# ANALYSIS AND DESIGN OF HEAT ENERGY CONTROL SYSTEM

**Thesis**

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**Degree Programme in Industrial Management**

**Engineering and International Business**

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## Abstract

As technology progresses, many kinds of control systems are being developed using the concept of control theory to keep pace with modern day application requirements, ranging from simple to sophisticated types of control system. Control systems can be found in different practical application such as biological systems, robotic systems, space applications, home appliances and so many more.

The thesis has been carried out to analyze the fundamental theory of control systems and its main elements including the common classification of control systems and to discuss the various kinds of control mode that are used to make a system behave in a manner desired and support the discussion with practical examples.

A heat energy close-loop control system was designed and built using the concept of control system theory to assist in the selection of the best control mode to conduct an experiment that will help achieve a desired setpoint of heat transfer from hot water to the cold water.

A control system was built to help measure and regulate the flow of hot and cold water and temperature of both waters.

After that, the data collected from the experiment was used to draw a graph on how much heat energy generated between the cold and hot water.

Finally, the coefficient of heat energy transfer between cold and hot water was found.

Keywords
ccontrol, closed loop, open loop, valve, actuator, sensor, control modes, heat exchanger, heat transfer

Confidentiality
Public

## ACKNOWLEGDEMENTS

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# DEDICATION

I dedicate my thesis work to almighty God, He alone is my rock and my salvation, He is my fortress and with him I will never be shaken. I also dedicate to my lovely niece, Akua Serwaa Baffour Awuah. You are more than a niece to me, you inspire me with your presence and am so proud to have you as my niece.

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DEDICATION

ABSTRACT

# 1 INTRODUCTION

Today, the concepts of control systems have become a topic which is constantly changing in order to meet and keep pace with modern day application requirements. Practically, these systems are used by mankind to boost his capabilities, to compensate for his physical limitations, relieve him of routine tasks and to save money.

The law of nature is such that everything that is known in the universe is controlled and the extent of control varies from one parameter to another. [1]

Take for example, human eyes as the sensor which can see incoming object and quickly communicate to the brain, which is the controller, to change the body direction from the incoming object, thus our body is a form of control system.

Control system has become an integral part of our day to day activities such as industrial process, modern industrializations and home appliances. The concept of control system is very vital in controlling the speed of automobile to a desirable speed limit or to keep the aircraft to autopilot so that the pilot should not continue to operate the controls to maintain the desired heading and altitude. In autopilot mode, the pilot is free to perform other tasks. That helps to reduce the crew number and operating cost.

Control systems are also found in a number of practical applications such as chemical plants, refineries, traffic control, robotics, manufacturing, power systems and space application just to mention a few, all for the benefit of our everyday life.

Therefore, it is very important as an engineer to get acquainted with the analysis and method of designing a control system.

This thesis emphasizes the fundamental concept of control systems and design, the analysis of heat energy transfers, common classification of control systems and support with a number of practical examples.

## 1.2 Significance of Control Systems

For a company to stay in business and compete with other competitors both locally and internationally, a company must place more emphasis on quality and efficiency of their products. For these reasons more companies are now finding ways to developed and improve control systems in order to be able to achieve best possible productivity at all stages.

Some of the significance of control systems in a company are as follows:

- Enhanced product quality
- Waste minimization
- Environmental protection
- Greater throughput for a given installed capacity
- Greater yield
- Deferring of costly plant upgrades, and
- Higher safety margins.

## 1.3 Needs for the Project

This project will highlight the importance of control system theory and its basic applications especially how to measure fluid (water) temperature, to maintain levels to a desired setpoint and to measure the flow rate for a given period of time with the help of the control system.

The design of energy control system will effectively assist in determining the heat energy produce by the system and the coefficient of heat energy transfer from a hot water to cold water. Heat transfer will be explained in a later chapter of this thesis.

Finally, students who are interested in control systems engineering will find this thesis book useful as it will help explain the basics of control system theory.

## 1.4 Objectives of the Project

The objectives of this thesis project are as follows:

- To design and analyze the concept of a control systems.
- To measure water levels and temperature using control theory.
- To determine heat energy produce by the system based on the data gathered.
- To determine and calculate the coefficient of a heat energy transfer.

## 1.5 Research Methodology

Quantitative and qualitative research methods were used to gather information and data during the writing phase of the thesis.

The quantitative research method here focuses on the numerical data which was collected from the experiment conducted at Savonia University of Applied Sciences' physics laboratory in Varkaus, Finland.
Due to limited resources and time constrain, qualitative research method was also used to gather additional information and data for the project such as literature reviews, observation, case-study, internet sources and interviewing experts who are in the field of control engineering.

At the end of the research work, the data collected and the findings were collated and analyzed to draw conclusion for the research work.

## 1.6 Scope and Limitations

The scope and limitation of this project was to focus on the design of a control system that is able to control and maintain the stability of heat energy transfer in a heat exchanger. This was done by analyzing a control model which is capable of stabilizing the system.

On the other hand, time frame and resources were other limitations that the project faced and because of that secondary research materials were used to gather important information for the project.

# 2 BASICS OF CONTROL SYSTEM

## 2.1 Control System

To have an in-depth understanding of the meaning of control systems, we should first understand the meaning of a *system* then we can relate it with control systems.

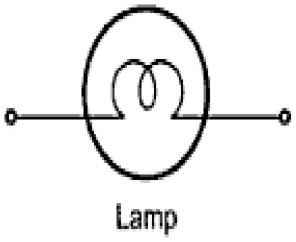
What is a System?

A system is a combination or arrangement of different physical components which act together as an entire unit to achieve certain objectives. [2]

One typical example of a physical system is a lamp which consists of glass and filament. Whereas, a control can be explained as a means to regulate, to direct or command a system, thus a control system is an arrangement of different physical elements connected in such a manner so as to regulate, direct or command it or some other systems. [2]

In a more simple way, a control system is an interconnection of components forming a systems configuration that will provide desired systems responds. [3]

Typical example of physical system and control system are illustrated below in figure 1.1 and 1. 2.



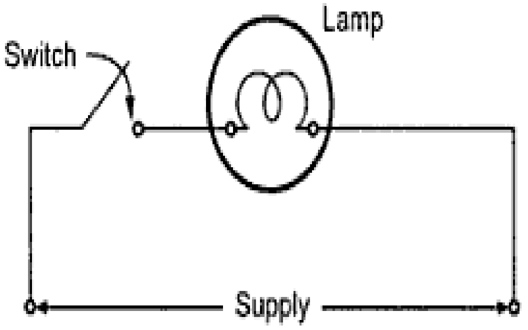


**Figure 1.1. Physical system [2]**

**Figure 1.2. Control system [2]**

## 2.2 Classification of Control Systems

The classifications of control systems are very broad and the way in which they are classified depends mainly on certain factors such as the following,

1. The method of analysis and design, as linear & non-linear systems.
2. The type of the signal, as time varying, time invariant, continues data, discrete system etc.
3. The type of system component, as electro mechanical, hydraulic, thermal, pneumatic control system etc.

Nevertheless, in a more simple way most engineers tend to group the above mentioned classification of control system into *open* and *closed-loop* control systems which will be discussed later in this thesis.

Below are brief explanations of some of the most common types of control system use today.

### 2.2.1 Linear and Non-Linear Control Systems

#### I. Linear Control System

A control system is said to be linear if it obeys the principle of superposition and homogeneity.

In the case of superposition principles, the response to several inputs can be achieved as one input is considered at a time and the individual results are added algebraically. [2]

Mathematically the superposition principle of linear control system can be expressed as;

$$F(x+y) = f(x) + f(y) \tag{1.1}$$

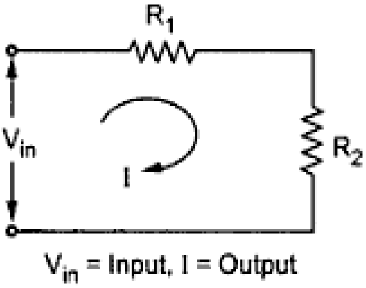
Where *x* and *y* are domains of function *F*.

The homogenous property of the linear system state that, for any *x* belonging the domain function of *F* is expressed as;

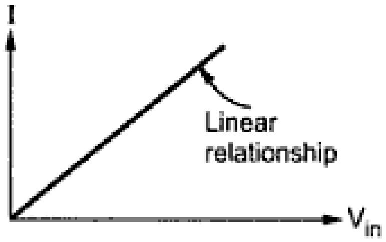
$$F\ (\alpha x) = \alpha f\ (x) \tag{1.2}$$

Where, $\alpha$ = constant.

The figure below shows a resistive network that describes a linear system in Figure 2.1 and the linear relationship existing between input and output in Figure 2.2



**2.1. Linear system [2]**



**2.2. Response of system [2]**

### II. Non-Linear System

Non-linear systems are not proportional and small changes do not cause small response.

Non-linear systems do not obey the principles of superposition and the equations describing the systems are non-linear in nature. [2]

The function $f(x) = x^2$ is non-linear, because

$$f(x_1+x_2) = (x_1+x_2)^2 \neq (x_1)^2 +( x2)^2 \tag{2.1}$$

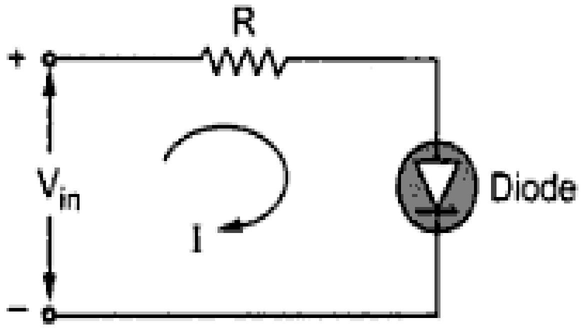
Therefore,

$$f(\alpha\ x) = (\alpha\ x)^2 \neq \ \alpha\ x^2 \tag{2.2}$$

where $\alpha$ = Constant.

In general, non-linear systems are not proportional and a small change does not affect the response, thus the system is unpredictable yet completely deterministic.

The figures 3.1 and 3.2 on the next page show the voltage-current equation of a diode which is exponential and non-linear hence the system is example of nonlinear system.



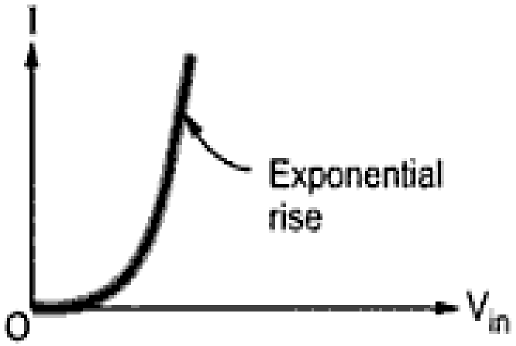


**Figure 3.1. System [2]**

**Figure 3.2. Response [2]**

Based on Figure 3.2 it can be realized that when $V_{in}$ increases up to a certain value, current remains almost zero. This means that voltage-current are exponentially related to each other which is non-linear function.

### 2.2.2 Time Varying and Invariant Systems

A system is said to be time varying if the parameters of the systems are affected by time. In this case, the system is not dependent whether or not the input and output functions with time. [2]

For example, a space vehicle’s mass can decrease with time as it leaves earth. However, if the parameters are unaffected by the time then the system is said to be time invariant, i.e. the parameters of system are independent of time.

The Figures 4.1 and 4.2 illustrate a distinction between time varying and invariant system.

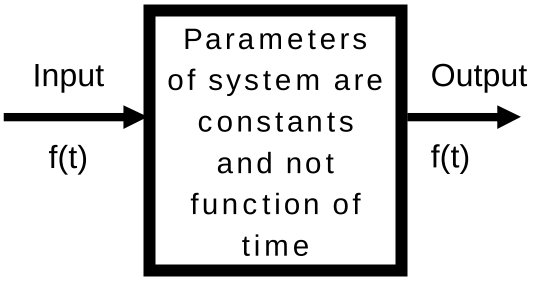


Figure 4.1. Time invariant system [2]

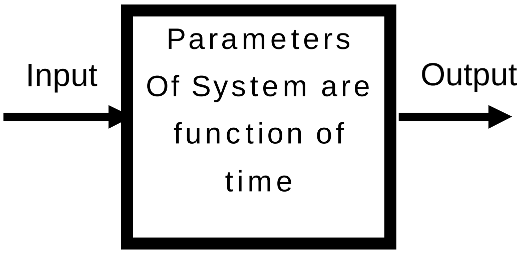
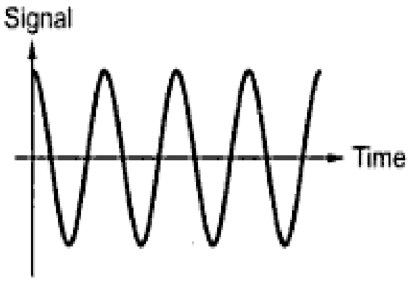


Figure 4.2. Time variant system [2]

### 2.2.3 Continuous and Discrete time control system

In continuous time control system all system variables are the functions of a continuous time (t). An example is the speed control of a D.C. motor using techno-generator feedback. Nevertheless, the discrete time system control variables can be known at certain intervals. For example, computer and micro process depends on discrete signals.

Continues time system uses the signals as illustrated in figure 5.1 which are continuous with time whilst discrete system uses signals as illustrated in the figure 5.2.



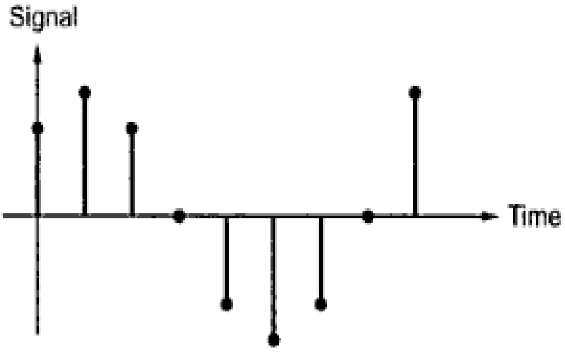


Figure 5.1. Continuous signal [2]

Figure 5.2. Discrete signal [2]

### 2.2.4 Open-Loop System

As it was stated previously, some engineers tend to classify control systems into open-loop and closed-loop system.

An open-loop system is one in which the control input to the system is not affected in any way by the output of the system [4]. (I.e. the system input is entirely independent of the output of the system). This kind of system is simple in construction, less expensive and easy to maintain.

A good example of an open-loop system is an automatic toaster where the control is provided by a timer which indicates the total length of time at which the bread will be toasted. Here, the output of the toasting system is the bread that is being brownish. In this case, the toaster timer is set and the user will only wait for the bread and examines it.

Another real application of open-loop control systems is water heating system which is illustrated in Figure 6 below.

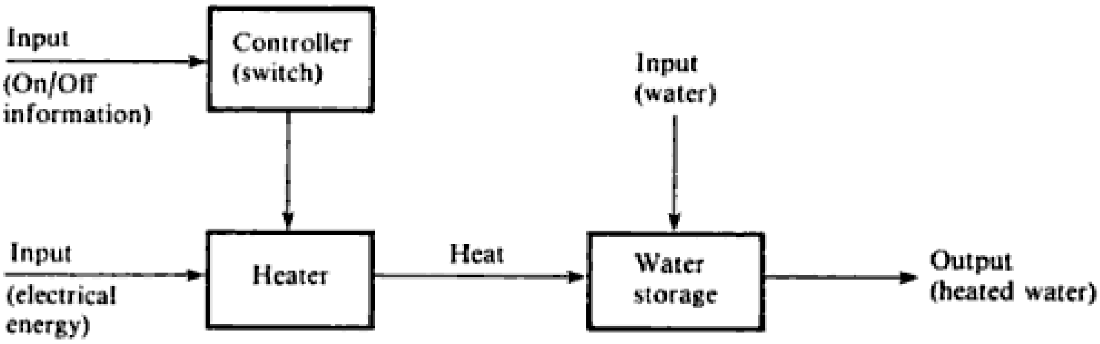


**Figure 6. Water heating device [4]**

As can be seen in the diagram, the controller is working as on/off switch which regulates the amount of heat. The heater transfers the heat to the water in the water storage, thus the input (electrical energy) has no effect on the output of the system.

However, the open-loop system has some draw-backs such as the system is inaccurate and unreliable because the accuracy of the system is totally dependent on the accurate pre-calibration of the controller, the system also gives inaccurate results when there are variation in external environment (i.e. the system cannot sense environmental changes) and also the system cannot sense internal disturbances in the systems after the controller stage. [2]

### 2.2.5 Closed-Loop System

To overcome all the draw-backs of the open-loop control system, closed-loop system can be selected. In closed-loop systems, the actual input is affected by the system output. This system uses *feedback* from the output to compare with the reference input to generate the error signal for a desirable controlling action to be taken.

The reference input is directly proportional to the desired value of the system output and if the value is proportional to the time it is called *setpoint input*.

Moreover, the close-loop control system can be referred to as *negative feedback* system. This is because always the system output is subtracted from the reference input.

Thus, error signal = reference input-system output.

#### Some Significance of a Closed-Loop System

- For computing the value of the output.
- For measuring the value with the desired value and to generate an error signal.
- A controller which changes the output of a process in a way relies on the error signal.

The controller for that reason must be able to control enough power to produce the desired output.

