that errors of drag under laminar and turbulence could be overcome using cascaded brand of controllers.

Validation of the controllers was made using Routh – Hurwitz stability criterion from characteristic equation of (3.52) the roots and tabulation of Routh-Hurwitz as shown in Table 4.1 was observed to have no sign change and all the roots lying in the left side of the s-plane.

s^6	a_0	a_2	a_4	a_6
s^5	a_1	a_3	a_5	a_0
s^4	$\frac{a_1a_2-a_0a_3}{a_1}=A$	$\frac{a_1a_4-a_0a_5}{a_1}=B$	$\frac{a_1a_6-a_0X0}{a_1}=a_6$	0
s^3	$\frac{Aa_3-a_1B}{A}=C$	$\frac{Aa_5-a_1a_6}{A}=D$	$\frac{AX0-a_1x\,0}{A}=0$	0
s^2	$\frac{BC-AD}{C}=E$	$\frac{Ca_6-A\times 0}{C}=a_6$	$\frac{C\times 0-A\times 0}{C}=0$	0
s^1	$\frac{ED-Ca_6}{E}=F$	0	0	0
s^0	$\frac{Fa_6-E\times 0}{F}=a_6$	0	0	0

Table 4.1: Routh Hurwitz tabulation for sixth order-characteristics equation.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In this research work, maintenance of constant flow rate of fluids was achieved through the use of combination of controllers. The research work reviewed how the adverse effect of friction could cause devastating effect on flow of fluids.

In the work, modeling of measuring of flow device was done in which orifice plate was specifically considered and modeled for use in process fluid like gas, crude oil, gasoline, steam etc, Coefficient of discharge was adequately looked into to know its impact on flow processes.

A flow controller was specifically PID for use in the control of the flow and to see how effectively it can be used to overcome over shoot and other disturbances that could be caused by reduction of pressure in the system due to drag and frictional issues and to see how fast these could be achieved within a very short time. The performance of the PID was monitored and simulated and it was found that in as much as it tried to mitigate the problems associated with flow there were still issues of disturbance but not as much as when there were only sensors, actuators and pumps.

Direct Synthesis (DS) methodology was applied in all the processes. In these, mass transfer coefficient was considered. Design of the flow controller was done to see how the modeled PID could effectively communicate with other devices in the control loop.

After the design, PID controller was simulated in a MATLAB/Simulink environment to see the performance. This was explained in chapter four under Results and Discussion. The research did not stop at that, cascading of the PID with DCS controller was done to see if a better result could be achieved. It was discovered that the combination of the two controllers yielded fantastic result as the over shoot was drastically reduced to a level that it became inconsequential in the output result obtained comparing it with set or reference point already set out.

In final conclusion, the research work was completed as scoped and the yielded result indicates that hybridization or cascading of two controllers is better than using only one controller. The work was validated using Routh - Hurwitz stability criterion.

5.2 Recommendation

The four important elements (Flow, Level, Pressure and Temperature) of process industries which flow is one of them has continued to attract attention of researchers on how to mitigate the problems associated with these elements. Flow is a very crucial subject of discussion because it is involved in all process sectors. In this research, Direct Synthesis (DS) control mechanism was adopted and cascading of PID and DCS controllers was used to achieve the results obtained.

Therefore, it is recommended that Artificial Intelligence should be used in some of the areas that ordinary electronic, pneumatic and hydraulic controllers could not be adequately accessed such as control of fluids under the water (River, Sea and Oceans). Also, hybridization of other controllers apart from DCS and PID for better results could be adopted.

5.3 Contribution to Knowledge

As earlier said, flow is an important research area and many researchers have been and continue to delve into the area. None has cascaded two important controllers to achieve a better result. In as much as PID independently could try to control the system, there will still be issue of time of arriving at robust and optimal stability. Overshoot and duration of transients is still an impediment to achieving good results. Also, DCS is a good controller using it independently, will also have some disturbance hindering achieving stability at a very short time, due to drag, friction, pressure lost etc.

From the above experience, **Cascading or Hybridization** of the two controllers such as Distributed Control System (DCS) and Proportional Integral Derivative (PID) properly designed and configured is a new system or technology that will add and continue to add values to flow control technology in process industry. In all the literature assessed, none has used two different controllers at-a-go to control flow disturbances.

