THE DEVELOPMENT OF A MODEL FOR THE ANALYSIS OF HYDROCARBON RELEASE (HCR) FOR A FULL BORE RELEASE AGAINST THE SPEED OF CLOSURE OF THE EMERGENCY SHUT-DOWN VALVE (ESDV)

BY

TUOKPE BRIKINNS, B.Sc.

A dissertation submitted in partial fulfillment of the requirements of the award of Master of Science in Safety and Reliability Engineering at the University of Aberdeen

(September, 2012)

ABSTRACT

The Emergency Shutdown Valve ESDV is a safety critical element used as a major barrier to stop the escalation of dangerous event from happening beyond control system or human intervention especially in a case of Full bore Rupture FBR. The time of closure is of great importance because it actually determines how the ESDV eventually performs in minimizing HCR inventory loss to the environment.

This study considered the use of VBA in Excel environment to model and analyzes the effect of variant HCR parameters on the time of closure of the ESDV of a gas pipeline. Parameters of major importance used in the model were, differential pressure, fluid velocity and volumetric flow rate. The valve size used for this model was 150mm nominal diameter ball valve type.

The result suggests that a faster closure time will minimize inventory loss of HCR in-terms of the eventual volumetric outflow at the rupture point of a gas pipeline. It also concludes that pressure increase is the most varying HCR parameter effecting the time of closure of an ESDV. It finally explains the concept of time subsequent to closure which explains what happens to HCR inventory after total time of closure. The study suggests that a faster ESDV will reduce the time subsequent to closure which shows a time decaying relationship with varying HCR Parameters in a gas pipeline during FBR conditions.

DEDICATION

This project work is dedicated to my affectionate parents, Mr. and Mrs. G. Brikinns, my beloved brother Mr. Brikinns, T. my sister in-law Mrs. Brikinns, E., and my fiancée Miss Ugbesia, C. as a token of my appreciation for their love, patience and understanding.

ACKNOWLEDGEMENT

I wish to express my sincere gratitude to my supervisors, Dr. J. John C. and Mr. Peter Adam, who stirred up my interest with their guidance and encouragement. I also express my appreciation to the entire staff of the Safety and Reliability department who gave me both moral and academic support.

Great thanks to all my lecturers in my department, Dr. John Hariagn, Dr. S. Sriramula, to my Mentor Mr. Tom McLaren and Mr. Mike Bilio. I appreciate you for all the knowledge, direction and advice you gave to me.

Very many thanks to my brother, Mr. Brikinns, T. who kindly read through the script and made suggestions toward the progress of this work.

Furthermore, I extend my sincere appreciation to my friends, Yomi Obisesan, Edet Ebiekpe and Leziga Bakor who were my source of inspiration.

Finally, I salute all my mates for their support, determination towards success and for making the class interesting.

Above all, I rejoice always with praises to give Glory and Honour to my Lord, whose favour I sought and found.

TABLE OF CONTENTS

CONTENTS	**PAGE**

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND NOTATION

A_f	Valve flow Area for ball valves (mm^2)
A_0	Valve flow area for butterfly valves (mm^2)
A_v	Valve opening Area for Butterfly valves (mm^2)
A_{c_r}	The area of hole of Puncture (mm^2)
A_{pipe}	Cross-sectional area of pipe (mm^2)
c	Celerity (m/s)
C_d	Valves Coefficient of discharge.
C_o	Coefficient of discharge from rupture
C_T	Dynamic flow Coefficient
i_1	Boundary upstream section of pipeline close to rupture point
k_2	Boundary Downstream section of pipeline close to the valve.
J_0	Rupture Junction.
L_k	Distance of pipeline from rupture point to valve (m)
$\dot{m}$	Maximum release rate of gas (kg/s)
α	Decay constant
P_i	Initial pipeline pressure (bar)
P_j	Pressure at rupture junction (bar)
P_u	Final outflow pressure downstream of valve (bar)
P_k	Initial inflow pressure upstream of valve (bar)
ΔP	Differential pressure (bar)
ρ	Fluid density (kg/m^3)
Q	Volumetric flow rate across valve (m^3/s)
Q_i	Total Volumetric flow Upstream before rupture junction (m^3/s)
Q_j	Volumetric flow at rupture junction (m^3/s)
Q_k	Volumetric flow upstream of valve (m^3/s)
Q_{rk}	reverse volumetric flow (m^3/s)
$Q_{outflow}$	Total Volumetric outflow (m^3/s)
Q_{mj}	mass outflow of fluid @ rupture junction (kg/s)
γ	Specific gravity of gas.
t_c	Valve time of closure (s)
t_{c_i}	Discrete time at which equations are solved numerically(s)
Δt_{ci}	Valve closure time interval(s)
u(t)	Fluid velocity at time t (m/s)
$u_r(t)$	reverse velocity of fluid @ time t (m/s)
Δu	time dependent Fluid velocity (m/s)
V_Z	Limiting volume of gas release.
z_c	Standard Normal Space for Celerity
z_p	Standard Normal Space for Pressure
z_ρ	Standard Normal Space for Density

LIST OF ABBREVATION

ALARP	As low As Reasonably Practicable.
ANSI	American National Standard Institute
API	American Petroleum Institute
ASME	American Society for Testing and Materials
BSI	British Standards Institution
CAPEX	Capital Expenditure
CBA	Cost Benefit Analysis
C5	Cast Carbon Steel grade 5
CENELEC	The European Committee of Electrochemical Standardization
CF8M	Austenitic Stainless Steel
CWP	Cold Working Pressure
EExd	Flame proof Protection
EExi	Intrinsic Safety Classification
EExn	Type n Protection
DC	Diagnostic Coverage Factor
ESD	Emergency Shutdown
ESDV	Emergency Shut-Down Valve
FERUM	Finite Element Reliability Using Matlab
HC	Hydrocarbon
HCR	Hydrocarbon Release
ICAF	Implied Cost of Averting a Fatality
IEC	International Electro technical Commission
IR	Individual Risk
ISO	International Standard Organization
LEL	Lower Explosive Limit.
PFD	Probability of Failure of Demand

PLC	Programmable Logic Controller
PLL	Potential Loss of Life
PPS	Pneumatic Pressure Switch
PST	Partial Stroke Test
QEV	Quick Exhaust Valve
QRA	Quantitative Risk Assessment
RBD	Risk Based Design
SCE	Safety Critical Element
SDV	Shutdown Valve
SCFH	Standard Cubic Feet per Hour
SCFM	Standard Cubic Feet per Minute
SIL	Safety Instrumented Level
SIS	Safety Instrumented System
SOV	Solenoid Valve
VT	Volume Tank
WCB	Weldable Cast-B grade Carbon Steel

CHAPTER ONE

INTRODUCTION

1.1 General Background

An Emergency Shutdown Valve is an actuated valve designed for the isolation and segregation of Hydrocarbon Release HCR inventories upon detection of a dangerous event in sections of plants or entire plant. Also it is well known that the petroleum industry is involved in the transportation of highly flammable pressurized hydrocarbons in long pipes. Any possible release caused by rupture of pipelines serving as a containment vessel during production, processing and transportation of hydrocarbons HC can lead to a serious incident. This off-course increases the likelihood of a serious safety hazard in cases of HCR in Full Bore Release FBR situations during transportation. Apart from, total or unit shutdown of systems in a plant, the ESDV is part of the Safety Critical Element SCE. That is why it is of up-most importance that this SCE works to its maximum capacity. The ESDV is designed to close fast in an event of full bore pipeline rupture, an event poised to risk of an extreme fire/gas explosion with a possible source of ignition, especially in remote areas like an offshore platform. Such incidents like Piper Alpha tragedy and the BP Horizon in GOM incident would have been averted if the ESDV systems one of the barriers needed to mitigate such incident were functional.

The ESDV is always needed for rapid response in situations of emergency. This means that the availability of such element must be high. Consequently, it must have a high reliability on demand when requested to perform its function during such situations, meaning that the ESDV must maintain a good isolation under emergency conditions.

Generally, the ESDV is closed in two basic scenarios **(1)**. The first case is known as a Process Shut down PSD, when isolation is provided as part of a normal process shutdown when equipment on a platform is shut down and processing of hydrocarbon is ceased. The second case is in an Emergency Shutdown ESD situation; this is to provide total isolation during emergency situations. This could include; a leak, a fire and an explosion event which could be injurious to personnel, facilities and the environment **(1)**

Hence, the time of closure a design parameter that corresponds to the time it takes for the valve to close when it is activated is a very significant factor which can be used to determine the actual performance of the ESDV. An actual norm in the industry expected of any ESDV is a closure time of 1 second for every 1 inch diameter of pipe **(2)**. A major problem faced by Safety Engineers is the choice of appropriate valves that responds fast to inventory loss following a FBR situation. A major reason is because a massive amount of inventory is released in a very short space of time. Invariably, the time of closure of an ESDV should influence the appropriate choice of and selection to guarantee an inherently safe design factor.

This study is to provide ways to implement better design approach in determining the accuracy of speed of closure, also to see how the speed of closure of an ESDV can be improved upon in a FBR situation. It also involves ways to determine the interaction of HCR parameters with the time of closure of an ESDV.

1.2 Objectives

The main objectives of this work are as follows:

- To review the different types of ESDVs and their applications
- To review the operation of ESDV in order to model the response understanding all parameters affecting the ESDV.
- To determine the total time of closure significance of an ESDV
- To establish relationship with time of closure of an ESDV with HCR inventories.
- To develop a programmable application used to determine the closure time of various ball valve sizes used for ESD procedures.
- To determine the Cost Benefit Analysis of using quick closing ESDV valves.

1.3 Scope of Study

The work is however limited in scope as follows:

- The study shall involve the use of past reports, standards, transient flow equations and HCR inventory data from manufacturers and incident during FBR situations. Properties of HCR parameters which shall be considered are; flow rate, pressure, diameter of pipe, length of pipe and volume.

1.4 Justification of Study

The increasing need of inherent safety designs in the oil and gas industry because of past incidents of hazardous event is becoming alarming. More so, the oil and gas industry deals with chemicals prone to activities of Major Accident Hazards MAH. An ESDV is designed to close fast during emergency cases; time of closure is a major design criterion to determine this critical component's functionality.

There is therefore a need to determine a model to improve on the time of closure of an ESDV, which will proffer better design approach in determining emergency response of such SCE.

1.5 Concept of 1 second/inch Closure time of the ESDV

The major factors that affect the speed of closure of the ESDV are the standard speed of operation which is dependable on the valve's torque or thrust and the differential pressure to which the valve is subjected to under operational conditions. Other factors which affect the speed of closure includes; the discharge coefficient of the valve, volumetric flow rate and the degree of openness of the valve disc attached to the stem of a valve assembly.

The maximum torque or thrust is connected to the force produced by the actuator of the valve. For offshore pipeline ESDV's in the United Kingdom, the speed of closure should be in accordance with SI 1029. Also for hydraulic or pneumatic linear actuators the standard speed of operation is "1 Inch/Second" or 2.54 cms^{-1} and the standard speed for electrical actuators is 24rev/min **(2)**.

1.6 Project Overview

The project extensively discusses about the time of closure of an ESDV and how this element relates with HCR inventory during a FBR situation.

Chapter two gives us a vivid general description of valves and their mode of operation. It also explains the type of shutdown valves and their components, selection process of valve and types of ESD systems and their applications. The last aspect introduces us to past reviewed work on the Dynamic Response of the ESDV and geometric characteristics of SDV types.

Chapter three presents the valid concept behind transient flow in ruptured pipelines, introducing us to the laws of conservation equations in boundary transient flow conditions in pipes. It later went on to discuss about gas release rates in pipes and allowable leakage rate a concept of regulation.

Chapter four presents the model used for this report involving the parameters affecting the dynamic response of the ESDV and its time of closure. It also explains the concept of time subsequent to closure and the sensitivity of the HCR parameters using the FORM approach.

Chapter five presents the obtained hypothetical results used to model the analysis of time of closure of the ESDV with HCR parameters in a FBR situation. It also describes what happens to variant HCR parameters after valve closure time bringing us to the aspect of subsequent time to closure and it finally explains the sensitivity of the HCR parameters with time of closure.

Chapter six presents the concept of Quantitative Risk Assessment in determining the CBA of using quicker closing ESDV valves. It introduces the concept of the ALARP triangle in comparing different risk levels in comparison with benefit gained in the reduction of risk by using quicker closing ESDV valves.

Finally, chapter seven presents the conclusion of the study suggesting certain modifications to enhance the speed of shutdown valves to improve on the time of closure of the ESDV and it also introduces concepts which can be used for further research to be done on this model.

CHAPTER TWO

GENERAL KNOWLEDGE OF EMERGENCY SHUT-DOWN VALVES

2.1 History of Valves

Necessity they say is the mother of all invention, early men learned to regulate the flow of water by building some kind of artificial dams or valves by blocking with falling trees and large stones. The Egyptians and Greeks were able to drive the flow of water from rivers for public use and irrigation through this simple technique.

The Romans were the first to ever develop mechanical and hydraulic machines and first use valves. These valves were mainly made from bronze materials, early valves were either plug or stopcock type. There is also evidence that the Romans used check valves to stop back flow.

In modern times, industrialization sparked up the valve industry. In 1705 Thomas NewComen invented the first steam machine which made use of valves to regulate steam at high pressure **(3)**. Further improvement came as a result of the petrochemical industry that dealt with hazardous fluids; this further brought technical improvements in the general design of valves because of the key importance of safety.

2.2 Key Functions of Shutdown Valve Component

A shutdown valve also referred to an ESDV is an actuated mechanical device, designed to stop the flow of hazardous fluid. The SDV makes part of a Safety Instrumented System SIS **(4)**. A SDV has the same design features like any other valve. The following are key features of a valve as shown in Figure 2.1.

- Valve Actuator
- Valve Body
- Valve Bonnet
- Valve Trim
- Valve Packing

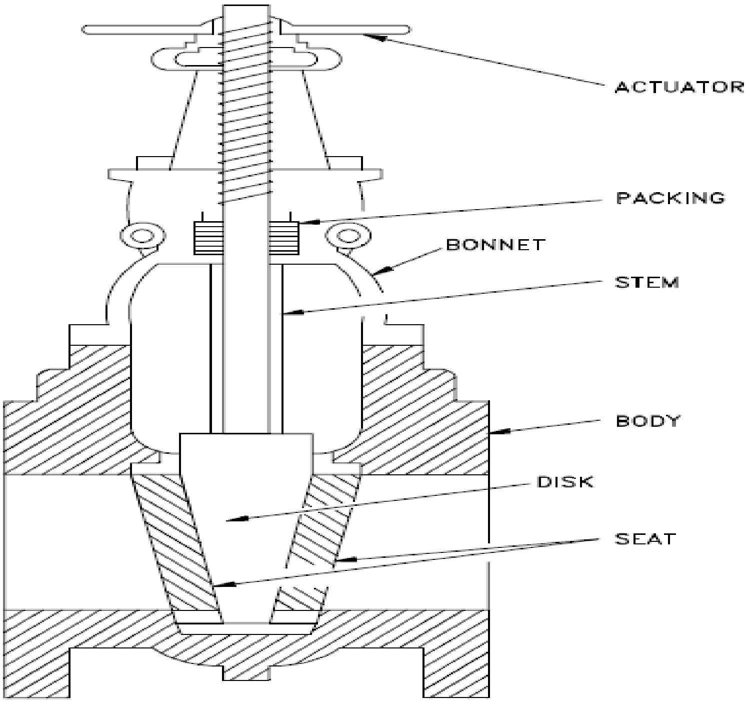


Figure 2.1: The Basic Parts of a Valve [(5)].

2.2.1 Valve Actuator

The actuator is the mechanical device that operates the stem and disk assembly. The actuator can be manually operated, motor operated, pneumatically or hydraulically operated and electrically operated **(6)**.

In case of an ESDV it is expected that the actuators are automated operated and are fail safe power type. The actuator pressure signal can be tripped by a mechanical pilot assembly, a solenoid valve or a combination of both. There are 3 types used for an ESDV.

- Pneumatic Cylinder
- Hydraulic Cylinder
- Electro-Hydraulic Cylinder

2.2.1.1 Pneumatic Cylinder

This actuator is also called Air cylinder. It makes use of power of compressed gas to produce the reciprocating motion to operate the stem and disk assembly. The pneumatic cylinder works with the principle of stored potential energy of a fluid, converts it to kinetic energy which causes expansion of air in the cylinder that forces a piston to move.

Engineers prefer pneumatic actuators because they are quieter, cleaner and do not require a large amount of space for fluid storage.

2.2.1.2 Hydraulic Cylinder

These are example of mechanical actuators that gives one directional force through one-directional stroke. Hydraulic cylinders work under the principle of force produced by the power of a pressurized hydraulic fluid like oil.

2.2.1.3 Electric Actuator

This involves the use of electric motor and some form of gear reduction driven by electric power to move the valve. Electric actuators are much expensive than pneumatic actuators for the same performance levels. One major disadvantage of using electric actuators is that they are possible sources of ignition unless made instinctively save which makes it relatively very expensive to do.

2.2.2 Valve Body

The valve body serves as the first pressure boundary of a valve which is designed to withstand pressure from connecting pipes. Usually referred as the shell, it is made of casted material forged into economical shapes, either spherical or cylindrical. Most valve bodies are partitioned to support the seat opening.

2.2.3 Valve Bonnet

The valve bonnet serves as a cover; it is also cast and forged from the same material as the body of the valve. It is connected to the body by a threaded, bolted or welded joint. Sometimes the bonnet is designed as a valve cover, otherwise as support valve internals and accessories. In valves the bonnets are potential leakage source.

2.2.4 Valve Trim

The valve trim refers to all internal components of a valve. These include; the disk, seat, stem and sleeves. The trim is responsible for the basic motions and flow control of the valve. The trim can either be designed as a linear motion trim, where the disk lifts transversely away from the seat or rotational motion. The other is a case where the disk slides closely past the seat to produce a change in flow.

2.2.4.1 The Disk

The disk is designed for allowing or stopping fluid flow. It serves as the third primary principle pressure boundary. Disks are sometimes required to resist and retain pressure, for this reason the disk is designed with good wear characteristic material.

2.2.4.2 The Seat

This part is also known as the seal rings. The seat major function is to provide a seating surface for the disk. However, the seat is not regarded as a pressure boundary part. Seats are sometimes incorporated in the body of the valve, in other designs they are seal rings threaded or welded to the valve's body to provide the seating surface.

2.2.4.3 The Stem

This part connects the actuator and the disk. The stem is connected to the disk with threaded or welded joints and designed to position the disk.

2.2.5 Valve Parking

A valve parking is normally a fibrous material that forms a seal between the internal parts of a valve and extends through the outer body. The parking is used to prevent leakage from the space between the stem and bonnet

Valve parking should be done with precision because if parking is too tight it will impair the movement and damage the stem, also if it was too loose the valve will leak **(7)**.

2.3 Types of Shutdown Valves

Generally, SDV are valves incorporated with spring return actuators, such that when the actuator pressure signal is released the valve is forced closed by the actuator spring. The actuator pressure signal can be tripped by a mechanical pilot assembly, a solenoid valve or a combination of both. The types of SDV have to deal with the geometry of the closing disk which controls or inhibits the flow of fluids. Basically, SDV's can come in forms of ball valves, butterfly valves and gate valves.