### Advantages of Closed-Loop System

Closed-loop systems have enormous advantages over the open-loop such as the;

1. Faster response to an input signal
2. More accurate control of plant under disturbances and internal variation
3. Less sensitive to changes in calibration errors (i.e. recalibration is not necessary)
4. The output is compared with the reference input and the difference is used as a means of control
5. It is used to make unstable open loop systems stable by means of feedback mechanism

Apart from these advantages of closed-loop system, the system has its own disadvantages such as it always requires the use of a sensors, comparison element and correction unit and that makes the system more expensive as compared to the open-loop system. The system is more complex in design and difficult to build and also it tends to be more unstable as the controller gains increases beyond certain limit.

Closed-loop system can broadly be illustrated by a block diagram model as shown in Figure 7.

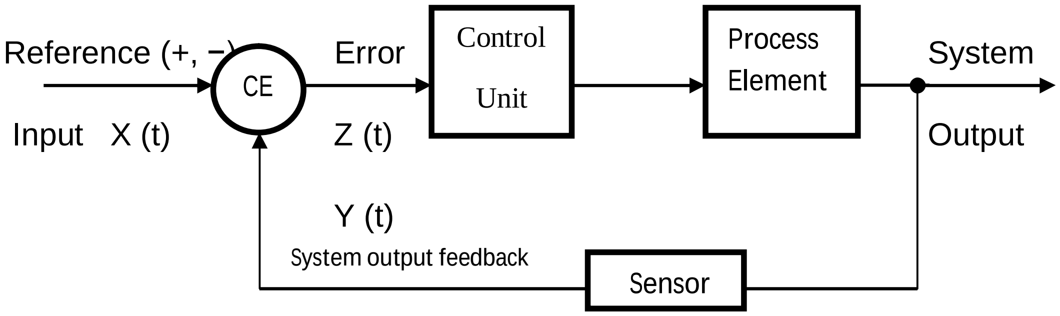


**Figure 7. Elements of a Closed Loop Control System**

Figure 7 shows the real example of a closed-loop system which could be used to control room temperature. The basic elements include a comparison element (*CE*), a control unit, a process element or an object to be controlled and a sensor.

In this case, the actual room temperature or the system output signal $y(t)$ is feedback to the sensor where the comparison element compared with the reference input signal $x(t)$ or the desired temperature of the room and the temperature of the room is measured and control according to the error signal $z(t)$ generated. Therefore,

$$Z(t) = x(t) - y(t). \qquad (3)$$

Table 1. Comparison of Open-Loop and Closed-Loop Control System [2]

| SR. No | Open Loop | Closed Loop |
|---|---|---|
| 1. | Any change in output has no effect on the input (i.e. feedback does not exists). | Changes in output, affects the input which is possible by the use of feedback |
| 2. | Output measurement is not required for operation. | Output measurement is necessary. |
| 3. | Feedback element is absent. | Feedback element is present. |
| 4. | Error detector is absent. | Error detector is necessary. |
| 5. | It is inaccurate and unreliable. | Highly accurate and reliable |
| 6. | Highly sensitive to the disturbances. | Less sensitive to the disturbances. |
| 7. | Highly sensitive to the environmental changes. | Less sensitive to the environmental changes. |
| 8. | Bandwidth is small. | Bandwidth is large |
| 9. | Simple to construct and cheap. | Complicated to design and hence costly. |
| 10. | Generally stable in nature. | Stability is the major consideration while designing. |
| 11. | Highly affected by nonlinearities. | Reduced effect of nonlinearities. |

# 3 PROCESS INSTRUMENTATION

## 3.1 Measurement System

The application of a measurement system plays a very vital role not only in science but in all branches of engineering, and almost all human activities. For any given quantity or parameters, a measurement system compares the measured values to the unknown values. Some of the functions of a measurement system are to obtain data from the process and to inspect or test the obtained data and also act as a source of information for a control system about the actual value of the controlled parameter of the process. Take for example, a feedback control system; in order to control any variables accurately or precisely the systems must be incorporated with one or more measuring instrument.

This measuring instrument gives the user numerical values corresponding to the variables being measured. The instrument consists of different kinds of elements which are used to determine a measurement of a particular process. These elements are *sensors* which measure the physical quantity and convert it into signal, the *signal processor* which converts the output of a sensor into suitable condition for display or onward transfer to the display element. In the case of a thermocouple, the signal processor is the amplifier which makes the electromotive force (e.m.f) big enough to display on the display element.

The final element of a measuring instrument is the *display element* which measures the values from the signal processor that are suitable to be displayed for an observer to notice. It could be the pointer moving across the scale of display element or the change of numbers in the display element monitor. Figure 8 shows a block diagram of measurement system elements.

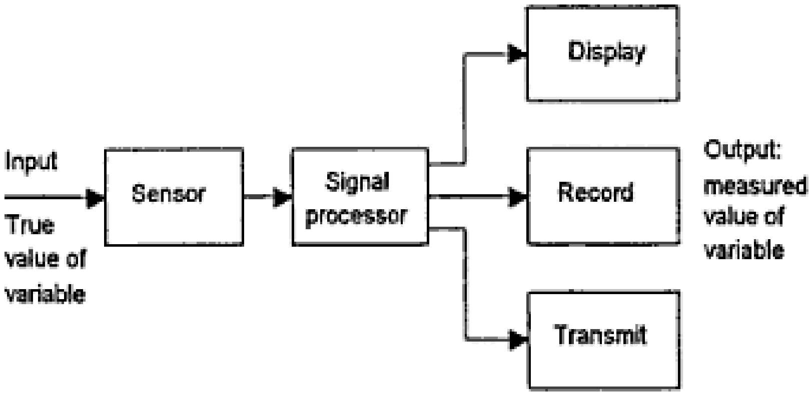


**Figure 8. Measurement system elements [5]**

### 3.2 Basic Performance Terms of Measurement Systems

The quality of measurement systems depends on various outside and inside factors and it can be described using 10 main characteristics [6].

1. The accuracy of a device – it is the extent to which the reading the device display might be wrong. Accuracy is often quoted as a percentage of the full-scale deflection of the device.

   *For example: the accuracy of the voltmeter between 0-5 V is quoted ±5%. It means that when the voltmeter reading was 3V, actual voltage is between 2,75 ÷ 3,25 V.*

2. Error of the measurement – is the difference between the result of the measurement and true value of the measured quantity.

   *For example: if the speed of the car is 140 km/h and a speed parameter shows 139 km/h, the error is +1km/h; if the device shows 141 km/h, the error is –1km/h.*

3. Precision – the closeness of the agreement occurring between obtained results when the parameter is measured several times under the same conditions.

4. Reliability – the probability that a device will operate to an agreed level of performance under the conditions specified for its use.

   *For example, it is mentioned that accuracy of device is ±1% when device is used at* $t^0=20^0C$*, then the reliable device will give this level of the accuracy in this temperature conditions.*

5. Sensitivity – S = Change in device scale reading/ Change in measurement parameter.
6. Resolution – the smallest change of measured parameter that produces an observable change in the reading of the device.
7. Lag – the response of the device until it indicates the actual value of the measured parameter.
8. Range – the limits between readings which can be made, using the device (range of thermometer $-50^0C$ - $+50^0C$).
9. Dead space – the range of values of measured parameter for which device gives no reading.
10. Zero drift – the change of zero reading of a device with time (for example. per month, per half a year, etc.) [6].

## 3.3 Sensors (Transducer)

A sensor, as already mentioned, is the first element of measurement system. It takes information about actual value of the measured (controlled) parameter and transforms the value of measured parameter into the signal, which is more suitable for a measurement (or control) systems.

A sensor or transducer can be define as a device which is capable of being actuated by energizing input from one or more transmission media and in turn generating a related signals to one or more transmission systems.

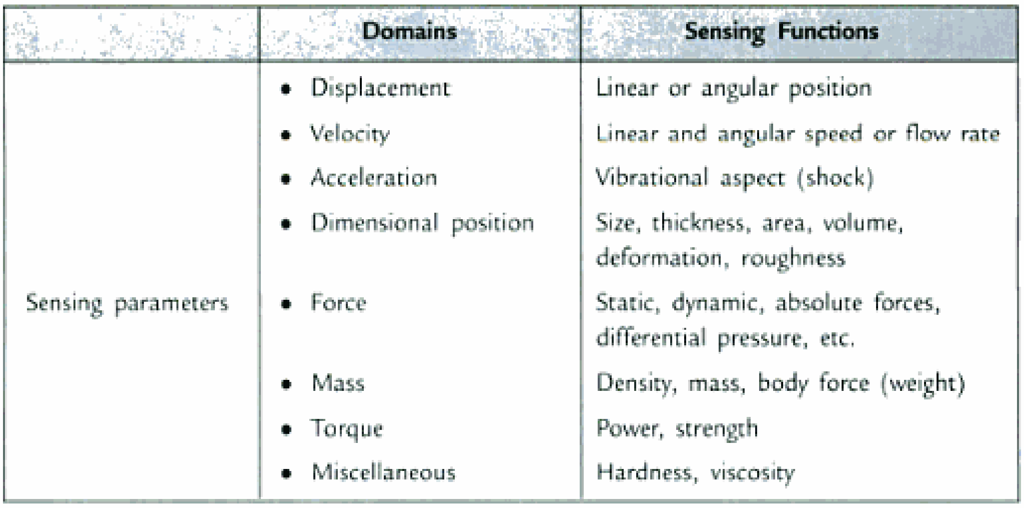
However, it is sometimes confusing when sensors and transducers are still interchangeable when it comes to the field of measurement but the common distinction between them is that an element that senses a variation in input energy to produce a variation in another or same form is called a *sensor* whereas a *transducer* uses transduction principles to convert a specified measured into useable output. Thus, a property cut piezoelectric crystal can be called a sensor whereas it becomes a transducer with appropriate electrode and input or output mechanism attached to it. [7]

Furthermore, transducers can be subdivided into two types, namely *passive* and *active* transducers. The passive transducer is an element whose energy is supplied entirely or not entirely by its input signal whereas on the other hand active transducer has a secondary source of power which supplies most of the output power while the input signal supplies only an insignificant portion.

### 3.3.1 Classification of Sensor (Transducer)

Sensors are classified based on functions, performance and output. The parameters of the function are gradually mechanical in nature such as displacement, velocity, acceleration, force, torque, dimensions, mass etc. For mechanical function the sensors can be divided into mechanical type, electrical type or electronic type decided by the electrical and the principles governing the functioning of the sensor [8]. Table 2.1 shows classification of sensor by function.

**Table 2.1. Classification by function [8]**

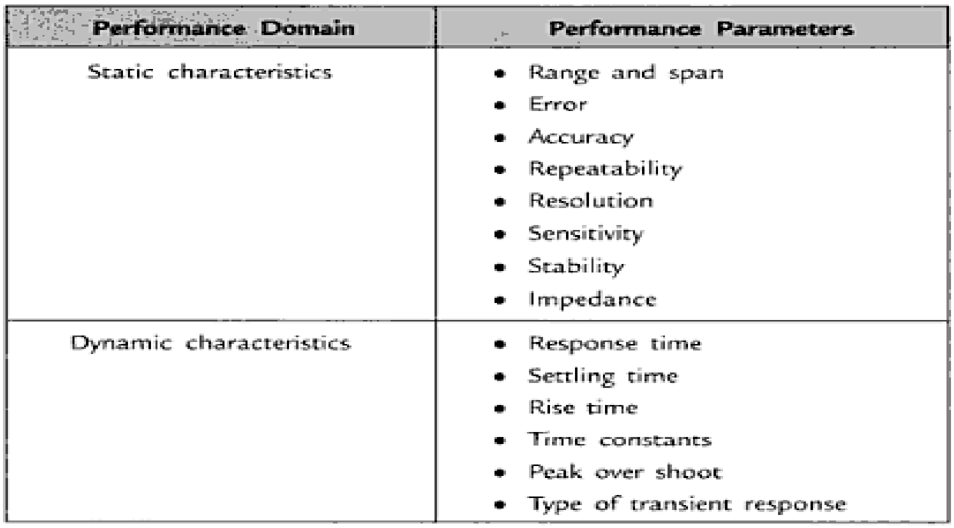


| | Domains | Sensing Functions |
|---|---|---|
| Sensing parameters | • Displacement | Linear or angular position |
| | • Velocity | Linear and angular speed or flow rate |
| | • Acceleration | Vibrational aspect (shock) |
| | • Dimensional position | Size, thickness, area, volume, deformation, roughness |
| | • Force | Static, dynamic, absolute forces, differential pressure, etc. |
| | • Mass | Density, mass, body force (weight) |
| | • Torque | Power, strength |
| | • Miscellaneous | Hardness, viscosity |

Again, the classification of sensors based on performance is characterized by static and dynamic performance which plays a major role in choosing a type of sensor for a particular parameter. The accuracy, range, error, stability and sensibility are some of the static performance parameters which are taken into consideration when it comes to the selection of the right sensor. [8]

On the other hand, response time, rise time, time constant and setting time are some of the main dynamic characteristics normally considered when choosing a sensor to measure a parameter.

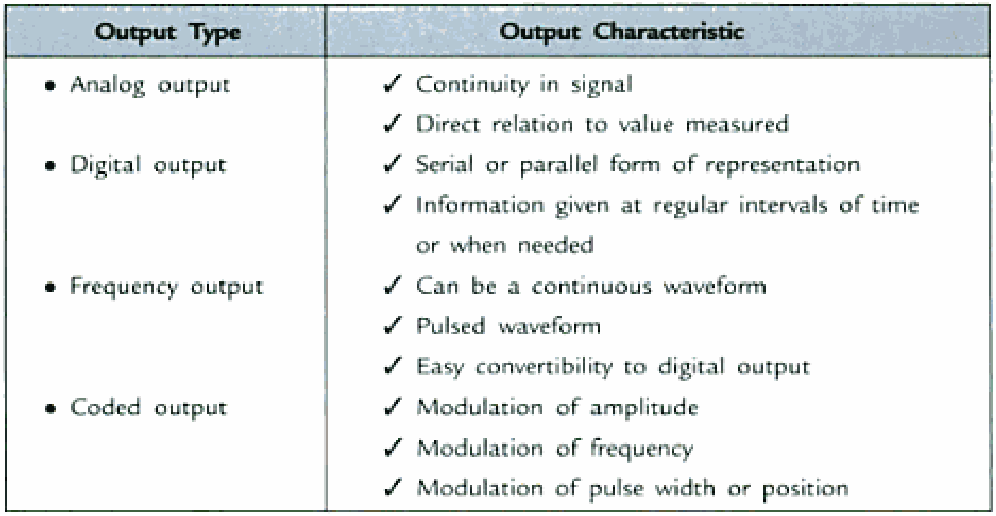
**Table 2.2. The classification of sensor by performance [8]**



| Performance Domain | Performance Parameters |
|---|---|
| Static characteristics | • Range and span<br>• Error<br>• Accuracy<br>• Repeatability<br>• Resolution<br>• Sensitivity<br>• Stability<br>• Impedance |
| Dynamic characteristics | • Response time<br>• Settling time<br>• Rise time<br>• Time constants<br>• Peak over shoot<br>• Type of transient response |

Finally, classification of sensors based on output indicates how the measured data are displayed. The output can be analog data, digital data, coded data or the frequency waveform.

**Table 2.3 shows the classification of sensor by output [8]**



| Output Type | Output Characteristic |
|---|---|
| • Analog output | ✓ Continuity in signal<br>✓ Direct relation to value measured |
| • Digital output | ✓ Serial or parallel form of representation<br>✓ Information given at regular intervals of time or when needed |
| • Frequency output | ✓ Can be a continuous waveform<br>✓ Pulsed waveform<br>✓ Easy convertibility to digital output |
| • Coded output | ✓ Modulation of amplitude<br>✓ Modulation of frequency<br>✓ Modulation of pulse width or position |

## 3.4 Measurement of Parameters

### 3.4.1 Measurement of Temperature

Temperature is simply defined as the degree of coldness or hotness of a body or an environment measured on a definite scale.

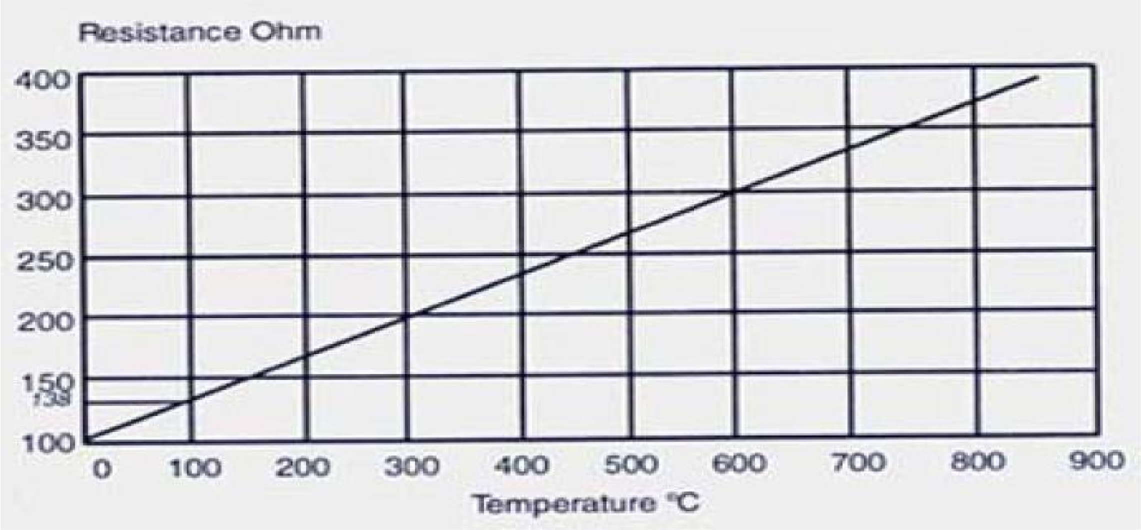
It is frequently measured and controlled in most industrial application. Chemical reaction in industrial processes and desired quality of a product solely depends on accurately measured and controlled temperature. However, temperature measured plays a very important role when it comes to thermodynamic and transfer of heat operation such as automobile engines and steam raising. Further, temperature is also important in the production of glass, plastic and other materials such as steel and aluminum alloys.