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APPENDIX A

MATLAB GENERATED CODE FOR THE PID MODEL

```
/*
 * File: PID_Controller.c
 *
 * Code generated for Simulink model 'PID_Controller'.
 *
 * Model version                  : 1.3
 * Simulink Coder version         : 9.5 (R2021a) 14-Nov-2020
 * C/C++ source code generated on : Fri Mar 29 08:46:22 2024
 *
 * Target selection: ert.tlc
```

```
 * Embedded hardware selection: Intel->x86-64 (Windows64)

 * Code generation objectives:

 *    1. Execution efficiency

 *    2. RAM efficiency

 */


#include "PID_Controller.h"

#define NumBitsPerChar                 8U

#ifndef rtmIsMajorTimeStep

#define rtmIsMajorTimeStep(rtm)        (((rtm)->Timing.simTimeStep) == MAJOR_TIME_STEP)

#endif

#ifndef rtmIsMinorTimeStep

#define rtmIsMinorTimeStep(rtm)        (((rtm)->Timing.simTimeStep) == MINOR_TIME_STEP)
```

```
#endif

#ifndef rtmSetTPtr

#define rtmSetTPtr(rtm, val)            ((rtm)-
>Timing.t = (val))

#endif

X rtX;

DW rtDW;

static RT_MODEL rtM_;

RT_MODEL *const rtM = &rtM_;

extern void PID_Controller_derivatives(void);

static real_T rtGetInf(void);

static real32_T rtGetInfF(void);

static real_T rtGetMinusInf(void);

static real32_T rtGetMinusInfF(void);
```

```
extern real_T rtInf;

extern real_T rtMinusInf;

extern real_T rtNaN;

extern real32_T rtInfF;

extern real32_T rtMinusInfF;

extern real32_T rtNaNF;

static void rt_InitInfAndNaN(size_t realSize);

static boolean_T rtIsInf(real_T value);

static boolean_T rtIsInfF(real32_T value);

static boolean_T rtIsNaN(real_T value);

static boolean_T rtIsNaNF(real32_T value);

typedef struct {

  struct {

    uint32_T wordH;
```

```
    uint32_T wordL;
  } words;
} BigEndianIEEEDouble;
typedef struct {
  struct {
    uint32_T wordL;
    uint32_T wordH;
  } words;
} LittleEndianIEEEDouble;
typedef struct {
  union {
    real32_T wordLreal;
    uint32_T wordLuint;
  } wordL;
```

```
} IEEESingle;

real_T rtInf;

real_T rtMinusInf;

real_T rtNaN;

real32_T rtInfF;

real32_T rtMinusInfF;

real32_T rtNaNF;

static real_T rtGetNaN(void);

static real32_T rtGetNaNF(void);

static real_T rtGetInf(void)

{

  size_t bitsPerReal = sizeof(real_T) *
(NumBitsPerChar);

  real_T inf = 0.0;
```

```
  if (bitsPerReal == 32U) {

    inf = rtGetInfF();

  } else {

    union {

      LittleEndianIEEEDouble bitVal;

      real_T fltVal;

    } tmpVal;

    tmpVal.bitVal.words.wordH = 0x7FF00000U;

    tmpVal.bitVal.words.wordL = 0x00000000U;

    inf = tmpVal.fltVal;

  }

  return inf;

}
```

```
static real32_T rtGetInfF(void)
{
  IEEESingle infF;
  infF.wordL.wordLuint = 0x7F800000U;
  return infF.wordL.wordLreal;
}
static real_T rtGetMinusInf(void)
{
  size_t bitsPerReal = sizeof(real_T) *
(NumBitsPerChar);
  real_T minf = 0.0;
  if (bitsPerReal == 32U) {
    minf = rtGetMinusInfF();
  } else {
```

```
    union {
      LittleEndianIEEEDouble bitVal;
      real_T fltVal;
    } tmpVal;
    tmpVal.bitVal.words.wordH = 0xFFF00000U;
    tmpVal.bitVal.words.wordL = 0x00000000U;