2.3.1 SDV Ball Valve Type

A ball valve is a valve with a spherical disc. The spherical disc is the part which controls the flow of fluid; the sphere is incorporated with a hole through the centre so that when the hole is in line with both ends of the valve flow will occur. When the valve closes the hole is perpendicular to the ends of the valve **(8)**. The ball is controlled from outside the valve either by a handle or actuator that turns it 90 degrees, or a quarter turn, back and forth to open and close the valve. The ball valve is able to achieve perfect shut-off of fluid; they are mostly used as SDV **(9)**. ESDV's are most often times quarter-turn actuated ball valves and are good for isolation of gas pipelines. Figure: 2.2 show a typical example of the sectional drawing of a ball valve. The ball valves are best used for emergency shutdown purposes.

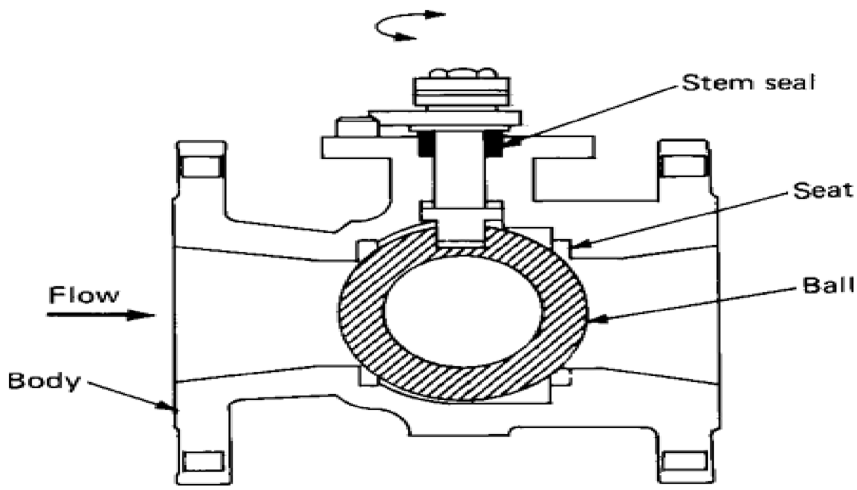


Figure 2.2: A Sectional Diagram of a Ball Valve [(10)].

2.3.2 SDV Butterfly Valve Type

The closing mechanism looks exactly like a disc and operates in a similar way to a ball valve. However, unlike the ball valve, the disc is always present within the flow causing a pressure drop in the liquid. This valve also belongs to the family of the quarter-turn valves. Generally the butterfly valves are used to control and regulate the flow of fluid **(9)**. They are not typically too good for shutdown of hazardous fluids but may be used as shutdown as air intake shut down for diesel engines, Figure 2.3 shows a cross-sectional drawing of a butterfly valve.

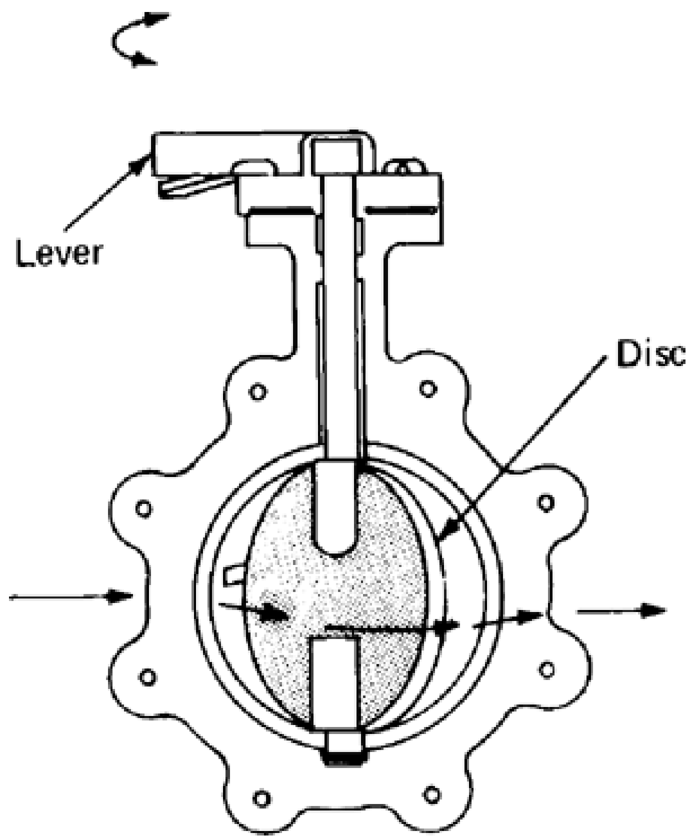


Figure 2.3:Cross-Sectional Diagram of a Butterfly Shutdown Valve [10] .

2.3.3 SDV Gate Valve Type

These valves are also known as sluice valve. The closing mechanism in this case takes the shape of a rectangular gate or wedge. The wedge opens or closes to control fluid flow. Gate valves are used when a straight line flow of fluid and minimum flow restriction are needed. When the valve opens wide, the gate is fully drawn up into the valve bonnet. This leaves an opening for flow through the valve the same size as the pipe. Gate valves are primarily used to permit or prevent flow but shouldn't be used typically to regulate fluid flow. They are not suitable for throttling purposes, because the flow of fluid smashing against a partial open gate can cause eventual wear and tear of the valve **(7, 9)**. Gate valves are classified either; as rising stem as indicated in Figure 2.4, or non-rising stem. In rising stem, the stem is attached to the gate such that the gate and the stem rise and lowers together. However, for non-rising stem, the gate moves up and down the stem on the threads.-

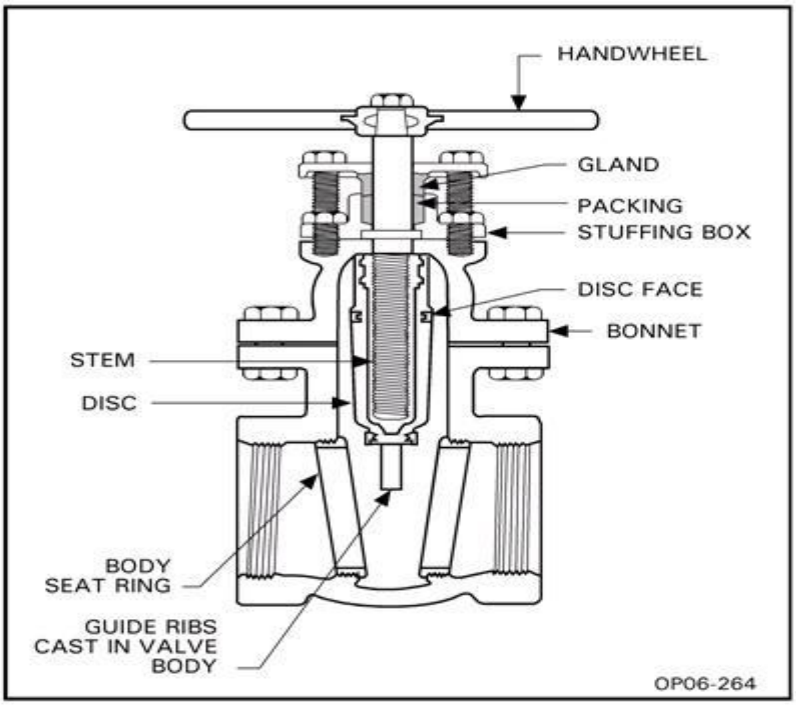


Figure 2.4: The Rising Stem Gate Valve [10].

2.4 Design Requirement and Selection Process of Valves

A major problem in design is the actual selection process of equipment and instrumentation to be used in a process plant. This is mostly done by qualified professionals, like, piping engineers, process engineers, instrumentation engineers and safety engineers. An actual knowledge of the chemical properties as well as both engineering and physical properties of fluid from the reservoir is a major input in the design and selection phase.

Selection of the appropriate specified valve is a major safety requirement in inherent safe design procedures, Table. 2.1 below show a breakdown of the ESDV selection process. Invariably, cost benefit analysis is also very important at the final stage because of what is provided in the capital expenditure CAPEX. Other things to be considered in the selection and design are; good knowledge of the manufacturer's product, statutory laws and specifications and safety requirement for the location being considered and notable standards like **(11)** (ANSI, API, ISO, ASME, BSI and IEC).

Table 2.1: Breakdown of Shutdown Valve Selection Process

Application Type	Emergency closing or venting, note if selection valve is capable for PST e.g. (Venting vs. butterfly)
Pressure	Shut-off pressure, operating pressure
Temperature	Soft parts, body materials, coatings, seat construction bearings, high temperature extension, low temperature/cryogenic.
Fluid	Corrosive, solids, toxic, explosive(O_2), viscosity, erosion, corrosion, solidifying, coke build-up
Materials	CF8M, WCB, LCC, C5, not temperature, chemical resistance, NACE
Valve Type	Ball valve reduced bore of full bore, butterfly valve, fail open or close, tightness, operating speed, floating or trunnion.
Actuator Type	Spring return or double acting, operating speed, hand wheel. Jammer, seal cylinder, fire box.
Fire Safety	API 607, BS6755
Accessories	SOV, LS, Booster, QEV, PPS, VT
Area Classification	EExi, EExd, EExn, FM, CSA, CENELEC
Power Supply	Supply pressure, SV voltage.

2.4.1 Valve Standards

The purpose of standards is to give uniformity, safety and technical requirements and general specifications and recommendation on the use of specific equipment. Standards are also used to ensure good technical practices globally such as to avoid confusion in the use of metrics, engineering designs and specification. Basically the standards used for valves includes; ANSI, API, ASME, ISO and BSI **(12)**.

2.4.1.1 Outline of some Specific Valve Standards

API SPEC 6D: This standard is used specifically for the specification for pipeline valves. It is adopted from ISO 14313:1999. It specifies requirements and gives recommendation for the design, manufacturing, testing and documentation of ball, check, gate and plug valves.

ANSI/API 608: This standard is meant for ball valves with flanged and butt-welding ends. The standards cover class 150 and class 300 metal ball valves and are for use in on-off service.

API 6RS: This is meant for Reference Standards for committee 6, standardization of valves and wellhead equipment

API 598: This standard is meant for valve inspection and testing. These include; supplementary examination, pressure test required for both resilient-seated and metal to metal seated gate, globe, plug, ball, check and butterfly valves.

ANSI/API 600: This standard is associated with bolted bonnet steel gate valves for petroleum and natural gas industries. It is modified natural adoption of ISO 10434: 1998.

2.4.2 System Requirements

This is an important aspect in design that deals with system design pressure and temperature ratings. Most piping code recommends that the pressure and temperature ratings be equal or greater than the system design temperature to ensure system integrity and safety. Thereby, putting into consideration the pressure and temperature requirement for both system design conditions and normal operating conditions.

2.4.3 Temperature Requirement

Temperature is a very critical property in selection of valves. The cold working pressure CWP temperature of a valve in design and selection is an essential parameter requirement. This implies that any range below the CWP is given special consideration because most materials especially non-metals loss their strength and ability to seal at low temperatures. Also lubricants and other sealants harden at cold temperature and this may cause some loss of integrity to valves generally.

2.4.4 Environmental Requirement

This is a major factor which also must be given much consideration. The environment itself has a major effect on the valves operation mode. This all depends on the nature of the environment either if it is a very cold location, corrosive location and windy environment. All these have some effects on the valve, for instance the North Sea is known for its corrosive environmental impact on offshore installations which have damaging impact on external body parts of valves as well reducing their integrity at the end.

2.4.5 Material Properties Requirement

The property of materials used in any equipment plays an important role in determining its eventual reliability. Properties such as yield strength, allowable stress, tensile strength and safety factor should be considered while selecting valves.

2.4.6 Valve Ratings

All manufactured valves come with a manual which indicates its rating. Generally valve ratings indicate the, CWP rating, pressure rating and temperature rating of the valve. It is the duty of all manufacturers to put this piece of information on all valves manufactured by them. The ratings determine the eventual performance and efficiency of valves which cumulates to the reliability of the valve.

CWP Rating: This is the allowable cold working pressure of a valve at ambient conditions usually from -28^{o}C to 37^{o}C.

Pressure Rating: This is the maximum allowable working pressure of a valve at the specified range of temperature relating to the Body material rating of valves.

Rating Temperature: This is the temperature of the pressure containing-shell of the valve. It is assumed to be the same as the system fluid temperature.

Temperature Ratings: This is the maximum and minimum temperature at which the valves are functional.

2.4.7 Location of ESDV in Process plant

The location of shut down valves is an important aspect in the design of pipework in plant design. Valves are fashioned close to fittings which can create severe flow disturbance. They are normally placed close to the wellhead, risers, flanges, joints, compressor, pumps and points along a process line that has a potential source of HCR or leakage. Commonly in process plants we see shut down valves placed close to the well head, riser and process vessel because these are major areas where we can have a release incident or loss of containment. It is also very essential that ESDVs are located far enough away from probable fire areas to ensure the valve is not enveloped by fire during a fire incidence **(13)**.

2.4.8 Valve Sizing

This is a computational means for appropriate selection of correct valve size for a given application of process conditions that the valve will actually undergo during operation or service. Properties of the fluid being considered, flow line and pipeline are very essential inputs for valve sizing. Such properties are; pressure differential (ΔP) of fluid, flow rate (Q), viscosity of fluid (μ), fluids coefficient of discharge (C_v), density of fluid (ρ) and operating temperature (T). Also one important input for selecting a valve is the actual size of the pipeline used. The practice of valve sizing design is based on the combination of theory and experimentation.

2.4.8.1 Volume Flow rate in Valve Sizing

The principles of conservation of energy, Daniel Bernoulli equation are very important to determine the flow rates of fluids. When fluids flow through an orifice, the square of the fluid velocity is directly proportional to pressure differential across the orifice and inversely to the specific gravity of the fluid as shown in Figure. 2.5. This implies that the greater the pressure differential, the higher the velocity and the greater the density, the lower the velocity. Hence the volume flow rate for liquids can be calculated by multiplying the fluid velocities with the flow area.

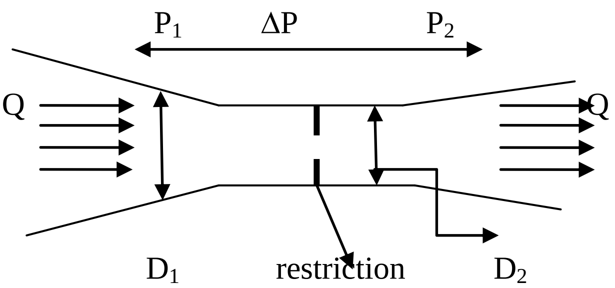


Figure 2.5 Diagram Showing Flow through an Orifice

Also taking into account the above proportionality relationship with energy losses due to friction and turbulence, and varying discharge, the coefficient for various types of orifices (or valve bodies), a basic liquid sizing equation can be given by;

$$Q = C_v\sqrt{\frac{\Delta P}{G}}, \tag{2.1}$$

Where; Q is the capacity of flow in m^3/s or gallons per minute, C_v is valve sizing coefficient (using water at standard conditions as the test fluid), ΔP is the pressure differential in N/mm^2 or psi/ bar and G is the specific Gravity of the fluid in for water at 60^0F assumed as 1.0 .

However the sizing of gases can be based on the adoption of the basic liquid sizing equation (2.1). This is done by introducing conversion factors to change flow units to cubic per feet (SCFH), and to relate specific gravity in meaningful terms of pressure. Which can be derived for the flow of air at 60^0F, this is because on Rankine absolute temperature scale corresponds to 520 at 60^0F and the specific gravity of air is 1.0 at the same temperature. The resulting equation now becomes;

$$Q_{SCFH} = 59.64\, C_v P_1 \{\sqrt{(\Delta P / P_1)}\sqrt{(520/G.T)}\}, \qquad (2.2)$$

Where; ΔP is the pressure drop, P_1 is the inlet pressure, G is the specific Gravity, T is the absolute temperature and C_v is the valve sizing coefficient.

2.4.8.2 Flashing and Cavitation in valve Sizing

Flashing and cavitation are two physical phenomena which have a significant effect on valve sizing procedure. These two physical phenomena cause actual changes to the form of the fluid media. The valve is just like a restriction in the flow path of the fluid along a flow line. As the fluid flows through this restriction (Valve), a change of state occurs, liquid state to vapour state causing increase in fluid velocity downstream. When the fluid passes through this restriction, a point called "Vena contracta", there is a necking down or contraction of the flow stream, as shown in Figure. 2.6.

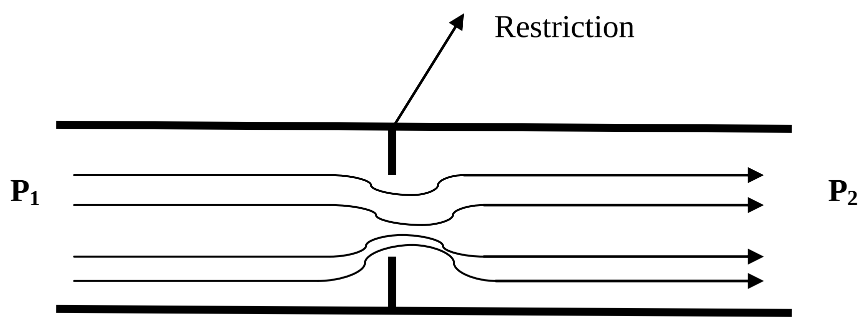


Figure. 2.6: The Vena Contracta.

To maintain a steady flow of fluid through the valve, the velocity must be greater at the vena contracta, where the cross-sectional area is list. A pressure differential exists across the valve which is the measure of the amount of energy dissipated in the valve.

Regardless, of the recovery characteristics of the valve, the pressure differential of interest pertaining to flashing and cavitation is the differential pressure between the valve inlet and the vena contracta. If pressure at the vena contracta should drop below the vapour pressure of the fluids, bubbles will form in the flow stream, resulting to flashing which can lead to damage of the valve.

However if downstream pressure recovery is sufficient to raise the outlet pressure above the vapour pressure of the fluid, the bubble formation will be minimal or implode producing cavitation. Cavitation causes damage to the downstream pipeline structure.

The equation below shows the relationship between allowable pressure dropped with key parameters in valve sizing that is effective in producing flow eventually reducing the effect of flashing and cavitation.

$$\Delta P_{allow} = K_m\,(P_1 - r_c P_v), \qquad (2.3)$$

Where; ΔP_{allow} is the allowable differential pressure for sizing purposes in psi, K_m is the valve recovery coefficient from the manufacturer's manual, P_1 the inlet pressure, r_c the critical pressure ratio and P_v is the vapour pressure of the liquid at body inlet temperature.

The value of ΔP_{allow} is now substituted into the basic liquid sizing equation (2.1) to determine Q and C_v respectively.

2.5 Partial Stroke Testing PST of SDV

One of the major requirements by HSE in a safety case often times for facilities, instrumentation and equipment used in the oil industry is to demonstrate that risk is reduced to ALARP even during operation. This off-course would involve maintenance schemes used to determine the reliability and availability of the equipment's performance standard. The SDV is very critical equipment and follows suit with these procedures, therefore indicating that maintenance and testing is key to the functionality and reliability of this element.