This parameter could be measured by various types of sensors, which are working under different physical principles. Usually temperature is measured using ordinary glass thermometers, but the same thermometer cannot be used as a sensor in the control systems. For temperature measurement, a sensor must be a device which is capable to change temperature into signals that are suitable for onward transfer to further elements of control system. There are two main types of devices often used as sensors for the temperature measurement in control systems. These are resistance thermometer and thermocouple sensor.

#### I. Resistance thermometer

The electrical conductivity of metal depends on the movement of electrons through its crystal lattices. Due to thermal excitation, the electrical resistance of a conductor varies according to its temperature and forms the basic principles of resistance thermometry [9].

The resistance in a substance is directly proportional to its temperature so the increase in temperature of a substance gives a corresponding increase in resistance. Graph 1 shows a graph of Resistance/Temperature characteristics.



**Graph 1. Resistance/Temperature characteristics [9]**

The relationship between the temperature and the electrical resistance is normally non-linear and its mathematically a polynomial order which is written as,

$$R(t) = R_o (1+A \cdot t + B \cdot t^2 + C \cdot t^3 + \ldots\ldots\ldots\ldots) \quad (8)$$

where $R_o$ is the nominal resistance at a specified temperature and the number of higher order terms is considered as a function of the required accuracy of the measurement. The co-efficiency of A, B and C etc. depends on the conductor material and basically define the temperature-resistance relationship. [9]

When the resistance thermometer is used as a sensor it can measure temperatures up to approximately from -200 to 900°C depending on the material used.

The most commonly used materials for resistance thermometer are platinum, copper and nickel. Figure 9 shows the construction of a platinum resistance thermometer (PRT).

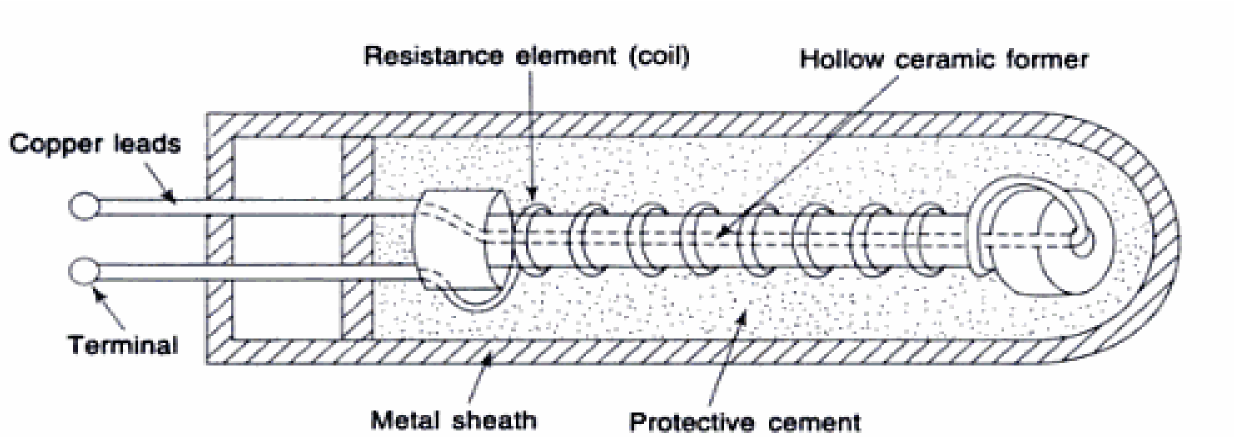


**Figure 9. Construction of a platinum resistance thermometer (PRT) [10]**

A resistance thermometer has one big advantage when used as a measurement system. It does not require any signal conditioner (SC) therefore the output signal (I.e. resistance) passed straight through the display element called Wheatstone bridge for the user to read from it.

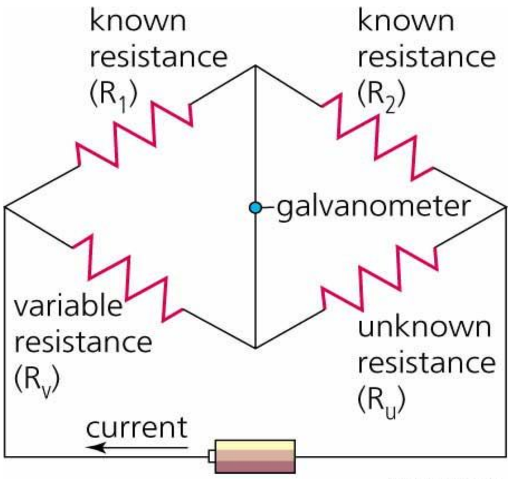


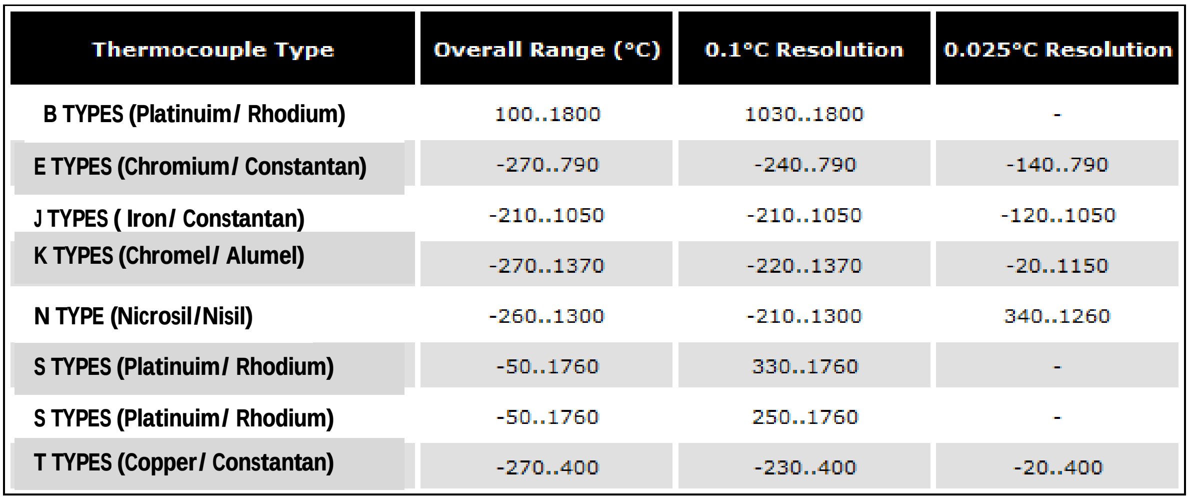
**Figure 10. Wheatstone Bridge Circuit**

## II. Thermocouple Sensor

Thermocouples are another form of a temperature sensor used for measurement and control a system and it is also used to change heat energy into electric energy. It is less expensive, interchangeable and has standard connectors thus it is the most commonly used temperature sensor and it can measure a temperature up to 1800°C or more depending on the materials used. Thermocouples are made up of two dissimilar metals joined together at one end. The difference in temperature between the junction produce electromotive force that is used as a signal to determine the temperature on the display element. The main problem or limitation is the accuracy. The system error of less than 1°C can be difficult to achieve. [11]

Table 3. Shows the various range of temperatures for each thermocouple type.

**Table 3. Range of Temperatures for Each Thermocouple Type [11]**



| Thermocouple Type | Overall Range (°C) | 0.1°C Resolution | 0.025°C Resolution |
|---|---|---|---|
| B TYPES (Platinuim/ Rhodium) | 100..1800 | 1030..1800 | - |
| E TYPES (Chromium/ Constantan) | -270..790 | -240..790 | -140..790 |
| J TYPES ( Iron/ Constantan) | -210..1050 | -210..1050 | -120..1050 |
| K TYPES (Chromel/ Alumel) | -270..1370 | -220..1370 | -20..1150 |
| N TYPE (Nicrosil/Nisil) | -260..1300 | -210..1300 | 340..1260 |
| S TYPES (Platinuim/ Rhodium) | -50..1760 | 330..1760 | - |
| S TYPES (Platinuim/ Rhodium) | -50..1760 | 250..1760 | - |
| T TYPES (Copper/ Constantan) | -270..400 | -230..400 | -20..400 |

A practical example of a K type of thermocouple is shown in Figure 11.

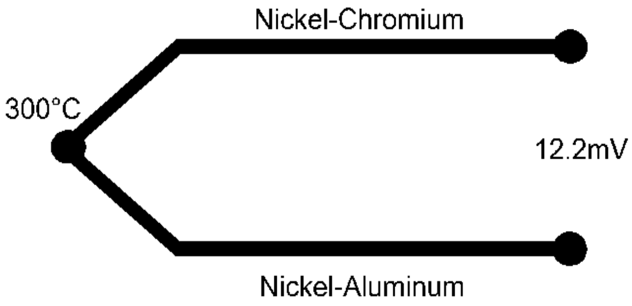


**Figure 11. K type of thermocouple [12]**

### 3.4.2 Measurement of Pressure

Pressure is defined as force per unite area. The method in which pressure can be measured sometimes depends on the kind of pressure it exists, whether it is a moderate pressure, low or high pressure and whether the pressure is static or dynamic.

In the case of moderate or static pressure, an instrument such as barometer and manometer can be used to measure the value of the pressure whereas in the case of low pressure (vacuum), gauge pressure such as McLeod, Ionisation and Knudsen gauge pressure can be used to measure the pressure. A pressure value above 1000 atm is considered as a high pressure. High pressure is measured by high-wire pressure transducers.

Dynamic pressure measurement from a reciprocating compressor or an engine can be easily converted into displacement for measurement by elastic element and coupled with electromechanical transducer. Further, the accuracy of measurement is influenced by the elastic element, the electromechanical transducer and the fluid used. These elastic elements used as pressure transducers or sensing elements are categorized as Burdon tube, Diaphragm and Bellows.

However, the most widely used sensing element is the bourdon tube and it is the basis of most mechanical pressure gauge and it is used as electrical transducers for measuring the output of displacement with potentiometer, differential transformers, etc. Figure 12 shows the constructional view of a C-type of bourdon tube which is one of the most commonly known pressure sensor in use.

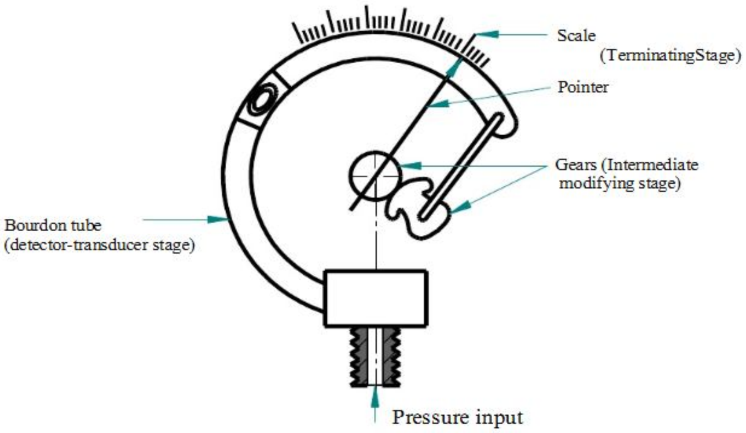


Figure 12. Pressure Gauge Using C-Type of Bourdon Tube [13]

The bourdon tube pressure gauge is made up of a C-shape metal tube. One of the ends of the tube is sealed, whereas the other end is connected to the source of pressure that is being measured and it is mounted in such a way that it cannot move. When the pressure is applied inside the tube, the sealed end of the tube strengthens out which causes small amount of movement of the sealed end of the tube. This is amplified by gears which cause the pointer to move and the direct reading is taken from the scale.

### 3.4.3 Measurement of Flow

A flow means simply the amount of fluid that flows or streams at a given time but fluid flow measurement is the movement of smooth particles that fill and match to the piping in an uninterrupted stream to determine the amount flowing.

According to Osborne Reynolds experiment conducted in 1880s, flow can be classified into three categorize namely laminar, transitional and turbulence. He built a tank and filled it with water and connected a glass tube to the tank as shown below in figure 13.

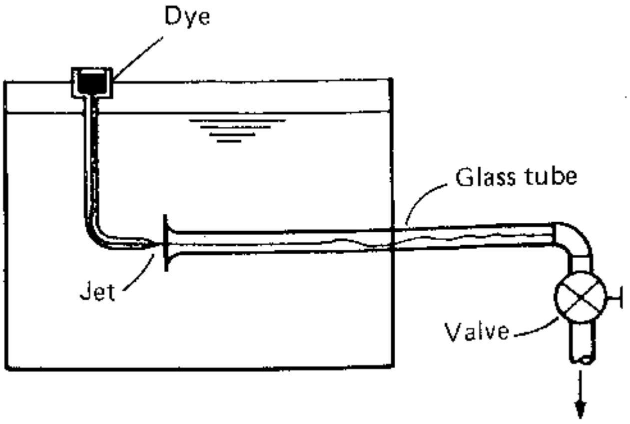
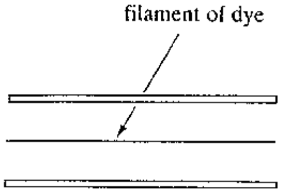
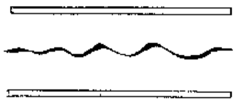


**Figure 13. Water tank [14]**

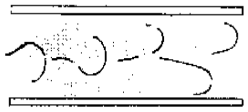
After that he injected a dye through a needle and the outcome was experienced as the following [14].



Laminar (viscous)



Transitional



Turbulent

These expressions means that

Laminar flow (Re) < 2000

Transitional flow 2000<Re<4000

Turbulence flow Re > 4000

This can be interpreted that if the value is less than 2000 then the flow is laminar, if greater than 4000 then turbulent and in between these then in the transition zone [14].

These values was achieved based on Reynolds equations as

$$Re = \rho DV/\mu \qquad (9)$$

Where Re: Reynolds number, a dimensionless number;

$\rho$ = density of the fluid

D = diameter of the passage way

V = velocity of the fluid

M = viscosity of the fluid

Further, Reynolds numbers are dimensionless due to the fact that all units are the same so when they are multiplied together all units cancel out.

Reynolds numbers are directly proportional to velocity and inversely proportional to viscosity.

Real-life example for Reynolds numbers are:

- Blood flow in brain ~ 100
- Blood flow in aorta ~ 1000
- Typical pitch in major league baseball ~ 200 000
- Blue whale swimming ~ 300 000 000

Mathematically, we can determine the glycerin flowing in a pipe at a temperature of 25°C as with the values below;

Pipe diameter (D) = 160 mm = 0.16 m

Velocity (V) = 4.7 m/s

Density ($\rho$) = 1249 $kg/m^3$

Viscosity ($\mu$) = 0.89 pa.s(kg/m.s)

By using Reynolds equation above

Re = 4.7x0.16x1249/0.98 = 958

Since Re < 2000 therefore flow is laminar. However, if the Re value is > 4000 the flow will be turbulent or if the value is in between 2000<Re;< 4000 then the flow is transitional flow.

## Flow meters

Flow meters are devices used to measure the quantity of fluid and the flow rate of a liquid. There are four basic categories of devices used, namely:

1. Differential pressure (DP)
2. Positive displacement (PD)
3. Velocity and
4. True mass.

Differential pressure flow meters obtain the flow rate by measuring the pressure differential and extracting the square root (I.e. Difference in pressure between fluid at rest and in motion depends on the fluid velocity). Some commonly used DP meters include cone-type devices, elbow tap meters, flow nozzles, laminar flow elements, orifice plates, Pitot tubes, rotameters, target meters, variable area flow meters, and Venturi tubes [15]. Figure 14.1 below shows example of venturi tube used to measure flow.

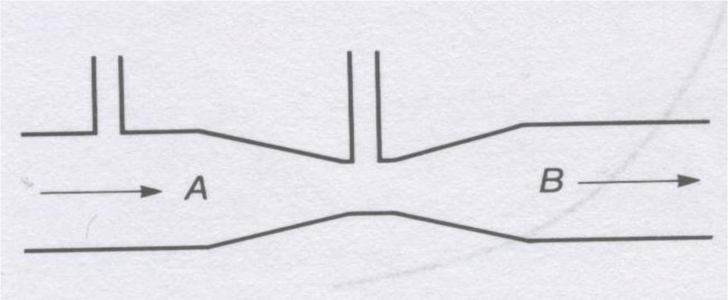


**Figure 14.1. Venturi Tube [6]**

Positive displacement (PD) flow meters divide the media into specific increments which can be counted by mechanical or electronic techniques. Examples of PD meters include nutating disc devices, oval gear meters, and piston-based designs**.**

Velocity flow meters operate linearly with respect to the flow rate. Because there is no square-root relationship, their range is greater than DP devices. Choices for velocity meters include electromagnetic meters, paddlewheels, sonar-based devices, turbine meters, ultrasonic meters and vortex or shedding meters [15].
Example of turbine meter is shown in figure 14.2 where the rate at which a turbine in a fluid rotates depends on the flow rate of the fluid.