    minf = tmpVal.fltVal;
  }
  return minf;
}
static real32_T rtGetMinusInfF(void)
{
  IEEESingle minfF;
  minfF.wordL.wordLuint = 0xFF800000U;
```

```
  return minfF.wordL.wordLreal;

}

static void rt_InitInfAndNaN(size_t realSize)

{

  (void) (realSize);

  rtNaN = rtGetNaN();

  rtNaNF = rtGetNaNF();

  rtInf = rtGetInf();

  rtInfF = rtGetInfF();

  rtMinusInf = rtGetMinusInf();

  rtMinusInfF = rtGetMinusInfF();

}

static boolean_T rtIsInf(real_T value)

{
```

```
  return (boolean_T)((value==rtInf ||
value==rtMinusInf) ? 1U : 0U);

}

static boolean_T rtIsInfF(real32_T value)

{

  return (boolean_T)(((value)==rtInfF ||
(value)==rtMinusInfF) ? 1U : 0U);

}

static boolean_T rtIsNaN(real_T value)

{

  boolean_T result = (boolean_T) 0;

  size_t bitsPerReal = sizeof(real_T) *
(NumBitsPerChar);

  if (bitsPerReal == 32U) {

    result = rtIsNaNF((real32_T)value);

  } else {
```

```
    union {
      LittleEndianIEEEDouble bitVal;
      real_T fltVal;
    } tmpVal;
    tmpVal.fltVal = value;
    result = (boolean_T)((tmpVal.bitVal.words.wordH & 0x7FF00000) == 0x7FF00000 &&
                         ( (tmpVal.bitVal.words.wordH & 0x000FFFFF) != 0 ||
                          (tmpVal.bitVal.words.wordL != 0) ));
  }
  return result;
}
static boolean_T rtIsNaNF(real32_T value)
{
```

```
  IEEESingle tmp;

  tmp.wordL.wordLreal = value;

  return (boolean_T)( (tmp.wordL.wordLuint &
0x7F800000) == 0x7F800000 &&

                     (tmp.wordL.wordLuint &
0x007FFFFF) != 0 );

}

static real_T rtGetNaN(void)

{

  size_t bitsPerReal = sizeof(real_T) *
(NumBitsPerChar);

  real_T nan = 0.0;

  if (bitsPerReal == 32U) {

    nan = rtGetNaNF();

  } else {

    union {
```

```
      LittleEndianIEEEDouble bitVal;

      real_T fltVal;
 } tmpVal;

    tmpVal.bitVal.words.wordH = 0xFFF80000U;

    tmpVal.bitVal.words.wordL = 0x00000000U;

    nan = tmpVal.fltVal;

  }

  return nan;

}

static real32_T rtGetNaNF(void)

{

  IEEESingle nanF = { { 0.0F } };

  nanF.wordL.wordLuint = 0xFFC00000U;

  return nanF.wordL.wordLreal;
```

```
}

static void
rt_ertODEUpdateContinuousStates(RTWSolverInfo *si )

{

  static const real_T rt_ODE3_A[3] = {

    1.0/2.0, 3.0/4.0, 1.0

  };

  static const real_T rt_ODE3_B[3][3] = {

    { 1.0/2.0, 0.0, 0.0 },

    { 0.0, 3.0/4.0, 0.0 },

    { 2.0/9.0, 1.0/3.0, 4.0/9.0 }

  };

  time_T t = rtsiGetT(si);

  time_T tnew = rtsiGetSolverStopTime(si);
```

```
  time_T h = rtsiGetStepSize(si);

  real_T *x = rtsiGetContStates(si);

  ODE3_IntgData *id = (ODE3_IntgData
*)rtsiGetSolverData(si);

  real_T *y = id->y;

  real_T *f0 = id->f[0];

  real_T *f1 = id->f[1];

  real_T *f2 = id->f[2];

  real_T hB[3];

  int_T i;

  int_T nXc = 9;

  rtsiSetSimTimeStep(si,MINOR_TIME_STEP);

  (void) memcpy(y, x,

                (uint_T)nXc*sizeof(real_T));
```

```
rtsiSetdX(si, f0);

PID_Controller_derivatives();

hB[0] = h * rt_ODE3_B[0][0];

for (i = 0; i < nXc; i++) {

  x[i] = y[i] + (f0[i]*hB[0]);

}

rtsiSetT(si, t + h*rt_ODE3_A[0]);

rtsiSetdX(si, f1);

