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Τμήμα Μηχανικών Βιομηχανικής Σχεδίασης και Παραγωγής

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Προτεινόμενος Τίτλος Αγγλικά:

Research and evaluation on the control methods and fault detection of flow control valves

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ΟΝΟΜΑ ΦΟΙΤΗΤΗ

Βασιλεία Τσούκστου

Μεταπτυχιακή Διατριβή που υποβάλλεται στο καθηγητικό σώμα για την μερική εκπλήρωση των υποχρεώσεων απόκτησης του μεταπτυχιακού τίτλου του Διιδρυματικού Προγράμματος Μεταπτυχιακών Σπουδών «Νέες Τεχνολογίες στη Ναυτιλία και τις Μεταφορές» του Τμήματος Ναυτιλίας και Επιχειρηματικών Υπηρεσιών του Πανεπιστημίου Αιγαίου και του Τμήματος Μηχανικών Βιομηχανικής Σχεδίασης και Παραγωγής του Πανεπιστημίου Δυτικής Αττικής.

Περίληψη

Summary

The subject of this thesis is the study of flow control valves. More specifically, to identify the methods used for flow control and analyze the various functions of flow-control valves in order to suggest the most compatible method of flow control per case.

Any failure of any single component in a hydraulic system can lead to loss of productivity and potentially present a threat to the safety of workers, the public and the environment. Operating faults may also lead to serious problems in a process, therefore identification of the means for fault detection and normalizing of the flow in a system will be analyzed here.

The right maintenance plan can save plants or vessels, both cost and downtime, thereby improving efficiency and allowing operations to run smoothly.

Maintenance methods will be identified, analyzed and evaluated in order to establish when and where they should be applied.

Keywords: Flow control, valve, maintenance, PID

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1. Introduction

It is an undisputed fact that rapid steps are being taken in the technological development in all fields of research and production, in order to provide solutions in problems which have, for many years, held back many productive processes.

These solutions are not only improving the already existing processes and methods, but are also providing the stepping stones for developing new ones –which, until recently, seemed almost impossible.

Unfortunately, in some cases, these solutions are so complicated that they are rendered impractical, or even unprofitable, being acceptable and applicable only in experimental uses in laboratories.

Therefore, it is important that such solutions should not only be technologically advanced, but also practical, easy to comprehend and applicable in a variety of cases in order to achieve:

- Extensive use
- Easy to install and handle
- Safe for use
- Environmentally friendly
- Financially robust
- Easy to maintain and replace.

One of the most widespread pieces of equipment - in almost all production lines - are flow control valves.

Far too little has been done over the years to sustain the performance of control valves once they go into operation. Rather than considering control valves as assets to be preserved, many companies treat them as liabilities – frequently replacing valves in critical positions during shutdown or docking for no other reason than length of service. Maintenance departments often deal with costly emergency repairs, making it necessary for a company to monitor and manage its physical assets. In recent years model based diagnostics and prevention has been investigated to improve the reliability of flow control valves.

Flow control valves come in all shapes, sizes, and designs. Their basic function, however, is the same -to control the flow. [1] All valves work by putting a variable restriction in the flow path. A typical example of a flow control valve is the simple water faucet installed in homes.

There are nearly countless types of valves for use across a variety of industries and applications. The subject of this thesis is the study of flow control valves. More specifically, to identify the methods used for flow control and analyze the various functions. Furthermore, maintenance methods will be identified, analyzed and evaluated in order to establish when and where they should be applied.

1.1 What is a flow control valve

A control valve is a variable restrain, capable of being adjusted in a conduit which contains a flowing liquid. This particular definition derives from several other, more formal, ones and is in essence extremely broad.

Flow control valves handle the rate of flow, of a liquid, through a hydraulic circuit. Their function is to either provide velocity control of linear actuators, or speed control of rotary actuators.

"A control valve is a power operated device which modifies the fluid flow rate in a process control system. It consists of a valve connected to an actuator mechanism that is capable of changing the position of a flow controlling element in the valve in response to a signal from the controlling system" ISA S75.05 [2]

The purpose of flow control in a hydraulic system is to regulate speed and to determine the rate of energy transfer at any given pressure. These two functions are related in that when the actuator force is multiplied by the distance through which it moves (stroke) it equals the work done on the load. The energy transferred this way must also equal the work done. Actuator speed determines the rate of energy transfer (i.,e. horsepower), thus making speed a function of flow rate.

On the other hand, directional control does not deal primarily with energy control, but rather with directing the energy transferring part to the proper place in the system - at the proper time. Directional control valves can be considered as fluid switches which make the desired ‘contacts’ - they direct the high energy input stream to the actuator inlet and provide a return path for the lower-energy oil, since it is of little consequence to control the energy transfer of the system through pressure and flow controls, unless the flow stream arrives at the right place at the right time.

There are quite a few types of flow control valves, some include orifices others are sophisticated closed-loop electrohydraulic valves that automatically adjust to variations in temperature and pressure.

Flow control is achieved in a system when a liquid is passed through an orifice, creating a drop in pressure & increase in Velocity (Kinetic Energy). But the flowrate on inlet and outlet would be same. In this way pressure can be controlled keeping the flow constant. A flow control valve delivers a constant flow regardless of the pressure drop through the valve. The flow rate is the ratio between the pressure gradient between inlet and outlet and the fluidic resistance of the device. To get a constant flow, the fluidic resistance shall vary in linear format with the pressure gradient. In a simple orifice, the flowrate increases with the applied pressure.

Pressure control valves accommodate a mechanism that opens the valve when it reaches a predetermined pressure threshold, the pressure at the outlet remaining substantially constant while the flow increases dramatically after valve opening. Almost all passive valves on the market or valves in the human body (cardiac valves etc) are based on this principle. [3]

Flow control valves are special fittings designed for use in complex hydraulic and pneumatic systems. They regulate either the flow or pressure of the fluid. Control valves usually respond to signals generated by independent devices such as flow meters or temperature gauges. These valves include simple tool orifices, along with a complex set of closed loops set of electrohydraulic valves that are perfectly designed to adjust to the different variations in system temperature and pressure.

The control valve fittings are used to reduce the actual flow rate in a specific area of a pneumatic circuit. This decreases the actuator speed. While a needle valve controls the flow in two directions, a flow control valve fitting is used to direct it to the system flow in only one direction. This way, free flow of the gas or liquid is allowed in the opposite direction.

1.2 Historic data

The concept of a control valve goes at least as far back as the Roman Empire where bronze plug cocks were used in the aqua ducts.

The concept of a moving-stem valve was introduced by James Watt in the late eighteenth century as a part of his fly-ball governor, which was developed to regulate the speed of his steam engine. Predecessors of the control valve developed concurrently with the age of steam throughout the nineteenth century. Late in the century, self-contained pressure and level regulators were applied to the ever-larger steam boilers in central power stations. The valve stem of a pressure regulator was moved by pressure from the process through a diaphragm; the stem of the level regulator was moved by a mechanical linkage to a ball float.

In 1880, in Marshalltown, on Iowa, constant manual regulation was required because of the extreme demand made on the system to supply water to fight a fire. William Fisher, an engineer at the city waterworks, had to work continuously for over twenty-four hours to manually maintain constant discharge pressure on a steam-driven water pump. From this experience, Mr. Fisher invented the constant-pressure pump governor and was founder of the Fisher Controls Company. By 1907, these governors were installed in a number of power plants in the United States, Canada, and England.

In 1882, William B. Mason founded the Mason Regulator Co. Mr. Mason had served as chief engineer on a steam-powered ship and also in a small stationary plant. He patented a steam pressure-reducing valve in 1885. The pressure-reducing valve was key factor to steam heat railroad cars and was used in that service for many years. In 1890, the regulator was introduced on U.S. Navy ships to secure the efficiencies of higher steam operating pressures.

The turn of the century was also ground breaking for the oil and gas industry. At first, the crude oil was pumped into a tank, where the natural gas was taken off and the components were separated by a batch distillation. Existing regulators could easily handle this operation. However, due to the rapidly increased demand it became necessary to amplify production rates. At the same time, powerhouses became larger, requiring larger valve mechanisms. Larger valves called for more power in order to move a plug of greater area - although the pressure drop remained quite moderate.

The pilot-operated regulator was developed in response. The pilot was essentially a small direct-acting spring and diaphragm valve, which acted on the larger –main-throttling valve. The process fluid was still used as the pilot-operating medium. The pilot permitted the narrowing of the control band, making possible the operation of larger valves.

In the early part of the twentieth century the individual oil well - with its individual tank and still - was replaced by collection tanks for a number of wells and continuous distillation. Pressure, temperature, and capacities increased, followed up by demand for larger valves, more powerful positioning mechanisms, and improved materials of construction. Up to that point, small regulators were of bronze and the larger regulators were of cast iron with integral seats and quick-opening disks for maximum flow at minimum lift. Oversizing combined with the quick-opening disks led to periodic instability and the need for some sort of a slow-opening characteristic. These developments were pioneered by the Hanlon-Waters Company of Tulsa, in

Oklahoma. This company made many innovative contributions to valve technology in the refineries in the 1920s and 1930s.

Supplying adequate power to position the valve plug continued to be a challenge. In 1906, a double-seated design was introduced to balance the dynamic forces on the plug and to stabilize the assembly by guiding the plug. The balanced seats accommodated valve sizes between 2 and 12 inches. Actuation was from a ball float in a self-contained level regulator.

In the 1915 Fisher Governor catalog, the bad experiences that resulted from the oversizing of control valves were commented. The catalog contains a nomograph for accurately selecting the valve size for the service conditions – based on experimental results. Nomographs, which were based on experimental results for each valve style, were in use until 1930, when Ralph Rockwell and Dr. C. E. Mason of the Foxboro Company published valve sizing formulas.

The process for cracking crude oil at very high temperatures and pressures was developed in the 1920s. During this period the Neilan Company on the West Coast developed a line of regulators as well as models of remarkably sophisticated pressure and temperature controllers. By that time, automatic control was booming, and the concept of using 15 psi air pressure for actuation came into being. The live zero lower end of the scale remained unsettled for some years.

The Neilan Company specialized in very rugged equipment and produced control valves for the refineries with cast steel bodies and heavy flanging. They also produced a very rugged valve actuator with multiple springs and ball bearing guides. By 1930, the valve had developed into the control valve as it is known today. Innovations on the valve included the machine-turned parabolic plug and seat ring guiding. [4]

1.3 Applications

Typical application includes regulating cutting tool speeds, spindle speeds, surface grinder speeds and the travel rate of vertically supported loads moved upward and downward by forklifts, and dump lifts.

Controlling the flow is a common requirement in standard industrial and process control applications.

When putting up an HVAC system, it usually requires a precise amount of constant flow for it to properly size piping, pumps, and other necessary accessories. If the flow control valves are placed improperly, there will be fluctuations in the pressure systems.

In a refinery, the feed-stream flow rate and composition are defined before the equipment is designed. For a facility, the composition is usually estimated based on drillstem tests of exploration wells or from existing wells in similar fields. The design flow rates are estimated from well logs and reservoir simulations.

Effective recycling and processing of waste water into potable water

Sprinkler irrigation is a method of sprinkling water similar to natural rainfall. Water is distributed through a system of pipes usually by pumping. It is then sprayed into the air through sprinklers so that it breaks up into small water drops which fall to the ground. The pump supply system, sprinklers and operating conditions must be designed to enable a uniform application of water.

1.3.1 Process plants

Process plants consist of hundreds, or even thousands, of control loops all networked together to produce a product to be offered for sale. Each of these control loops is designed to keep some important process variable, such as pressure, flow, level, or temperature, within a required operating range to ensure the quality of the end product. Each loop receives and internally creates disturbances that detrimentally affect the process variable, and interaction from other loops in the network provides disturbances that influence the process variable.

When all the measuring, comparing, and calculating are done, some type of final control element must implement the strategy selected by the controller. The most common final control element in the process control industries is the control valve. The control valve manipulates a flowing fluid, such as gas, steam, water, or chemical compounds, to compensate for the load disturbance and keep the regulated process variable as close as possible to the desired set point.