The Partial Stroke Test is a kind of semi-automated testing done on a SDV without disturbing the process in the plant. The objective of the PST is to extend the plant running time while testing shut down valves. The PST is a very good approach for functional testing of SDVs because the period between, scheduled Shutdown SD for maintenance can be used to maximize the cost of running and maintenance together **(14)**.

PST is a diagnostic technique used to test valves for dangerous, undetected failures that may be inherent in valves that have remained in an open position for an extended period of time. The three common methods used for PST testing is a PLC- based system that pulses the power (on and off) to the valve solenoid, resulting in partial movement of the valve disk.

The operation mode of process SDV is low demand in operation according to IEC61508 1998. This implies that valves are kept in open positions for long periods and are expected to close in cases demanded for. The SDV is required to have pneumatic or hydraulic fail-safe actuators.

As regarded by Safety Instrumented Systems SIS by international standards of IEC 61508 and IEC 61511, SDVs are regarded as the Final Element FE. Generally, SIS of an ESD system consist of a detector (initiator), Programmable Logic Unit PLU (Logic Solver) and the FE (a SDV), “Figure. 2.7”, Shows the configuration of a typical SIS for an ESD system.

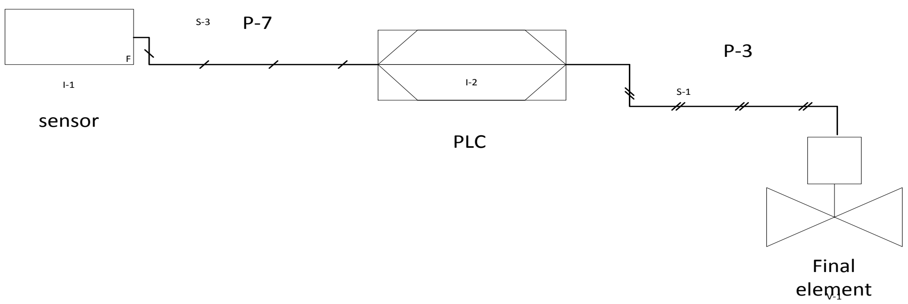


Figure. 2.7: Diagram Showing the Configuration of a SIS for an ESD System.

The PST has some basic advantages as well as disadvantages which are highlighted below;

Advantages of PST

- Cost effective installation
- Simple to calibrate, operate and test
- Safe on-line repair
- Minimum impact on the existing SIF

- Does not decrease the availability of the SIF
- Does not violate process Safety time

Disadvantages of PST

- At regular intervals testing increases wear and tear of moving parts of valves, especially the stem and parking
- PST is automated and there is possibility that the instrumentation can fail
- There is high possibility of leakage points because of regular interval testing.

2.5.1 Diagnostic Testing

This is an automated on-line test used to determine and detect a percentage of possible failure modes of SDVs.

2.5.1.1 Offline Diagnostic Test

These are processes which can only be runned during plant shut down. Examples are; a step response test or stroking the valve over its entire travel range, that is when logging the set point of an actual valve and actuator or driving signals for the positioner pneumatics **(15)**.

2.5.1.2 Online Diagnostic Test

This method is used while the process is running. Invariably, the state of the valve is analyzed under actual operating modes. In this method the maximum interval between tests can be determined quantitatively by Probability of Failure of Demand PFD and assignment to the desired SIL. Examples are the bye pass valves and PST .Also "Table: 2.2" shows the detectable faults while using an online diagnostic method.

$$PFD = DC * \lambda_d * T|_a/2 + (1 - DC) * \lambda_d \times T|_m/2 \ (15), \qquad (2.4)$$

Where; λ_d is the dangerous failure rate, $T|_a$ is the partial stroking testing interval, $T|_m$ is the interval between proof test and DC is the diagnostic coverage factor.

Table 2.2: Detectable Faults and Diagnostic Method [15]

Fault	Reference used in diagnosis
Set point friction and Valve friction	Directly from the raw data step response test, hysteresis test.
Valve Shut-off impaired (Internal Leakage)	Zero shift, eternal ultrasonic sensor
External valve leakage, packing leakage	Packing chamber monitored by external pressure switch, change in valve friction
Packing or bellows wear	Travel counter, cycle counter, and change in valve friction.
Valve plug wear or damage	Zero shift, change in valve friction around zero point
Actuator spring broken	Pressure/travel/characteristics
Change process characteristics	Valve position history, cycle counter, cycle counter histogram.

2.6: Failure Modes of SDV

Generally SDVs are classified as Isolation valves. ESDV valves have special classification, according to HSE **(16)** document of assessment of valve failures, valve failure modes can be classified into 3 levels. Table 2.3 briefly describes the classification of valve failure modes.

Level 1 Initial valve problem: This is a problem classified based on first symptoms.

Level 2 Primary Problems: These are problem classification when valves have been removed and examined for possible failures.

Level 3 Underlying Cause: This is the final assessment after taken into consideration circumstances that led to valve failure.

Table 2.3: Sub-Categories of the Classification Levels [16]

Level 1 (Initial)	Level 2 (Primary)	Level 3 (Underlying Cause)
Failed to operate open or close	Valve sized stem, seal problem	Inadequate maintenance Design inadequate material deficient
Through valve leakage	Activation Problem eg.debris, hydraulics and pneumatics.	Lack of training and inexperienced staffs
Difficult Operation	Activation Problem e.g. debris, hydraulics and pneumatics.	Lack of training and inexperienced staff
External corrosion	Control system problem e.g. communications faulty, software problem	Corrosion and sand erosion
Valve not operating properly	Control system problem e.g. communications faulty, software problem	Corrosion and sand erosion
Other e.g. redundant, specification change	Human error, seat and seal problem and body/bonnet flange trunion problem	Signal data communications, Incorrectly specified Quality assurance issue.
Reasons not specified	Erosion, design, defect materials, corrosion and valve not stripped	Procedures of operator's deficient e.g. dismantling procedure in correct, process operating procedure defective.

2.7 Emergency Shutdown ESD System

The ESD is a method associated with isolating incoming and outgoing flows of fluid to reduce the probability of an unwanted event occurring or escalating. The ESD system is designed to initiate a facility shutdown either by **(17)**;

- Manual activation from a control panel.
- Manual activation from strategically located stations within facility.
- Automated activation f4rom gas detection systems.
- Automated activation from Piping and Instrumentation Diagrams PID set points during major process upset.

2.7.1 Levels of Shutdowns SD

The degree of unwanted event or hazard within specific or an entire area of a facility would have an outcome on the type of SD to be made. Basically, Dennis P. Molan **(17)**, states that they are 4 levels of shutdowns.

2.7.1.1 Total Shutdown

A total ESD shuts down the total plant under emergency conditions. The activation of ESD should not impede fire protection systems and critical utilities such as instrumentation or process air.

2.7.1.2 Unit Shutdown

The unit shutdown is done to isolate a process unit or process area involved in an emergency incident. Unit shutdown is applicable to depressurization of pressure vessels to reduce Boiling Liquid Expanding Vapour Explosion BLEVE.

2.7.1.3 Equipment Shutdown

Equipment shutdown is the isolation of system equipment within a process unit which can lead to potential release of a hazard or loss in containment.

2.7.1.4 Equipment Protective System Shutdown

These are shutdown systems designed to provide protection for some basic equipment within the process plant or area. Such equipment includes; gas compressors, centrifugal pumps, generators and gas turbines **(17)**.

2.8 Dynamic Response of ESDV

The major concept behind the dynamic response of an ESDV is its evaluation of release rate and its variation with time during an event of HCR. The ESDV is meant for total isolation during such conditions of FBR or hydrocarbon release in Puncture Pipelines and respond to pressure drop.

The total time of response is a function of the activation time and time of closure of the ESDV itself. The activation time is the combination of time it takes a sensor or pressure detector to detect an upset process situation normally a drop in pressure in this case and the signal being sent to a logic solver which interprets the condition and send it to the final element (the valve). It takes some very few micro-seconds for the logic solver to interpret the information it receives from the senor or detector, process such information and initiates an action in the form of signals. This signal is then made to initiate the ESDV to perform its function, leading to the second time regime called the time of closure. The summation of both time regimes gives the total response time as explained in the equation below.

$$t_r = t_a + t_c, \tag{2.4}$$

where t_r is total time of response, t_a the activation time and t_c the time of closure.

When an ESDV closes, it does that very fast and this causes shock waves resulting into a pulse pressure (P), Fluid velocity (v) and acoustic velocity(a) to the fluid at a given time t and distance x along the pipeline. The theory of this is based on the unsteady one-dimensional flow which incorporates heat transfer and friction.

According to (Magerefteh) **(18)**, the analysis of dynamic response of ESDVs in FBR situations involves solving mass, momentum and energy equations using a numerical approach such as the Method of Characteristics MOC. Three conservation equations of mass, momentum and energy can be replaced by their characteristics and compatibility equations.

$$[\frac{dt}{dx}]_p = \frac{1}{u} \quad \text{Path-line characteristic} \tag{2.5}$$

$$[\frac{dt}{dx}]_\pm = \frac{1}{u+a} \quad \text{mach line characteristic} \tag{2.6}$$

$$dP - a^2 d\rho = (\psi/u)dx = \psi dt \quad \text{path-line compatibility,} \tag{2.7}$$

Where P, ρ, u and a are; the fluid pressure, density, fluid velocity and acoustic velocity as a function of time t and distance x along the pipeline, while ψ is the non-isentropic term incorporating heat transfer and frictional effects **(18)**.

The characteristic equation 2.5 and 2.6 dictates how an ESDV responds in terms of response time in a propagated flow field.

2.8.1 Understanding Geometric Characteristic of Shutdown Valves

Valves are known to be integral parts of any piping system used for controlling and transporting fluid. The primary purposes of valves are; flow control, energy dissipation and isolation. In design it is very important to know and understand the hydraulic characteristics of valves. This characteristic depends on a number of factors, one of which is the geometry of the controlling mechanism of the valve itself. Of-course for isolation valves which are also called block valves this can either be a, ball valve, butterfly valve of gate valve.

Valve characteristic depends on their geometry, expressed in terms of cross-sectional area at any opening, sharpness of edges, type of passage and the valve shape. The geometry feature of a valve has a bearing on the valve hydraulic performance, but should not be used directly for prediction of hydraulic performance either steady state or transient. In order to understand the hydraulic characteristics of valves it is useful to express projected areas of the valve in-terms of geometric quantities **(19)**.

2.8.1.1 Flow Features of ball Valves vs. Closure time

The ball valve closure geometry is quite complex, this is because of its spherical shape and quarter- turn rotating degree. The rotating degree is between 0^0 to 90^0, the valve is fully opened at 90^0 and fully closed at 0^0.

The variation of fluid properties is essential to evaluate valve closure as a function of time. As fluid flow across the ball valve, pressure drop is experienced a differential pressure between upstream pressure and down-stream pressure. This can be explained by compatibility equations (2.4) to (2.6) considering boundary pressure for upstream and downstream pressure **(18)** as shown in figure. 2.8.

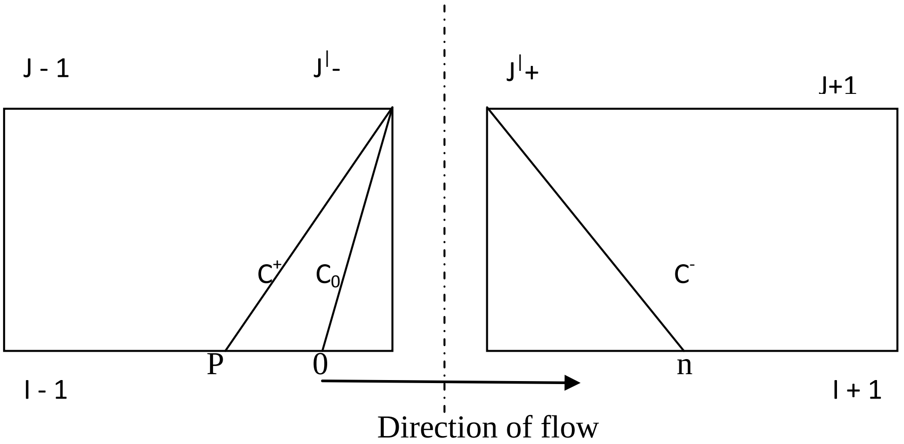


Figure. 2.8: Pressure Boundary at sides of ball valves[18]

Using the above pressure boundary of the diagram above, the compatibility equations for upstream, downstream pressure becomes.

$$P_{j'+} - P_{p} + (\overline{\rho a})_{pj'+}(u_j - u_p) = (\overline{\psi} + \overline{a\beta})_{pj'+}\,\Delta t = k_1 \qquad (2.8)$$

$$P_{j'-} - P_{n} + (\overline{\rho a})_{nj'+}(u_j - u_n) = (\overline{\psi} + \overline{a\beta})_{nj'-}\,\Delta t = k_2 \qquad (2.9)$$

$$P_{j'+} - P_{0} + (\overline{a^2})_{0j'+}(\rho_j - \rho_0) = (\overline{\psi})_{0j'+}\,\Delta t = k_3 \qquad (2.10)$$

Generally the basic liquid equation as stated in equation (2.1) is also very useful, but with consideration of time of closure of the valve at time t, this now becomes;

$$Q(t) = C_d(t)A_f(t)\sqrt{\frac{2\Delta P(t)}{\rho(t)}}\ , \qquad (2.11)^{(18)}$$

Where Q is volumetric flow in m^3/s through the valve at any time t during closure, C_d is the valve discharge coefficient and A_f is the valve open area. The pressure drop or loss across the ball valve during closure is given by,

$$\Delta P(t) = P_{j'+} - P_{j'-} \qquad (2.11.1)$$

The valve f area (A_f) is a function of pipeline radius and x is the distance transverse by the valve at time t, the equation below show this relationship **(18)**;

$$A_f = 2\begin{bmatrix} \pi R^2 2cos^{-1}\left(\frac{R-\left(\frac{2R-x(t)}{2}\right)}{360}\right) - \left(R - \frac{(2R-x(t))}{2}\right) \\ \{\sqrt{R^2 - (R - \frac{(2R-x(t))}{2})^2}\} \end{bmatrix} \qquad (2.12)$$

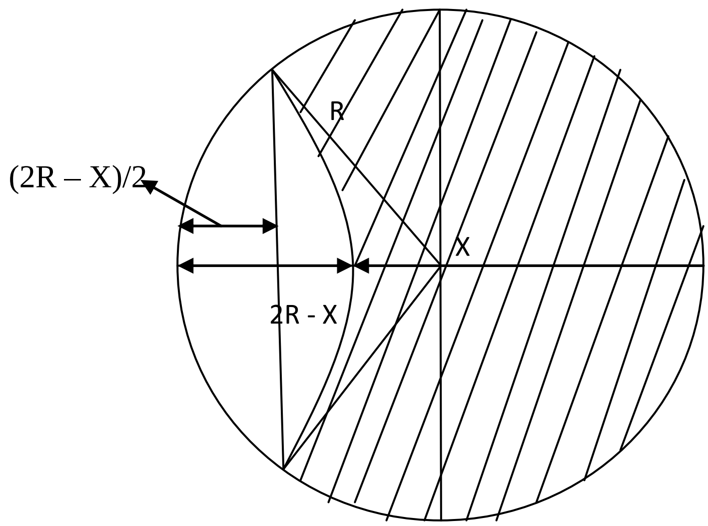


Figure. 2.9: Diagram showing Ball Valve Geometry[18].

The coefficient of discharge which is a function of valve type and degree of opening is given by;

$$C_d = A_o + A_{1\omega} + A_{2\omega}^2 + A_{3\omega}^3 + A_{4\omega}^4 \quad (2.13)$$

The values of coefficient of discharge C_d vary for different flow regimes, it is very complex for two-phase gas liquid mixtures because of the possibility of movement at different speeds, where A_o to A_4 are curve fitting constant and ω is the percentage area of valve opening.

2.8.1.2 Flow features of butterfly Valves vs. Closure Time

Butterfly valves are also quarter turn valves with adjustable rotating angles between 0^0 to 90^0. Just like the ball valves when fully closed it is at 0^0 and 90^0 when fully different, the only different is that the valve has the geometry of a Circular disc as shown in Figure. 2. 10.

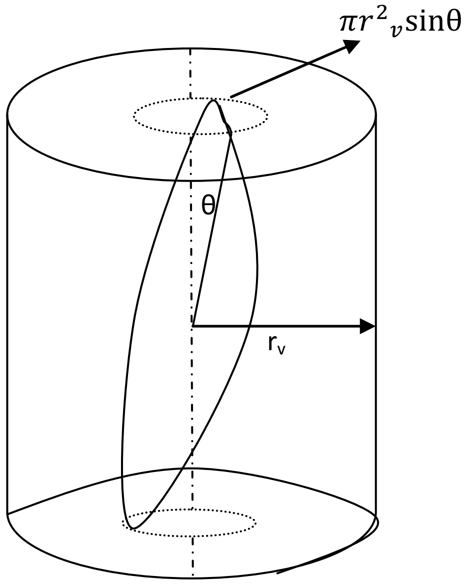


Figure. 2.10: Geometry Diagram of Butterfly Valve [20].

The valve opening area and valve flow area are given by;

$$A_v = \pi r_v^2 \quad (2.14.1)$$

$$A_0 = \pi r^2{}_v - \pi r^2{}_v \sin\theta = A_0 \pi r^2{}_v\,(1 - \sin\theta) \quad (2.14.2)$$

The ratio of the valve opening area A_v and the valve flow area gives the flow area percentage ∅ as indicated in equation (2.16)

$$\emptyset = \frac{A_0}{A_v} \text{ x } 100 \quad (2.14.3)$$

From the basic liquid sizing equation (2.1) we can determine the dynamic flow coefficient for butterfly valves which is a function of Torque T(θ) given at an opening angle θ, diameter of the valve and pressure drop across the valve ΔP_{net} as indicated in the equation below **(21)**.

$$C_T = \frac{T(\theta)}{\Delta P_{net} d^3} \tag{2.15}$$

2.8.2 Concept of water Hammer and Valve Closure Time

Fluid hammer occurs in closed conduit flowing full when there is either a retardation or acceleration of the flow, such as with the change in opening or closing of a valve this is shown in Figure. 2.11 below. If the changes are gradual, the calculation may be carried out by surge methods, considering the liquid incompressible and conduit rigid **(22, 23)**. When a valve is rapidly closing in a pipeline during flow, the flow through the valve is reduced. This increases the pressure on the upstream side of the valve and causes a pulse of high pressure to be propagated upstream at sonic wave speed c. The action of this pressure pulse is to decrease the velocity of flow. On the downstream side of the valve the pressure is reduced and a wave of lowered pressure travels downstream at wave speed c, which also reduces the velocity **(23, 24)**.

At an instant of valve closure (t= 0) the fluid nearest the valve is compressed and brought to rest, and the pipe wall is stretched. This procedure is repeated with a succession of layers of fluid until the fluid is compressed back to the source. The high pressure moves upstream as a wave, bringing the fluid to rest, the wave which reaches the upstream end of the pipe at ; (t = L/c). This flow returns to the valve which has normal pressure before closure with a velocity V_0 in the backward sense or the fluid velocity v_r in the reverse direction **(25)**, with a speed of sound c, this then gives an instant time of (2L/c), where L is the length of pipe as shown in Figure. 2.11.