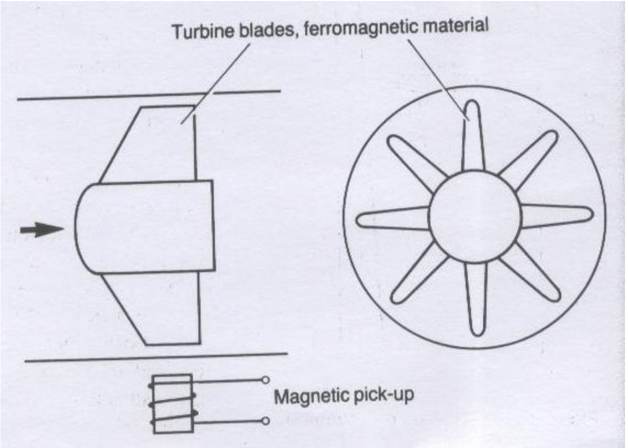


**Figure 14.2. Turbine Meter [6]**

True mass flow meters are used to directly measure the mass rate of flow. These flow meters include both thermal meters and Coriolis meters. [15]

### 3.4.4 Measurement of Level

Measurement of a level especially of liquid is very essential in both domestic and industrial environment. Often, a float system is used to measure liquid level in a container. The float system consists of a float connected to a magnet that moves in casing with reed switch. As the float rises or falls, it turns the reed switch on and off. The reed switch is also connected to a circuit that sends the voltage signal to a signal conditioner for onward transfer to the display element. Figure 15 shows the example of a float system for level measurement.

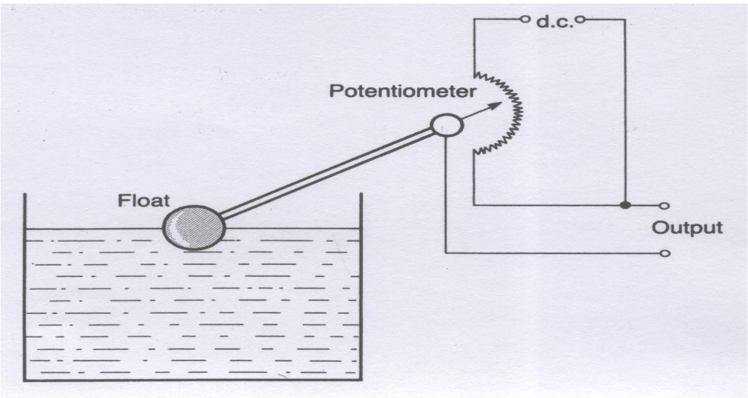
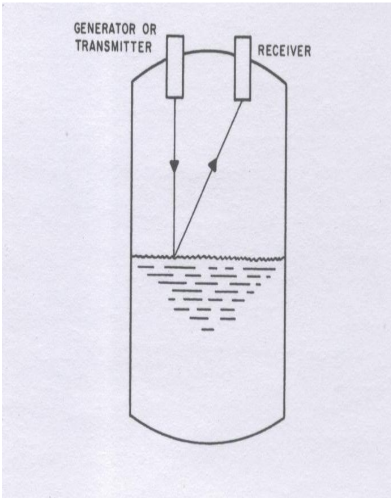


**Figure 15. Level Measurements [6]**

Moreover, there are other sensor such as ultrasonic sensor, optical sensor and inductive sensor which are used to measure the level of liquid in a container or vessel. Ultrasonic sensors consist of ultrasonic transmitters and receivers. The transmitter transmits the ultrasonic signal towards the surface of the liquid and ultrasonic signal reflects from the surface to the receiver. The time of ultrasonic signal transmission towards the surface of the liquid and back to the receiver is proportional to the level. The ultrasonic sensor can be either contact or non-contact. Figure 16.1 illustrates a non-contact ultrasonic sensor while figure 16.2 shows an optical sensor which measures the liquid level in a container when liquid reaches minimum or maximum level.



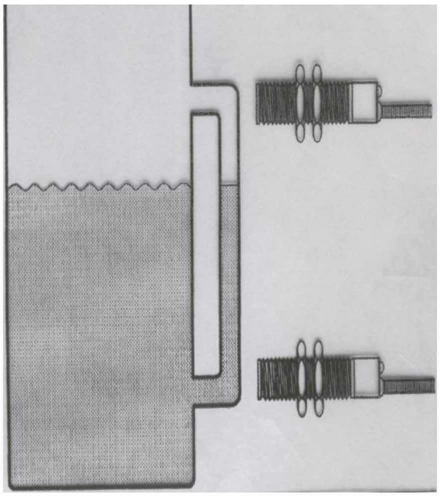


**Figure 16.1. Non-contact ultrasonic sensor [6]** **Figure 16.2. Optical sensor [6]**

### 3.5 Control Valves

A control valve plays a vital role when it comes to design of a control system especially controlling a flow. Controlling flow can sometimes be very cumbersome due to the various systems, type of fluid, pressure and the construction of passages in which the fluid flows in. This flow must be controlled and the medium at which it is controlled is done by a device called *valve*.

A valve is a mechanical device which regulates either the flow or the pressure of the fluid. Its function can be stopping or starting the flow, controlling flow rate, diverting flow, preventing back flow, controlling pressure, or relieving pressure. Basically, the valve is an assembly of a body with connection to the pipe and some elements with a sealing functionality that are operated by an actuator. [16]

There are so many different types of valve design which have been developed and these designs are based on the use of each valve type during operation.

Table 4 shows some of the commonly known valves types.

**Table 4. Examples of Valve Types**

1. Globe Valves
2. Ball Valve
3. Diaphragm Valves
4. Safety/relief Valves
5. Gate Valves
6. Needle Valves
7. Pinch Valves
8. Reducing Valves
9. Plug Valves
10. Butterfly Valves
11. Check Valves

### 3.5.1. Gate Valve

A gate valve or sluice valve as it is sometimes known, is a linear motion valve used to start or stop a fluid flow. However, it does not regulate or throttle the flow. The name gate is derived from the appearance of the disk in the flow stream. [17] Figure 14 shows a gate valve.

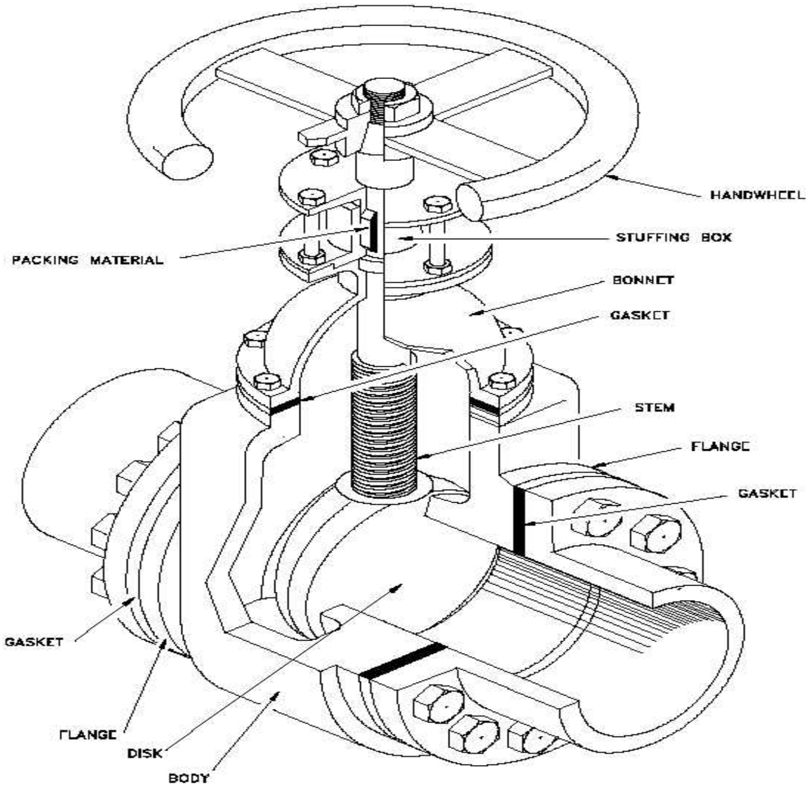


**Figure 16. Gate Valve [17]**

The turning moment of the handle in anticlockwise direction opens the disc of the gate valve and enlarges the flow stream. This allows the fluid to flow thus reducing the internal pressure in the fluid.

When the valve is fully closed, a disk-to-seal ring contact surface exists for 360°, and good sealing is provided. With the proper mating of a disk to the seal ring, very little or no leakage occurs across the disk when the gate valve is closed. [17]

Gate valves are typically constructed from materials such as cast iron, cast carbon steel, gun metal, stainless steel, alloy steels, and forged steels.

### 3.5.2 Relief Valves

The relief valve (RV), sometimes known as safety valve, is a type of valve used to control or limit the pressure in a system or vessel which can be built up by a process upset, instrument or equipment failure, or fire. Figure 17 illustrates the main components that form a pressure relief valve.

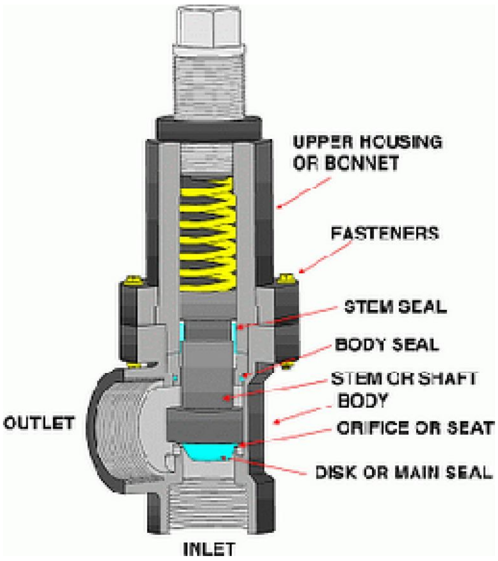


Figure 17. Pressure relief valve [18]

The pressure valve consists of a shaft which is spring loaded and it moves laterally in a body or its vessel. The shaft has some seals at its edges to prevent any leakages from occurring when the valve is closed. The relief valve is set to a predetermined position to prevent excess pressure from damaging the vessel and other components when the pressure exceeds its limit.

When the pressure in the pressure vessel exceeds its predetermine limit the excess fluid pressure diverted through the pressure relief valve at the inlet side and forces the shaft against the spring loaded. This opens the outlet side of the relief valve and the fluid pressure passes out to save the system from any kind of damage that may occur as a result of excess fluid pressure.

When the fluid pressure drops below the predetermined set pressure, the spring forces the shaft to a closed position and this avoids the fluid from continuously diverting through the relief valve thus maintaining the pressure in the system to its required level.

### 3.5.3 Diaphragm Valves

Diaphragm valves or membrane valves, sometimes called linear motion valves, are used to start, regulate, and stop fluid flow. The name is derived from its flexible disk, which mates with a seat located in the open area at the top of the valve body to form a seal. [18]

The valves are constructed from either plastic or steel and are particularly suited for the handling of corrosive fluids, fibrous slurries, radioactive fluids, or other fluids that must remain free from contamination.

Diaphragm valves are categorized into two namely ‘weir’ type (also known as saddle valve) and ‘straight way’ type (also known as seat type). The difference between them is that weir type has its port parallel to each other whilst the straightway type has input and output port situated to each other at an angle of 90°. The most common type of valve used in process applications is the weir type.

Figures 18.1 and 18.2 below illustrate ‘’straight way’’ and ‘’weir’’ diaphragm valve respectively.

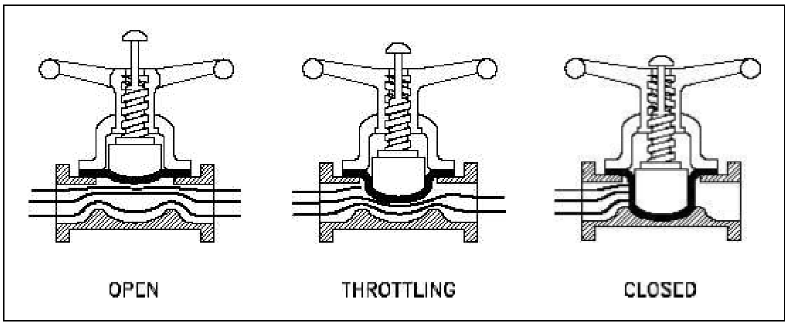


Figure 18.1. ‘’straight way’’ diaphragm valve [17]

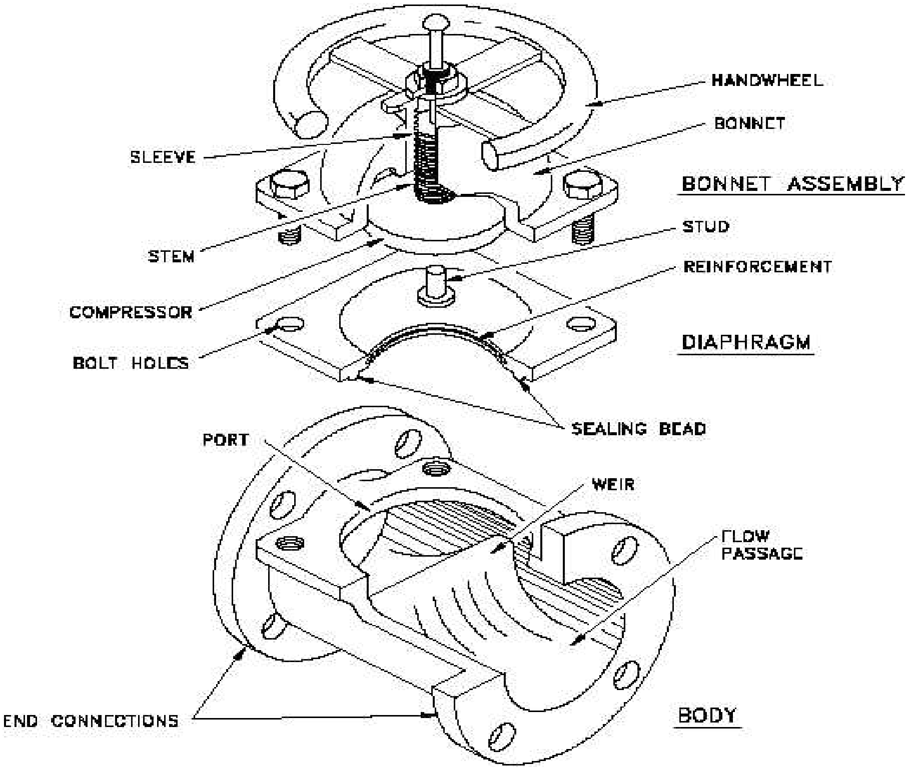


Figure 19. Weir Diaphragm Valve [17]

## 3.6 ACTUATORS

A valve cannot control a process alone. It needs an operator to regulate the process variables or control actions. These control actions or process can be manually operated by a valve or special devices are required to move the valve to-and-fro when implementing the process or control remotely and automatically. This device is called an *actuator*.

As automation is widely used in many applications, work that demand physical human strength, are now replaced by different kinds of machines and their automatic controls. The used of valve actuators is to provide the interface between the control intelligence and the physical movement of the valve has increased.

Most working environments are very hazardous to human beings. Therefore, work safety and environmental protection is very paramount in these areas and for these reasons different kinds of valve actuators are now employed to replace the human activities in this hazardous area to improve work safety and environmental protection by minimizing any form of risks and accidents.

According to Chris Warnett (Rotark Control Inc.) definition of an actuator, actuator is a device that produces linear or rotary motion from a source of power under the action of a source of control. In other words, actuators take fluid, electric or some other source of power and convert it through a motor, piston or other device to perform work (i.e. the actuator basically performs work by opening and closing the valve to ensure correct control of the process fluid). [19]

To do this, the actuator must be sufficiently powerful to produce positive, accurate and rapid response to a control signal and be able to return the valve to a suitable predetermined position in the event of signal failure. It is therefore important to specify the correct type and size of actuator in order to meet the demands of accuracy, reliability and economy. [20]

### 3.6.1. Actuator Types

There are so many types of actuators that transfer energy from one form to another form.

These actuators are categorized in three groups:

1. Electromechanical actuators
2. Fluid power actuators
3. Active material based actuators

#### 1. Electromechanical Actuator

Electromechanical actuators are used to efficiently convert electrical energy into mechanical energy. Magnetism is the basis of their principles of operation. They use permanent magnets, electromagnetic and exploit the phenomenon in order to produce the actuation.

Electromechanical actuators are DC, AC and Stepper motors. DC motors requires a direct current or voltage source as the input signal while the AC motors require an alternating current or voltage source, on the other hand Stepper motors are used as another type of electromechanical actuating device which also rely on the principles of magnetism.

The fundamental principle of operation of such actuators come from the fact that when an electric current is passed through a group of wire loops placed in a magnetic field, the loops rotate, and the rotating motion is transmitted to a shaft, providing useful mechanical work [21].

Figure 20 below shows the schematic of a permanent magnetic DC motor (sometimes known as rotating machine) which consists of a stator housing the magnetic poles and a rotor with wire winding or loops placed between the magnetic poles. When electric current is passed through the winding wire on the rotor it generates electromagnetism. The two fields of the magnet (the permanent magnetic and the electromagnetic fields) result in a torque which tends to rotate the rotor to produce work.