1.3.2 Medical Product Coating & Spray Atomizing

In this application a proportional valve and a flow monitor can accurately control the flow of air in an atomizing spray and medical product coating application. The spray is used to coat medical products. The flow is measured and a second loop feedback signal is provided to either increase or decrease the flow. As the pressurized air combines with the coating material, the material is atomized for spraying. It coats consistently and accurately.

In this atomizing spray flow control application, as the nozzle clogs, the flow is increased to maintain the plume. This increase can easily be monitored to know when a nozzle cleaning is due. This prevents bad product from irregular coatings and limits downtime.

1.3.3 Pig Velocity Control with Mass Flow Controller

Pipeline pigging is a vital and common process used in many industries, but rarely is pig velocity control performed. It is used to clean pipes, ensure proper flow and perform diagnostics on the pipe itself. Too often, this process is controlled with pressure, resulting in damaged pigs and pipes. The damage occurs when the pig gets stuck and pressure is increased until the pig breaks free at a very fast and uncontrollable rate.

By controlling the flow in the pipe, the velocity of the pig can be controlled. When the pig gets stuck, the mass flow controller allows pressure to build up – to break the pig free, but as soon as the pig breaks away, the mass flow controller senses the increase in flow and immediately reduces flow, thus reducing the velocity of the pig and the potential for damage.

Pig speed is adjustable based on a command signal from the controller and a signal output showing flow.

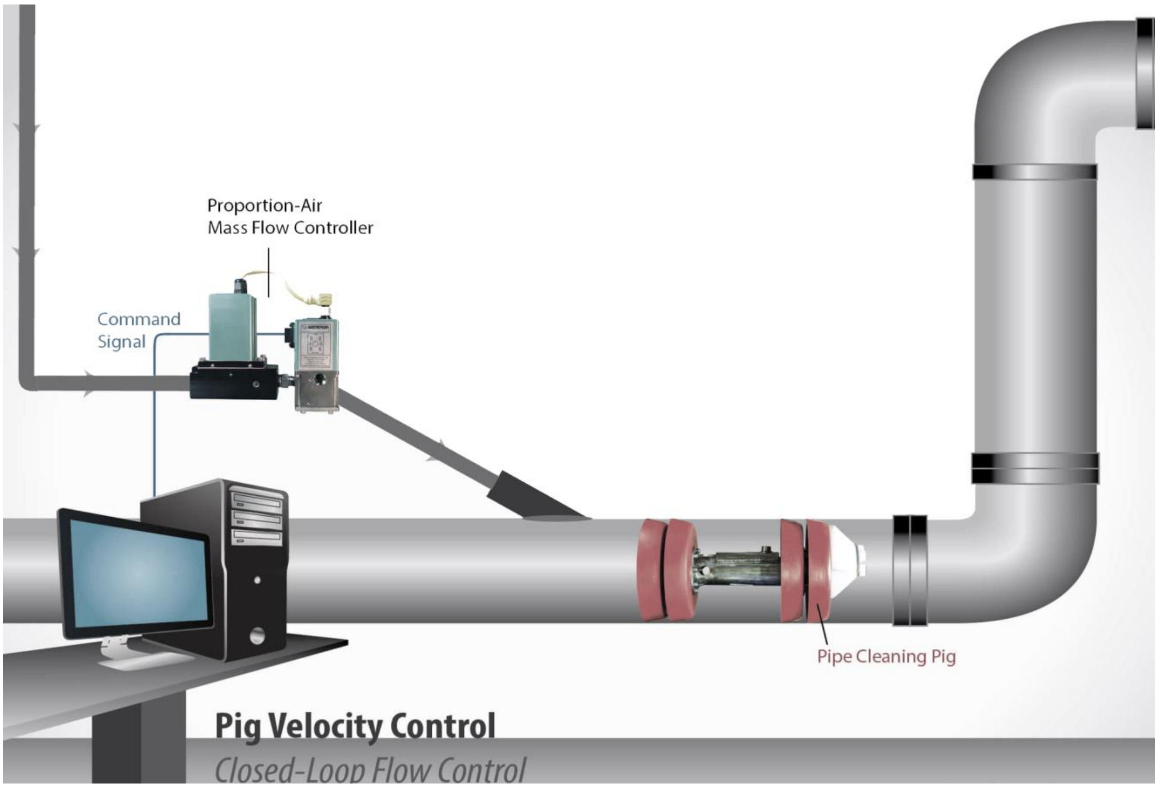

Figure 1: Pipeline Pig velocity control [5]

1.3.4 Marine applications

The marine and offshore industry operates in extremely challenging and harsh conditions, in addition to that all interruptions and downtime quickly results in high costs. This requires specialized flow control solutions where reliability, efficiency and safety are key factors.

1.3.4.1 Fuel injection systems

The fuel injection system is one of the most important parts of a marine diesel engine. A fuel injection system provides the right amount of fuel to the engine cylinder at the right moment. It is also extremely important that the fuel injected inside the engine enters the cylinder at the right combustion situation for the highest combustion efficiency. It is for this reason that there is a need of a measured fuel supply system which times and monitors the delivery of the fuel and oil in the combustion chamber.

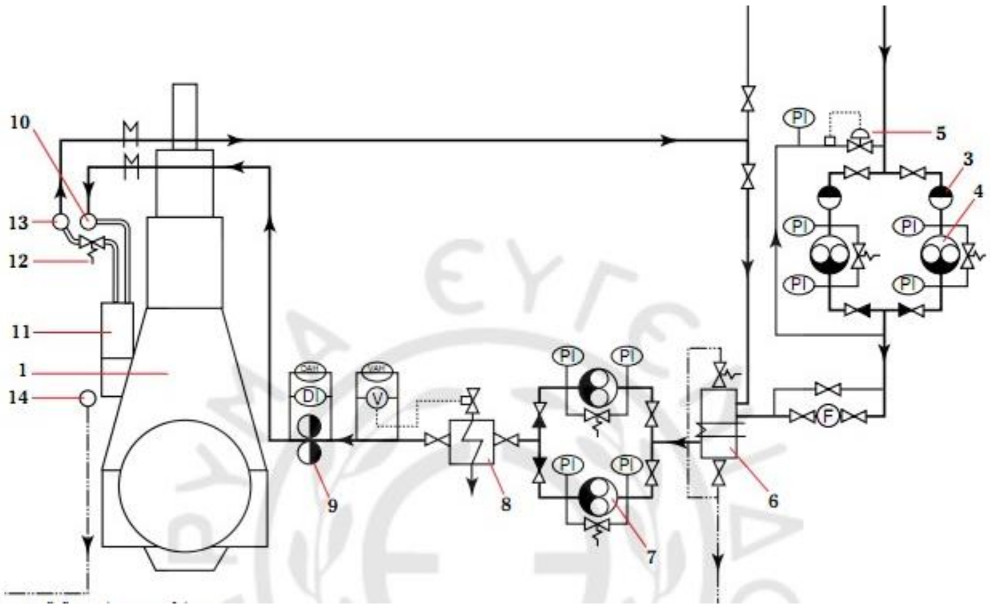

Figure 2: Part of fuel injection diagram - item 5 is a pressure regulating valve and item 12 a pressure retaining valve [6]

1.3.4.2 Fresh water generation

Fresh water is generally produced on board using the evaporation method.

There are two things that are available in plenty on a vessel to produce fresh water – Seawater and heat- thus fresh water is produced by evaporating sea water using heat produced from the main engine.

Heated seawater is used as feed water (brine) for the evaporating –and evaporating temperature is controlled by vacuum pressure. During evaporation, pure water vapor passes through the deflector, demister and then enters the condenser

Suction and discharge valves of the sea water pump, which will provide water for evaporation, cooling and to the eductor for creating vacuum, open.

The sea water discharge valve opens, from where the water is sent back to the sea after circulating inside the fresh water generator. The vacuum valve situated on top of the generator closes to build up vacuum. When vacuum is achieved the control valve for feed water treatment opens.

Hot water (jacket water) inlet and outlet flow control valves open slowly and increase the opening to full open.

The distillated pure water is checked on its salinity. If the salinity exceeds the specified level, a solenoid valve opens in the discharge line.

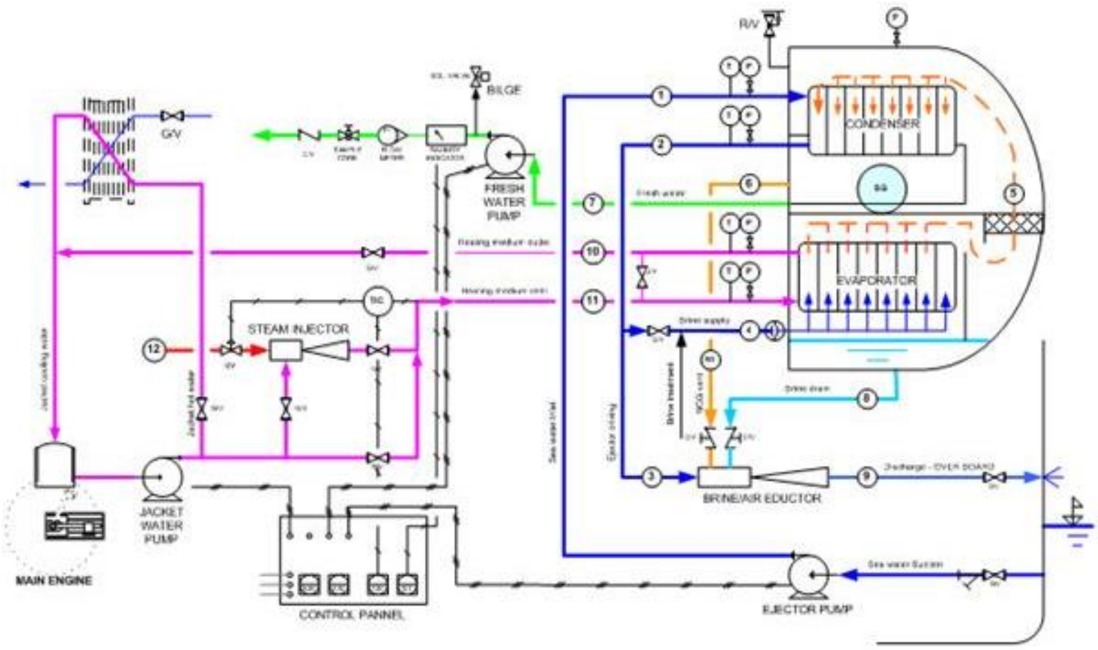

Figure 3:Fresh water generator diagram

1.3.4.3 Ballast water treatment – via electrolysis

Ballast Water Treatment System (BWTS) is a system designed to remove and neutralize biological organisms (zooplankton, algae, bacteria) from ballast water. The need to regulate and control the flow of the incoming (ballasting) water is essential.

Inlet flow control valve opens and water goes through the BWTS. Sensors confirm the flow inside the electrolytic cell and the production of TRO is initiated (via electrolysis). Outlet flow control valve opens and the water is send to the ballast tanks.

When incoming sea-water flow capacity is higher than the system’s designed standard, inlet flow control valve closes slightly to regulate the flow. In the case where incoming flow is not adequate – to fill the electrolytic cell and initiate the electrolysis stage – the outlet flow control valve closes as much as necessary to throttle the incoming water.