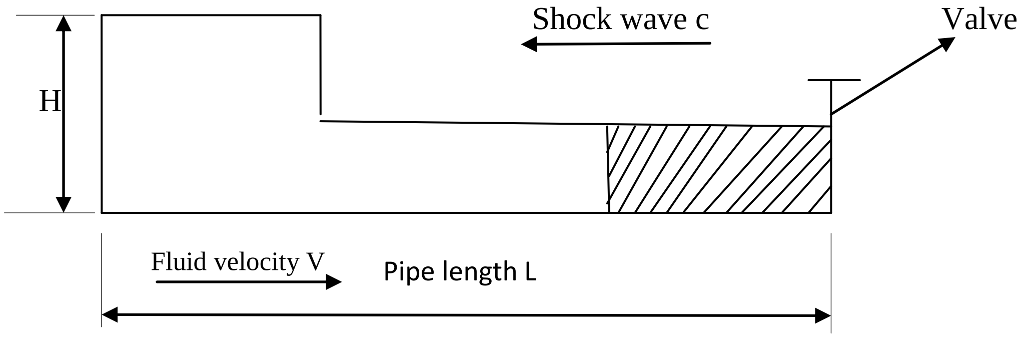


Figure. 2.11: The propagation of fluid Hammer Wave.

Generally, the Joukowsky equation explains the effect of time of closure of valves for both incompressible and compressible fluids. As explained in equation 2.16.1 – 2.16.2 **(23, 24)**

$$\frac{\partial P}{\partial t} = \rho c \frac{\partial v}{\partial t} \quad \text{(Instant Valve closure Compressible Fluid)} \qquad (2.16.1)$$

$$\Delta P = \rho c \Delta v \qquad (2.16.2)$$

$$\Delta P = \rho(cv_r + v_r^2), \qquad (2.16.3)$$

Where ρ is the density, c is the sonic speed, ΔP is the differential pressure or surge pressure and v is the fluid velocity? The pressure change ΔP can be considered as a fluid which undergoes deceleration dv/dt, along the pipe length L as indicated in equation (2.17)

$$dP = \rho L \frac{dv}{dt} \qquad (2.17)$$

For an incompressible fluid in a condition of slow valve closure the equation becomes;

$$P - P_i = \frac{0.070vL}{t} \qquad (2.18)$$

$$\Delta P = \frac{0.070vL}{t}, \qquad (2.19)$$

where ΔP is differential pressure, v is the flow velocity, L the length of pipe and t is the time of closure.

CHAPTER THREE
TRANSIENT FLOW IN RUPTURED PIPELINES

3.1 Understanding Transient Flow in Pipeline

Transient conditions arising in the transportation of hydrocarbon HC in long oil pipelines can be properly analyzed and predicted by use of the characteristic method. Attenuation, line packing, pyramiding and rarefaction can be completely taken into account. Oil pipelines are normally very long and divided into several sections comprising of several process units, valving systems and several pumping stations. These pipelines may have units in series or parallel and with special speed controls or valving actions affecting the overall boundary conditions which would have an eventual effect of heads along the pipeline **(26, 27)**.

Control and adjustment of flow through piping systems and networks by valving and several pump stations causes transient flow conditions. Some peculiar transient flow parametric conditions such as, hydraulic gradient shifts, wave speeds, surge pressure, acoustic velocity are altered during flow conditions.

General transient equations include; unsteady state equation of mass, momentum and energy equations with suitable equation of state. Applying, the basic laws of conservation of mass, linear momentum and energy leads to the basic equations for homogeneous, geometrically one dimensional flow systems. In terms of partial differential equations, these equations can be expressed as the Navier Stokes Conservation equations which represent the most suitable way of describing fluid flow situations **(26, 27)**.

3.1.1 Conservation of Mass

The law of conservation of mass states that mass may be neither created nor destroyed. A general way of explaining this is the control volume diagram in Figure. 3.1.

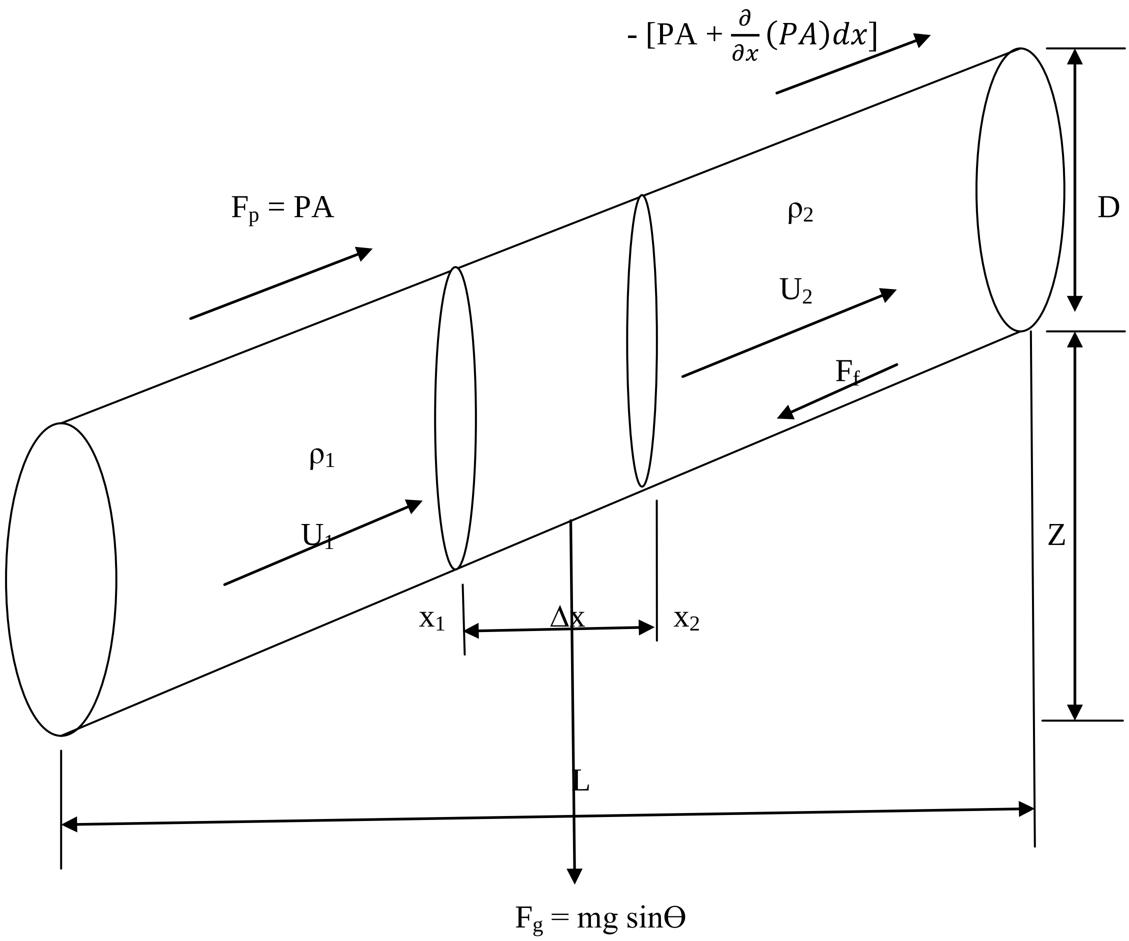


Figure. 3.1: Schematic Diagram of Control volume of a Pipe Section [28].

The control volume shows how the mass conservation equation can be derived as fluid flows through the system as shown in equation statement below.

Rate of mass flow mass in control Volume − Rate of mass efflux from control volume = Rate of accumulation of within control volume

The mass of fluid within the control volume is given by $\rho_{(x,t)}$ Adx and the mass flow rate across x_1 and x_2 is given by $\rho_1 u_1 A$ and $\rho_2 u_2 A$. This can be expressed as;

$$\frac{\partial}{\partial t}\int_{x_1}^{x_2} \rho(x,t)A\,dx = (\rho u A)_{x_1,t} - (\rho u A)_{x_2,t} \qquad (3.1)$$

Where ρ(x,t) is the density of the fluid at any point (x) at any time (t) as the fluid is transported along the pipe section and dividing equation (3.1) by area of pipe cross-section A the equation becomes.

$$\int_{x_1}^{x_2} \frac{\partial \rho}{\partial t} dx = -\int_{x_1}^{x_2} \frac{\partial (\rho u)}{\partial x}\, dx \quad (3.2)$$

Which holds for points x_1 and x_2 at time t being considered, the equation finally becomes;

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} = 0, \quad (3.3)$$

Where ρ and u are the density and velocity of the fluid respectively.

3.1.2 Conservation of Momentum

This is derived from Newton's second law of motion which states that the rate of change of momentum of a system is directly proportional to the net force of the system and takes place in the direction of the force and considering the control system volume in Figure. 3.1, this can be expressed as **(28)**;

Sum of forces =	Rate of change of momentum +	Net rate of momentum to	(3.4)
	Within control volume	fluid flow across boundary	

$$\sum F_x = \frac{\partial}{\partial t}(\rho A u)dx + \frac{\partial}{\partial x}(\rho A u^2)dx, \quad (3.5)$$

Where $\sum F_x$ represents all forces acting on the fluid which are; gravitational force F_g, frictional force F_f experienced within the walls of the pipe and fluid and the pressure forces F_p.

$$F_g = \rho A dx g sin\theta \quad (3.5.1)$$

$$F_p = PA - [\, PA + \frac{\partial (PA)}{\partial x} dx] \quad (3.5.2)$$

$$F = \frac{-\rho u^2}{2} \frac{4 f_w}{\partial x} A dx, \quad (3.5.3)$$

Where f_w is the fanning factor and substituting equations (3.5.1) to (3.5.2) into equation (3.5) the equation becomes,

$$\frac{-2\rho u^2 f_w}{D} - \rho g sin\theta = \frac{\partial P}{\partial x} + \rho\frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial x} + u[\frac{\partial \rho}{\partial t} + u\frac{\partial \rho}{\partial x} + \rho\frac{\partial u}{\partial x}] \quad (3.6)$$

The expression in the bracket equals zero is that of a continuing equation, which brings the expression as,

$$\rho\frac{\partial u}{\partial t}+\ \rho u\frac{\partial u}{\partial x}=\ \frac{-\partial P}{\partial x}-\ \rho gsin\theta+\ \beta_x \tag{3.7}$$

Expression equation (3.7) in terms of total derivative it finally becomes;

$$\rho\frac{du}{dt}=\ \frac{\partial P}{\partial x}-\ \rho gsin\theta+\ \beta_x \tag{3.8}$$

Where $\beta_x=\ \frac{2f_w\rho u|u|}{D}$

3.1.3 Conservation of Energy

The conservation of energy is derived from the first law of thermodynamics, which states that in a cyclic system the total heat added to the system from its surrounding is proportional to the work-done by the system on its surrounding **(28)**. The general expression is given by;

$$\frac{\partial(\rho E)}{\partial t}Adx+\ \frac{\partial(\rho Eu)}{\partial x}Adx=W_n+Q_h, \tag{3.9}$$

Where E is the total energy per unit mass of the fluid, Q_h is the rate of heat transfer of fluid and W_n is the net rate of work done by pressure.

3.2 Transient flow for Pipeline Rupture

In the oil and gas industry large amount of flammable hydrocarbons is often transported in long pipes and this imposing serious safety hazards, which in an event of pipeline rupture can cause serious damage to operating personals, facilities and the environment if such is ignited. The prediction of the ensuing release rate and its variation with time are two critical information required to in assessing and quantifying the consequences of such failures. History has shown that they are numerous pipeline rupture which had led to tragic incident which fatalities **(26, 29)**, Table. 3.1 shows some historic pipeline rupture events and the aftermath disaster caused by released HC.

Table.3.1: Historical Events of Pipeline Rupture **(18)**.

Accident	Damage Caused
Major oil pipeline rupture at Usinsk in Russia October 1994.	Leakage over 14,400m^2 occurred. 120,000 tonnes of oil split over tundra river Pechora.
Rupture of natural gas pipeline Caracas Miranda State Venezuela 29th September 1993	60 fatalities as a result of the blast.
Oil pipeline explosion at San Juan De Les Reyes Mexico 28h July 1988	80 people injured and 11 fatalities recorded and about 10,000 people evacuated.
76.2 cm natural gas pipeline ruptured and caused extensive damage at Book-side Village Texas USA 24th October 1978.	41 injuries and 6 fatalities recorded.
Rupture of 20.32cm propane pipeline releasing 60 tonnes of gas at Port Hudson, Missouri, USA 9th December 1070.	Ignition of gas caused an explosion and firestorm resulting in a total of 10 injuries.

Flow form ruptured pipelines is based on unsteady generalised I-D flow with the assumptions based on thermodynamics and phase equilibrium between constituent phases and continuity equations of momentum and energy conservation for an element of fluid in a rigid body **(18)**.

$$\frac{d\rho}{dt} + \rho\frac{\partial u}{\partial x} = 0 \tag{3.10}$$

$$\rho\frac{\partial u}{\partial t} + \rho u\frac{\partial u}{\partial x} + \frac{\partial P}{\partial x} = \propto \tag{3.11}$$

$$\rho\frac{dh}{dt} - \frac{dP}{dt} - \left(q_h - u\beta_y\right) = 0, \tag{3.12}$$

Where ρ, u, P, h, q_h and β_y are the density, velocity, pressure, specific enthalpy, internal energy and fiction force term.

The internal energyq_h, friction force termβ_y and $\propto$ is given by;

$$q_h = \frac{4}{D} U_h \left(T_{amb} - T_f\right) \tag{3.13}$$

$$\beta = -2 \frac{f_w}{D} \rho u|u|, \tag{3.14}$$

$$\propto = \left(2 \frac{f_w}{D} \rho u|u| + \rho g sin\theta\right), \tag{3.15}$$

Where U_h is the total heat transfer coefficient, T_{amb} and T_f denoting ambient emperature and fluid temperature respectively?

Combining equations (3.10) to (3.12), given a function f(x,t) = ρ,u,P we have,

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + u \frac{\partial f}{\partial x} \tag{3.16}$$

Using the simple thermodynamic transformation, the total derivative of density with respect to time in equation (3.10) becomes,

$$\frac{d\rho}{dt} = \frac{1}{a^2} \left[\frac{dP}{dt}\left(1 + \frac{\varphi}{\rho T}\right) - \frac{\varphi}{T} \frac{dh}{dt}\right], \tag{3.17}$$

Where a, is the speed of sound and φ is the thermodynamic function.

3.2.1 Boundary Conditions

The schematic diagram below shows the boundary conditions assumed to be isolated downstream upon puncture with the values of pressure (P), speed of sound (a), enthalpy(h), density and velocity (u) as a function of time along the distance L of a pipeline. The various boundary conditions B_1 to B_6 indicated in Figure. 3.3 are placed at the following locations and conditions along the pipeline closed by a valve at the downstream end at an instance of time t. To have a proper understanding of boundary condition during puncture equations (2.6) of mach-line compatibility in two phase boundary situation in chapter two is used as shown in Figure. 3.2.

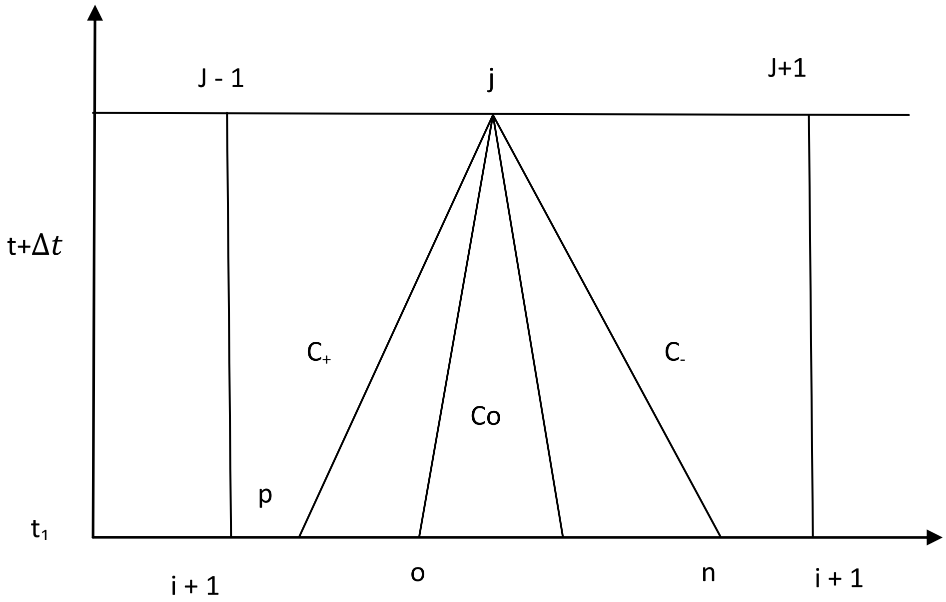


Figure. 3.2 Schematic diagram of Mach- Compatibility Boundary Conditions [(29)]

The path-line, positive and negative mach-line compatibility equations of figure. 3.2 and 3.3, are explained in equations

$$(\rho)_o(h_j - h_o) - (P_j - P_o) = \psi_o(t_j - t_o) \tag{3.18}$$

$$(\rho a)_n(u_j - u_n) - (P_j - P_n) = \left(a\alpha - \frac{\varphi\psi}{\rho T}\right)_n (t_j - t_n) \tag{3.19}$$

$$(\rho a)_p(u_j - u_p) - (P_j - P_p) = \left(a\alpha - \frac{\varphi\psi}{\rho T}\right)_p (t_j - t_p) \tag{3.20}$$

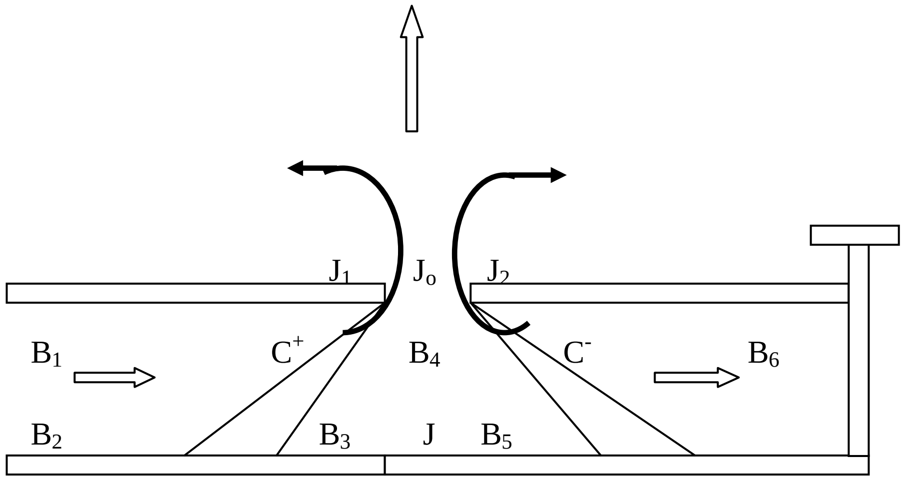
While the second-order approximations are given by the path-line compatibility equation.

$$\frac{1}{2}\left[(\rho)_o + (\rho)_j\right](h_j - h_o) - (P_j - P_o) = \frac{1}{2}\left[\psi_o + \psi_j\right](t_j - t_o) \tag{3.21}$$

The positive and negative mach-line numbers now becomes;

$$\frac{1}{2}\left[(\rho a)_p + (\rho a)_j\right](u_j - u_p) - (P_j - P_p) = \frac{1}{2}\left[\left(a\alpha - \frac{\varphi\psi}{\rho T}\right)_p + \left(a\alpha - \frac{\varphi\psi}{\rho T}\right)_p\right](t_j - t_p) \tag{3.22}$$

$$\frac{1}{2}\left[(\rho a)_n + (\rho a)_j\right](u_j - u_n) - (P_j - P_n) = \frac{1}{2}\left[\left(a\alpha - \frac{\varphi\psi}{\rho T}\right)_n + \left(a\alpha - \frac{\varphi\psi}{\rho T}\right)_{jp}\right](t_j - t_n) \tag{3.23}$$



$Q_{j1} = \rho_j u_{j1} A$ $\quad$ $Q_o = \rho_o u_o A_o$ $\quad$ $Q_{j2} = \rho_j u_{j2} A$

$$P_{j1} = P_j = P_{j2}$$

$$a_{j1} = a_j = a_{j2}$$

Figure 3.3: Schematic Diagram of a Punctured plane closed at one end by a Valve **(30)**.