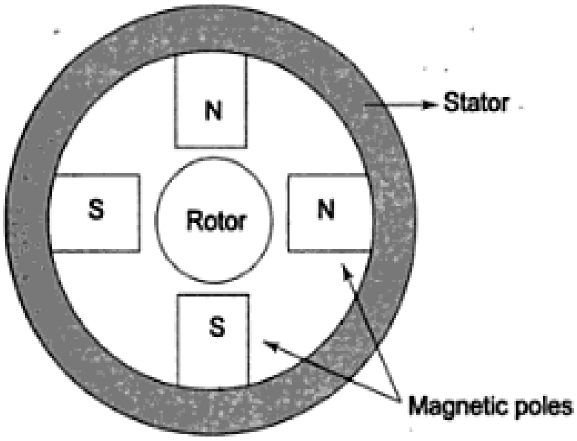


**Figure 20. DC Motor [21]**

The DC motor has a disadvantage of inability to produce accurate positioning control and also high torque at low speed and upon this reason alternative solution is the introduction of Stepper motor which is able to provide a precision angle motion in any direction and it is widely used in digital control technology. [21]

Some application areas of electromechanical actuators are as follows:

1. Automatic Door
2. Electric Drill
3. Starter Motor
4. Vacuum Cleaner
5. Mixer
6. Fan

## 2. Fluid Power Actuator

Fluid power actuators are simply actuators that transmit energy through fluid under pressure. The fluid can be either hydraulic (such as oil or water) or pneumatic (such as compressed air or inert gases). The most widely known pneumatic actuator is the pneumatic diaphragm actuator which can be either direct acting or reverse acting or double acting actuator. The most commonly used hydraulic actuator is the piston and a vane type.

## I. Pneumatic Actuator

Pneumatic actuators are widely used to control processes that require quick and precise response as they do not need large amount of motive force. The pneumatic actuators have the following advantages:

1. Very strong for its size and weight
2. Simple, inexpensive construction
3. No material compatibility problem with dry air
4. They are the most economical solution for thrust of up to 10 KN
5. The actuators can be set to return the valve to predetermined position, open or closed, in the event of supply air failure [20].

Figure 21 shows a typical pneumatic diaphragm actuator which is spring loaded on top of the diaphragm, actuator stem couple with the valve and an inlet valve that allows air into the confine chamber below the diaphragm.

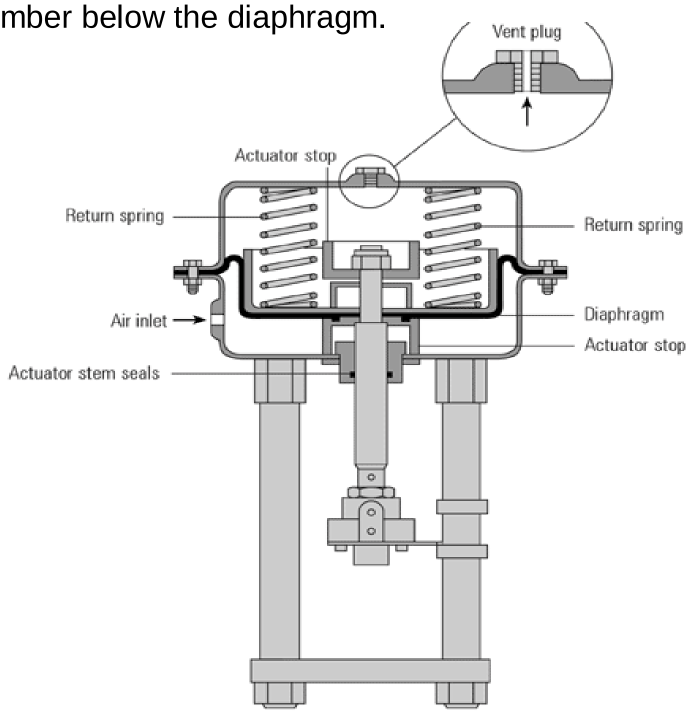


Figure 21. Pneumatic Diaphragm Actuator [22]

Moreover, when the compressed air passes through the air inlet into the confine chamber, it exerts thrust on the diaphragm to move it and the actuator stem couples with the valve against the spring loading thus moving the valve to open or close.

## II. Hydraulic Actuators

As it has been already mentioned, the pneumatic actuator can respond quickly and precisely in controlling a process and they do not need large amount of motive force. On the other hand, when large amount of a motive force is needed to operate a valve, hydraulic actuators are widely used. The hydraulic actuator comes in different forms and designs but the most commonly used is the piston type.

A typical piston-type hydraulic actuator is shown in the illustration in Figure 22 below. It consists of a cylinder, a piston, a spring, hydraulic supply and return lines, and a stem. The piston slides vertically inside the cylinder and separates the cylinder line into two chambers. The upper chamber contains the spring and the lower chamber contains hydraulic oil. The hydraulic supply and return line is connected to the lower chamber and allows hydraulic fluid to flow to and from the lower chamber of the actuator. The stem transmits the motion of the piston to a valve [23].

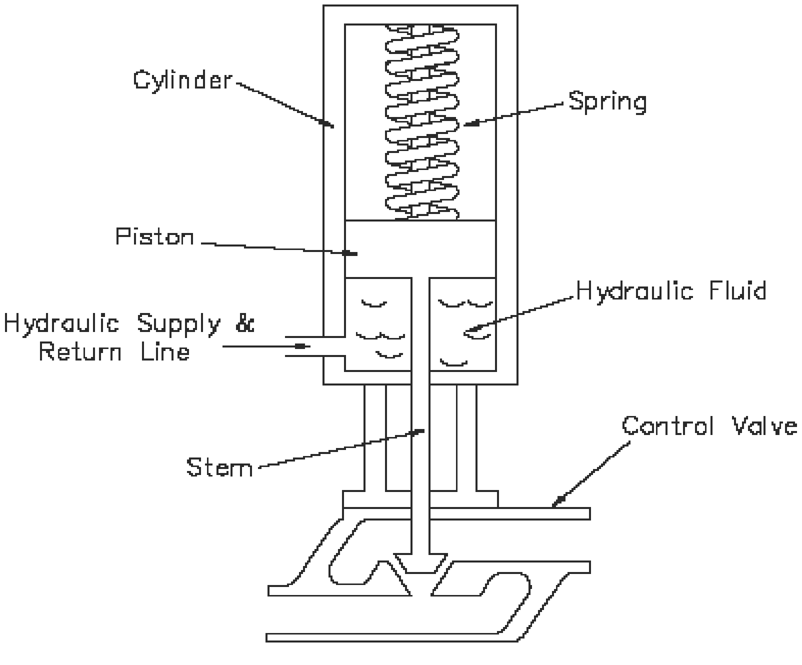


Figure 22. Hydraulic Actuator [23]

At the beginning, when there is no hydraulic fluid pressure in the cylinder, the spring exerts force on the valve to a closed position. As fluid enters the system through the lower chamber, the pressure in the chamber raises. This action of the fluid pressure act on the bottom of the piston and when the pressure is greater than the spring force, the piston begins to move upward against the spring, thus the valve begins to open.

As the hydraulic pressure increases, the valve continues to open but as soon as the hydraulic pressure is dropped or hydraulic oil is drained from the cylinder, the hydraulic force becomes less than the spring force, the piston moves downward caused by the spring force and the valve closes. By adjusting the amount of oil supplied or drained from the actuator, the valve can be positioned between fully opened and fully closed. [24]

Similarly, the principles of operation of pneumatic and hydraulic actuators are the same. Each uses some motive force to overcome the spring force to move the valve. Also, hydraulic actuators can be designed to fail-open or fail-closed to provide a fail-safe feature. [24]

# 4 PROCESS CONTROLLERS

A feedback controller which is part of control unit is designed to generate an output that causes some corrective effort to be applied to a process so as to drive a measurable process variable towards a desired value known as the setpoint. The controller uses an actuator to affect the process and a sensor to measure the results. [25]

Virtually all feedback controllers determine their output by observing the error between the setpoint and a measurement of the process variable. Errors occur when an operator changes the setpoint intentionally or when a disturbance or a load on the process changes the process variable accidentally. The controller's mission is to eliminate the error automatically. [25]

Controllers can be grouped into two types according to the process that they control. These are Continuous and Discrete processes.

1. Continuous processes are process whereby the input and output variables are uninterrupted by time. The production of chemical, plastics and fuels are some of the examples of continuous processes.
2. Discrete processes are where the sequence of operation is controlled. Robotics assembly and many manufacturing processes are examples of discrete processes.

However, there are some processes which are mixtures of continuous and discrete processes. Usually, programmable logical control (PLC) is more widely used in discrete and a mixture of processes.

## 4.1 Control Modes

The method in which the controller can react to error signals are called control mode (sometime called control action) and there are basically seven modes:

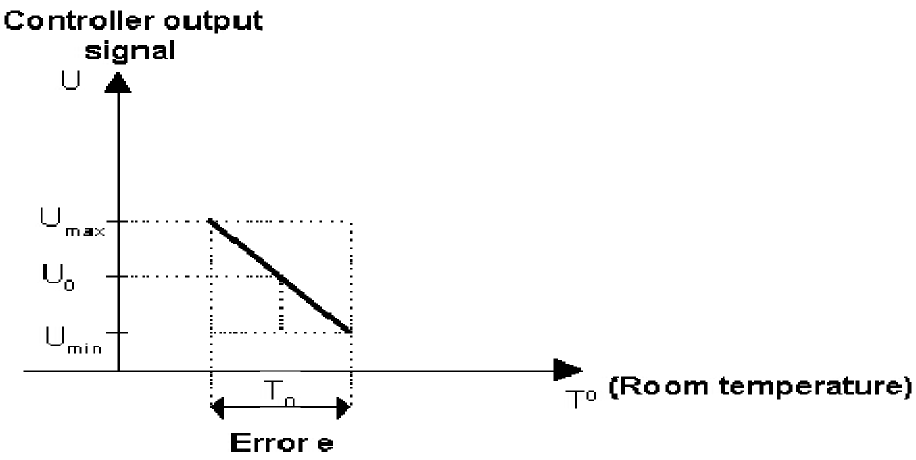
1. The two-step mode, where the controller is just a switch, (i.e. the control action is just on-off).
2. The proportional mode (P), where the controller produces a control action, which is proportional to the error of controlled parameter.
3. The derivative mode (D), where the controller produces a control action, which is proportional to the rate at which error is changing.
4. The integral mode (I), where the controller produces a control action that continues to increase as long the error persists.
5. Combination of proportional plus integral modes (PI).
6. Combination of proportional plus derivative modes (PD).
7. Combination of proportional, integral and derivative modes. (PID)

The I mode and D mode are not used as separate controllers but only in combination like PI, PD, and PID mode as mentioned above.

### 4.1.1 Proportional (P) Control Mode

If the controller is acting according to the *P* control mode, the output signal of controller is proportional to the size of error of the controlled parameter.

Let us take the example of room heating system where the room is heated by hot water in a radiator. The *P* controller receives the feedback signal about the actual temperature of the room and acts proportionally to the size of the error. The output signal from controller acts as the correction unit of the control system (valve on the hot water tubes) and the correction unit controls the amount of hot water proportionally to the room temperature deviation (error). The room heating system can be expressed graphically as shown in Graph 2.



**Graph 2. Room Heating System [6]**

In the graph $T_0$ is the set point of temperature, $U_0$ is the set point of controller output signal and e is the error.

Change in controller output from set point can be expressed mathematically as,

$\Delta u = K_p \Delta e$; where $K_p$ is constant.

The equation of $P$ controller mode can also be expressed as:

$U(t) = K_p e(t)+P_o$; $K_p = 100/PB$ (10)

where $U(t)$ = Controller output (0 →100)

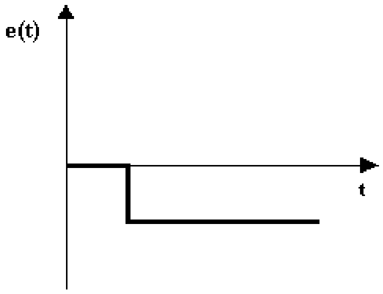
$K_p$ = Proportional Gain

PB = proportional band in percentage (i.e. the amount the input would have to change in order to cause the output to move from 0 to 100% or vice versa).

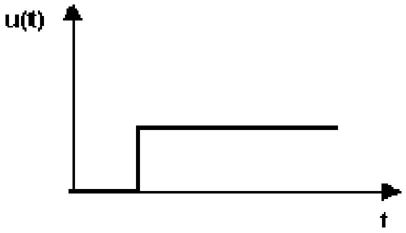
$E(t)$ = Error = measurement - setpoint (direct action)

$P_o$ = controller output without bias (sometime known as manual reset)

In addition, controller output signal $u(t)$ and error $e(t)$ like functions of time can be expressed as:



Graph 3.1 Error e (t) [6]



Graph 3.2 Output signal u (t) [6]

A real time proportional controller can be made by summing an amplifier with an inverter as shown below.

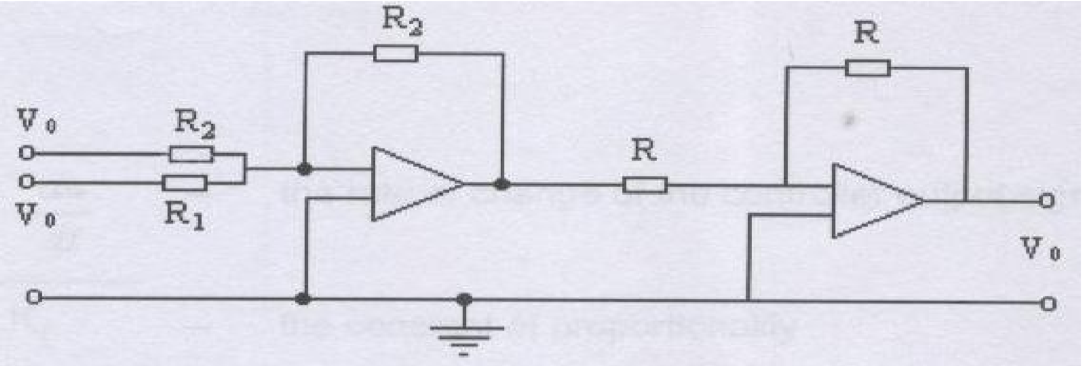


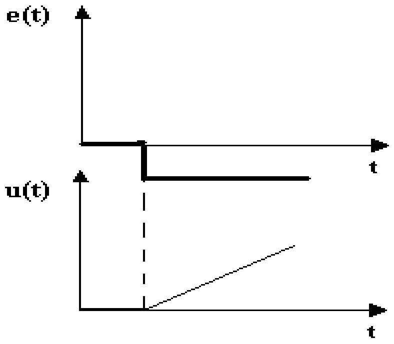
Figure 23. Amplifier circuit [6]

Proportional control mode alone will not bring the process to the setpoint unless the process is manually adjusted to the bias (or manual reset) terms of the equation. In most cases, when the operator realizes an offset in the control loop the operator corrects the offset by manually "reseting" the controller (i.e. adjusting the bias).

### 4.1.2 Integral (I) Control Mode

The integral (*I*) control mode requires no operator to “manually reset" the control loop whenever there is a load change or a disturbance. Rather, the control functions have been developed to "automatically reset" the controller by adjusting the bias term whenever there is an error. This "automatic reset" is also known as "reset" or as "integral".

*I* mode can be expressed graphically as:



**Graph 4. I mode [6]**

where, *e(t)* is error and *u(t)* is output signal of I controller.

We can express the ***I*** control mode with equation:

$$u(t) = K_i \int e\,dt$$

or

$$U\ (t) = \frac{du}{dt} = K_i e \qquad (11.1)$$

The constant of proportionality $K_i$ can be expressed as:

$$K_i = 1 + \frac{1}{Ti} \qquad (11.2)$$

where

$T_i$ – integral time (in seconds)

Integral time is very important parameter of *I* control mode. It is the time, when the correction unit (for example, the valve) moves from one limit position to another limit position.

From the previous example (room heating system), in the case of *I* control, when the error of control parameter occurs, the correction unit of the control system (valve) start to move and the change of hot water supply will be proportional to the error of room temperature.

The circuit of the integral controller consists of an operational amplifier connected as an integrator plus another operational amplifier connected as a sum shown in the figure below.

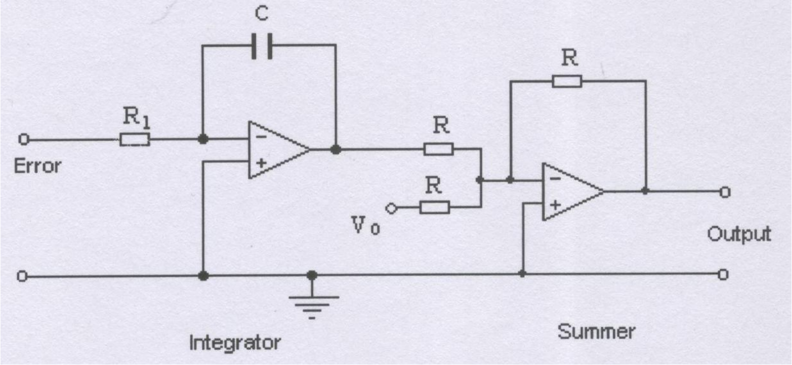


**Figure 25. Amplifier connected with Integral Controller [6]**

### 4.1.3 Derivative (D) Control Mode

Derivative (*D*) control is the control mode, where the change of controller output signal from the set point value is proportional to the rate of change of error of a controlled parameter.

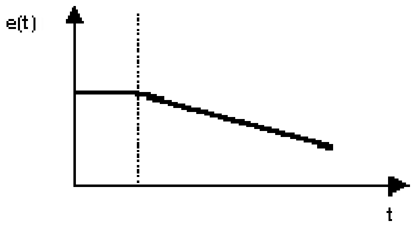
*D* control mode is expressed by the equation:

$$U(t) = K_d \frac{de}{dt} \tag{12}$$

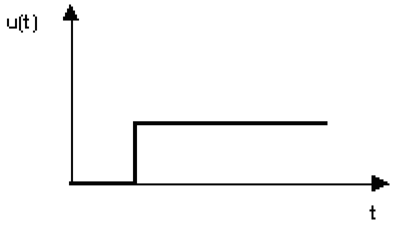
Where $K_d$ = constant of proportionality (Sometimes called “derivative time”).