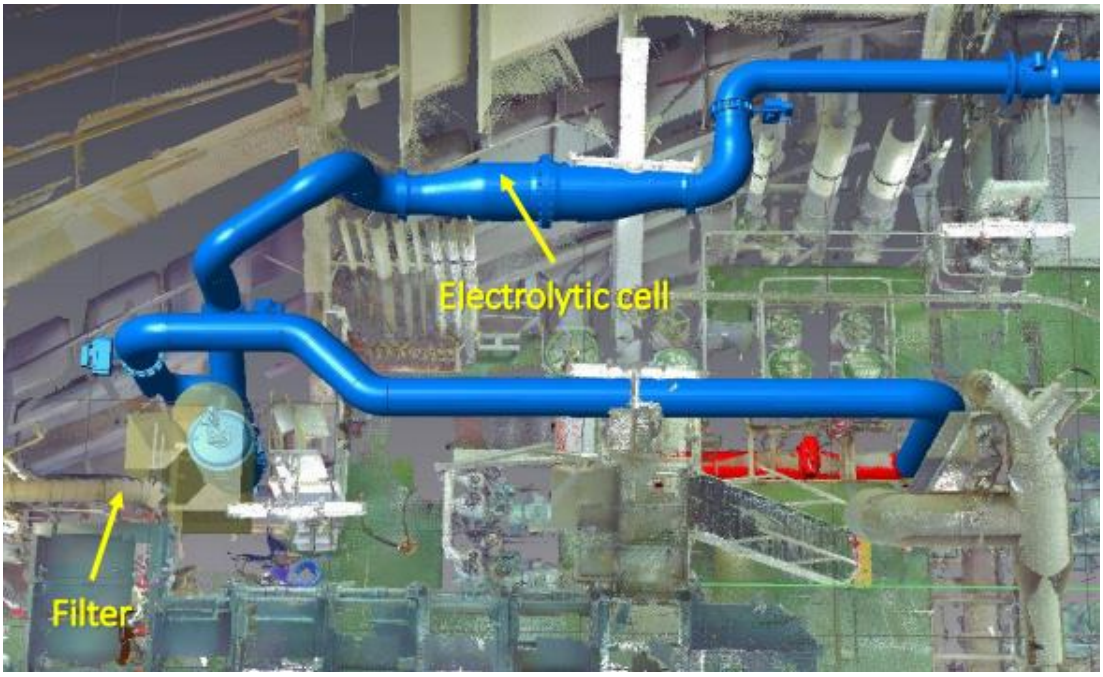

Figure 4: Ballast water treatment system with two flow control valves

2. Flow regulation

Flow control valves are designed to adjust, automatically, on variations in pressure and temperature.

The purpose of flow control in a hydraulic system is to regulate the speed of an actuator by regulating the flow rate. Flow rate is also determined as rate of energy transfer at any given pressure. From these two variables occurs that the actuator force multiplied by the distance through which it moves (stroke) equals the work done on the load. The energy transferred equals the work done. Since actuator speed determines the rate of energy transfer, speed is thus a function of flow rate.

2.1 Classification of flow-control valves

Flow control valves can be classified into pressure and non-pressure compensated.

Pressure compensated flow-control valves change the size of the orifice in relation to the changes in the system pressure. This is accomplished through a spring-loaded compensator spool that reduces the size of the orifice when pressure drop increases. Once the valve is set to a position, the pressure compensator reacts to keep the pressure drop nearly constant. It works based on a kind of feedback mechanism from the outlet pressure. This way the flow is kept through the orifice almost constant.

Non-pressure compensated flow-control valves are used when the system pressure us relatively constant and the motoring speeds are not too critical. The operating principle behind these valves is that the flow through an orifice remains constant if the pressure drop across it stays the same. The disadvantage of these valves is that the flow rate depends on the workload, therefore the speed of the piston cannot be defined accurately when the work-load varies.

2.2 Types of flow-control valves

There are eight different types of flow-control valves which are commonly used in hydraulic systems. From these eight, half are pressure compensated and the other half are non-pressure compensated. All these types control the speed of an actuator by regulating the flow rate.

2.2.1 Orifices

A simple orifice in a hydraulic line is the most elementary method for controlling flow and can also be used as a pressure-control device (see figure 1a). In order to control the flow, the orifice is places in series with a pump. Usually, an orifice is calibrated by a needle valve (variable orifice). (see figure 1b)

Both orifice types are non-compensated flow-control devices.

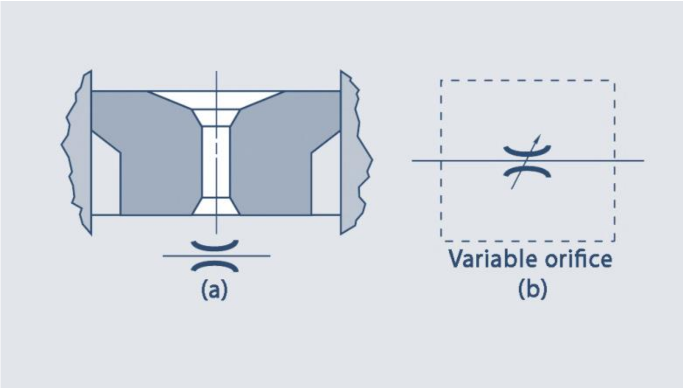

Figure 5: Simple fixed orifice (a) and variable orifice (b) flow controls. [6]

2.2.2 Flow regulators

A little more sophisticated devices, compared to a fixed orifice, they consist of an orifice which senses flow rate as pressure drop (ΔP) –across the orifice A compensating piston adjusts to a variation of inlet and outlet pressures. This way, a closer control of flow rate is provided, under varying pressure conditions.

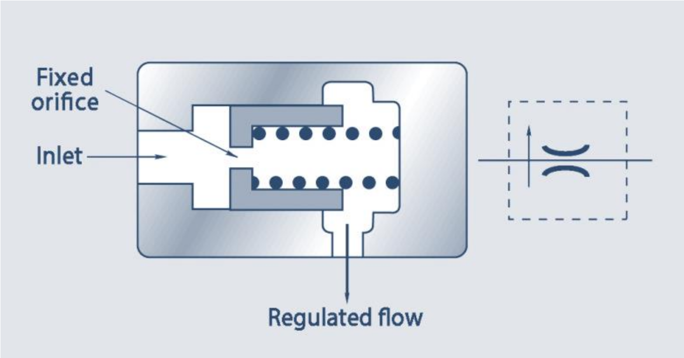

Figure 6: Flow regulator adjusts to variations in inlet and output pressures. [6]

2.2.3 Bypass flow regulators

In this case, flow excess of the set flow rate returns to a reservoir through a by-pass port. The flow rate is controlled by throttling the fluid across a variable orifice, which is regulated by the compensator piston.

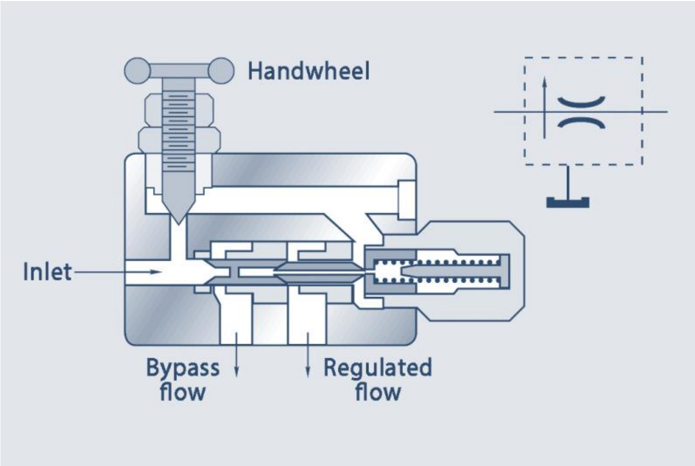

Figure 7: Bypass flow regulators return excess flow from pump. [7]

2.2.4 Demand-compensated flow controls

Alternative case is to bypass excess system flow to a secondary circuit, by routing the fluid at a controlled flow rate to the primary circuit. By-pass fluid can be used for work functions in secondary circuits. In order for this valve type to function, there should be flow to the primary circuit, otherwise (if it is blocked) the valve will route the flow to the secondary circuit.

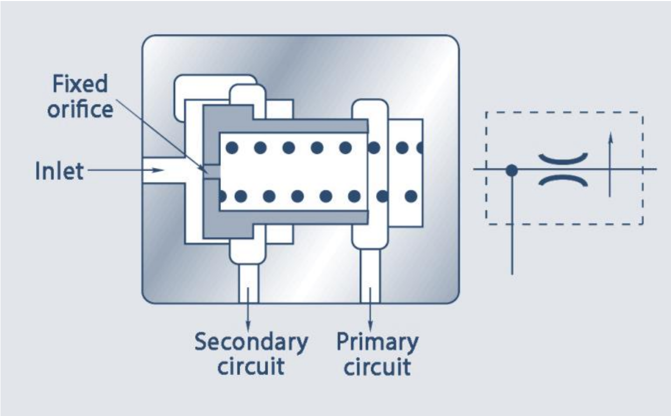

Figure 8: Demand-compensated flow control bypasses full pump output to tank during idle portion of work cycle. [6]

2.2.5 Pressure-compensated, variable flow valves

Flow control is achieved via an adjustable variable orifice, placed in series with a compensator which automatically adjusts to varying inlet load pressure – while maintaining an essentially constant flow rate.

Pressure-compensated, variable flow-control valves are escort by integral reverse-flow check valves, which give fluid unrestricted flow in the opposite direction, and integral overload relief valves, which route fluid to tank when a maximum pressure is exceeded.

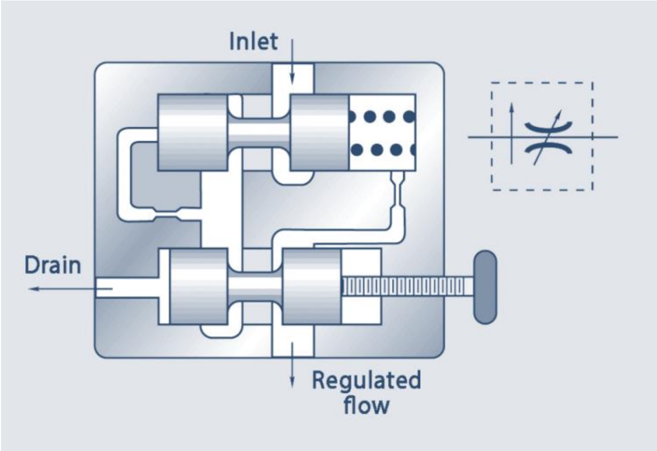

Figure 9: Pressure-compensated, variable flow-control valve adjusts to varying inlet and load pressures. [6]

2.2.6 Pressure- and temperature-compensated, variable flow valves

In order to avoid effects caused by temperature variations, temperature compensators adjust the control orifice openings to correct the effects of viscosity changes-caused by temperature fluctuations of the fluid. This is achieved in combination with adjustments to the control orifice for pressure changes as well.

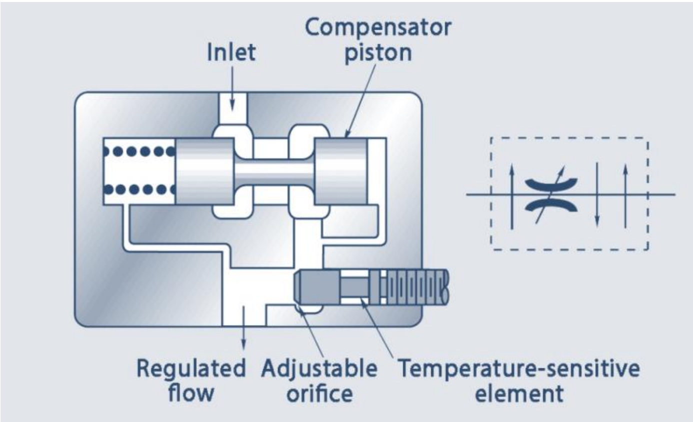

Figure 10: Pressure- and temperature-compensated, variable flow-control valve adjusts the orifice size to offset changes in fluid viscosity. [6]

2.2.7 Priority valves

They are, in essence, flow control valves which supply fluid, to the primary circuit, at a set flow rate thus functioning as a pressure-compensated flow control valve. The excess flow is by-passed to a secondary circuit at a lower pressure from that of the primary circuit. The primary circuit has priority over the secondary, in case inlet and/ or load pressure vary.