Where;

1. B_1 is the reservoir inlet
2. B_2 is the ceassation of pumping inlet
3. B_3 is the downstream end of pipeline section 1
4. B_4 is the common junction at puncture point
5. B_5 is the upstream end of pipeline section 2
6. B_6 is the intact end and path-line (C_o).

The boundary conditions obey the law of conservation, at the orifice junction which is considered as the rupture plane. The junction P_{j1} (pressure downstream pipeline section 1), P_{j2} (pressure upstream section 2) and P_j junction pressure, must all be equal. This means that the junction pressure P_j should be equal to the upstream and downstream pressures at the common junction $P_j = P_{j1} + P_{j2}$ with the assumption that flow through the puncture plan and control volume is isentropic **(30)**.

3.3 Evaluation of Gas Release Rates in Pipes

The release of a gas from a punctured pipe will initially form a rising mushroom cloud, quickly decaying into a transient jet fed by the outflow of gas from the two pipeline ends in case of a rupture or a hole. Likewise, if this where a hole puncture the gas will come out rapidly at a very fast momentum and speed. Initially the mass flow rate will rapidly fall until a steady state is reached. Then the gas is dispersed is influenced by other factors like presence of wind, he size of the hole or bore, gravity and the module area as well **(27, 31)**.

The release rate through a hole can be modelled using the flow rate through an orifice considering the state equation of a gas in equation (3.24), the Poisson equation and continuity equation respectively (31,32).

$$P = \frac{\rho ZRT}{M} \tag{3.23}$$

$$Q = C_o\, A_{c_r}\, P_2 \sqrt{\frac{2M}{ZRT_2}\, \frac{K}{K-1} \left(\frac{P_a}{P_2}\right)^{2/k} - \left(\frac{P_a}{P_2}\right)^{k+1/2}}\ , \tag{3.24}$$

Where Z is the compressibility factor, T is the temperature in Kelvin; M is the Molar mass of the gas, $C_o\ coefficient\ of\ discharge,\ A_{c_r}$ is the area of hole and Q is the mass flow rate of the gas in Kgs^{-1}.

However, when the hole of the puncture is equal to the pipe diameter in a case of a FBR, the pressure inside the pipeline decreases gradually when the valve is closed at a certain time t, and the release rate is a function of time t.

$$Q(t) = -V_P\, \frac{d\rho(t)}{dt}\ , \tag{3.25}$$

Where Q(t) is the mass flow rate of gas, V_P the volume of the fluid from hole and ρ the density of the fluid.

3.4 Allowable HC/Gas Release a Concept of Regulations

The release of unwanted or unwarranted hydrocarbon or gaseous mixture can have a great negative destructive impact on personnel's, marine environment if from an offshore facility or the environment and loss of the facility itself if there was an explosion of fire event from the incident. Also environmental damages are anticipated and created by spillage of oil from leaks in pipelines, from manual operational failures, accidental release of oil blow-outs. The release of a hydrocarbon can cause incidents like, pool fire if liquid HCR, Explosion and jet fires if it is a gas release, Asphyxiation involving release of dangerous gases into the atmosphere, an oil spill into the environment causing pollution of Aquatic bodies and pollution of land-formations. They have been examples were a little amount of release of poisonous gasses caused the death of operators.

In order, to regulate the environmental pollution and other disasters associated with oil spill and gas release the government of various countries were the exploration of oil and gas is done, have developed various types of regulation to serve as ways either to prevent, control and mitigate against the resulted consequences **(33, 34)**.

Currently, they are two data bases used by the HSE in the United Kingdom for dealing with offshore release namely; hydrocarbon Release (HCR) and RIDDOR database. Both data base give information about platform location, release size and type, as well as possible causes of failure. Hydrocarbon release can be classified in the order of severity of classification and Criteria **(35)**.

Severity of classification of hydrocarbon release is categorized into three groups;

Major: This is a major release which has the potential to quickly impact on the local area e.g. Affect the TR, escape routes and escalate to other areas of the installation causing serious injuries or fatalities.

Significant: A significant release which if ignited has the potential to cause an event severe enough to be viewed as a major accident causing serious injuries or fatalities to personnel within the local area.

Minor: A minor leak even if ignited would not be expected to result into a multiple fatality but could cause serious injuries or a fatality local to the release site or within the module only.

Furthermore, in terms of criteria HCR can be categorized into groups using the amount or quantity of the release and duration of release. The quantity of a major gas release is termed to be greater than 300kg or a mass release rate of 1kg/s and for duration greater than 5 minutes. A minor gas release rate is less than 0.1kg/s for duration less than 2 minutes. While a significant release fall within the range of major and minor for duration of 2-5 minutes.

A major way of controlling HCR is to deal with the minor releases because these are lagging indicators which in a whole would contribute to a major release if not checked and given appropriate consideration in-time. A major contributing factor of release in the north-sea is the contribution of ageing facilities like pipe or flow lines, of which most of them have outlived their design life. Although ageing facility is a major problem to loss of containment but good routine and regular maintenance schemes can help reduce and prevent such. The HSE initiative now is to stop all possible forms of release from occurring because no release, no matter the criterion or amount of release can inflict some harm. Therefore a zero discharge goal is achievable and this is one of the Key Programme Initiatives KPI of the HSE.

There are API specifications which specify allowable leakage rates for surface safety valves (SSV) and sub-surface safety valves (SSSV). The API 14A series specifies leakage rates for both liquids and gases as described in Table.H.1 of Appendix H **(36)**. Generally the allowable leakage rate is described by API 598 test for metal seated valves, which includes, gate, globe, ball and check valves as shown in Table. 3.2. This leakage rates are the permissible leakage rates for valves during testing regimes. It should be noted that NPS in this case stands for nominal pipe size and SCC is standard Cubic Centimetre.

Table.3.2: Specifications for allowable leakage rates and testing frequency **[37]**.

NOMINAL SIZE (NPS)	GATE AND GLOBE VALVES		CHECK VALVES	
	LIQUID TEST (Drops Per Min)	GAS TEST (Bubbles Per Min)	LIQUID TEST	GAS TEST
≤ 2”	0	0	3 scc x NPS/ minute	700 scc x NPS/ minute.
$2^1/_2$” – 6”	12	24		
8” – 12”	20	40		
≥ 14”	D	e		

3.4.2 The Concept of Safety Criterion and Allowable Gas Release.

The concept is viewed on the amount of release of gas which gives rise to a gas cloud compared to the safety criterion as 50% of the Lower Explosive Limit (LEL) volume of leaked gas under alarm conditions to occupy no more than 0.1% of the net enclosure volume valid for all sizes of enclosure. The BS EN 60079-10:2003 stipulates the access degree of ventilation and zone classification type by establishing the maximum release rate of gas at source ṁ with the limiting volume for a given release rate and air change rate as **(38)**;

$$V_Z = \frac{f}{C} \frac{\dot{m}}{k.LEL_m} \cdot \frac{T}{293}, \qquad (3.26)$$

Where V_Z is the limiting volume for a given release rate, LEL_m the minimum lower explosive limit which often taken as 50% of LEL expressed in kg/m^3, f is a correction factor, k a safety factor assumed to be 0.5 for second grade release and C is the ventilation rate in fresh air/unit time.

Generally, V_Z provides information about volume of flammable gas cloud but is not equal to the volume of the zone, listed below are safety criterion used in the industry **(39)**;

- The modelled gas release should be the largest gas release which when fully mixed with air and passing through the enclosure is sufficient to just initiate the automatic trip.
- In all cases gas leak rate should be based on a hole size no smaller than 0.25mm^2 and no larger than 25mm^2.
- Worst case leak scenarios should be considered and flammable cloud volume should be less than 0.1% of the net enclosure volume.
- A safety factor should be applied based on risk assessment to the allowable flammable cloud.
- The 100% LEL should be less than 1m^3 in all cases.
- The strength of the enclosure should be able to withstand 10mbar static overpressure.
- If criterion cannot be met, and the enclosure cannot be demonstrated to be capable of withstanding 15mbar, then the 100% LEL equivalent stoichiometric should be less than 0.15% of the net enclosure volume.

CHAPTER FOUR

MODELLING THE TIME OF CLOSURE OF THE ESDV IN FBR

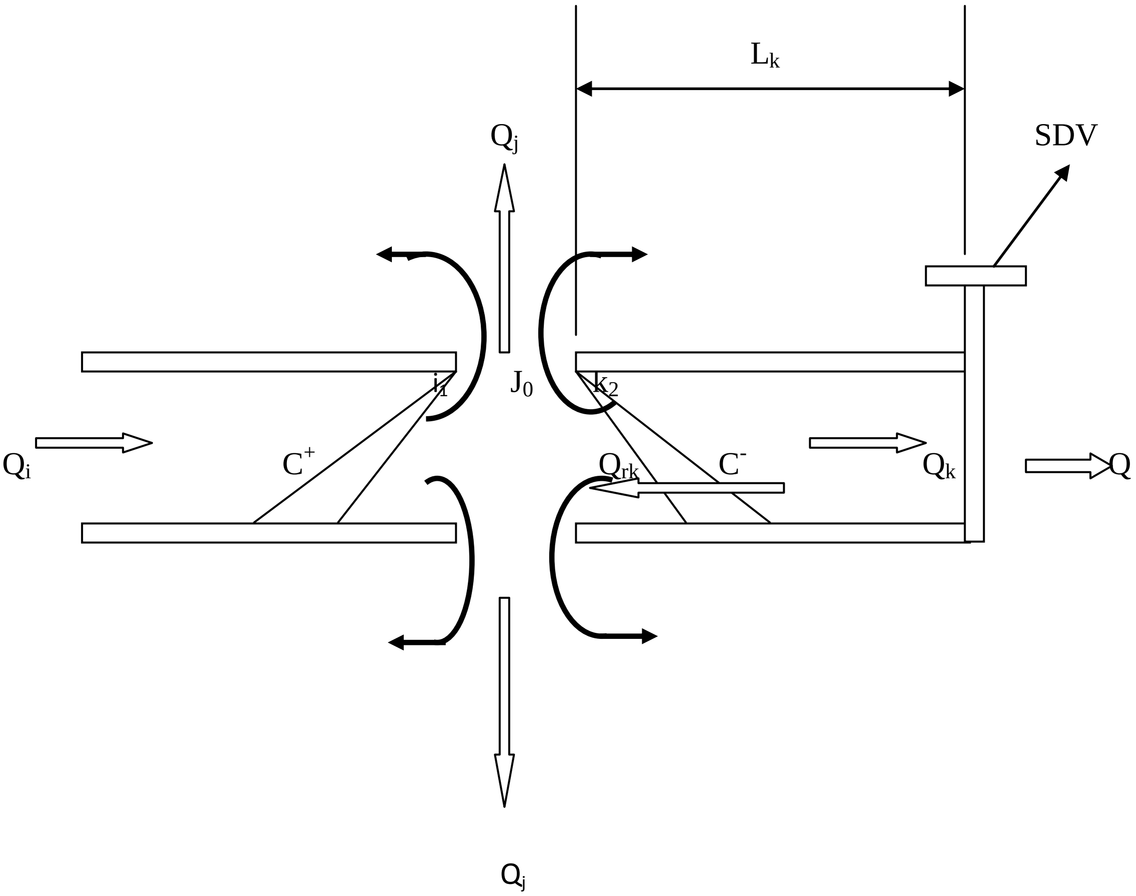
4.1 Modelling the Parameters Affecting the Dynamic Response of the ESDV

The modelling of the dynamic response of the ESDV is based on the variation of volumetric release rate with time and HCR Inventories in a FBR situation, a situation of total rupture of the pipeline. The basic concept used are boundary situations considering both mach-line and path-line characteristics as well as path-line compressibility equations based on the law of conservation of mass, momentum and energy equations previously discussed in Chapter's Two and Three.

The assumption is based on the rupture of the upstream section of a pipe, some distance L_k away from an ESDV. The model is based on natural gas flow in a pipeline of nominal diameter 150mm or 6 inches and ball valve of size 150mm.

The rupture is likely to be caused by degradation of the pipeline walls. This can be due to prolonged corrosion activities, continual cyclic stress from the resulting pressure on the walls of the pipeline. The following are the likely boundary conditions expected with the junction of rupture plane denoted as J and the upstream of pipe section denoted as i and downstream section close to the valve denoted as k. The schematic boundary diagram in Figure's 4.1 and 4.2, depicts the boundary situations for volumetric flow rate and pressure when the valve closes at the downstream end of the ruptured pipeline. The assumption is that the ESDV is made to close at the detection of a pressure drop resulting from the situation of a full bore rupture of massive release of fluid into the atmosphere and since pressure differential has a direct relationship with the volumetric flow rate. This also indicates that there will be a decrease in the volumetric flow rate as a result of the discharge of the fluid from the ruptured plane to the downstream section close to the valve.

As the valve closes gradually two things happen simultaneously, a shock wave is sent in the opposite direction downstream of the section of the valve as layers of fluid are compressed due to gradual reduction of flow area across the valve and there is a partial reverse in flow as the fluid is partly sent back in the reversed direction with a reverse velocity $u_{r.}$ The reverse volumetric flow in this case is denoted as Q_{rk}.



$Q_i = \rho_{i1} u_{i1} A$ $\qquad$ $Q_j = \rho_0 u_0 A_0$ $\qquad$ $Q_k = \rho_{k2} u_{k2} A$

$Q_{rk} = \rho_{k2} u_{rk2} A$

Figure.4.1: A Schematic Modelling Diagram Showing Volumetric Discharge Rate In FBR Situation.

The volumetric flow rate boundary conditions are stated below;

$$Q_i = Q_j + Q_k \, , \tag{4.1}$$

Where Q_i is the total volumetric flow upstream before the rupture plane in pipeline section 1, Q_k is the volumetric inflow upstream of valve immediately after the rupture plane in pipeline section 2, Q is the volumetric outflow of fluid from the downstream section of the valve and Q_j is the volumetric outflow of fluid at the junction of the rupture plane. In conduit flow systems, pressure affects the flow of fluids. The reverse volumetric outflow Q_{rk} is caused because the rupture at junction j creates a pressure differential, where the upstream section of the valve is at lower pressure than the downstream section. This is because fluids are expected to flow from a region of higher pressure to a region of lower pressure.

This indicates that the total outflow is the summation Q_j and Q_{rk}. Also Q_j depends on the area of hole of rupture or puncture A_0. Hence, the total volumetric outflow, $Q_{outflow}$, is the summation of flow from the rupture junction Q_j and the reverse flow Q_{rk} as a result of valve closure as indicated in equation (4.2).

$$Q_{outflow} = Q_j + Q_{rk} \tag{4.2}$$

$$Q_{rk} = A_f\, u_r(t) \tag{4.3}$$

$$Q_{mj} = C_o\, A_{\ pipe}\sqrt{\left(\frac{M\gamma}{RT}\right)\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)(\gamma-1)}} = A_{pipe}.\, C_1\sqrt{P(t).\,\rho(t).\ c_2}\ , \tag{4.4}$$

Where A_{pipe} is the cross-sectional area of pipe, *P(t)* time dependent pressure in the pipe, $\rho(t)$ time dependent density of the fluid, C_1 is the coefficient of discharge taken at (0.98 for the FBR condition) and c_2 is a material constant called here (1.29) **(40)**.

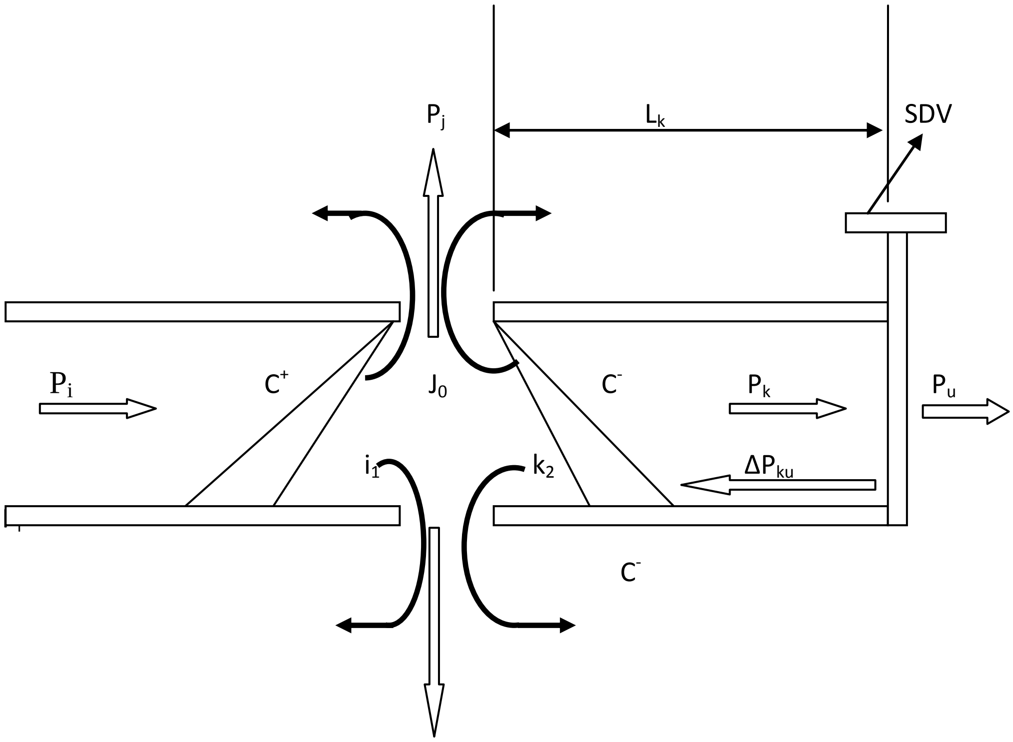


Figure.4.2: Schematic Modelling Diagram showing Pressure Boundary Dispersion in FBR Situation.