PID_Controller_step();

PID_Controller_derivatives();

for (i = 0; i <= 1; i++) {

  hB[i] = h * rt_ODE3_B[1][i];

}

for (i = 0; i < nXc; i++) {
```

```
    x[i] = y[i] + (f0[i]*hB[0] + f1[i]*hB[1]);

  }

  rtsiSetT(si, t + h*rt_ODE3_A[1]);

  rtsiSetdX(si, f2);

  PID_Controller_step();

  PID_Controller_derivatives();

  for (i = 0; i <= 2; i++) {

    hB[i] = h * rt_ODE3_B[2][i];

  }

  for (i = 0; i < nXc; i++) {

    x[i] = y[i] + (f0[i]*hB[0] + f1[i]*hB[1] +
f2[i]*hB[2]);

  }

  rtsiSetT(si, tnew);
```

```
  rtsiSetSimTimeStep(si,MAJOR_TIME_STEP);

}

void PID_Controller_step(void)

{

  if (rtmIsMajorTimeStep(rtM)) {

    rtsiSetSolverStopTime(&rtM->solverInfo,((rtM-
>Timing.clockTick0+1)*

      rtM->Timing.stepSize0));

  }

  if (rtmIsMinorTimeStep(rtM)) {

    rtM->Timing.t[0] = rtsiGetT(&rtM->solverInfo);

  }

  {

real_T rtb_Sum;

    real_T rtb_Sum1;
```

```
    real_T rtb_Sum2;

    real_T *lastU;

    rtb_Sum2 = !(rtM->Timing.t[0] < 1.0);

    rtDW.Sum = rtb_Sum2 - ((0.0 * rtX.Plant_CSTATE[0]
+ 0.0 * rtX.Plant_CSTATE[1])

      + 50.0 * rtX.Plant_CSTATE[2]);

    rtb_Sum1 = rtM->Timing.t[0];

    if ((rtDW.TimeStampA >= rtb_Sum1) &&
(rtDW.TimeStampB >= rtb_Sum1)) {

      rtb_Sum1 = 0.0;

    } else {

      rtb_Sum = rtDW.TimeStampA;

      lastU = &rtDW.LastUAtTimeA;

      if (rtDW.TimeStampA < rtDW.TimeStampB) {

        if (rtDW.TimeStampB < rtb_Sum1) {
```

```
          rtb_Sum = rtDW.TimeStampB;
          lastU = &rtDW.LastUAtTimeB;
        }
      } else if (rtDW.TimeStampA >= rtb_Sum1) {
        rtb_Sum = rtDW.TimeStampB;
        lastU = &rtDW.LastUAtTimeB;
      }
      rtb_Sum1 = (rtDW.Sum - *lastU) / (rtb_Sum1 -
rtb_Sum);
    }
    rtb_Sum1 += 2.0 * rtX.Integrator_CSTATE + 2.0 *
rtDW.Sum;
    if (rtb_Sum1 > 2.0) {
      rtDW.Saturation = 2.0;
    } else if (rtb_Sum1 < -2.0) {
```

```
      rtDW.Saturation = -2.0;
    } else {
      rtDW.Saturation = rtb_Sum1;
    }
    rtb_Sum2 -= (0.0 * rtX.Plant1_CSTATE[0] + 0.0 *
rtX.Plant1_CSTATE[1]) + 50.0
      * rtX.Plant1_CSTATE[2];
    rtDW.FilterCoefficient = (1.8 * rtb_Sum2 -
rtX.Filter_CSTATE) * 100.0;
    rtb_Sum1 = (3.5 * rtb_Sum2 +
rtX.Integrator_CSTATE_j) +
      rtDW.FilterCoefficient;
    if (rtb_Sum1 > 9.0) {
      rtDW.Saturation_b = 9.0;
    } else if (rtb_Sum1 < -9.0) {
      rtDW.Saturation_b = -9.0;
```

```
    } else {
      rtDW.Saturation_b = rtb_Sum1;
    }
    rtDW.IntegralGain = 3.5 * rtb_Sum2;
  }
  if (rtmIsMajorTimeStep(rtM)) {
    real_T *lastU;
    if (rtDW.TimeStampA == (rtInf)) {
      rtDW.TimeStampA = rtM->Timing.t[0];
      lastU = &rtDW.LastUAtTimeA;
    } else if (rtDW.TimeStampB == (rtInf)) {
      rtDW.TimeStampB = rtM->Timing.t[0];
      lastU = &rtDW.LastUAtTimeB;
    } else if (rtDW.TimeStampA < rtDW.TimeStampB) {
```

```
      rtDW.TimeStampA = rtM->Timing.t[0];
      lastU = &rtDW.LastUAtTimeA;
    } else {
      rtDW.TimeStampB = rtM->Timing.t[0];
      lastU = &rtDW.LastUAtTimeB;
    }
    *lastU = rtDW.Sum;
  }
if (rtmIsMajorTimeStep(rtM)) {