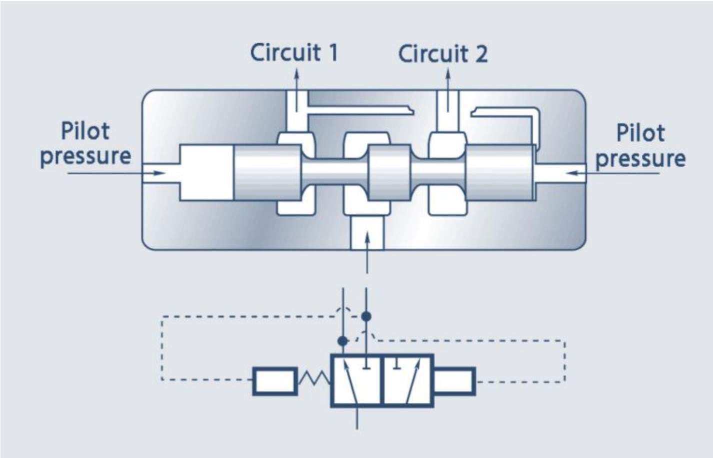

Figure 11: Priority valve supplies a set flow rate to a primary circuit [6]

2.2.8 Deceleration valves

They are modified two-way valves which are cam actuated and have spring offset. They are used for decelerating a load driven by a cylinder. The valve closes gradually either by a cam attached to the cylinder rod or by the load. This provides an orifice which gradually increases backpressure in the cylinder as the valve closes.

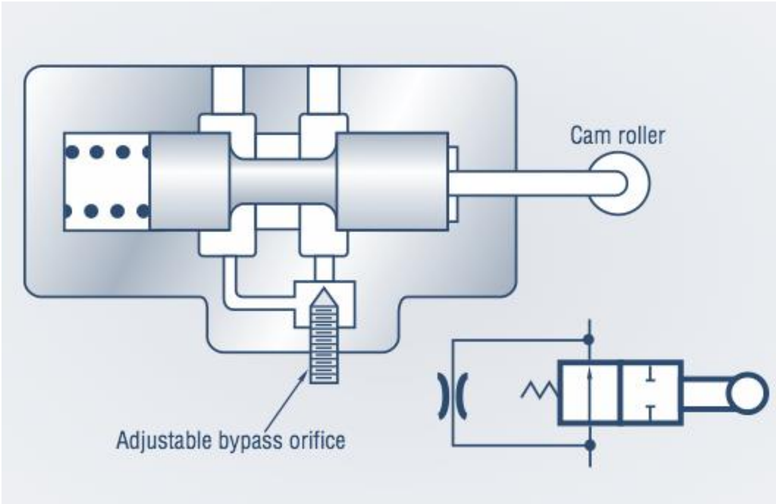

Figure 12: Deceleration valve slows load by being gradually closed by action of cam mounted on cylinder load. [6]

2.3 Other flow controls

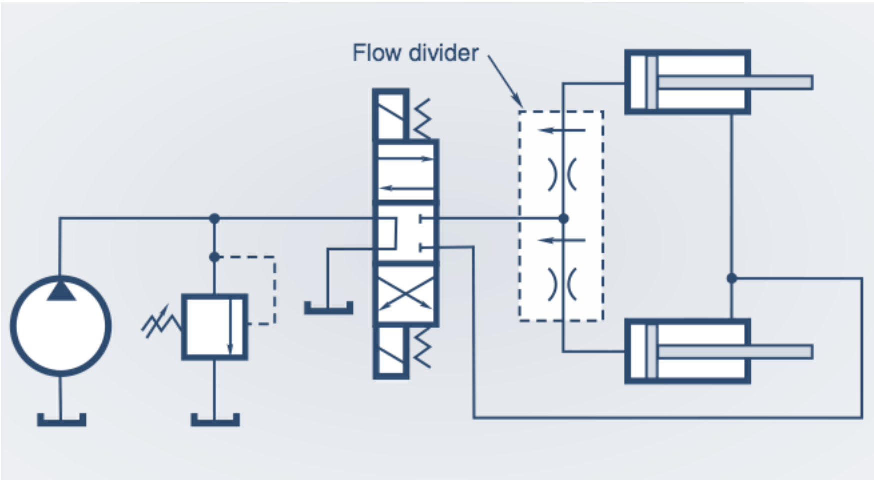

Figure 13: Linear-type flow divider splits single input into two output flows. [6]

2.3.1 Flow dividers

This is a pressure-compensated flow control valve that receives one input flow and then splits it into two output flows. The output flows can either be delivered equally or under a pre-determined ratio.

Flow dividers operate over a narrow bandwidth, and not at one set point, therefore it is likely to have variations in the secondary branches.

2.3.2 Rotary flow dividers

A rotary flow divider is another technique to divide one input flow into proportional, multiple-branch output flows. It usually handles larger flows than flow divider valves, and consists of several hydraulic motors connected together mechanically by a shaft. One input fluid stream is split into as many output streams as the number of motor sections in the flow divider. Since all motor sections have the same speed, output streams' flow rates are proportional and equal to the sum of displacements of all the motor sections.

2.3.3 Proportional flow-control valves

Proportional flow control valves modulate fluid flow in proportion to the input current they receive.

Most proportional flow-control valves are pressure-compensated, in order to minimize flow variations caused by changes in inlet or outlet pressure.

An electrohydraulic proportional valve consists of three main elements:

- a pilot or proportional solenoid
- a metering area
- an electronic position-feedback device

A pressure compensated proportional flow control valve is a two-port valve in which the main control orifice is adjusted electronically. They maintain constant flow output by keeping the pressure drop constant across the main control orifice. The difference is that control orifice is modified to work in conjunction with a stroke controlled solenoid.

2.3.4 Proportional flow logic valves

They are electrically adjustable flow control valves, which fit into a standard logic valve cavity. The cover, which consists of a proportional force solenoid and a pilot controller, and the cartridge are assembled as a single unit.

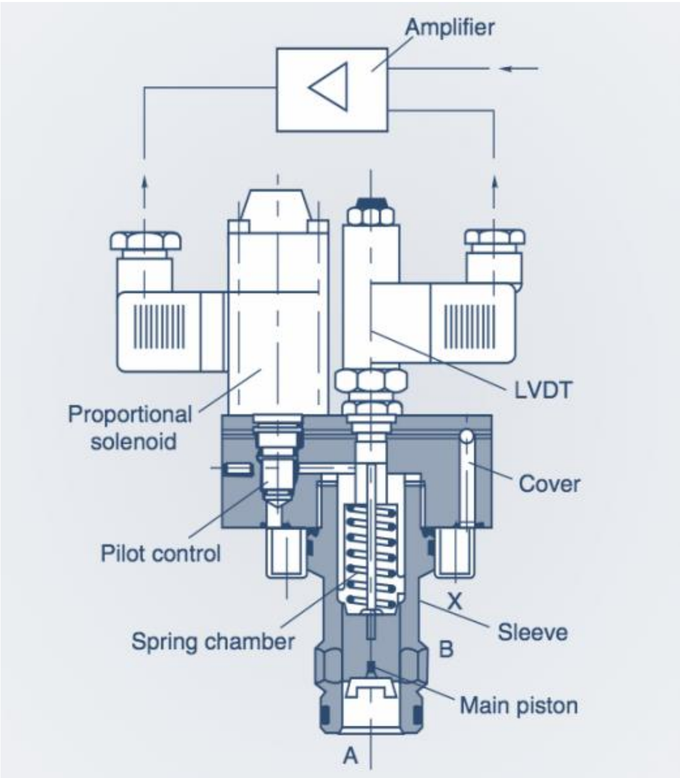

Figure 14: Cross-sectional view of proportional flow logic valve [6]

The valve is unaffected by changes in system pressure, therefore it can open and close the orifice in the same length of time.

The amplifier can be used

- As an external electronic control, which can make the orifice remotely adjustable while maximum spool acceleration is still limited by an internal ramp;
- As a switch that can be added to turn the ramp on and off - in case of power failure, the element will return to its normally closed position.

3. Control method

Proportional Integral Derivative (PID) control is a form of closed loop control. In a closed loop control, the process variable is measured and compared to the set point. The controller changes its output (manipulated variable), until the measured variable meets the set point.

The PID features found in the control loops of today's controllers have enabled us to achieve much greater accuracy, compared to that available only a few years ago.

When setting up PID loop control the difficult part is to achieve proper operation, due to the complex setup parameters and the need to comprehend the sequence of implementing them.

Proper operating control is the ability to control a variable at a given set point within an acceptable degree of accuracy, not an easy feat considering the dynamics of a control system.

In case it is not properly set up, then abrupt changes -in the set point or system's loading- can cause system's controls to either oscillate, or to control with excessive error between the set points and the actual control point.

All control loops have a tendency to oscillate, due to the built-in timing constants of the control system components and the dynamically changing variables - such as set point shifts or load changes.

Typical period values encountered in control system loops range from 30 seconds to twenty minutes. Loop oscillation is undesirable in control systems therefore it is eliminated by increasing the proportional band of the loop.

Proportional band, commonly referred to as the throttling range (TR), is defined as "the amount of change in the controlled variable required to drive the loop output from 0 to 100%" [8]

Systems subjected to abrupt changes, in load or set point will typically require a wider proportional band in order to achieve stability in. Very quick system response times, such as those found in static pressure control, will require much wider proportional bands to prevent overshoot.

In general, the decrease of the throttling range will increase the amount of over shoot - the gain of the loop is inversely proportional to the throttling range or proportional band.

3.1 The Working Principle of a PID Controller

PID controllers use three control modes:

- Proportional Control
- Integral Control
- Derivative Control

Each of these three modes reacts differently to the error. The amount of response produced by each control mode is adjustable by changing the controller's tuning settings.

While Proportional and integrative modes are also used as single control modes, a derivative mode is rarely used on its own in control systems.

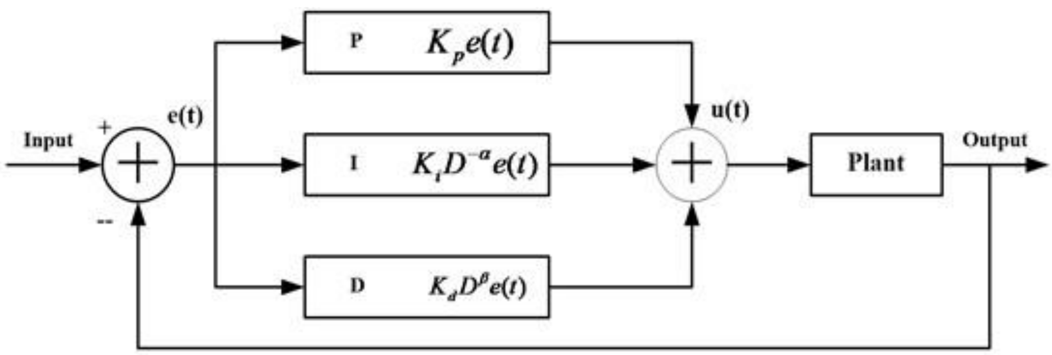

Figure 15: Working principle of PID controller

A common characteristic of proportional control is an error between the set point and control point, which is referred to as offset or droop. As the system load and/ or the proportional band increases, so does throttling range. Offset is an undesirable characteristic of proportional only control loops and is easily eliminated by adding Integral Action.

PID controller maintains the output in such a way that there is zero error between process variable and set point/ desired output by closed loop operations.

3.1.1 Proportional Control Mode

This is the main driving force in a controller. It changes the controller output in proportion to the error [Figure 16: Proportional control action]. If the error increases, the control action increases proportionally. This is very useful, since more control action is needed to correct large errors.

The adjustable setting for proportional control is called the Controller Gain (Kc). A higher controller gain will increase the amount of proportional control action for a given error. If the controller gain is set too high the control loop will begin oscillating and become unstable. If the controller gain is set too low, it will not respond adequately to disturbances or set point changes.