Figure.4.2, shows the pressure dispersion during a full bore rupture when the shutdown valve closes at a time t. P_i represents the total upstream pressure of pipe before rupture plane. This is likely going to be equal to the pressure from the reservoir during production or the pressure from the pressure vessel if there are no discrepancies in various pipe diameters and other conditions during the transportation of the fluid. Also, P_j represents the outflow pressure exposed to the atmosphere, mostly going to be a factor of initial P_i, the bore size or diameter and prevailing atmospheric pressure during rupture. P_k is the inflow pressure upstream of the valve and P_u is the outflow pressure downstream as the SDV closes at instant time t_{ci} . A differential pressure ΔP_{ku} is experienced across the valve as it closes; this can be explained via the vena contracta previously discussed in chapter two of this report. The resulting pressure differential ΔP_{ku} between the downstream pressure and upstream pressure across the valve causes a backward pressure pulse known as the surge pressure. The phenomenon can be described by the Joukowsky equation called the fluid hammer equation.

$$\Delta P_{ku} = P_k \pm P_u \tag{4.5}$$

4.1.1 The Effect of Volumetric Flow Rate on Dynamic Response of the ESDV

The volumetric flow rate across the valve shall be modelled as a time variant quantity which depends on the fluid flow velocity u(t), the discharge coefficient (a dimensionless quantity), the degree of opening of valve, the area of flow of the valve and the pressure differential across the valve at various time intervals as shown in equation (2.11) of Chapter Two.

Similarly,

$$Q(t) = A_f(t) \times u(t) \tag{4.6}$$

The equation describing the valve flow area A_f and u(t) the fluid velocity is equation (2.13).

4.1.2 The Effect of Pressure on Dynamic Response of the ESDV

The response of the ESDV is affected by the changes in pressure during the closing period. Although the assumption is based on, that there is an initial loss of pressure because of the rupture point? The model also includes pressure differential in normal conditions without rupture.

4.2 Time of Closure a Significant Design factor of the ESDV

The time of closure is defined as the time it takes for a valve to completely stop fluid flow through it when it is activated. The ESDV is a SCE expected to carry out a shutdown process during cases such as a pipeline puncture or rupture. This model shall consider a total shutdown which involves the total impediment of the excess outflow of fluid from the downstream section of the ESDV to the upstream section of the valve with the ruptured point some distance away from the ESDV.

The closure time is an interaction of several factors affecting the performance of the valve itself. The concept of time of closure model shall be derived from the Joukowsky's equation, considering a situation where a valve closes causing pulse waves reflected in the reverse direction with a sound velocity c called celerity. This phenomenon often explains the fluid hammer effect which results in a pressure surge after valve closure. Referring back to equations (2.16.2) of Chapter Two, where ΔP is the surge pressure or differential pressure across the valve, c celerity or acoustic velocity, ρ the density of the fluid and Δu the velocity of the fluid.

In this case $\Delta u = u_i - u_{i-1}$, shall imply time dependent fluid velocity when the valve closes at various time intervals, where u_i is the final velocity and u_{i-1} initial velocity at a particular time interval of closure. Although, the equation explaining the differential fluid velocity above applies across every wavelet, the effect of complete valve closure over a period of time is greater than $2L_k/c$, where L_k is the distance to the rupture plane. For times of valve closure $t_c \leq 2L_k/c$, it is expected that the valve closes at variant differential pressure across it as it compresses different layers of the fluid in this process. Also if $t_c \leq 2L_k/c$, then there can be a reduction in ΔP and $Q_{outflow}$ resulting from the dissipating effect of the variant HCR parameters with time at the FBR junction.

The time of closure for this model is to be obtained from the extraction of the fluid hammer or Joukowsky's equation, for both incompressible and compressible fluids as explained in equations (2.19) and (2.16.1) in Chapters Two of this report, as shown in equations(4.7 – 4.10).

$$\Delta P = c\,\rho\frac{\partial L}{\partial t} \tag{4.7}$$

$$\int_{t_{c_{i-1}}}^{t_{ci}} \Delta P\, dt = c\rho L \tag{4.8}$$

$$\Delta t_{c_i} = \frac{c\rho L}{\Delta P} \tag{4.9}$$

$$t_{c_i} = t_{c_{i-1}} + \frac{c\rho L}{\Delta P}, \tag{4.10}$$

where Δt_{c_i} is the valve time interval of closure at various differential pressures across the valve and t_{c_i} is the discrete time at which equations are solved numerically.

The Visual Basic Excel programme as seen in the data tables of Appendix J was used to model a software application to determine the closure time of different valves sizes, using in particular a 150mm valve size as our case study. This application can be used to run the outcome for other ball valve sizes. A vivid explanation of how to run the valve closure time application is also explained in Appendix J of this report. The algorithm that explains this is shown in Figure. 4.3.

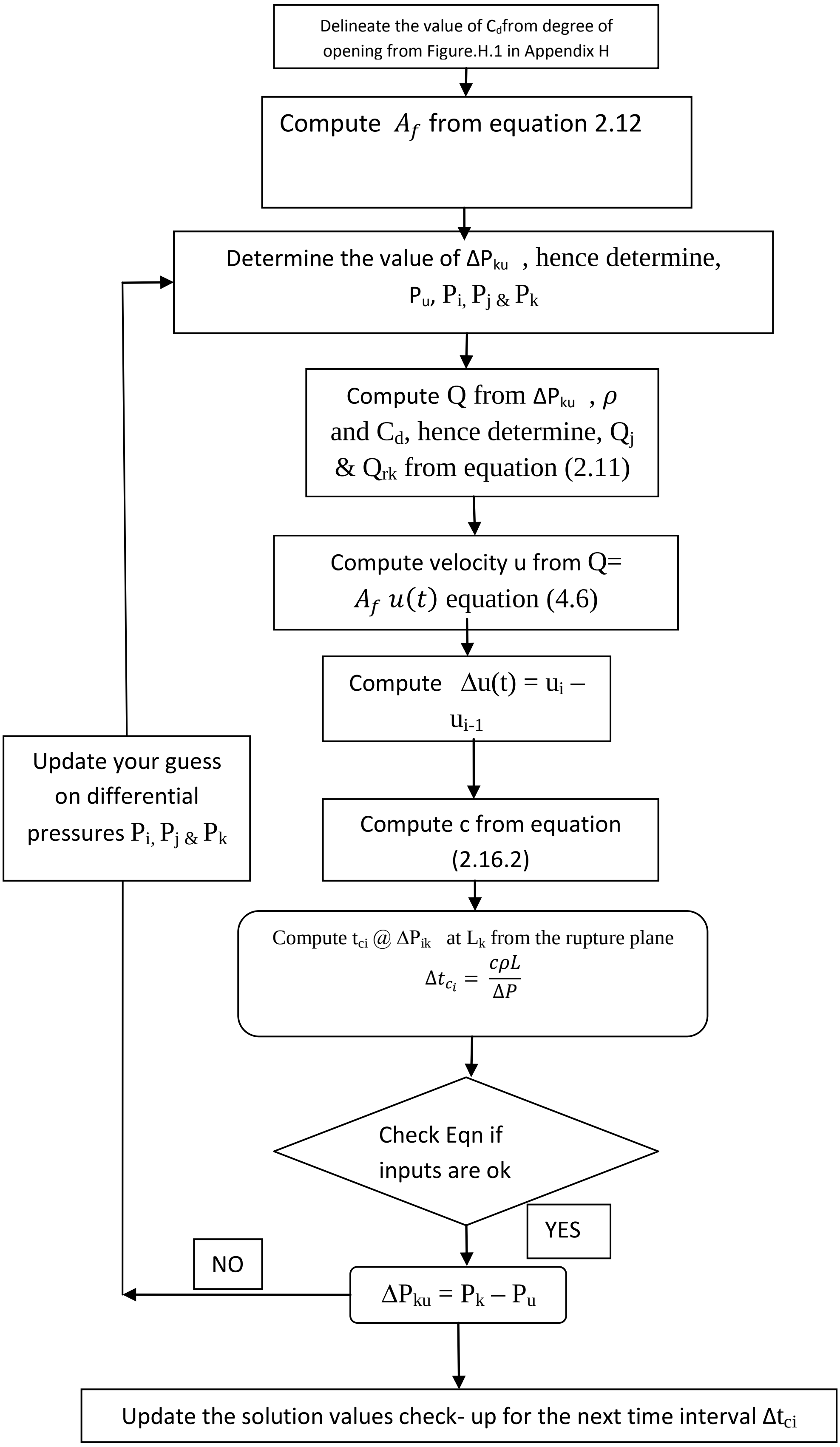


Figure.4.3: Algorithm Model for Time of Closure of the ESDV.

4.2.1 Time Subsequent to Closure

This model also shall consider what happens to the HCR parameters after closure of the valve. The time subsequent briefly explains what happens to volumetric, mass flow rate and pressure after closure of the ESDV.

The release rate of mass and volumetric flow shall be modelled using the time decay constant approach **(41)**. This is because the HCR parameter being considered gradually dissipates with time even after closure of valve as indicated in equation (4.11).

$$f(y) = y_o \exp(-\alpha t) \tag{4.11}$$

Equation (4.11), explains the concept behind a variable decaying with time. Using the above decay constant equation to model the subsequent time relating with HCR inventories like mass flow rate, volumetric flow rate and pressure we obtain the following basic equations below **(41, 42)**.

$$Q_m = Q_{m_0} exp^{-\alpha t} \tag{4.12}$$

$$Q = \ Q_0 exp^{-\alpha t} \tag{4.13}$$

$$P = P_0 exp^{-\alpha t} \tag{4.14}$$

The decay constant α was derived from an empirical regression approach **(41).**

$$\alpha = D^{0.25} \left[0.22A - 0.13A^{1.5} + 0.00068 \ (T - 15)\right] \tag{4.15}$$

For the value of R = 0.973

Where α is the constant of decay (s^{-1}) , D is the radius ratio (pipe diameter in mm) /50, A is the area ratio (Area of orifice/internal area of pipe), T is the temperature of the fluid in ^{0}C and R is the coefficient of multiple correlation.

The decay constant was obtained from a statistical analysis of fluid conditions. The data were collected from 20 load cells of LPG release experiment and found using least square fit of an exponential curve as shown in Figure.4.4 **(41)**.

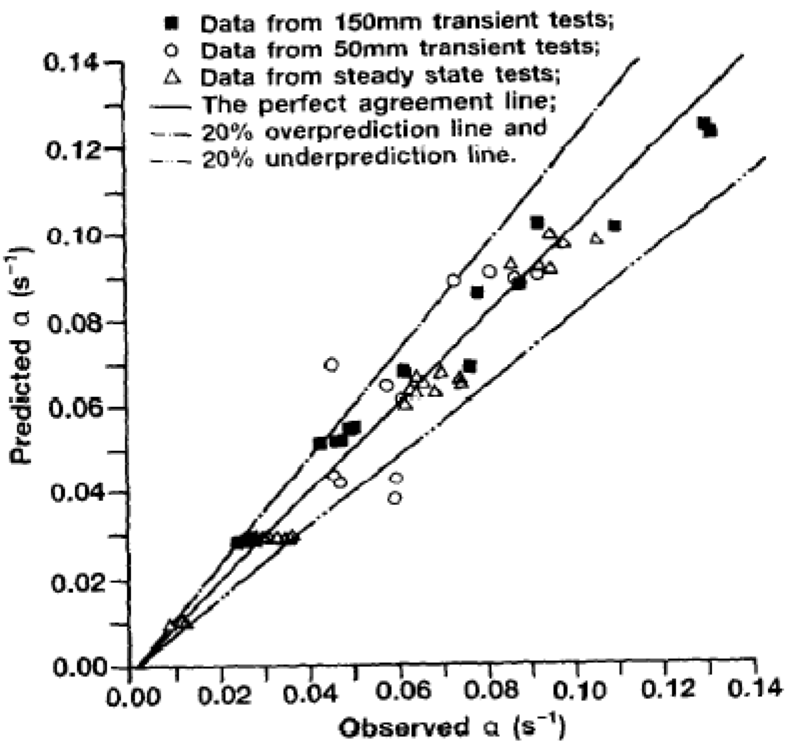


Figure.4.4 Comparison of Predicted and Observed mass decay constant[41].

4.3 Relating time of Closure to HCR Parameters

Looking closely at equations (4.7) we can establish the parameters that affect the time of closure of a SDV. Such parameters like celerity c, density of fluid ρ, the velocity of the fluid v and the differential pressure ΔP across the valve during different closure time intervals.

Mathematically, the time of closure t_{ci} has the following relationships with the interacting HCR parameters. These two parameters (pressure and fluid velocity) have the most significant effect because they are varying parameters, whilst others (celerity and fluid density might be constant), although still have effect on the time of closure.

$$t_{ci}\ \alpha\ \frac{k}{\Delta P} \tag{4.16}$$

$$t_{ci}\ \alpha\ v \tag{4.17}$$

The above mathematical relationships shows how differential pressure and fluid velocity will affect the time of closure.

4.4 Using FORM Approach to Determine the Sensitivity of HCR Parameters with Time of Closure of the ESDV.

The First Order Reliability Method FORM is a concept used in determining the sensitivity of estimate of failure probability to changes in distribution parameters. These sensitivities are useful because they quantify the importance of distribution parameters such as mean, standard deviations and correlations. The basic concept behind FORM is the approximation of the failure surface by the set of 1st order Taylor series surface and then to calculate the probability using these approximated surfaces **(43, 44)** .

The sensitivity for FORM shall be determined using hypothetical data and shall involve the determination of the limit state function for the time of closure of the ESDV. We shall consider the equation (4.10) which shows the relationship between the time of closure and HCR parameters, to actually determine the limit state function of time of closure. The valve is expected to have failed if, $t_{ci} > t_{ci_{max}}$. Hence the value used for $t_{ci_{max}}$ shall be the expected range of closure for a 150mm shutdown valve. Hence the safe domain for time of closure is $t_{ci} \leq t_{ci_{max}}$ otherwise any time above $t_{ci_{max}}$ simply means that the SDV valve has failed.

Generally for shutdown valves at this range the maximum time shall be 6 seconds. The limit state function thus can be stated as,

$$t_{ci} \leq t_{ci_{max}} \tag{4.18}$$

$$G: t_{ci} - t_{ci_{max}} \leq 0, \tag{4.19}$$

The variant parameter of pressure increase, celerity and density is considered as variables, while the length of pipe as constant. The standard normal distribution is used to model the sensitivity for the time of closure of the ESDV. All data, used includes the mean, standard deviation, coefficient of variation and correlation are all hypothetical data as shown in Table. 4.1.

Table.4.1: Normal Distribution Parameters

HCR Variant Parameters	Mean(μ)	Standard Deviation (σ)	Cov	Correlation
Celerity (m/s)	314.52	4.10	0.017	0.40
Density (ρ)kg/m^3	415	9.16	0.021	0.40
Pressure(bar) ($P_{increase}$)	60	18.6	0.31	0.40

Expressing the limit state function in the standard normal space gives,

$$G: \frac{L(\mu_c + \sigma_c z_c) * (\mu_\rho + \sigma_\rho z_\rho)}{(\mu_p + \sigma_p z_p)} - t_{max} \leq 0 \qquad (4.20)$$

$$G: \rho(\mu_c + \sigma_c z_c) * (\mu_\rho + \sigma_\rho z_\rho) - 6(\mu_p + \sigma_p z_p) \leq 0 \qquad (4.21)$$

$$a_c = \frac{\partial G}{\partial Z_c} = L\sigma_c \qquad (4.22a)$$

$$a_\rho = \frac{\partial G}{\partial Z_\rho} = L\sigma_\rho \qquad (4.22b)$$

$$a_p = \frac{\partial G}{\partial Z_p} = -6L\sigma_p \qquad (4.22c)$$

Where, z stands for the standard normal space, $\mu_{c,}\mu_\rho$ and μ_p stands for the mean values of celerity, density and pressure.

The incorporation of FERUM and mathlab programme is used to determine the sensitivity of the parameters that affects the time of closure of an ESDV for this model.

CHAPTER FIVE

DISCUSSION AND INTERPRETATION OF RESULTS

5.1 Relationship of HCR Parameters with time of Closure of an ESD Ball valve during a FBR Situation.

The parameters that relate to the time during closure includes, the pressure difference across the valve, the volumetric flow rate, the mass flow rate and the fluid velocity, Table.5.1 shows the data of HCR parameters with time during closure an extract of the of data displayed on excel spread sheet in Appendix J. The data used in this report are hypothetical in nature and allows for discrepancies subject to other empirical and experimental research.

Table.5.1: HCR Model Parameters with time during Closure of a 150mm SDV.

X (mm)	C_d	Θ	ΔP(bar)	Q (m^3/s)	Q_j (kg/m^3)	$Q_{outflow}$ (m^3/s)	$u_i(t)$ (m/s)	$t_{ci}(s)$
0	1.00	90	205	5.155	3.686	0.023614	1.62063	0.00
15	0.90	80	138.29	4.344	2.685	0.457270	1.38424	0.68
30	0.75	70	93.96	3.582	1.866	0.919066	1.15713	1.35
45	0.58	60	63.61	2.742	1.309	1.176552	0.89841	2.03
60	0.40	50	43.06	1.874	0.931	1.150544	0.62259	2.71
75	0.30	40	29.15	1.393	0.673	1.003441	0.46952	3.39
90	0.20	30	19.74	0.2921	0.495	0.767648	0.31485	4.06
105	0.13	20	13.36	0.593	0.371	0.550832	0.20583	4.74
120	0.08	10	9.05	0.359	0.283	0.370591	0.12734	5.42
135	0.04	5	6.12	0.176	0.220	0.214988	0.06396	6.09
150	0.00	0	4.15	0	0.173	0.053862	0	6.43

5.11 Interpreting Pressure Differential vs. time of closure across the ESDV.

Critically looking at the trend of pressure differential across the valve as the valve closes at different time interval. This occurs when the, valve area A_f decreases with a decrease in the angle of opening Θ of the valve as the valve closes. The pressure differential gradually decreases as the valve closes at different time intervals because the difference between the upstream pressure and downstream pressure drastically reduces. The upstream pressure which was initially the pressure of the fluid in the pipeline decreases at a sonic rate because of the rupture point. It is expected theoretically that this pressure decrease to the point of the ambient prevailing pressure at some certain time as described in Figure. 5.1. The figure below also shows a drastic decline in pressure at the first instant of closure time from 0.00s to 6.43 seconds.

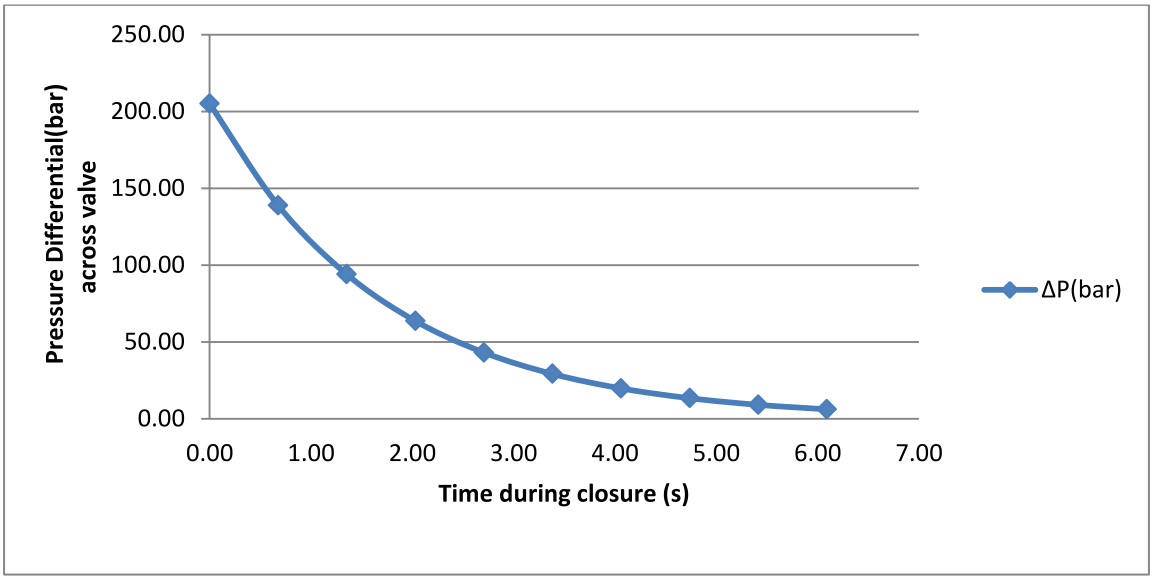


Figure.5.1: Model Graph of Pressure Differential vs. Time during Closure.