    rt_ertODEUpdateContinuousStates(&rtM-
>solverInfo);
    ++rtM->Timing.clockTick0;
    rtM->Timing.t[0] = rtsiGetSolverStopTime(&rtM-
>solverInfo);
    {
```

```
      rtM->Timing.clockTick1++;

    }

  }

}

void PID_Controller_derivatives(void)

{

  XDot *_rtXdot;

  _rtXdot = ((XDot *) rtM->derivs);

  _rtXdot->Plant_CSTATE[0] = 0.0;

  _rtXdot->Plant_CSTATE[0] += -20.0 *
rtX.Plant_CSTATE[0];

  _rtXdot->Plant_CSTATE[1] = 0.0;

  _rtXdot->Plant_CSTATE[0] += -30.0 *
rtX.Plant_CSTATE[1];

  _rtXdot->Plant_CSTATE[2] = 0.0;
```

```
  _rtXdot->Plant_CSTATE[0] += -0.0 *
rtX.Plant_CSTATE[2];

  _rtXdot->Plant_CSTATE[1] += rtX.Plant_CSTATE[0];

  _rtXdot->Plant_CSTATE[2] += rtX.Plant_CSTATE[1];

  _rtXdot->Plant_CSTATE[0] += rtDW.Saturation;

  _rtXdot->Integrator_CSTATE = rtDW.Sum;

  _rtXdot->Plant1_CSTATE[0] = 0.0;

  _rtXdot->Plant1_CSTATE[0] += -20.0 *
rtX.Plant1_CSTATE[0];

  _rtXdot->Plant1_CSTATE[1] = 0.0;

  _rtXdot->Plant1_CSTATE[0] += -30.0 *
rtX.Plant1_CSTATE[1];

  _rtXdot->Plant1_CSTATE[2] = 0.0;

  _rtXdot->Plant1_CSTATE[0] += -0.0 *
rtX.Plant1_CSTATE[2];

  _rtXdot->Plant1_CSTATE[1] += rtX.Plant1_CSTATE[0];
```

```
  _rtXdot->Plant1_CSTATE[2] += rtX.Plant1_CSTATE[1];
  _rtXdot->Plant1_CSTATE[0] += rtDW.Saturation_b;
  _rtXdot->Filter_CSTATE = rtDW.FilterCoefficient;
  _rtXdot->Integrator_CSTATE_j = rtDW.IntegralGain;
}
void PID_Controller_initialize(void)
{
  rt_InitInfAndNaN(sizeof(real_T));
  {
    rtsiSetSimTimeStepPtr(&rtM->solverInfo, &rtM->Timing.simTimeStep);
    rtsiSetTPtr(&rtM->solverInfo, &rtmGetTPtr(rtM));
    rtsiSetStepSizePtr(&rtM->solverInfo, &rtM->Timing.stepSize0);
    rtsiSetdXPtr(&rtM->solverInfo, &rtM->derivs);
```

```
    rtsiSetContStatesPtr(&rtM->solverInfo, (real_T
**) &rtM->contStates);

    rtsiSetNumContStatesPtr(&rtM->solverInfo, &rtM-
>Sizes.numContStates);

    rtsiSetNumPeriodicContStatesPtr(&rtM->solverInfo,

      &rtM->Sizes.numPeriodicContStates);

    rtsiSetPeriodicContStateIndicesPtr(&rtM-
>solverInfo,

      &rtM->periodicContStateIndices);

    rtsiSetPeriodicContStateRangesPtr(&rtM-
>solverInfo,

      &rtM->periodicContStateRanges);

    rtsiSetErrorStatusPtr(&rtM->solverInfo,
(&rtmGetErrorStatus(rtM)));

    rtsiSetRTModelPtr(&rtM->solverInfo, rtM);

  }

  rtsiSetSimTimeStep(&rtM->solverInfo,
MAJOR_TIME_STEP);
```

```
  rtM->intgData.y = rtM->odeY;

  rtM->intgData.f[0] = rtM->odeF[0];

  rtM->intgData.f[1] = rtM->odeF[1];

  rtM->intgData.f[2] = rtM->odeF[2];

  rtM->contStates = ((X *) &rtX);

  rtsiSetSolverData(&rtM->solverInfo, (void *)&rtM-
>intgData);

  rtsiSetSolverName(&rtM->solverInfo,"ode3");

  rtmSetTPtr(rtM, &rtM->Timing.tArray[0]);

  rtM->Timing.stepSize0 = 1.0;

  rtDW.TimeStampA = (rtInf);

  rtDW.TimeStampB = (rtInf);

  rtX.Integrator_CSTATE = 0.0;

  rtX.Plant_CSTATE[0] = 0.0;
```

```
  rtX.Plant1_CSTATE[0] = 0.0;

  rtX.Plant_CSTATE[1] = 0.0;

  rtX.Plant1_CSTATE[1] = 0.0;

  rtX.Plant_CSTATE[2] = 0.0;

  rtX.Plant1_CSTATE[2] = 0.0;

  rtX.Filter_CSTATE = 0.0;

  rtX.Integrator_CSTATE_j = 0.0;

}
```