$\frac{de}{dt}$ = the rate of change of the error.

Graphs 5.1 and 5.2 show the behavior of the *D* control mode which affects the output signal when the error signal changes.



**Graph 5.1 Error signal [6]**



**Graph 5.2 Output signal [6]**

In the case of *D* control, when the error signal begins to change, the large controller output signal occurs. On graph 5.2 above, the controller output signal *u(t)* is constant after when the error starts to change. *U(t)* is constant since the rate of change of the error signal is constant.

The *D* control is not usually used alone, but in combination with *P* control (PD) or in combination with P and I control together (PID).

### 4.1.4 PID Control Mode

For the best result of control, all control modes (*P, I* and *D*) must be combined together. In this case we have PID controller. The PID controller reduces the tendency for oscillations.

The equation of PID control mode:

$$U(t) = Kpe + K_i \int edt + \frac{de}{dt} \qquad (13)$$

Where *U* = control signal to the plant

E= error signal

$K_p$ = proportional gain

$K_i$ = integral gain

$K_d$ = derivative gain

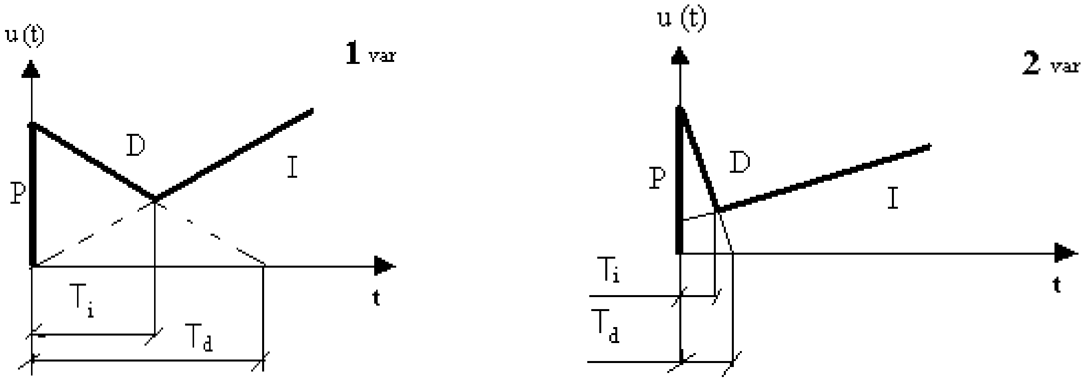
The main adjusting parameters of the PID controller are:

$K_p$ = constant of proportionality, which describes *P* component

*Ti* = integral time, which describes *I* component, (*Ki* = 1/ *Ti* )

*Td* = derivative time, which describes *D* component, (*Kd* = *Td*)

If different values of the adjusting parameters are chosen, two variations of PID graphs are obtained as shown in the following graphs.



**Graph. 6.1** **Graph. 6.2**

**Graph 6.1 and 6.2. Variation of PID control mode [6]**

From graph 6.1 it is clear that when different values are chosen to control the parameter, the derivative time ($T_d$) which describes the *D* component and the integral time which describe the *I* component overshoot but on the other hand when other values are chosen for graph 6.2 the derivative time and the integral time are shortened. That means that it is very important for the operator to know the kind of values to be chosen that best suits his operation to make the system stable at all stages.

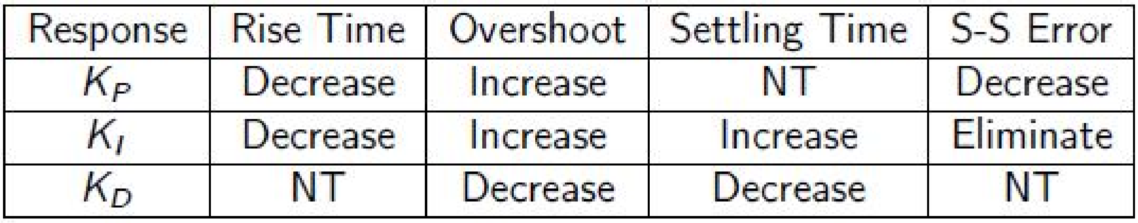
The four main characteristics of a closed-loop step responds that make the system unstable are as follows:

1. Rise Time – the time taken for the plant output to rise above 90% of the desired level for the first time.
2. Overshoot -- how much the peak level is higher than the steady state, normalized against the steady state.

3. Settle Time – the time it takes for the system to converge to its steady state.
4. Steady-state Error – the difference between the steady-state output and the desired output.

These characteristics make the system unstable and by using the *PID* control mode to control the parameters such as $K_p$, $K_i$ and $K_D$, the system will be stable. This is done by increasing each parameter.

**Table 5 . Effect of stabilizing the controller parameters [26]**



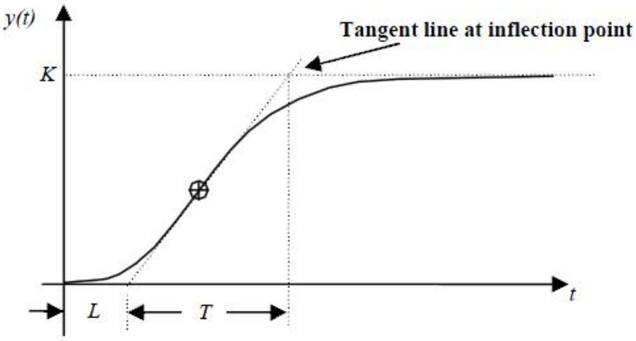
| Response | Rise Time | Overshoot | Settling Time | S-S Error |
|---|---|---|---|---|
| $K_P$ | Decrease | Increase | NT | Decrease |
| $K_I$ | Decrease | Increase | Increase | Eliminate |
| $K_D$ | NT | Decrease | Decrease | NT |

NT = No definite trend (minor change)

$K_p$ is used to decrease the rise time while the $K_D$ is used to reduce the overshoot and the setting time. $K_i$ is used to eliminate the steady-state error but in case this table did not work then the use of Ziegler Nichols' tuning method becomes necessary. [26]

## 4.2 Ziegler Nichols Tuning Method

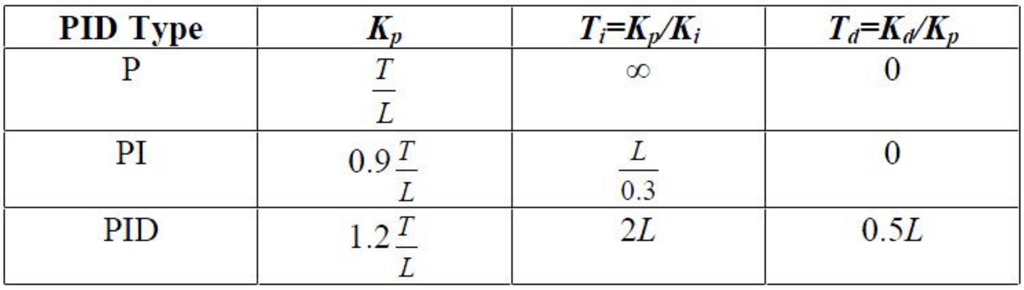
Ziegler and Nichols performed a series of experiments to determine the values of $K_p$, $K_i$ and $K_D$ based upon transient step response of a plant. The two were able to arrive with two methods which were simply named the first and second methods. However, this thesis will focus only on the first method which applied a step response and it is typical of first order system with transportation delay. The response gives an *S*-curve sometimes known as reaction curve when drawn and it is characterized by two parameters, *L* the delay time and *T* the time constant which is illustrated in Graph 7.This time is determined by drawing a tangent to the step response at its point of inflection and noting its intersection with the time axis and the steady-state value.



**Graph 7. Response Curve for Ziegler-Nichols First Method [27]**

Using the *L* and *T* parameters as explained above, $K_p$ , $K_i$ and $K_D$ can be set according to Ziegler-Nichols Model as shown in Table 6.

**Table 6. Ziegler-Nichols Model - First Method [27]**



| PID Type | $K_p$ | $T_i=K_p/K_i$ | $T_d=K_d/K_p$ |
|---|---|---|---|
| P | $\frac{T}{L}$ | $\infty$ | 0 |
| PI | $0.9\frac{T}{L}$ | $\frac{L}{0.3}$ | 0 |
| PID | $1.2\frac{T}{L}$ | $2L$ | $0.5L$ |

These parameters give a typical response with an overshoot of about 25% and setting time.

# 5. HEAT ENERGY TRANSFER

One of the branches of thermal science is heat transfer, also known as transfer of thermal energy by some scientists. Heat is a form of energy that can be transferred from one system to another as a result of temperature deference.

In practice, heat transfer is achieved when heat is transferred from a region of higher or medium temperature to a lower-temperature and the transfer of heat stop when the two media are on the same temperature or when there is no heat transfer between the two bodies in contact. In this case the bodies are said to be at thermal equilibrium [28].

Heat transfer is normally encountered in most engineering systems and other application of our daily life. When it comes to heat transfer, one does not need to look far to find some application areas of heat transfer, our body constantly realize heat to its surroundings and the body comfort is linked to the realization of the heat transfer and that is why we try to control this heat transfer by adjusting our clothing to the environment conditions. Some other household appliances are designed to use the principles of heat transfer such as irons, water heaters, refrigerators, air-conditioning systems etc.

Heat is a form of energy and energy is the ability of a physical system to do work. Energy can exist in many forms such as in mechanical, kinetic, thermal, electrical, magnetic and nuclear form. [28]

The international unit of energy is joules (J) or Kilojoules (1 KJ=1000J)

According to the first law of thermodynamic also known as the principle of conservation of energy, energy can neither be created nor destroyed, it can only be transferred from one state to another. The net change of total energy (i.e. increase or decrease) during a process of any system is equivalent to the difference in the total energy between the energy entering and the energy leaving the system. [28]

(Change in energy of system) = (total energy leaving the system) - (total energy entering the system). [28]

The basic transfer of energy from one state to another is by means of mechanical transfer such as heat *Q* and work *W.* Work per unit time is the power and its unit is watts or hp (1 hp = 746 w) which is equal to heat transfer rate (J/sec.). When work is done in a system, energy increases and decreases as energy does work.

For example, how to determine energy produced when heat is transferred from a furnace to a liquid in a tank.

The mathematical equation is:

$$Q = \frac{\acute{m}}{t} Cp \vartriangle T \qquad \text{(KJ/sec = Kw)} \qquad (14)$$

Where, $\acute{m}$ = mass of the substance (Kg)

Cp = specific heat capacity of the substance (KJ/Kg$^{o}$C)

Specific heat capacity of a substance can be defined as the energy required to raise the temperature of a unit mass of a substance by one degree. Specific heat capacity of a substance normally depends on two properties such as temperature and pressure. For instance water has a constant specific heat capacity of 4.12 KJ/Kg$^{o}$C. [28]

t = time in seconds

$\Delta T$ = the change in temperature ($^{o}$C)

Heat energy transfer can be transported by means of heat, work and mass flow. Particularly for a heat transfer there are three basic mechanisms in which heat can be transported. The mechanisms are

1. Thermal Conduction
2. Thermal Convection
3. Thermal Radiation

## 5.1 Thermal Conduction

Thermal conduction is defined as the transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interaction between the particles. [28]

Conduction can take place in solids, gas and liquids. Practical example of conduction is a cold canned drink in a warm room. The cold canned drink warms up to the room temperature due to the transfer of heat from the room to the drink through the aluminum can by conduction. This is because in thermal conduction, heat is always transferred from a hotter body to a colder body.

The rate of heat conduction solely depends on the geometry of the medium, the thickness of the material and the type of material used as well as the temperature differences across the medium. For instance, a hot water in a room temperature loses its temperature rapidly when the room temperature is lower than the hot water temperature and temperature is reduced when the container that contains the hot water is wrapped with glass wool.

The rate of heat transfer can be express as;

$$Q = \frac{(\text{Area})(\text{tempearture difference})}{\text{thinkness of the materia}}$$

Or mathematically the rate of heat transfer can be expressed using Fourier law of conductivity (Fourier's equation).

$$Q = -\mathrm{KA}\,\frac{\Delta \mathrm{T}}{\Delta \mathrm{X}} \qquad (\mathrm{W}) \quad \text{or } (\mathrm{Kw}) \tag{15}$$

Where K = Constant of proportionality of the thermal conductivity of material

(I.e. the thermal conductivity measures the ability of the material to conduct heat

(w/m $^{o}$c) ).

$T$ = is the temperature ($^{o}$C)

$A$ = the heat transfer per unit area (m$^2$)

$X$ = thickness of the material (m)

The negative sign indicates that the heat transfer is in the direction of decreasing temperature.

## 5.2 Thermal Convection

Thermal convection is the mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion, and it involves the combined effects of conduction and fluid motion. Here, the faster the fluid motion is the greater the convection of heat transfers. [28]

The rate of convection heat transfer follows Newton law of cooling that states that a hot body transfers heat to its surroundings (cools) at a rate proportional to the difference in temperature between the two.

$$Q_{conv.} = hA_s(T_S - T\infty) \qquad \text{(w) or (Kw)} \qquad (16)$$

where

$h$ = Convection heat transfer coefficient in (w/m$^2$.$^o$c)

$A_s$ = Surface area through which convection of heat transfer take place (m$^2$)

$T_S$ = Surface temperature ($^o$c)

$T\infty$ =Temperature of the fluid sufficiently far from the surface ($^o$c)

Furthermore, when the transfer of heat by convection takes place due to the fluid movement which is caused by the temperature dependent that changes the fluid density, such heat convection is called natural convection. Typical example of natural convection is the circulation of water in a vessel heated from below. On the other hand, when the convection current is induced artificially or when a heavy dense fluid is pushed away by less dense fluid, the phenomenon is called force convection. A typical example of force convection is the movement of a hot air by fan.

Nevertheless, some people do not consider convection as the mechanism of heat transfer since heat convection is the conduction of heat in the presence of fluid motion.

## 5.3 Thermal Radiation

Thermal radiation is the energy emitted by matter in the form of electromagnetic wave (photons) as results of the changes in configurations of the atoms or molecules.

Examples of this are the sun warms the earth by means of radiation of electromagnetic waves and light bulbs emit heat from the filament to the surroundings.

The transfer of heat energy by radiation does not require the presence of intervening medium. As a matter of fact, the transfer of thermal radiation is the fastest of all the heat transfer mechanism, its speed is as a speed of light and therefore does not suffer any attenuation in a vacuum [28].

The basis of thermal radiation is on the Stefan-Boltzmann law that states: the energy radiated by a blackbody radiator (Blackbody is the ideal surface that emits radiation at a fastest rate) per second per unit area is proportional to the fourth power of the absolute temperature. This law qualifies the heat transfer from a body of a surface area $A$ and emissivity $\alpha$ at a temperature $T$ to the total surrounding wall at a temperature $T_w$ as

$$Q = A\alpha\,\varrho\,(T^4 - T_W^4) \qquad \text{(w) or (Kw)} \qquad (17)$$

Where $\varrho$ is the Stefan-Boltzmann constant and it has a value of

$$\varrho = 5.67 \times 10^{-8}\ \mathrm{W/m^2K^4}$$

## 5.4 Heat Exchangers

Heat exchangers are devices that facilities the exchange of heat between two fluids that are at different temperatures while keeping them from mixing. [28]

Heat exchangers are generally used in heating systems, air-conditioning systems in households, chemical processing and in large production plants.

In heat exchangers both conduction and convection occur. The conduction takes place through the wall of the heat exchanger whiles the convection occurs by the movement of the fluid in the heat exchanger pipes. Thus, for analysis purpose, it is always convenient to work with overall heat transfer coefficient that accounts for the contribution of these effects on heat transfer.

The rate of heat transfer between the two fluids at an area in a heat exchanger depends on the magnitude of the temperature difference at that area and its temperature varies along the length of the heat exchanger. Hence forth it is also convenient to work with the logarithmic mean temperature difference *LMTD* [28].

### 5.4.1 Types of Heat Exchangers

Different types of heat exchangers are now designed to match different type of heat transfer applications.

Many of these heat exchangers are classified based on the fluid flow direction. In such applications, the flow of the fluid in the heat exchangers can be in a form of cross-flow, parallel-flow and counter-flow.

In cross–flow heat exchangers, the flow of the fluid path runs perpendicular to one another. In the parallel-flow heat exchanger, both cold and hot fluids enter the same end of the heat exchanger and move in the same direction in the heat exchanger. On the other hand, in the counter-flow heat exchangers, the fluid flows in opposite direction with each fluid leaving the heat exchanger where the other enters. [28]

By comparison, the counter-flow heat exchanger is more effective than other types of the exchangers.

Apart from classifying heat exchangers based on the direction of fluid flow, there are other ways in which heat exchangers can be classified such as classification of heat exchangers according to constructional arrangement.

This thesis will classify heat exchangers according to constructional arrangement. Four main classifications of heat exchangers can be obtained according to constructional arrangement. These are as follows:

**1. Tubular heat exchanger** also known as a double heat exchanger comprises of two concentric pipes where both hot and cold water flow in parallel directions. This type of heat exchanger is suitable for counter and parallel flow.

**2. Compact heat exchanger** is a type of heat exchanger which is designed to have a large heat transfer area per unit volume. The ratio of heat transfer area of a compact heat transfer to its volume is known as *area density* which is denoted by $\beta$. A heat exchanger whereby $\beta$ is greater than $700m^2/m^3$ is classified as compact heat exchanger. Real examples of a compact heat exchanger are a car radiator and a glass ceramic gas turbine.