5.12 Interpreting Initial Volumetric flow rate vs. time of closure across the ESDV.

When the valve closes it is expedient that the flow rate into the ball port decreases as the area of flow also decreases at various closing time intervals. The figure below explains this trend graphically; a point in the graph explains a transient point of the condition of flow rate through the ball port of the valve and can be divided into two flow regimes. This point is at time interval 2.03 seconds. At the first flow regime between 0 to 2.03 seconds there is a drastic sharp decrease of flow. The second flow regime between 2.03 to the time it finally closes a kind of a curve line with a gradual reduction of flow is obtained. The first transient point explains what happens when there is a quick interruption or restriction to an initial free flowing fluid, also comparing this with the pressure differential graph this point also shows a drastic decrease in pressure. However, the other transient point explains what happens to volumetric flow after what happens at the first transient point, here we obtain a gradual reduction of flow as explained in the second flow regime at this point.

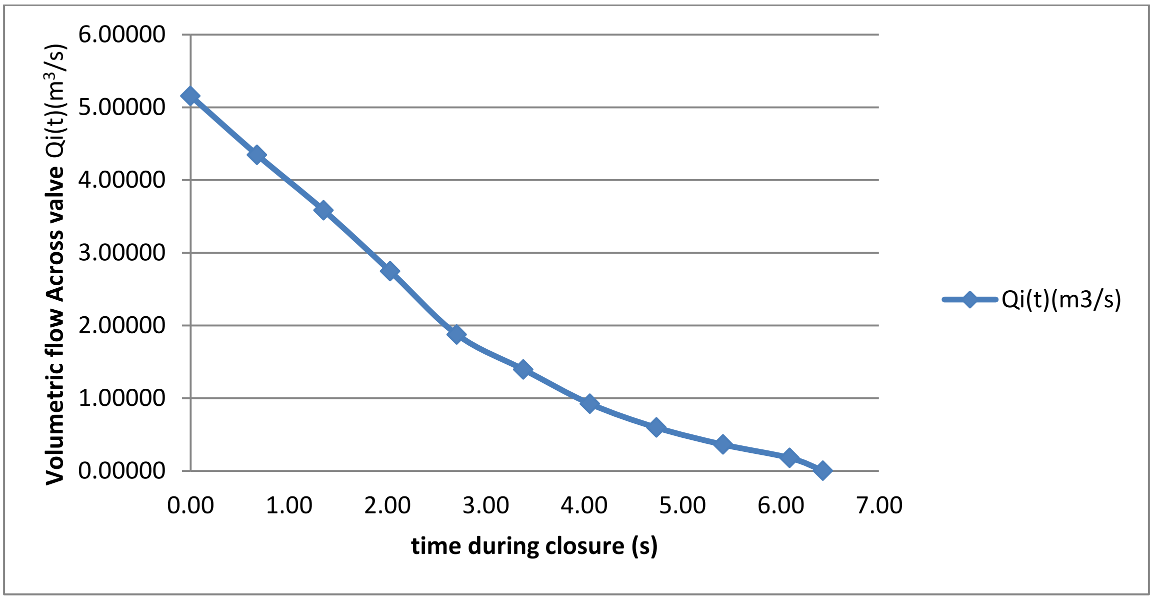


Figure.5.2: Graphical Model of Volumetric flow rate vs. time during closure.

5.13 Interpreting mass flow rate vs. time of closure at the Rupture Junction of Pipeline

The mass flow rate at the rupture junction is a function of the density of the fluid and the initial pressure of the fluid in the pipeline. Other factors which might affect the mass flow rate includes; the temperature of the fluid and the diameter of the pipe as well. Considering the values from VBA Excel spreadsheet in Appendix J, at the instance of rupture some time immediately after the ESDV has been activated to close or is in the process of closing. At the time before the ESDV is activated to close when there would have already been a major lost in inventory, Figure. 5.3 shows that the greatest inventory lost occurs at 0.00 seconds. The value of mass flow rate then gradually trickles down to a point but not equal to zero at full time during closure. This is because they will still be inventory loss after valve closure and this shall be explained by the time subsequent to closure of the valve.

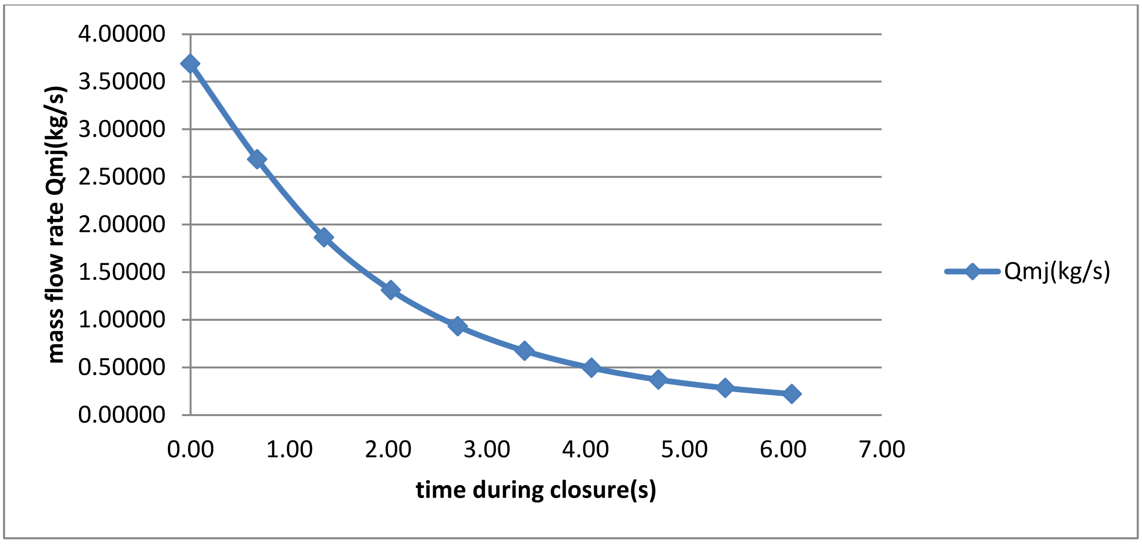


Figure.5.3: Graphical Model of Mass flow rate vs. Time during Closure.

5.14 Interpreting Volumetric Outflow at Rupture Point vs. time of Closure.

The volumetric outflow at the rupture point is considered as the sum of the reverse flow from the upstream section of the valve as the valve closes at different time interval and the rapid outflow at the ruptured point. Looking critically at the graph in figure, 5.4, at 0.00 seconds when the valve starts to close when they would have been some inventory lost at rupture point, the outflow gradually picks up from 2.4E-02 m^3/s at time at 0.00 seconds and reaches its maximum outflow $1.2m^3/s$ at 2.03 seconds. This is the point at which both reverse flow and volumetric outflow is maximum. Also after valve closure volumetric inventory loss continues and decays with time until there is no more inventory loss at rupture point.

It should also be noted that the trend of volumetric outflow in Figure.5.4 differs from the mass flow rate at Figure.5.3. This is because natural gas is an ideal gas and is affected by pressure, density, volume and temperature of the fluid as explained in equations (1 to 4) of Appendix A. This also explains why the value of initial volumetric outflow at 0.00 seconds is small compared to the initial mass release at the same instance. Although, this gradually increases with closure time as the gas released occupies more volume or space.

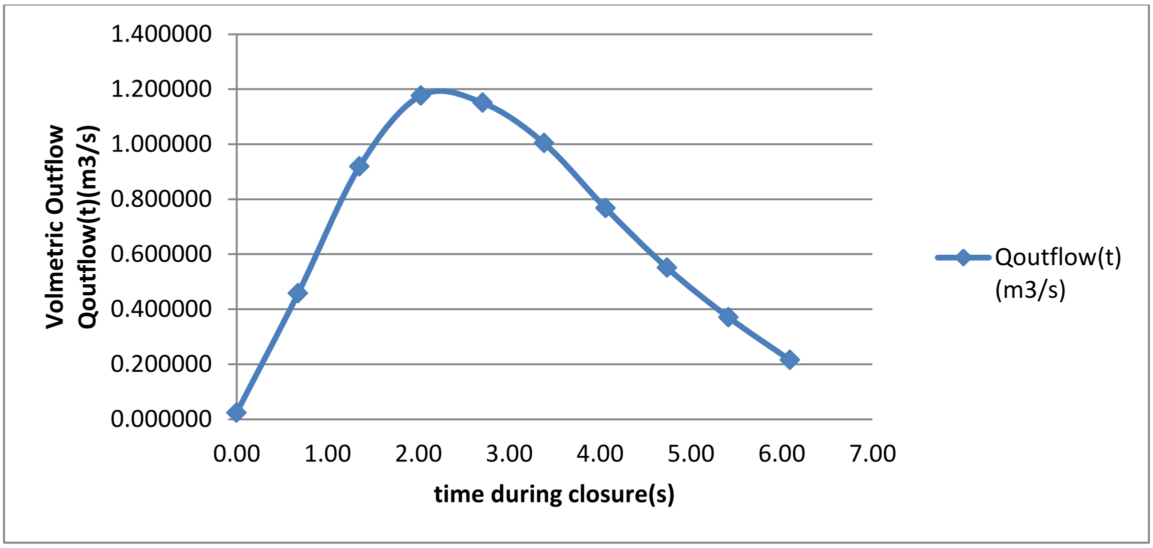


Figure.5.4: Graphical Model of Volumetric outflow vs Time during Closure.

The cumulative addition of volumetric outflow gives what is obtained in Figure.5.5. This will show the expected maximum outflow from the ruptured point during the time of closure intervals. From the graph we can actually delineate that the total outflow through the rupture point for a 150mm nominal size of pipe some distance of 1000m for an ESDV that closes at a maximum of six seconds is 1.1765 m^3/s. This is can be compared with the allowable leakage rate for SSV in API 598 standard and used to actually determine the performance standard of the valve. The stipulated allowed leakage rate for valve testing is 700SCC x 150mm/minute for gases in flow lines of this category, converting this to cubic meter per second we obtain a value of about 0.001750 m^3/s. Also using the API 14 series for SSV and SSSV the allowable leakage rate is 15 SCFM which is about 0.007079. This is showing that the actual time of closure for this model is not sufficient enough to curtail the inventory loss in terms of volumetric outflow as compared to the standard specified by API 598 and API 14 series **(36, 37)**. Hence to curtail inventory loss to the environment in order to reduce the aftermath effect of dangerous event from happening, the time of closure should be faster than 6s/6 inches pipe, which translates to a 1second per inch the normal closure time in the industry now. Although other factors affect inventory loss, the major factors are; the prevailing fluid flow pressure, the initial flow velocity and the size of the pipeline itself.

The highest value of the cumulative volumetric release (6.688m^3/s) can be used to determine the limiting volume V_Z as described in chapter three of this report for a worst case scenario involving the full rupture of a pipeline using the BS EN 60079-10 standard.

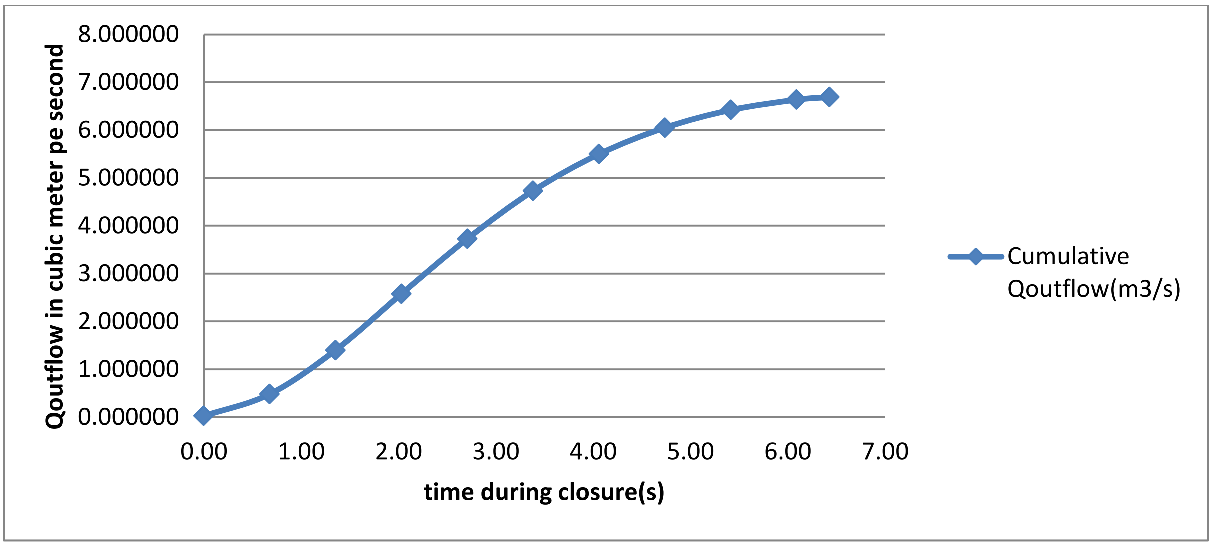


Figure.5.5: Model of Cumulative Volumetric outflow vs. Time during Closure.

5.15 Interpreting Fluid flow Velocity vs. time of closure.

The flow velocity across the valve as it closes decreases with time. It is known that fluid velocity has a direct relationship with volumetric flow; this means that likely same curve pattern is obtained like that of volumetric flow rate across the valve. The figure below show that same trend as explained for volumetric flow rate, two transient points are also noted here at point 0.46 seconds and 3.04 seconds on the curve of the graph.

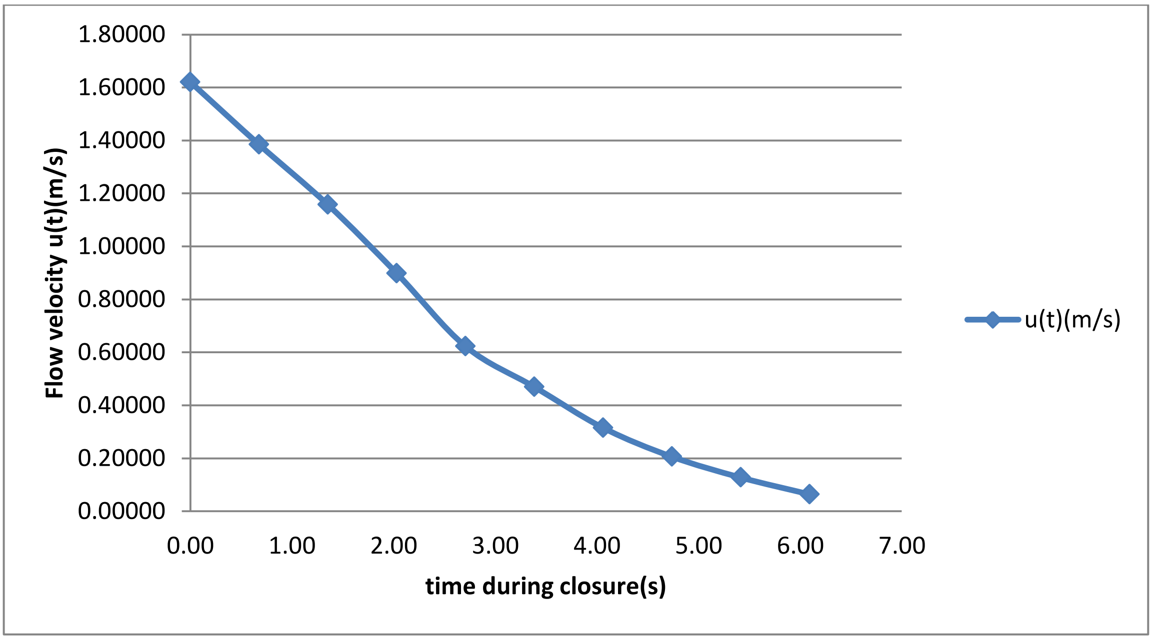


Figure.5.6: Graphical Model of flow velocity vs. Time during Closure.

5.16 Interpreting other HCR Parameters affecting Valve's time of Closure.

The interaction of some basic parameters which are also of importance to the modelling of the time of closure of an ESDV, such parameter are, Area of flow of the valve, the degree of opening, density of fluid, compressibility factor, the expected torque to close the valve and celerity. All these parameters have a way in affecting the major variant parameters (pressure, volumetric flow rate, mass flow rate and fluid velocity), being considered in this report. The graphs and tables that explain these relationships can also be found in Appendix (B-F).

Explaining the trend of Pressure Differential

The relationship of pressure differential with coefficient of discharge, degree of opening, density and volumetric flow across valve shows a decrease in trend with all these parameters from the fully open position at 90^0 to fully closed position 0^0 of the ball valve. Figure 5.7 shows the relationship between pressure differential and density with degree of opening of an ESDV ball valve type. The trend can be seen in Table. B.1 of Appendix B. Figure.B.1 of Appendix B shows the relationship of pressure differential with volumetric flow rate.

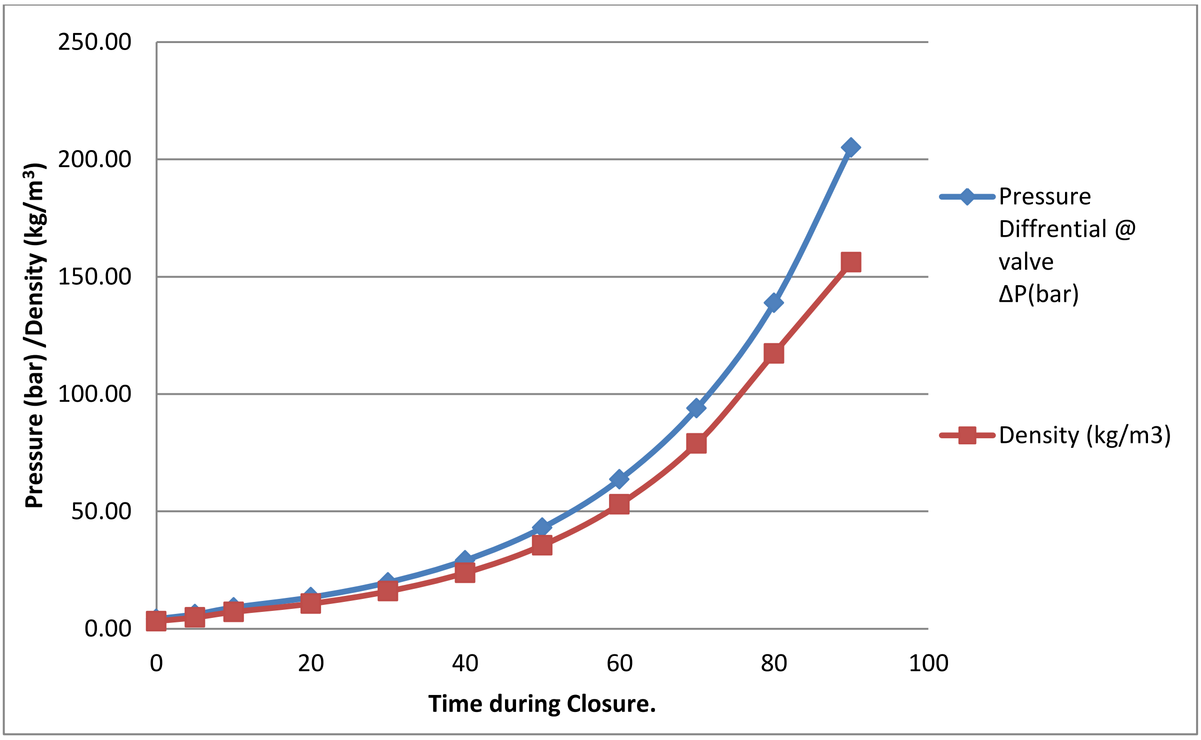


Figure.5.7: Graph of Differential Pressure vs. Degree of Opening.