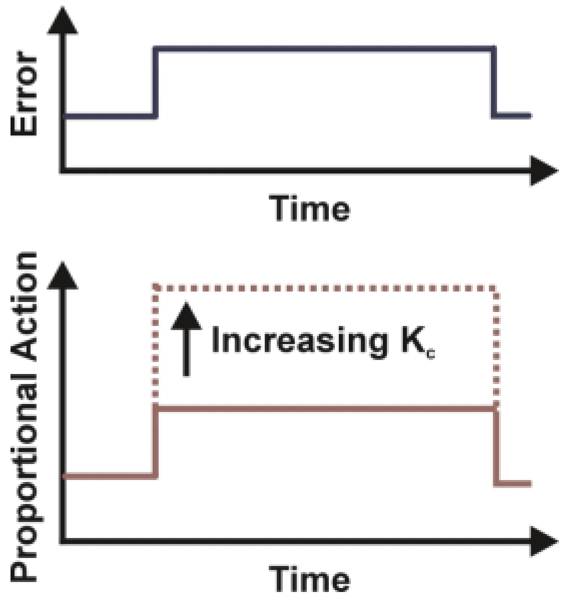

Figure 16: Proportional control action

For most controllers, adjusting the controller gain setting influences the amount of response in the integral and derivative control modes. This is why the parameter is called controller gain. However, there is one controller design (called a parallel or independent gains algorithm) in which adjusting the proportional gain does not affect the other modes.

3.1.1.1 P- Controller:

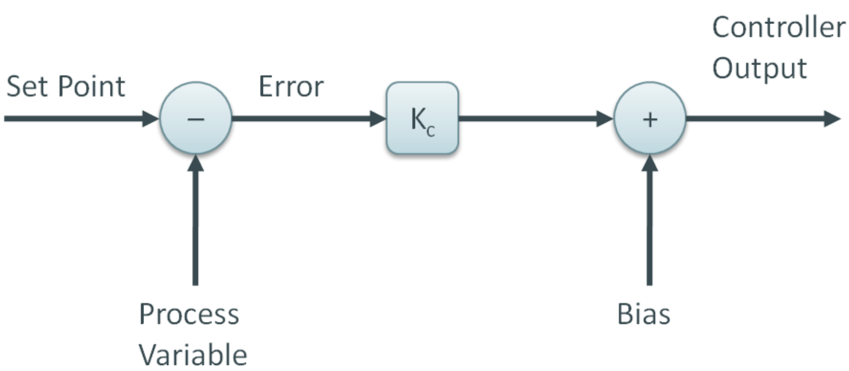

Figure 17: P-controller

Proportional or P- controller gives output which is proportional to current error e (t). It compares desired or set point with actual value or feedback process value. The resulting error is multiplied with proportional constant to get the output. If the error value is zero, then this controller output is zero.

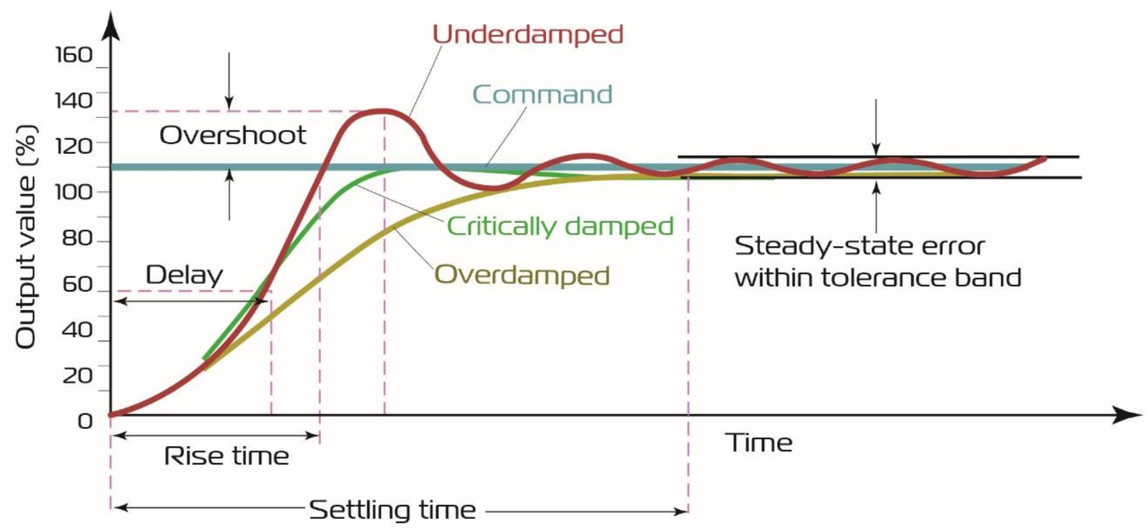

Figure 18: P-Controller Response

This controller never reaches the steady state condition. It provides stable operation but always maintains the steady state error; therefore it requires biasing or manual reset when used alone. Speed of the response increase along with the proportional constant Kc.

The use of proportional-only control has a sustained error that cannot be eliminated by proportional control alone.

3.1.2 Integral Control Mode

The need for manual reset, as described above, led to the development of automatic reset. The function of the integral control mode is to increase or decrease the controller’s output over time to reduce the error, as long as there is any error present (process variable not at set point). Given enough time, the integral action will drive the controller output until there is no error.

If the error is large, the integral mode will increase or decrease the controller output at a fast rate; and if the error is small then the changes will be slow. For a given error, the speed of the integral action is set by the controller's integral time setting (Ti). A long integral time (Ti) results in a slow integral action, and a short integral time results in a fast integral action [Figure 19: Integral control action]. If the integral time is set too long, the controller will be sluggish; but if it is set too short, the control loop will oscillate and become unstable.

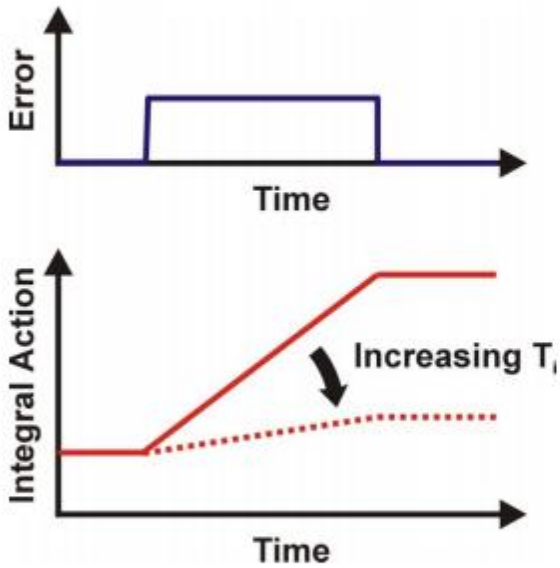

Figure 19: Integral control action

3.1.2.1 I-Controller

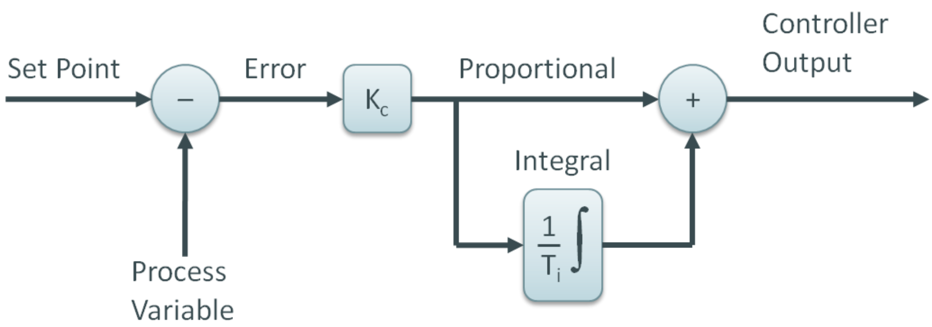

Figure 20: PI controller

I-controller provides necessary action to eliminate the steady state error. It integrates the error over a period of time until error value reaches to zero. It holds the value to final control device at which error becomes zero.

Integral control decreases its output when negative error takes place. It limits the speed of response and affects stability of the system. Speed of the response is increased by decreasing integral gain Ki.

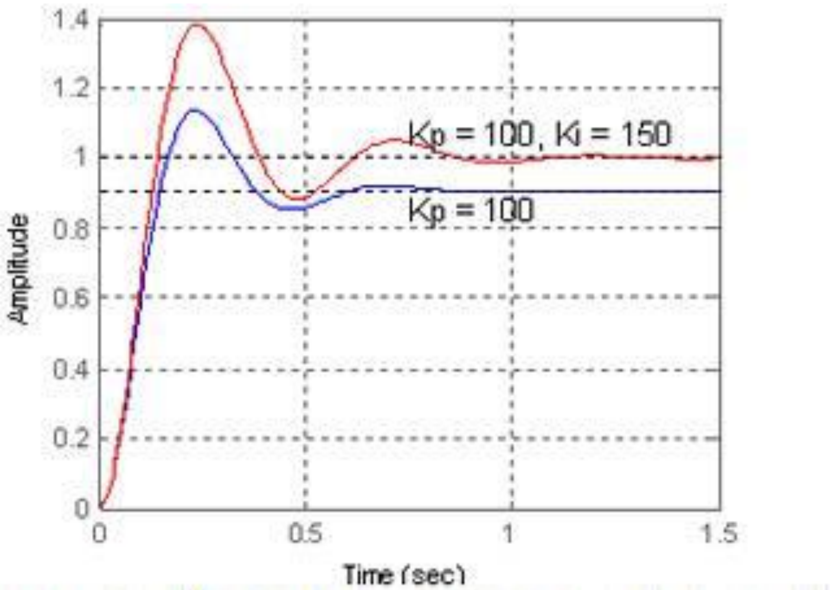

Figure 21: Closed loop response of P versus PI Controller

As the gain of the I-controller decreases, steady state error also goes on decreasing [Figure 21: Closed loop response of P versus PI Controller]. For most of the cases, PI controller is used particularly where high speed response is not required.

While using the PI controller, I-controller output is limited to somewhat range to overcome the integral wind up conditions where integral output goes on increasing even at zero error state, due to nonlinearities in the plant.

3.1.3 Proportional + Integral Controller

The proportional + integral controller's output is made up of the sum of the proportional and integral control actions. The PI controller is the most popular variation. The value of the controller output u(t) is fed into the system as the manipulated variable input.

e(t) = SP – PV

u(t) = ubias + Kce(t) + $\frac{Kc}{TI}\int_0^t e(t)dt$

3.1.4 Derivative Control Mode

The third control mode in a PID controller is the derivative control mode. Derivative control is rarely used in controlling processes, although it is often used in motion control. It is very sensitive to measurement noise, and it makes error tuning more difficult, therefore it is not absolutely required for process control. Nevertheless, using the derivative control mode of a controller can make certain types of control loops respond a little faster than with PI control alone.

The derivative control mode produces an output which is based on the rate of change of the error [Figure 22: Derivative control action]. The derivative mode produces more control action if the error changes at a faster rate. If there is no change in the error, the derivative action is zero. The derivative mode has an adjustable setting called Derivative Time (Td). The larger the derivative time setting, the more derivative action is produced. A derivative time setting of zero effectively turns off this mode. If the derivative time is set too long, oscillations will occur and the control loop will run unstable.

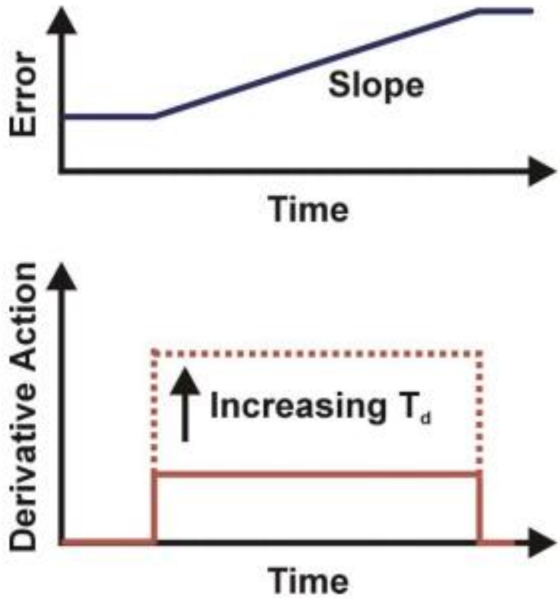

Figure 22: Derivative control action

Two units of measure are used for the derivative setting of a controller: minutes and seconds.