APPENDIX B

CODES FOR FLOW SIMULATION USING PID FOR PRESSURE VARATION DUE TO FRICTIONAL FORCE

```
function [pLYsds, pLaVslip, pLaGc, Dcfr, Cpas, Vas,
pLaGyr, pLaf, Gmorp]...

    = fcn(VKmr, Lads, Lays, Laqr,  Vgp, Vls, tt,
Laqr, Gya,  km)


SN=210e6; VN = 11e3; IN = SN/VN; ZB = VN/IN; PN =
120e6; wn=314; K = 6288; L= 50;  MN = SN/wn; M=PN/wn;


rfr = 0.001; rdr = 0.02; rqr = 0.02; rs=0.0013;

Xlqr = 0.11;   Xdcdr = 0.052; µlqr = 0.072;

Xls= 0.105;  Xmq = 2.044; Xmg=Xmq;


Xq = Xls+Xmq; Xq=Xls+Xmd; XF=Xlfr+Xmd; XD=Xmr+gmdr;
XQ=Xmq+dclqr;


ttq=ttr; P=4; al=2*pi/3; wb=314; H =
(1/2)*(2/P)^2*J*wb^2/SN;
```

```
CP=[XQ Xud Xqd; Xld XD Xqd; Xld Xvd XF];

MQ=[Xq Xml; Xuq XK];

LAD=[Lads; Ladr; Laf];

LAQ=[Laqs; Laqr];


ID=inv(MD)*LAD;
IQ=inv(MQ)*LAQ;


Ids=ID(1); Idr=ID(2); Ifr=ID(3);

Iqs=IQ(1); Iqr=IQ(2);


TM = 2/3*([cos(ttr) cos(ttr-al) cos(ttr-2*al);...

               -sin(ttr) -sin(ttr-al) -sin(ttr-
2*al);...

               1/2   1/2  1/2]);


Iabc = inv(TM)*([Ids; Iqs; 0]);     Ias = Iabc(1);

Vabc=inv(TM)*([Vds; Vqs; 0]);       Vas=Vabc(1);

pLads = Vds - rs*Ids + wm*Laqs;

pLaqs = Vqs - rs*Iqs - wm*Lads;


pLadr = -rdr*Idr;

pLaqr = -rqr*Iqr;
```

```
pLaf = Vfr - rfr*Ifr;


Tor=-(Iqs*Lads - Ids*Laqs);
```

APPENDIX C

SIMULATION OF VARAITIONS IN TEMPERATURE AND PRESSURE USIGN PID AND DCS CONTROLLERS

```
function [yfr, Vds, Cqs] = fcn(Vfr, kfr, cp)
% This block supports an embeddable subset of the
MATLAB language.
% See the help menu for details.


rgc = 0.0011; rfgm = 0.002; rdr = 0.03; rqr = 0.04;
Qlf = 0.12;  gldr = 0.062; qlkr = 0.052;
Gmls= 0.135; Gkm = 2.033;         Gmq=Gmd;


GF=Gmd+Glf;
Vslip=2; al=2*pi/3;


KmIpr=(VfCp-dfr*lfω)/(KmCp+Kmlfg);
Vgm=LCYgr*KmYl;
```

```
VDc = cp*(Lgm)*Kmμ;
```

APPENDIX D

A Close Real Time Setup for Flow Rate Simulation

S/N	VARIABLES/PARAMETERS	VALUES
1	Diameter of the pipe	½ inch
2	Velocity	90.01 Meters/Minutes
3	Flow Rate	200M^3/Hour
4	Length of the pipe	150 Km
5	Connecting Hose Diameter	5.3 inches = 6 inches

6	Control Valve size 3/4	18,000PSI (1240 Bar)