**3**. **Shell and tube** type of heat exchanger contains multiple tubes through which the flow of fluid flows. These tubes are divided into two sets. The first set of tubes contains liquid that are to be heated or cooled whilst on the other hand the second set of tubes contains liquid that are in charge of triggering the heat exchanger and removing and absorbing heat away from the first set of tubes.

When it comes to flow, a shell and tube heat exchanger can assume any of the flow path patterns.

**4**. **Plate heat exchanger** is a type of heat exchanger which is made up of thin plates joined together with minimum space between each plate. The space area of plates is large and the corners of each plate are designed in a way that heat can be exchanged between the plates as the fluid flow. The plate heat exchangers are normally used in refrigeration applications. This is because the plate heat exchangers have large surface area and more effective than shell and tube heat exchangers.

# 6 DESIGN OF HEAT ENERGY CONTROL SYSTEM

## 6.1 Essential Components of Control System

Generally, in designing a control system, there are four essential components that are needed. These components are:

1. A Plant
2. Sensor(s)
3. Actuator(s) and
4. Controllers

At least, a control system must have one sensor and one actuator to make the system operate effectively but sensors and actuators are very expensive, so designers of control systems tend to minimize them in their designs.

## 6.2 Building the heat energy control system

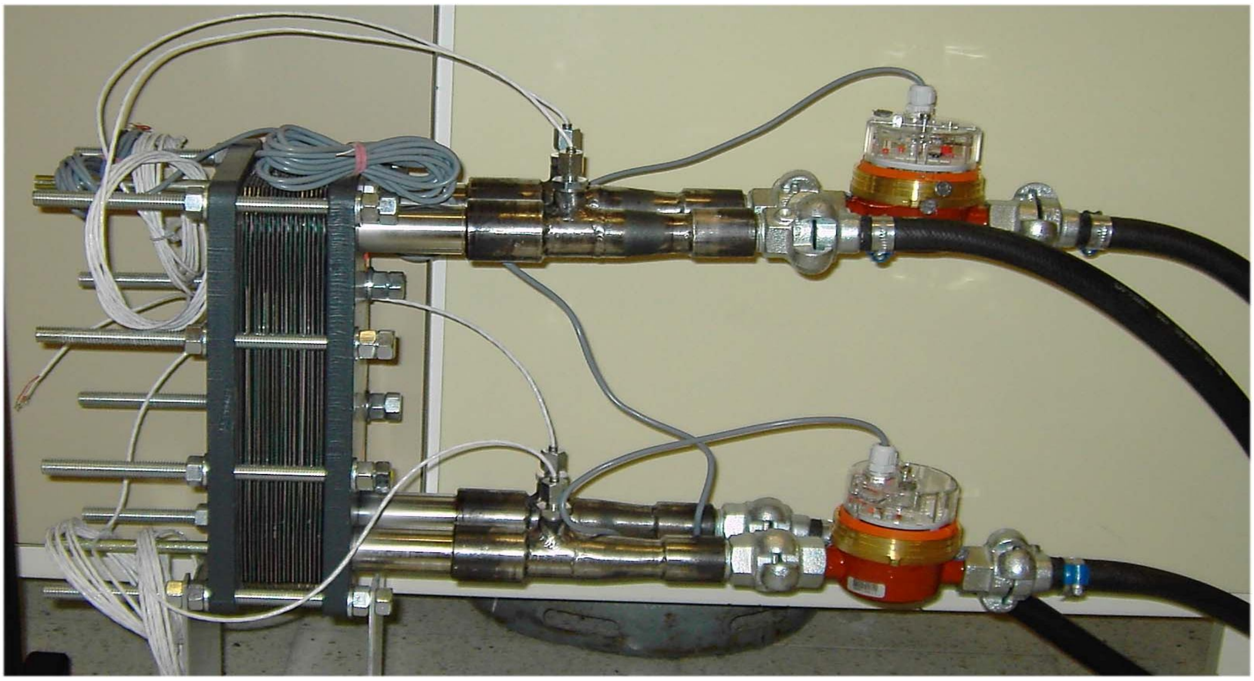


Figure 26. Heat energy control system

The plant or the system shown in Figure 26 above was built in the Savonia University of Applied Sciences physics laboratory. The system consist of a plate heat exchanger which has four holes all together, Two of the holes are located up for input and output of the cold water and other two holes are located at the bottom of the heat exchanger for the input and output of the hot water as show in Figure 27.

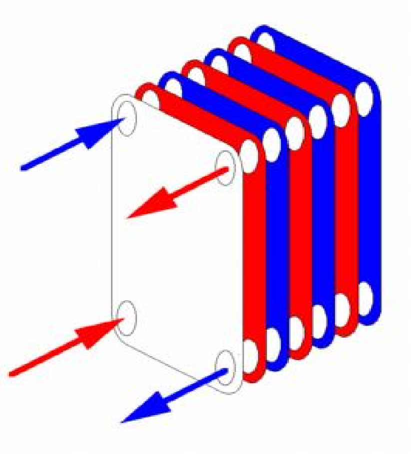


**Figure 27. Plate Heat Exchanger [29]**

Each of the holes was connected with a metal pipe that has a sensor drilled inside to measure the temperature of the water. At the end of the input metal pipe of the heat exchanger there is a flow meter which measures or records the quantity of water or mass flow rate that flows into the heat exchanger.

A valve was connected to the hot water output of the heat exchanger to regulate the amount of hot water that flows out from the system. The temperature sensor used in the system is resistance thermometer and, as already mentioned, the effect of temperature is directly proportional to the resistance so the sensor has a direct contact with the water. Therefore, as a temperature increases the resistance also increases thus the sensor send the resistance signal to the control unit (Figure 28 shows the control unit) to process the signal for onward transfer to the display unit (PC). The control unit is connected to the labview program installed on the *PC*.

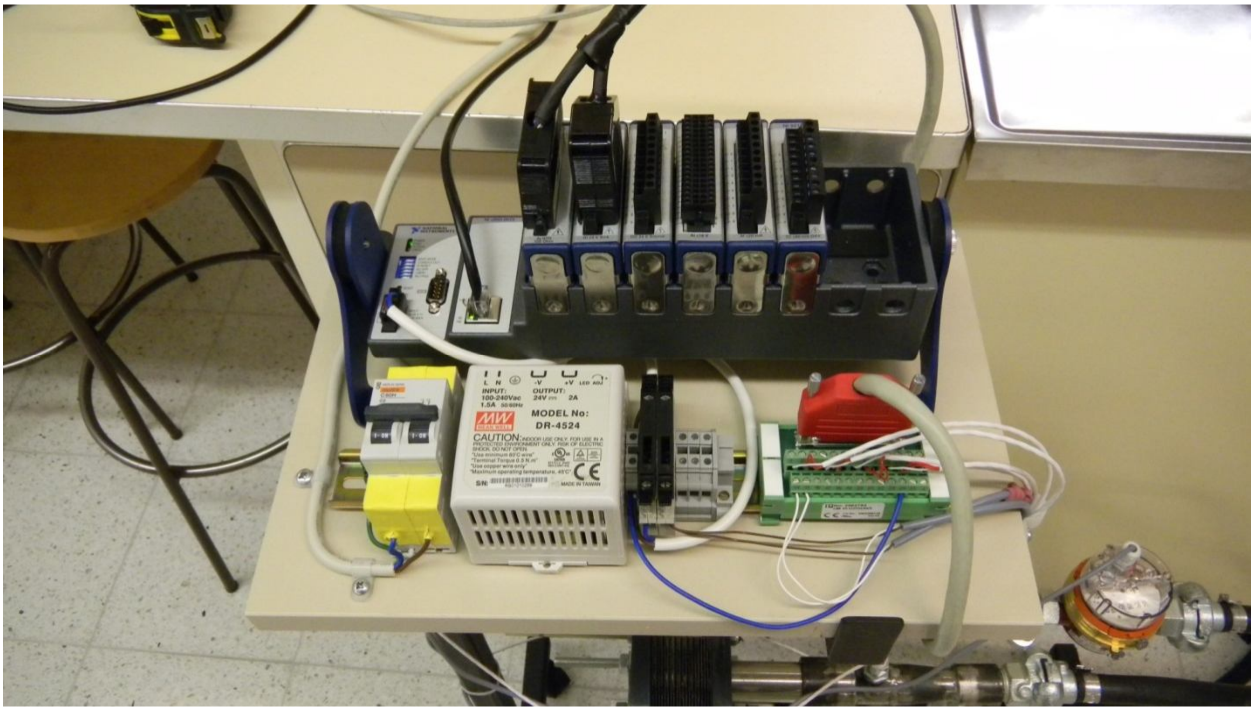


**Figure 28. Control Unit**

Labview programming is a graphical programming environment which is used by engineers to design sophisticated measurement, test, control system which uses intuitive graphical icons and wires that resemble a flowchart. This program offers integration with so many hardware devices and provides different kind of built-in libraries for advanced analysis and data visualization. [30]

The labview software designed on the *PC* panel is shown in Figure 29. On the *PC*, the program consists of *PID* controller which is proportional to *Gain* ($K_p$), derivative time $D_i$, integral time $T_i$ and the set point. The program also shows the records of the mass flow rate and the record of cold and hot temperature of the input and out of the water that passes through the heat exchanger.

On the left top corner of the panel is the valve output that shows the flow of the water in the output valve.

However, the middle right side of the panel shows a graphical view of the water movement both cold and hot water in the system.

Further, with this program it was possible to control all the hardware devices without touching them with the hand. For example, the output valve was remotely controlled to regulate the flow of the hot water without physically touching it.

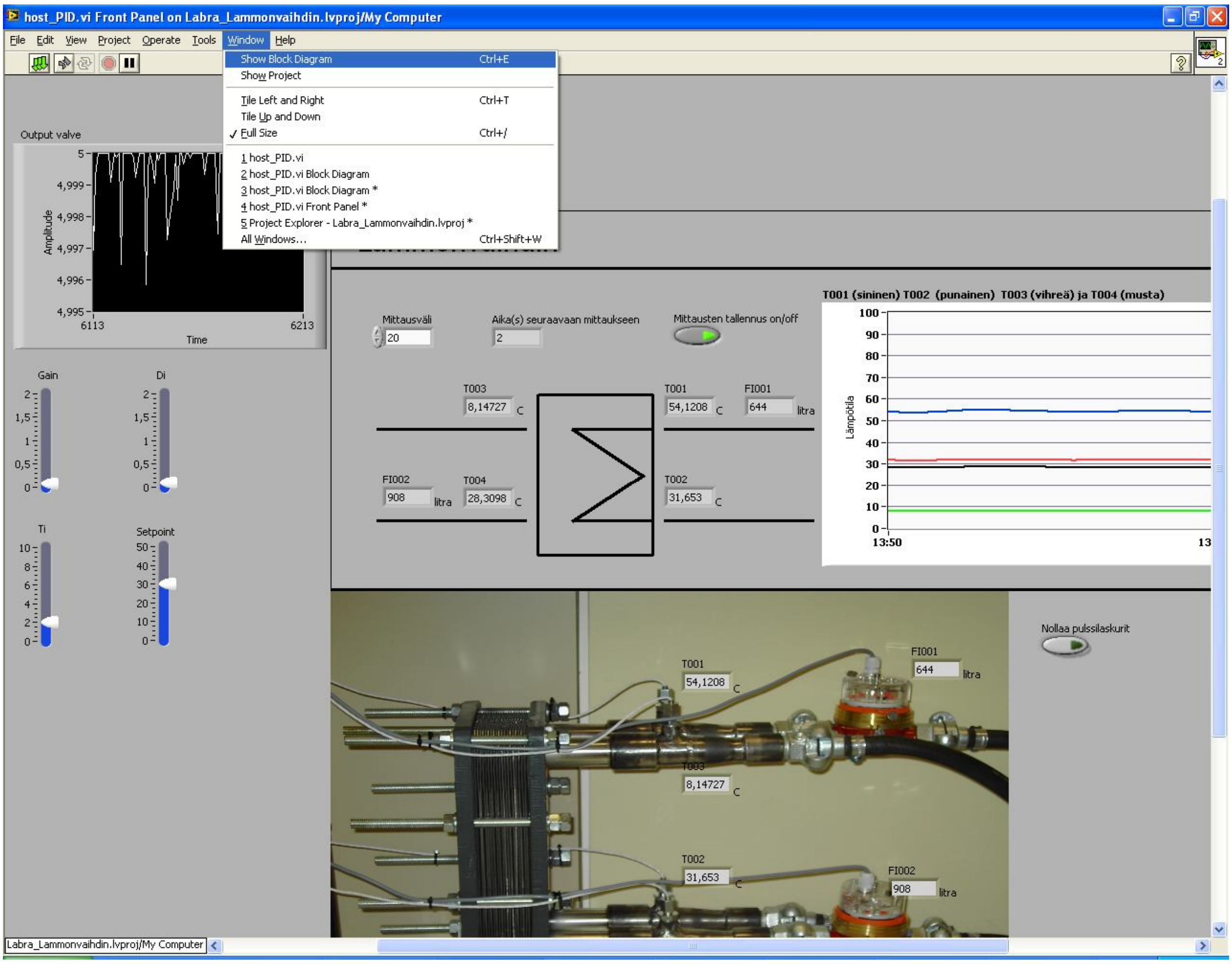


Figure 29. Control System Program

## 6.2 Experiment

The experiment was carried out by first setting the setpoint temperature to 10 $^{o}C$ for the cold water as the heat exchanger exchanges temperature between both cold and hot water which is higher than the cold water temperature. Then both hot and cold water were opened to flow through the input pipes of the heat exchanger. The output valves were used from time to time to regulate the output temperature of the hot water to assist in achieving our setpoint target.

Also, the sensor transmitted the water temperature signals of both cold and hot to the control unit to be processed for onward transfer to the display unit on the *PC* for examined.

However, the flow meter measured the mass flow rate of the input of cold and hot water that flows into the heat exchanger. This is done by the flow meter to transfer the mechanical movement of the water into current signals which is send to the control unit to be processed for onward transfer to the display unit (*PC*). It is very important to know the quantity of water per liters in the plant or the system from time to time so that accurate values can be determined from the experiment which will help us at the end of the experiment to know how much heat energy can be generated by the system and to determine the coefficient of heat exchanger.

As the cold water passes through the heat exchanger, it conducts heat from the hot water and the temperature increases. The rate at which the cold water temperature will increase to synchronize with the setpoint temperature which was initially set to $10^oC$ was determined by the *PID* controller on the *PC*. This was done by adjusting the values of the Gain, $T_i$ and *Kp* parameters values from the *PC* and then studying the results before making further adjustment when the needs were arisen.

Here, the proportional *Gain* $K_p$ were increased little-by-little knowing that if the proportional gain $K_p$ is increased too far, the system may become unstable.

On the other hand, the integral time constant $T_i$ was decreased knowing that when the integral time is decreased, the integral control action in the system will be increased.

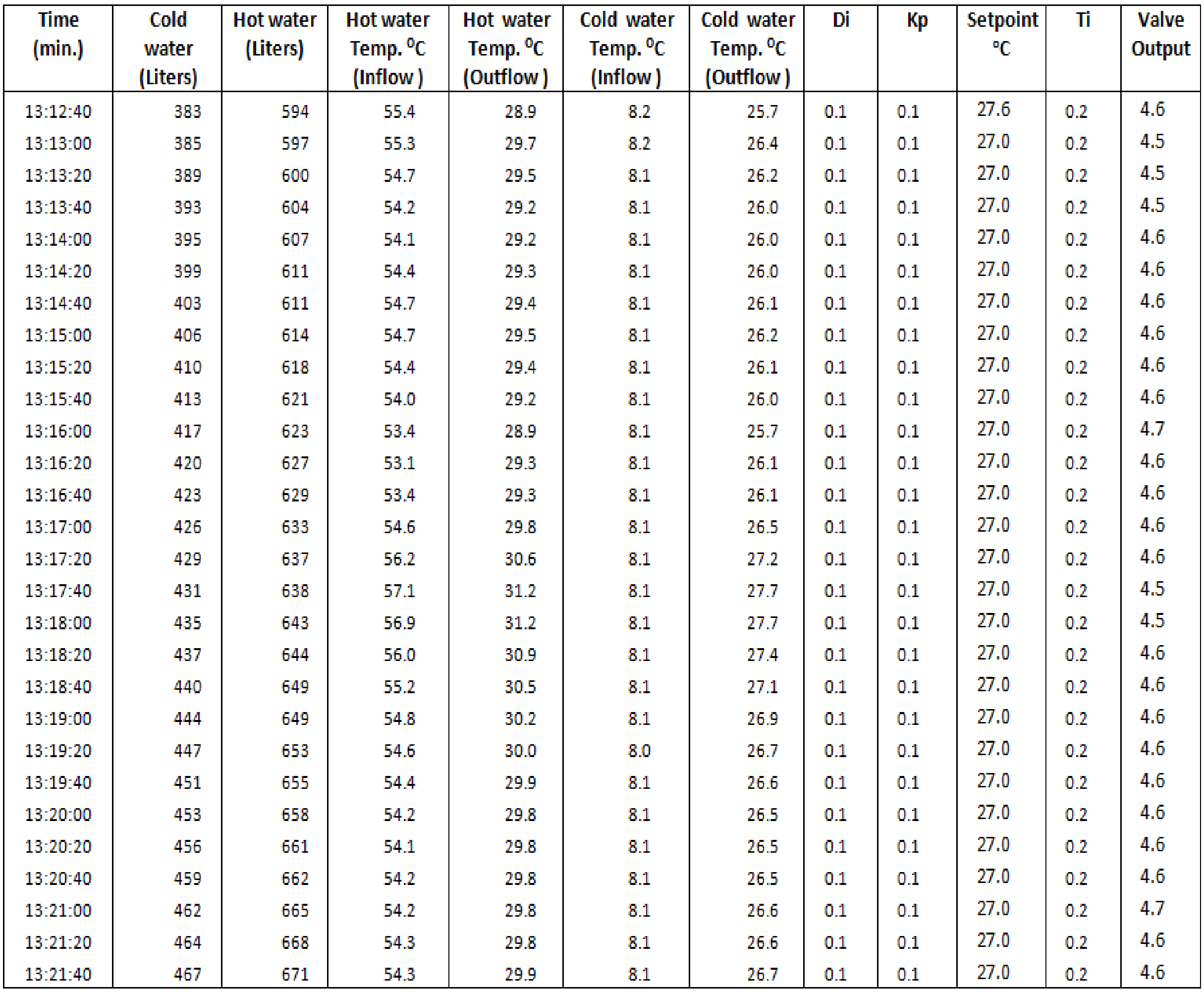
Finally, the derivative time constant $D_i = T_d$ was increased knowing that this will increase the derivative actions in the system.