3.1.5 D-Controller

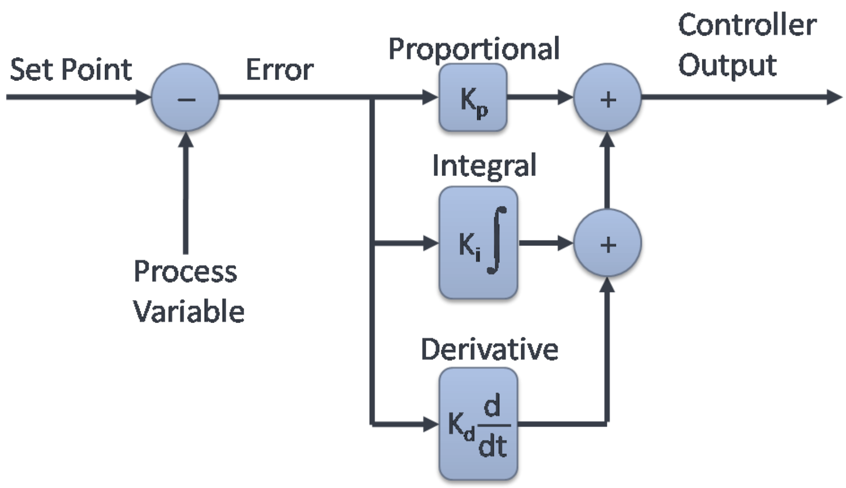

Figure 23: PID controller

I-controller doesn't have the capability to predict the future behavior of error. So it reacts normally once the set point is changed. D-controller overcomes this problem by anticipating future behavior of the error. Its output depends on rate of change of error with respect to time, multiplied by derivative constant. It gives the kick start for the output thereby increasing system response.

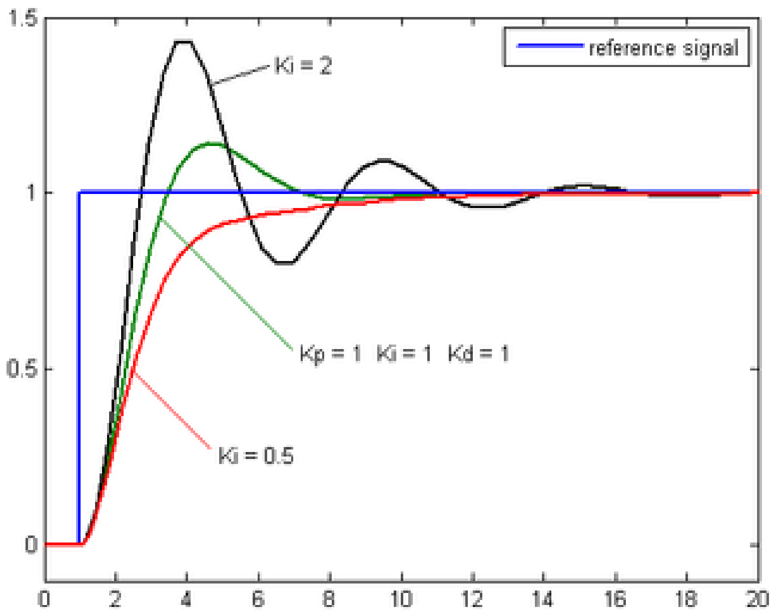

Figure 24: PID Controller Response

In the above figure response of D controller is more, compared to PI controller and also settling time of output is decreased. It improves the stability of system by compensating phase lag caused by I-controller. Increasing the derivative gain increases speed of response.

3.1.6 Proportional + Integral + Derivative Controller

Commonly called the PID controller, the Proportional + Integral + Derivative controller's output is made up of the sum of the proportional, integral, and derivative control actions.

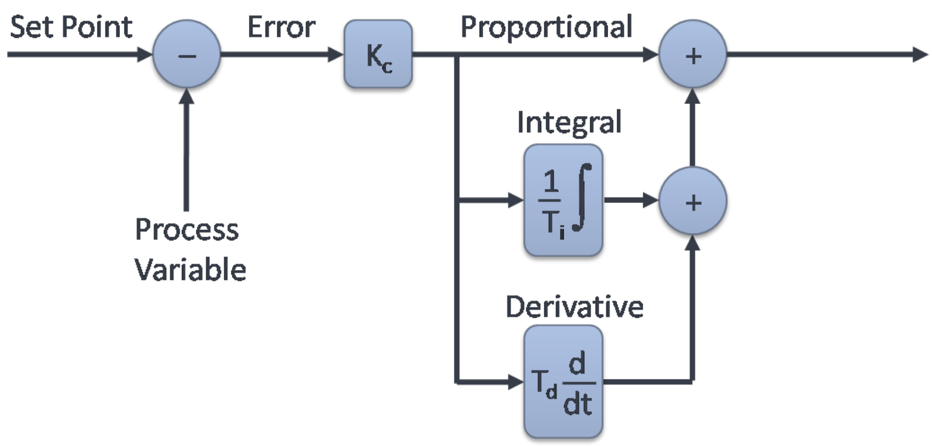

Figure 25: Non-interactive PID controller

The derivative mode of the PID controller provides more control action, and sooner, than it is possible with P or PI control. This reduces the effect of a disturbance and shortens the time it takes for the level to return to its set point [Figure 26: PID controller's response to a disturbance].

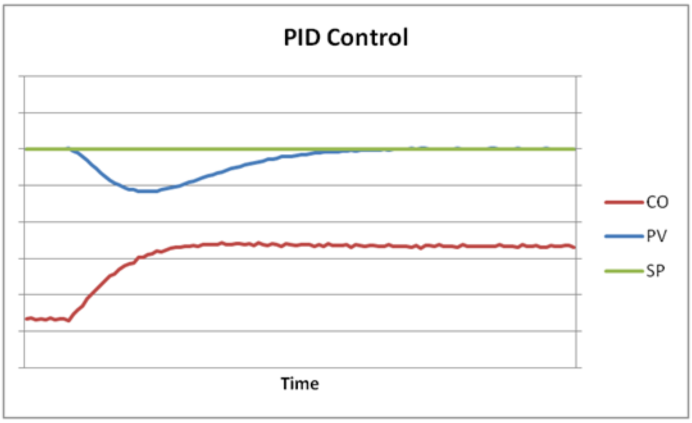

Figure 26: PID controller's response to a disturbance

Figure 27: P, PI and PID controller's response to a disturbance, compares the recovery under P, PI, and PID control of the process heater outlet temperature after a sudden change in fuel gas pressure as described above.

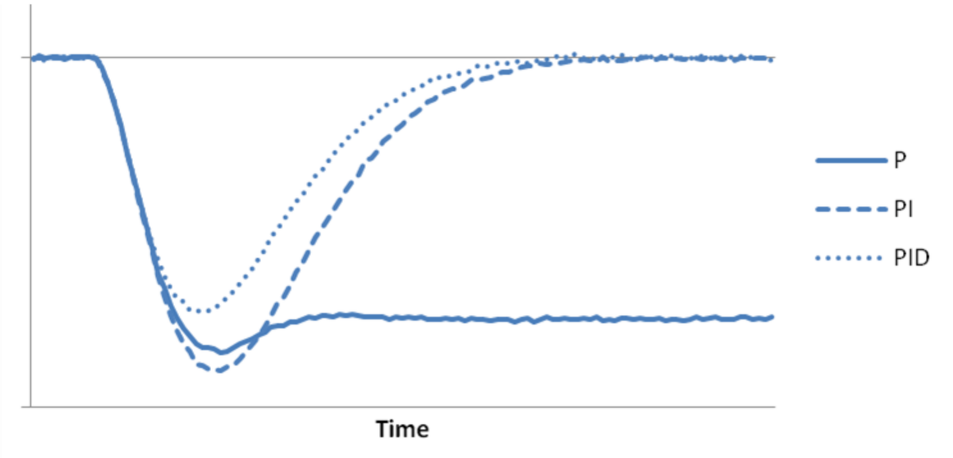

Figure 27: P, PI and PID controller's response to a disturbance

3.2 Tuning methods of PID Controller

Before the working of PID controller takes place, it must be tuned to suit with the dynamics of the process which is to be controlled. Even if the default values for P, I and D terms are given, these values couldn't give the desired performance - and sometimes they lead to instability and slow control performances.

Different types of tuning methods have been developed to tune the PID controllers and they require much attention from the operator to select the best values of proportional, integral and derivative gains.

3.2.1 Trial and Error Method

It is a simple method of PID controller tuning. We can tune the controller while the system or controller is working. First we have to set Ki and Kd values to zero and increase proportional term (Kp) until the system reaches oscillating behavior. Once it is oscillating, we adjust Ki (Integral term) so that oscillations stop. Finally we adjust D to get a faster response.

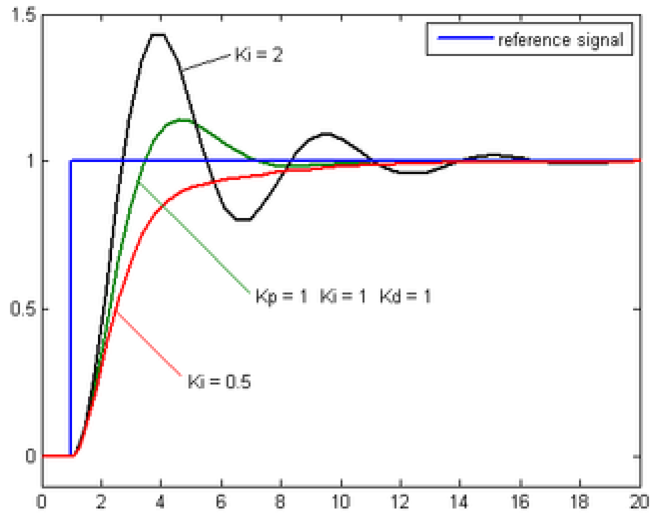

Figure 28: PID controller response

3.2.2 Process reaction curve technique:

This is an open loop tuning technique. It produces response when a step input is applied to the system. First we have to apply some control output to the system manually and then we record the response curve.

After that we need to calculate:

- slope,
- dead time,
- rise time of the curve

Then we need to substitute these values in P, I and D equations to get the gain values of PID terms.

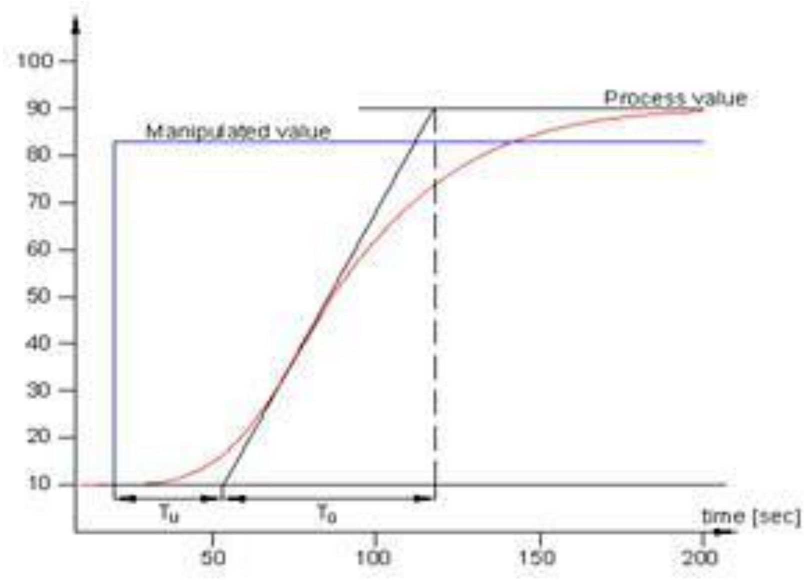

Figure 29: Process reaction curve

3.2.3 Zeigler-Nichols method

Zeigler-Nichols proposed closed loop methods for tuning the PID controller. Those are a continuous cycling method and a damped oscillation method. The procedures for both methods are the same, but the oscillation behavior is different. In this case, first we have to set the p-controller constant (Kp) to a particular value while Ki and Kd values are zero. Proportional gain is increased until the system oscillates at constant amplitude.

The Gain at which a system produces constant oscillations is called ultimate gain (Ku) and the period of oscillations is called ultimate period (Pc). Once it is reached, we can enter the values of P, I and D in PID controller by Zeigler-Nichols table, depending on the controller used like P, PI or PID, as shown below.

Controller	Kp	Ki	kd
P	Ku/2	-	-
PI	Ku/2.2	Pu/1.2	-
PID	Ku/1.7	Pu/2	Pu/8

Table 1: Zeigler-Nichols tuning chart

3.3 Selection of the proper control method

In a closed loop control system, the process of reading sensors to provide constant feedback and calculating the desired actuator output is repeated continuously and at a fixed loop rate.

Once the performance requirements have been specified, it is time to examine the system and select an appropriate control scheme. In the vast majority of applications, a PID control will provide the required results.

4. Maintenance methods

In an ideal world, valves in a process would go unnoticed and remain problem-free throughout a line’s entire functional lifetime. Valve integration cannot be ignored quite so easily. These components are indispensable for automated production processes, to ensure the appropriate routing paths and to shut off flows. They are required to exhibit maximum reliability in terms of design and function, and to be sturdy enough to effortlessly cope with any events occurring during process.

If a valve should fail, serious risks can take place – environmental impact, production loss or, even worse, personnel safety. If valves need to be properly maintained to avoid any of these scenarios, then it is important to determine when and how often they should be serviced.

Valves which have been examined after years of service, have shown that the number of open/close cycles that a valve experiences is not a reliable single criteria for preventive maintenance. The environment plays a key role in a valve’s life expectancy. Poorly exhausted enclosures and chemical leaks onto valve exteriors and other environmental conditions can negatively affect valve life.

An integrated approach to valve maintenance planning requires the consideration of many factors that may contribute to downtime, safety and environmental risks.

The right maintenance plan can save plants or vessels, both cost and downtime, thereby improving efficiency and allowing operations to run smoothly. This means that there’s a need for an effective maintenance program. The ideal maintenance program should be able to use a medley of different maintenance modes to make sure that the operation runs efficiently and effectively.

4.1 Reactive Maintenance

This is a plan that essentially operates on run to failure strategy, a hands-off approach which keeps low routine maintenance costs, but can be costly in the long run. It focuses on restoring equipment to normal operation after a breakdown, by replacing or repairing faulty parts and components.

Reactive Maintenance requires minimal maintenance costs and fewer staff members However, this is as far as these advantages go. When a machine fails without warning, it creates downtime, which can get quite expensive. This also drives up labor costs to get the apparatus back up and running, since in some cases back-up equipment is not easy to acquire, workers need to stop what they're doing to attend to the problem and especially if there's need for overtime.

4.2 Preventive Maintenance

Preventive maintenance has been more popular in principle than in practice over the years. One scarcely can argue with the idea of keeping equipment well maintained to extend its expected life and avoid future repair costs. Less clear is an understanding of the actual relationship between the cost of preventive maintenance and the returns such activities can be expected to deliver. [9]

Preventive Maintenance, when executed properly, can reduce overall costs in both the short and long term. It is event based. While there is still a risk of failure occurring, there's a far greater chance of catching and correcting issues before they become major problems. This requires more labor to perform tasks that may seem unnecessary, since it involves maintenance at specified time intervals.

The primary advantage of a Preventive Maintenance plan is cost effectiveness when it comes to the most expensive maintenance processes. The goal is to prevent failure by performing regular maintenance. Also, since everything operates in a most efficient way, it can save energy.

4.3 Predictive Maintenance

Predictive maintenance is a data-driven approach. It is based on the results of monitoring and testing equipment performance, by routinely inspecting using various developments including infrared and ultrasound technology. This maintenance mode works to eliminate unexpected breakdowns and scheduled maintenance down time that would otherwise be used to inspect a valve piece by piece.

Algorithms are critical to predictive maintenance success. Data in the form of temperature, pressure, voltage, noise, or vibration measurements is collected using dedicated sensors. It is processed using various statistical and signal processing techniques. This data is then used to monitor the health of the equipment by comparing it against the established markers of faulty conditions using data clustering and classification. In a model-based approach, this data can also be used to build predictive models of the system's behavior for condition-monitoring. This model is then employed to track changes in the equipment's condition and predict its remaining useful life.

4.4 Proactive Maintenance

This mode differs from the other three, because it addresses much more systemic elements of a maintenance program, rather than examining the machine itself. This approach is much more diligent and looks to control the problems that can lead to machine wear and tear as opposed to the deterioration itself.

It is based on the philosophy that supplants "failure reactive" with "failure proactive" by activities that avoid the underlying conditions which lead to fault and degradation. It aims at failure root causes and not failure symptoms. The root idea is to extend the "operational life" instead of making repairs – often in cases when nothing is wrong – or detecting impending failure conditions followed by remediation.

There are a number of techniques that are used to enact a proactive maintenance solution. For instance, making sure to train employees in the best practices for machine operation or using a chain of reliable suppliers for machine elements are great ways to help improve maintenance systems.

4.4.1 The outline of a proactive maintenance approach

Because most equipment fails at random ages, it should be examined regularly using predictive technologies. Time-based proactive maintenance should primarily be used to measure and identify age-related deterioration. A well-managed planning and scheduling process should ensure that the corrective actions are performed in an efficient manner.

This kind of program minimizes exceptions and investigations for equipment failure. The maintenance group sends the quality and operations groups weekly or daily reports, and important findings for each piece of equipment are stored in the maintenance-management system database. This program increases the equipment's capacity and reduces its costs of operation.

A proactive maintenance model fits perfectly into the corrective and preventive action process.

4.5 A balanced approach

Balance is important to every part of life. Having too much of any one thing can lead to major consequences, even with the best of intentions. Relying on a single strategy for every scenario can lead maintenance teams down a dark path. But how easy is it to create a balanced maintenance program?

The best maintenance plan is one that balances elements of each of these modes. There are reliability-centered maintenance programs which are largely less than 10 percent reactive, between 25 and 35 percent preventive and between 45 and 55 percent predictive.

Obviously, Proactive Maintenance is missing from this breakdown, but this could be because it is more of an approach-based strategy, rather than one that addresses maintenance directly. A proactive maintenance plan can help make these programs operate more efficiently and limit some of the major expenses that can emerge from putting a plan into action.

The end goal of a maintenance program is making sure that facilities are constantly up and running. As a result, it is important to make sure that these plans account for the machines and facilities that are unique to a plant and its operations.

Here are some aspects that should be taken into consideration when designing a balanced maintenance program for a specific case.

- Asset type and hierarchy. It is necessary to review how the valves operate and how important they are for the operation.
- Production/ operation and reliability. It is important to take into account the amount of time the equipment produces revenue (critical material), the impact of downtime on production and how long it can function efficiently before failure.
- Technology and budget. It is crucial to consider the quality of technology available to a facility or vessel and the financial ability to invest in technology when determining the right mix of maintenance practices.

	Maintenance types		
Maintenance considerations	Reactive maintenance	Preventive maintenance	Predictive maintenance
Asset type and hierarchy	▪ Assets are not critical to production ▪ Have no measurable time, meter or usage trigger	▪ Assets are operation critical ▪ Cost substantial time and money to repair ▪ Have measurable triggers	▪ Assets are operation critical ▪ Have failure modes predicted with regular monitoring ▪ Provide sufficient warning prior to failure
Production and reliability	▪ Assets have high reliability ▪ Have neither zero, low or very frequent production	▪ Assets have to moderate reliability ▪ Have low, moderate and high production	▪ Assets have low to moderate reliability ▪ Have low, moderate and high production

	Maintenance types		
Maintenance considerations	Reactive maintenance	Preventive maintenance	Predictive maintenance
Technology and budget	▪ Assets have very simple systems ▪ Cannot integrate easily with technology ▪ Are not expensive to repair	▪ Assets have moderate or highly complex systems ▪ Can integrate with technology ▪ Are highly expensive to repair	▪ Assets have cmplex systems ▪ Can integrate well with predictive technologies ▪ Are expensive to repair ▪ Ability of a facility or vessel to invest in potentially expensive technology

Table 2: Maintenance types per case

4.5.1 Use of maintenance metrics

Data is essential when determining which maintenance method is the most cost-effective. There are two metrics which can offer essential information:

- Mean time to repair
- Overall equipment effectiveness

Mean time to repair is the average time required in order to repair broken equipment and put it back to normal operating conditions. This way maintenance teams can measure the economic impact of unplanned downtime for each asset.

Take as an example a light bulb scenario. The mean time to repair for a light bulb may be five minutes every month, while preventive maintenance could take 10 minutes every month. Therefore run to failure is the most time and cost effective solution.

Overall equipment effectiveness refers to the availability of equipment, its performance versus technical specifications, and its production quality. Comparing an asset's overall equipment effectiveness percentage in all scenarios - with reactive, preventive and predictive maintenance – is way to evaluate which method is best for the bottom line.

For example, if a car breaks down less and needs less gas when the oil is changed at regular intervals, then preventive maintenance is the best approach.

Since collecting solid data s crucial when creating a balanced maintenance program, it's important to make this process easy by using a Computerized Maintenance Management Software. Such software allows users to track key metrics without having to shuffle through stacks of paper or Excel spreadsheets. It also provides a a simpler option for running reports and analyzing data, so that better decisions are taken faster.

Knowing how to combine preventive, reactive, and predictive into one, highly functioning plan may take a lot of work. But with the help of a maintenance software, it's possible to bring these strategies together in harmony.

Once the maintenance management program is set up properly, the amount of reactive maintenance due to equipment breakdowns will decrease, while time spent on preventive maintenance will increase. Cost savings in maintenance budget will appear, due to less emergency maintenance – plus the benefits in terms of better equipment availability, less downtime, increased production, fewer backlogs and a safer workplace.

4.6 Determining the economic value of preventive maintenance

In order to establish if it is worthy to invest in preventive maintenance when it comes to flow control valves, a study was executed. In order to determine the value of preventive maintenance the following aspects had to be identified:

- Actual cost of preventive maintenance
- Cost of repair maintenance
- Cost of replacing the valves
- Expected useful life of valves
- Effects of preventive maintenance on expected useful life
- Frequency of required repairs when valves are not maintained
- Effect of preventive maintenance on vessel's idle time.

The most difficult information to obtain was the latter, the effect of preventive maintenance on vessel's idle time. In order to identify those data operation manuals were studied, manufacturers provided information and articles on preventive maintenance were reviewed.

Although the main message was that preventive maintenance would extend the life of equipment, few sources provided estimates of the amount of life added.

4.6.1 Analysis

Supposing that a vessel has a ballast water treatment unit installed, and is operating it for five years. The unit is using flow control valves to regulate flow. Replacing these valves would cost 5.803€. Would an investment in preventive maintenance be justified?

With the information gathered, the valves will last approximately ten (10) years with proper preventive maintenance but only six (6) without it. Repairing the valves will cost 654,50€ per incident. If maintained properly, it will need to be repaired once every four (4) years. If they are not maintained they will need to be repaired every two (2) years.

Given these variables, and assuming a time frame of twelve (12) years, the results will prove if an investment in preventive maintenance is justified.

Applying preventive maintenance, the equipment will need to be repaired once every four years at a cost of 1.424,50€, a figure that translates to 356,13€ per year. . Lacking preventive maintenance, the valves can be anticipated to need repairs once every two (2) years at a cost of 1.309€, with the annual cost of 654,50€.

With preventive maintenance (PM), the valves will need to be replaced in ten (10) years. Without PM they will have to be replaced twice, in year six (6) and in year twelve (12). Comparing the two cases indicates that the one with PM has the amount of 1.078€ in gain. If the time period is extended to twenty five (25) years, the valves will need to be replaced twice in the PM case (instead of four times in our alternative), increasing the amount to 15.302€.