After adjusting the *PID* controller using the steps above, the setpoint was achieved and the data were recorded in every 10 minutes. The setpoint was raised little bit higher than before and the same steps were followed to achieve the other setpoints. The sequences of the setpoint raised were 10 $^oC$, 15 $^oC$, 20 $^oC$, 25 $^oC$ and $27^oC$ and time interval for each setpoint data recorded was every 10 minutes.

## 6.3 Interpretation of Measurement Records

Table 7 Shows the data collected during the experiment of heat energy control system.

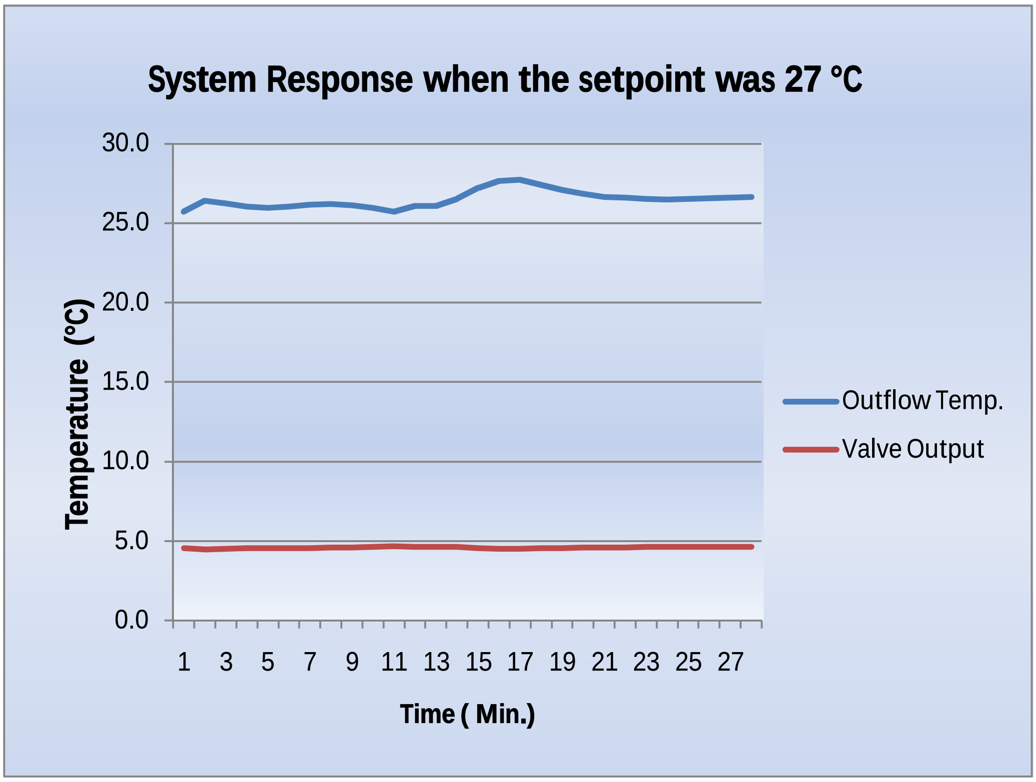
**Table 7. Data collected from the experiment**



| Time (min.) | Cold water (Liters) | Hot water (Liters) | Hot water Temp. °C (Inflow ) | Hot water Temp. °C (Outflow ) | Cold water Temp. °C (Inflow ) | Cold water Temp. °C (Outflow ) | Di | Kp | Setpoint °C | Ti | Valve Output |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 13:12:40 | 383 | 594 | 55.4 | 28.9 | 8.2 | 25.7 | 0.1 | 0.1 | 27.6 | 0.2 | 4.6 |
| 13:13:00 | 385 | 597 | 55.3 | 29.7 | 8.2 | 26.4 | 0.1 | 0.1 | 27.0 | 0.2 | 4.5 |
| 13:13:20 | 389 | 600 | 54.7 | 29.5 | 8.1 | 26.2 | 0.1 | 0.1 | 27.0 | 0.2 | 4.5 |
| 13:13:40 | 393 | 604 | 54.2 | 29.2 | 8.1 | 26.0 | 0.1 | 0.1 | 27.0 | 0.2 | 4.5 |
| 13:14:00 | 395 | 607 | 54.1 | 29.2 | 8.1 | 26.0 | 0.1 | 0.1 | 27.0 | 0.2 | 4.6 |
| 13:14:20 | 399 | 611 | 54.4 | 29.3 | 8.1 | 26.0 | 0.1 | 0.1 | 27.0 | 0.2 | 4.6 |
| 13:14:40 | 403 | 611 | 54.7 | 29.4 | 8.1 | 26.1 | 0.1 | 0.1 | 27.0 | 0.2 | 4.6 |
| 13:15:00 | 406 | 614 | 54.7 | 29.5 | 8.1 | 26.2 | 0.1 | 0.1 | 27.0 | 0.2 | 4.6 |
| 13:15:20 | 410 | 618 | 54.4 | 29.4 | 8.1 | 26.1 | 0.1 | 0.1 | 27.0 | 0.2 | 4.6 |
| 13:15:40 | 413 | 621 | 54.0 | 29.2 | 8.1 | 26.0 | 0.1 | 0.1 | 27.0 | 0.2 | 4.6 |
| 13:16:00 | 417 | 623 | 53.4 | 28.9 | 8.1 | 25.7 | 0.1 | 0.1 | 27.0 | 0.2 | 4.7 |
| 13:16:20 | 420 | 627 | 53.1 | 29.3 | 8.1 | 26.1 | 0.1 | 0.1 | 27.0 | 0.2 | 4.6 |
| 13:16:40 | 423 | 629 | 53.4 | 29.3 | 8.1 | 26.1 | 0.1 | 0.1 | 27.0 | 0.2 | 4.6 |
| 13:17:00 | 426 | 633 | 54.6 | 29.8 | 8.1 | 26.5 | 0.1 | 0.1 | 27.0 | 0.2 | 4.6 |
| 13:17:20 | 429 | 637 | 56.2 | 30.6 | 8.1 | 27.2 | 0.1 | 0.1 | 27.0 | 0.2 | 4.6 |
| 13:17:40 | 431 | 638 | 57.1 | 31.2 | 8.1 | 27.7 | 0.1 | 0.1 | 27.0 | 0.2 | 4.5 |
| 13:18:00 | 435 | 643 | 56.9 | 31.2 | 8.1 | 27.7 | 0.1 | 0.1 | 27.0 | 0.2 | 4.5 |
| 13:18:20 | 437 | 644 | 56.0 | 30.9 | 8.1 | 27.4 | 0.1 | 0.1 | 27.0 | 0.2 | 4.6 |
| 13:18:40 | 440 | 649 | 55.2 | 30.5 | 8.1 | 27.1 | 0.1 | 0.1 | 27.0 | 0.2 | 4.6 |
| 13:19:00 | 444 | 649 | 54.8 | 30.2 | 8.1 | 26.9 | 0.1 | 0.1 | 27.0 | 0.2 | 4.6 |
| 13:19:20 | 447 | 653 | 54.6 | 30.0 | 8.0 | 26.7 | 0.1 | 0.1 | 27.0 | 0.2 | 4.6 |
| 13:19:40 | 451 | 655 | 54.4 | 29.9 | 8.1 | 26.6 | 0.1 | 0.1 | 27.0 | 0.2 | 4.6 |
| 13:20:00 | 453 | 658 | 54.2 | 29.8 | 8.1 | 26.5 | 0.1 | 0.1 | 27.0 | 0.2 | 4.6 |
| 13:20:20 | 456 | 661 | 54.1 | 29.8 | 8.1 | 26.5 | 0.1 | 0.1 | 27.0 | 0.2 | 4.6 |
| 13:20:40 | 459 | 662 | 54.2 | 29.8 | 8.1 | 26.5 | 0.1 | 0.1 | 27.0 | 0.2 | 4.6 |
| 13:21:00 | 462 | 665 | 54.2 | 29.8 | 8.1 | 26.6 | 0.1 | 0.1 | 27.0 | 0.2 | 4.7 |
| 13:21:20 | 464 | 668 | 54.3 | 29.8 | 8.1 | 26.6 | 0.1 | 0.1 | 27.0 | 0.2 | 4.6 |
| 13:21:40 | 467 | 671 | 54.3 | 29.9 | 8.1 | 26.7 | 0.1 | 0.1 | 27.0 | 0.2 | 4.6 |

From the table, a system response was drawn graphically when the setpoint was set to particular values and Graph 8 shows a typical example when the setpoint was set to 27$^{o}$*C*.To determine the system response when the setpoint was set to 27$^{o}$*C*, a graph of cold water temperature (i.e. outflow) and the valve outflow values from the data collected in the table 7 above were use to draw the graph presented in Graph 8 and the results shows that the cold water temperature was able to rise up to obtained temperature of 27$^{o}$*C* just like the setpoint.

**Graph 8. System Response when the setpoint was 27°*C***



From the data gathered, heat energy consumption and coefficient of heat tranfer could be determined.

In determine the heat energy generated by the cold and hot water, Equation 14 was used,

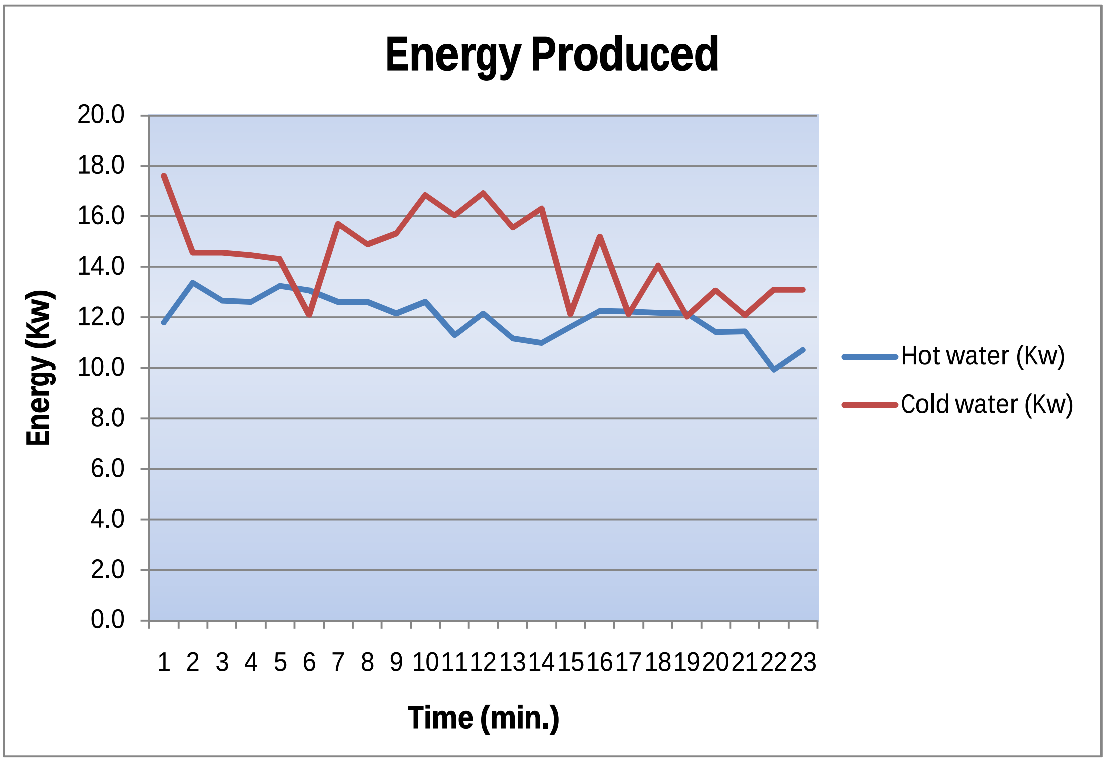
$$Q = \frac{\acute{m}}{t} Cp \vartriangle T \tag{14}$$

By putting the values of cold and hot water into the equation 14 from above we were able to determine heat energy generated by both cold and hot water in every minutes in the experiment. Table 23 shows the value of the energy for both cold and hot water.

### Table 8. Energy generated from cold and hot water

| Cold water energy (Kw) | Hot water energy (Kw) |
|---|---|
| 11.8 | 17.6 |
| 13.4 | 14.6 |
| 12.7 | 14.6 |
| 12.6 | 14.5 |
| 13.2 | 14.3 |
| 13.1 | 12.1 |
| 12.6 | 15.7 |
| 12.6 | 14.9 |
| 12.2 | 15.3 |
| 12.6 | 16.9 |
| 11.3 | 16.0 |
| 12.2 | 16.9 |
| 11.2 | 15.6 |
| 11.0 | 16.3 |
| 11.6 | 12.1 |
| 12.3 | 15.2 |
| 12.2 | 12.1 |
| 12.2 | 14.1 |
| 12.1 | 12.0 |
| 11.4 | 13.1 |
| 11.4 | 12.1 |
| 9.9 | 13.1 |
| 10.7 | 13.1 |

The energy produced by the cold and hot water was used to draw a graph to show the behavior of the energy transfer as the experiment was run (Graph 9).



**Graph 9. Energy produced by hot and cold water**

Moreover, not only the experiment focused on the energy produced by the water but the experiment was able to help to determine the coefficient of the heat energy transfer between the cold and hot water. Table 8 helps in the determination of the coefficient of heat energy transfer. In determining the coefficient of the heat energy transfer, the average energy for cold water was determined as 12.0 *Kw* and the hot water is 14.4 *Kw.* From Table 8, the cold water energy had been divided by the hot water energy as shown in Equation 18.

$$\text{Coefficient of heat energy transfer} = \frac{cold\ water\ energy}{Hot\ waterenergy} = \frac{12.0}{14.4} \quad (18)$$

$$= 0.8$$

The coefficient of heat energy transfer has no unit. This is because both cold and hot water energy unit are the same so when they multiplied together all units cancel out.

# 7 CONCLUSION

The analysis of control system has demonstrated the relevance of a control system theory in daily life activities as a system which, when incorporated with other systems such as science and engineering systems, will help to bring efficiency, productivity, minimize waste and save money especially for industries. Furthermore, at home control system relieves us from routine tasks, compensates us in our physical limitation, boosts our capabilities and increases our safety margins.

However, not all control systems give the optimum satisfaction needed in our process that is why it is very essential to carefully select the kind of control system that best suit the process in which one wants to control. In the earlier chapters, it was proven that with open-loop control system the input of the system is not affected by the system output, it would be very difficult to use this system to control certain processes such as room temperature to a desired limit because this system does not have a feedback from the output to measure the errors like disturbances from the outside temperature. That is why in such cases closed-loop control system is the most suitable to be used.

The main reasons why a closed-loop control system continue to dominate in control engineering is that closed-loop has a set of sensors that monitors the output and feeds the data to the control unit which continuously adjusts the control input (through actuators) as necessary to keep the control errors to a minimum hence producing a response that best suits the user’s wishes.

Control systems can be used to control almost all parameters but the method of controlling sometimes depends on different parameters for different control modes and not any control mode can control all parameters effectively. Sometimes, these control modes make the process oscillate and unstable but *PID* control mode has proven to be the best control mode that is able to reduce the tendency of oscillation and to bring the best stability to the process. The *PID* controller is the combination of *P, I* and *D* control mode combined together as *P* depends on the present error, *I* depends on the accumulation of past errors and *D* depends on the future errors based on current rate of change. These controllers frequently measure all the errors from the system and appropriate action is taken on it.

Nevertheless, one of the main objectives of this thesis was to design a heat energy control system that can control the transfer of heat from the hot water to the cold water and highlight the important of heat transfer and heat exchangers. At the end of this project, the objectives of the thesis were met as the heat energy control system was built and experiments was conducted on it to control how much heat energy can be transferred from the hot water to the cold water. This was achieved by setting a desired setpoint for the cold water. At the end of the experiment the desired set point were achieved that clearly confirmed to the principles of thermal energy transfer as the heat energy graph drawn indicated the rise in temperature of the cold water as both hot and cold water were passing through the heat exchanger. This was made possible from the experiment through the use of *PID* control mode. The data collected from the experiment was also used to determine the heat energy generated from the cold and hot water. The coefficient of the heat transfer was determined by dividing the average heat energy of the cold water by the heat energy of the hot water.

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