	With PM	**Without PM**
Every 2 years	-	1.309,00 €
Every 4 years	1.424,50 €	2.618,00€
After 12 years	8.652,00 €	9.730,00 €
After 25 years	13.146,00 €	28.448,00 €

Table 3: Calculation of repair cost over the years

For simplicity purposes, this example does not consider inflation, residual value, or lost revenue from downtime.

Three different scenarios were examined to further investigate if preventive maintenance has added value. For these scenarios, the following considerations were taken into account:

- All repairs will be made at the port of Shanghai.
- Cargo freight for a 20day voyage, on a 2016 built vessel
- The time-frame of the calculations will be 12 years

4.6.1.1 Scenario #1

It is assumed that the shipping company spends nothing on PM, reducing the PM cost to zero in this case. The cost of repair maintenance, the cost of downtime and the frequency of equipment replacement will increase, however, since the equipment will not be properly maintained. It is assumed that the frequency of repairs will increase in an amount similar to the expected-life degradation, which translates to an increase in downtime cost.

4.6.1.2 Scenario #2

In this case, the vessel carries stock of the sensitive components. PM cost remains zero, the cost of repair maintenance is reduced as well as the downtime cost. The frequency of equipment replacement is still increased but the cost of stocked items is added.

4.6.1.3 Scenario #3

This scenario assumes that the shipping company spends the industry benchmark amount on preventive maintenance activities. This scenario also assumes that the valves will last their full expected life and that downtime will be reduced to the zero.

4.6.2 Results

For each scenario the yearly cost of operating the valves was calculated, and a timeline of expenditures was built. The cost consisted solely of repair and preventive maintenance, stocked and replaced equipment.

The average life of the valves was used in order to determine when the items would need to be replaced.

Cost estimation for 12-year period	Scenario #1	Scenario #2	Scenario #3
Equipment in stock cost	0,00 €	3.372,00 €	0,00 €
Preventive maintenance cost	0,00 €	0,00 €	1.620,00 €
Repair maintenance cost	2.848,00 €	3.972,00 €	1.424,00 €
Downtime cost	230.454,55 €	230.454,55 €	76.818,18 €
Equipment replacement frequency	6	6	3

Table 4: Cost estimation for each scenario in a 12-year timeframe

The following figures indicate how the cost is divided per scenario. It is clear that the major issue is downtime.

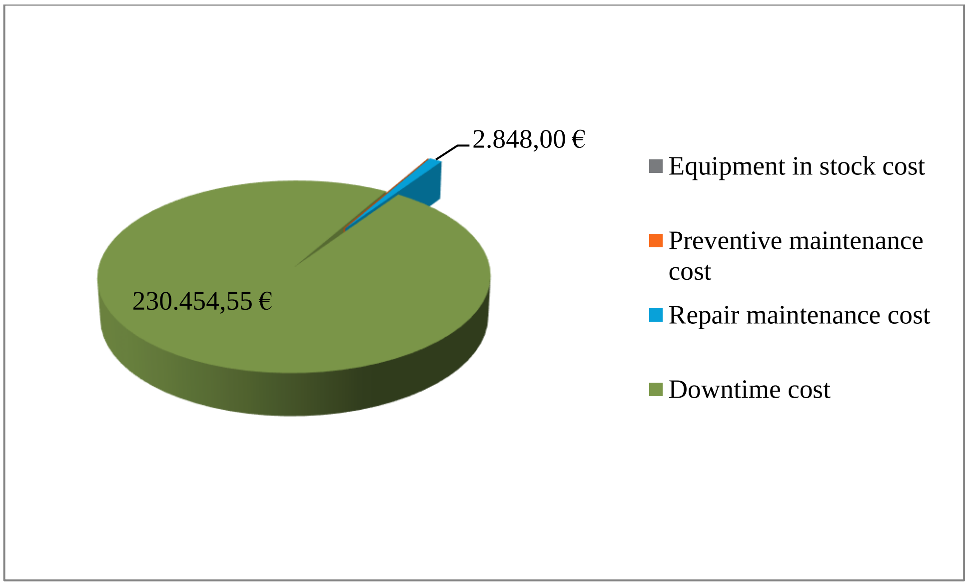

Figure 30: Cost estimation in a 12-year timeframe for Scenario #1

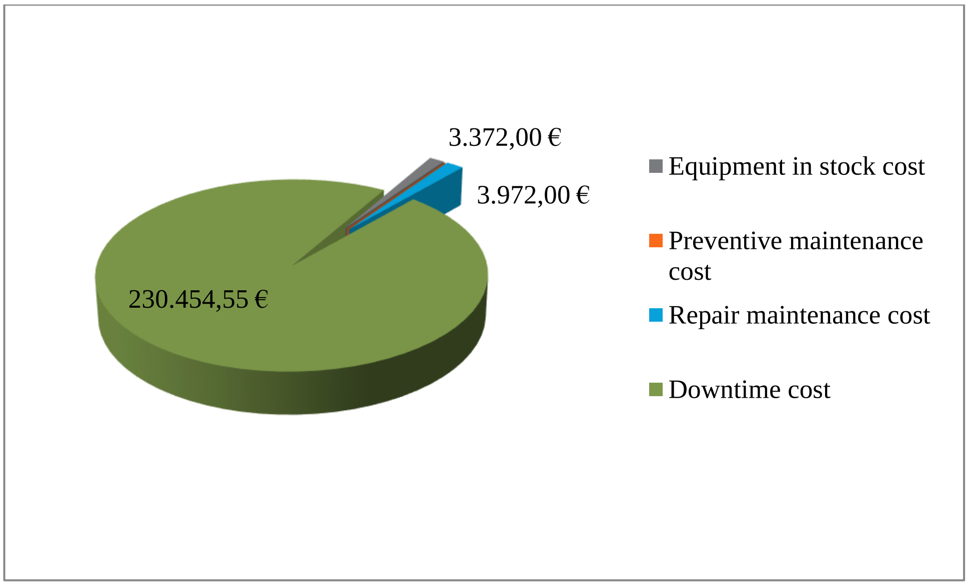

Figure 31: Cost estimation in a 12-year timeframe for Scenario #2

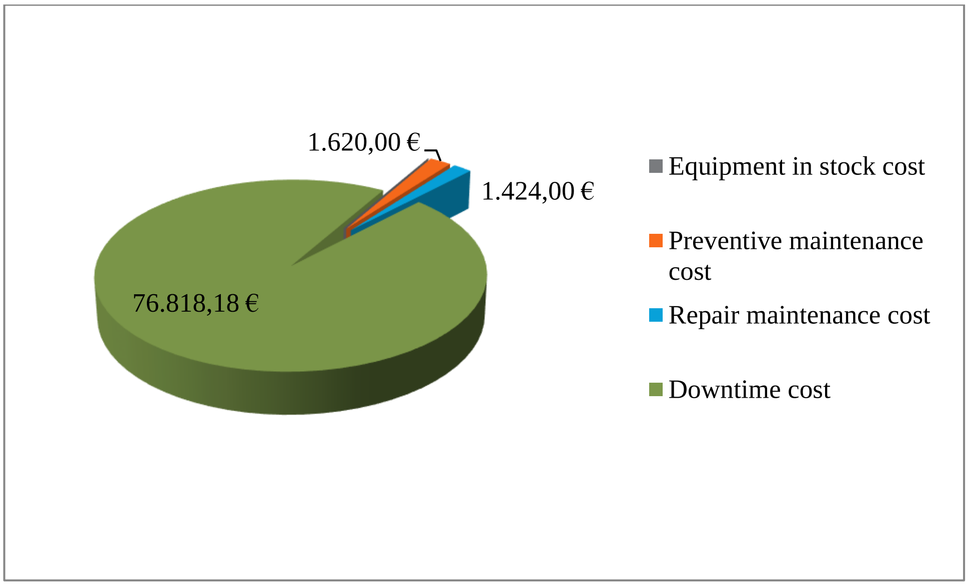

Figure 32: Cost estimation in a 12-year timeframe for Scenario #3

In Table 5 the breakdown of costs in annual level is provided, followed by a comparative chart. The annual cost consisted of the following parameters:

- Equipment in stock
- Preventive maintenance
- Repair maintenance
- Downtime

Years	Scenario #1	Scenario #2	Scenario #3
1	0,00 €	1.686,00 €	135,00 €
2	40.957,09 €	40.230,09 €	135,00 €
3	0,00 €	1.686,00 €	135,00 €
4	40.957,09 €	40.230,09 €	40.130,09 €
5	0,00 €	1.686,00 €	135,00 €
6	5.803,00 €	5.803,00 €	135,00 €
7	0,00 €	1.686,00 €	135,00 €
8	40.957,09 €	40.230,09 €	135,00 €
9	0,00 €	1.686,00 €	40.130,09 €
10	40.957,09 €	40.230,09 €	5.803,00 €
11	0,00 €	1.686,00 €	135,00 €
12	5.803,00 €	5.803,00 €	135,00 €
TOTAL	**175.434,36 €**	**182.642,36 €**	**87.278,18 €**

Table 5: Annual cost estimation for each scenario

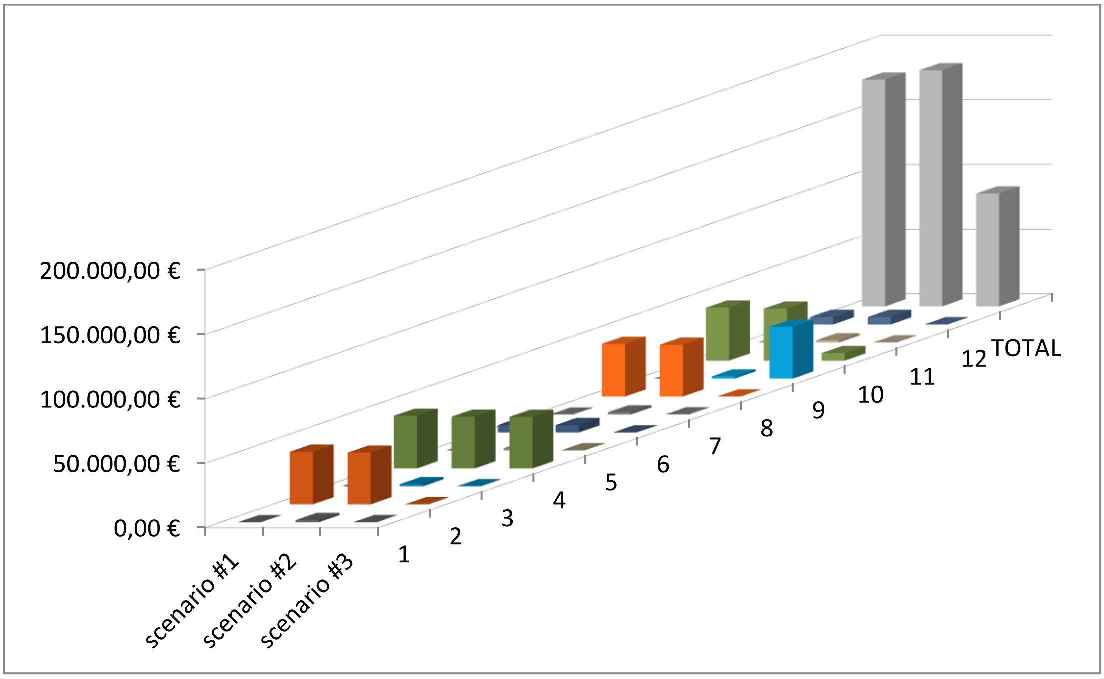

Figure 33:

4.6.3 Conclusion

The results of the analysis comparing the scenarios were overwhelmingly positive for performing preventive maintenance. Obviously, replacing equipment in later years is superior to replacing equipment earlier.

When it comes to shipping, one of the major problems is downtime cost. The analysis indicates that the expenses can be pushed out over time and can be programmed in such a way that the cost is reduced significantly.

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