Explaining the trend of the Area of flow of an ESDV.

A similar trend of decline is experienced in the relationship of Area of flow of the valve with parameters like coefficient of discharge, volumetric flow and differential pressure at fully open and closed position as shown in Figures.C.1-C.2 of Appendix C. Figure.5.8 shows this decline relationship with pressure.

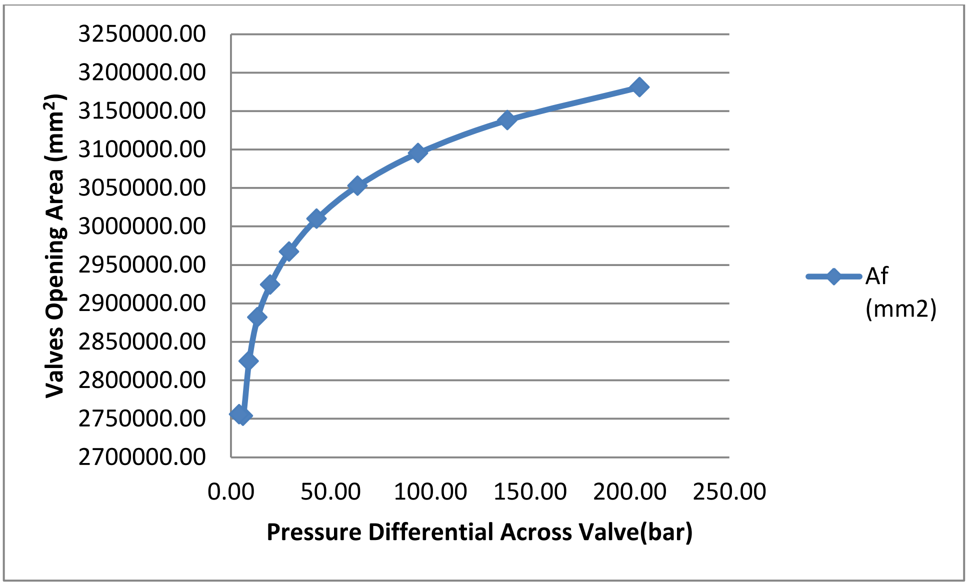


Figure.5.8: The Valve Area of flow vs. Pressure Differential across valve.

Also an important parameter usually associated with the fluid hammer effect called celerity shows a trend of gradual increase as the valve closes at different time intervals. This is because celerity has an inverse relationship with the density of the fluid, the velocity of the fluid and a direct relationship with the surge pressure resulted from the pressure differential of the SDV as shown in Figure.F.1 of Appendix F.

The Relationship of Torque and HCR Parameters.

The outcome of the expected torque required to close the valve with graphical representation is expressed in Figures.G.1 to G.3 of Appendix G. These graphs show the relationship of torque expressed in Nm from fully open to fully closed positions. The relationship between torque, valve differential pressure, volumetric flow rate and angular speed are expressed in equation 16 of Appendix A.

The effect of temperature was also considered. This is because Natural gas is an ideal gas and temperature and pressure will have an effect on the density, compressibility factor and the celerity produced from the closing effect of the gas and the conditions of rupture joint. All, these too have a way of affecting the eventual volumetric flow rate across the valve and volumetric outflow from rupture point, this effect is explained in equations (10) to (11) of Appendix A.

5.2 The Behaviour of HCR Parameters during Time after Closure of the ESDV

One major function of the ESDV in this scenario is to prevent a back flow of inventory downstream of the valve section from flowing pass it into the upstream section and discharge through the rupture point. It should be noted that the rupture point creates a pressure differential that causes fluid upstream to flow backwards. This has to be prevented from happening and really depends on how fast the ESDV is able to close to restrict backward flow of inventory from being discharged upstream of the valve through the rupture point of the pipeline.

Although, all inventory already upstream of the ESDV from the rupture point shall be lost from the rupture point. The after closure vividly explains what happens to this inventory. It is expected that this inventory follows a time decay variant order, a situation where the gradually decline with time. The inventory upstream shall in this case be the sum of interacting HCR parameters which are outflow and reverse flow caused by the closure of the valve, the surge or differential pressure and prevailing ambient or atmospheric pressure outside the pipe boundary area, Table. 5.2 Shows the data of time subsequent to closure with variant HCR Parameters. Also equations (17) to (22) in Appendix A, explains mathematically how the time subsequent to closure is determined from their mathematical relationship.

Table.5.2: Data of Time after closure with Variant HCR Parameters.

t_{mj}(s)	t_p(s)	$t_{outflow}$ (s)	Qj(m3/s)	$Q_{outflow}$(t) (m^3/s)	Pressure (bar).
1.675552574	1.899474454	4.955984895	0.018791428	0.012014682	173.66289
3.304096523	3.757414218	7.646633498	0.014582461	0.161207473	95.130100
4.942805709	5.556995973	9.886183861	0.012045416	0.238751633	53.418385
6.594498611	7.276165365	11.85639516	0.010050956	0.233639731	31.002761
8.261931779	8.887263282	13.71216078	0.008492476	0.177399079	18.772717
9.947280075	10.35746117	15.43686592	0.007281516	0.122296355	11.974341
11.6516109	11.65024384	17.09752351	0.006343999	0.074601805	8.115960
13.37459175	12.72781029	18.69376388	0.005617886	0.043060995	5.882864
15.11458775	13.55382756	20.14185988	0.005051900	0.02378017	4.576274
16.86909277	14.09578292	20.75022755	0.004604770	0.012697881	3.122347
17.00000000	15.00000000	21.00000000	0.004000000	0.012000000	3.123469

5.21 Interpreting Mass flow Rate with Time after Closure

The mass flow rate after closure rapidly dissipates with time. The factors which affect the rate of dissipation are, the initial pressure of the fluid, the conditional temperature, the length of pipe from the upstream section of the valve to the rupture point, the diameter of the pipe, the density of the fluid and prevailing atmospheric condition including the ambient temperature and direction and speed of wind. The Figure.5.9 shows that it takes about 17 seconds for total inventory to be lost after the actual time of closure of the valve. It also explains how the mass flow rate reduces with time after the valve has closed.

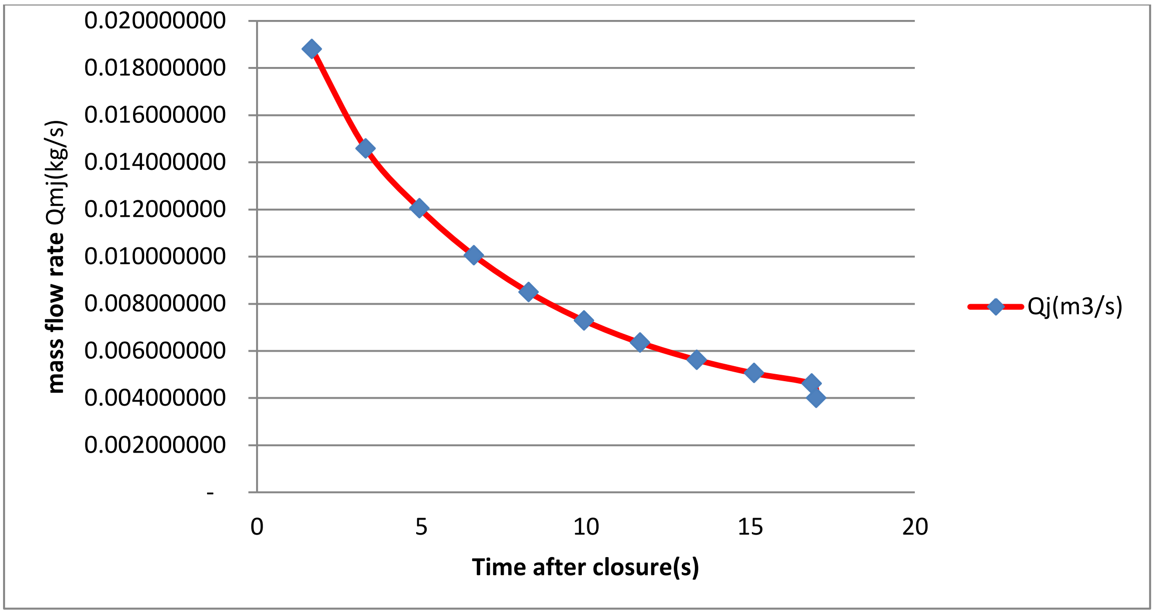


Figure.5.9: Graphical model of Mass flow rate vs. Time after Closure.

5.22 Interpreting Volumetric Flow Rate with Time after Closure

Immediately after the closure of the valve it is expected that inventory will still be flowing from the rupture point. The volumetric flow is the summation of the flow of the reverse volumetric rate along the length L_k to the rupture point where it is discharged and the initial volume of fluid along the entire length L_k of the pipeline from the upstream section of the valve to the rupture point. The discharge time from the rupture point is affected by the travel length of the fluid from the upstream section of the valve. Theoretically the first flow to be discharge is fluid very close to the boundary rupture point others far away from the rupture boundary is expected to travel to the point where they are eventually discharged. This explains a rise in the peak in Figure.5.10 from 4.955 seconds during closure to a certain time after closure at 9.88 seconds and then a steady flow to a point of about 11.856 seconds, beyond this point the flow drastically dissipates with time.

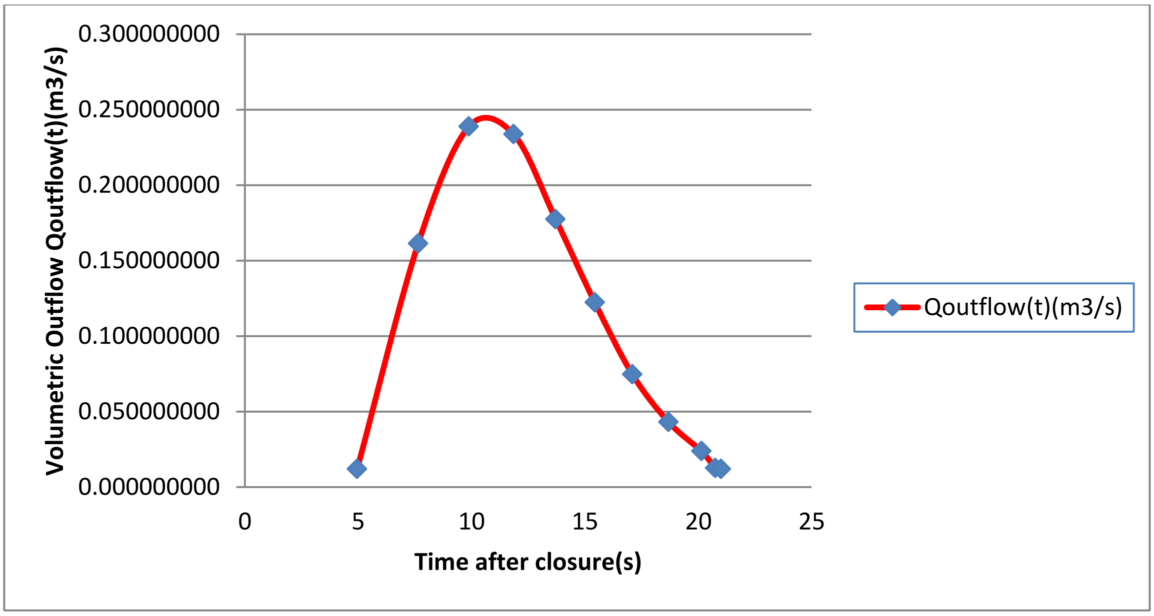


Figure.5.10: Graphical Model of Volumetric outflow vs. Time after Closure

5.23 Interpreting pressure with Time after Closure

Figure.5.11 shows how pressure dissipates with time even after the valve has been closed. The rate of dissipation is a factor of the initial pressure of the fluid flowing in the pipe, the pressure surge as the result of the fluid hammer effect at instant of valve closure time intervals and the prevailing environmental ambient pressure outside the boundary area of the pipe. The pressure is expected dissipates with time until it equals the ambient pressure of the prevailing environment. In this case the ambient pressure is 1 bar both might slightly differ in some cases. The pressure drop eventually affects the volumetric outflow until there is no inventory flow from rupture point at a pressure almost equal to the ambient pressure.

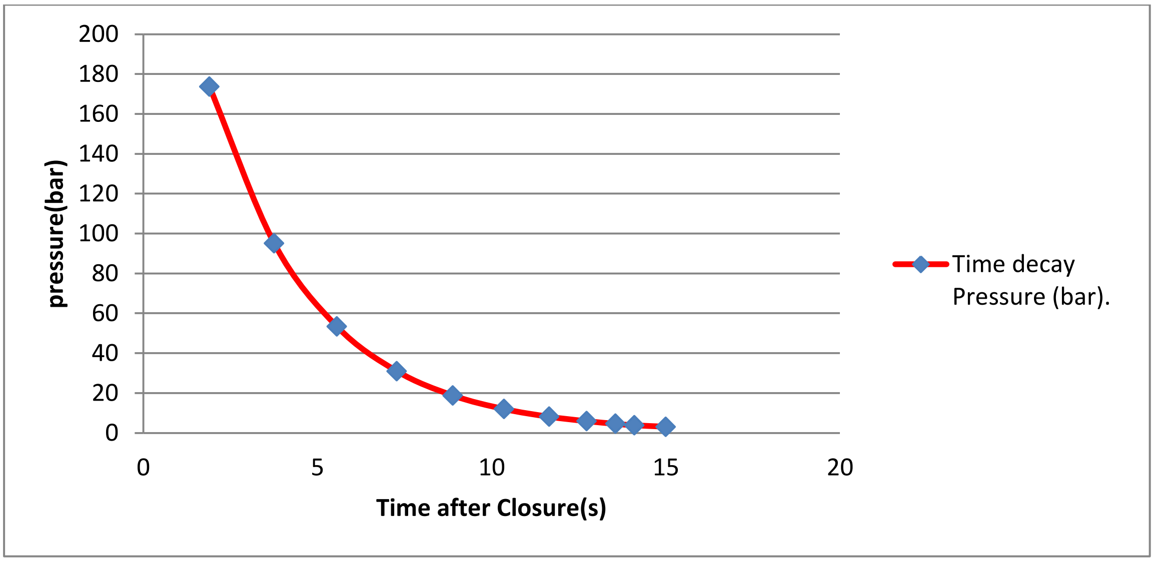


Figure.5.11: Graphical Model of Pressure Drop vs. Time after Closure.

5.30 Sensitivity of Parameters that Affects time of Closure.

The sensitivity was determined by the FERUM programme with input values of Table. 4.1 are; α_c = -0.1187, α_ρ = -0.1669 and α_p = 0.9788 as indicated Figure.5.10 and in the runned version in Appendix I. Where α_c stands for the sensitivity of celerity, α_ρ sensitivity of density of gas and α_p denote the sensitivity of pressure increase. The above sensitivity values show that pressure increase is the most significant factor that affects the closure time of an ESDV. This shows the effect of pressure increase on the expected torque required to close the valve at a required flow rate across the valve as shown in Figure. G.1. of appendix G and equation (16) of Appendix A.

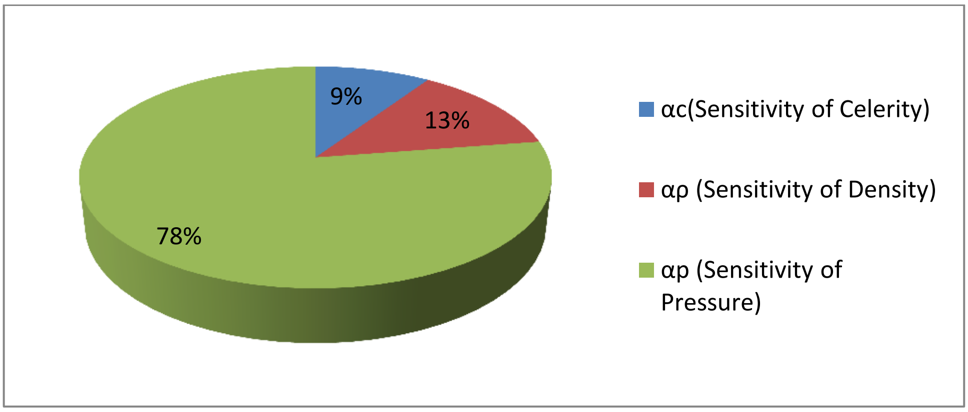


Figure.5.12: Pie- Chart for Sensitivity Parameters that affects the time of Closure.

CHAPTER SIX

COST BENEFIT ANALYSIS OF USING QUICK ESD VALVES

6.1 The Concept of QRA

Quantitative Risk Assessment (QRA) is the means by which risk of a hazard can be expressed as a value that indicates a function of that hazard's frequency and its consequences. Mathematically this can be expressed as;

Risk = Frequency x Consequence.

Quantitative risk assessment allows for the comparison of risk reduction options for a particular hazard. This project is considering the risk reduction of using quicker closing ESDV valves in a full bore rupture condition. The use of QRA in the oil and gas industry is to increase safety through Risk Based Design RBD and also to improve on cost effectiveness and savings in many areas **(45, 46)**.

The following are the steps used in evaluating QRA;

- Hazard identification
- Consequence Assessment
- Frequency Assessment
- Risk Characterization

Looking carefully at each step in QRA and comparing with this report, the likely hazard to be identified is loss of containment from a full bore ruptured pipeline. The resulting consequence is an explosion of a gas pipeline or asphyxiation if poisonous gases are released. This can eventually lead to injuries of personnel, fatality, loss of asset or facility and loss of the company's reputation or goodwill. The frequency assessments will involve defining the potential release source and subsequently determining the likelihood of various releases. This is usually determined by the use of historical data and can be used to determine the ignition probability. Risk characterization involves how risk is categorized and presented from resulted consequences. This report considers the risk outcomes if the EDSV fails, does not fail (closes very fast or closes slower than required) and if they are no ESDV's in the plant or pipe network. Risk considered are, risk to the public/environment, risk to employees and risk to Assets/production. Figure. 6.1 below show the expected resulted outcomes displayed in an event tree.

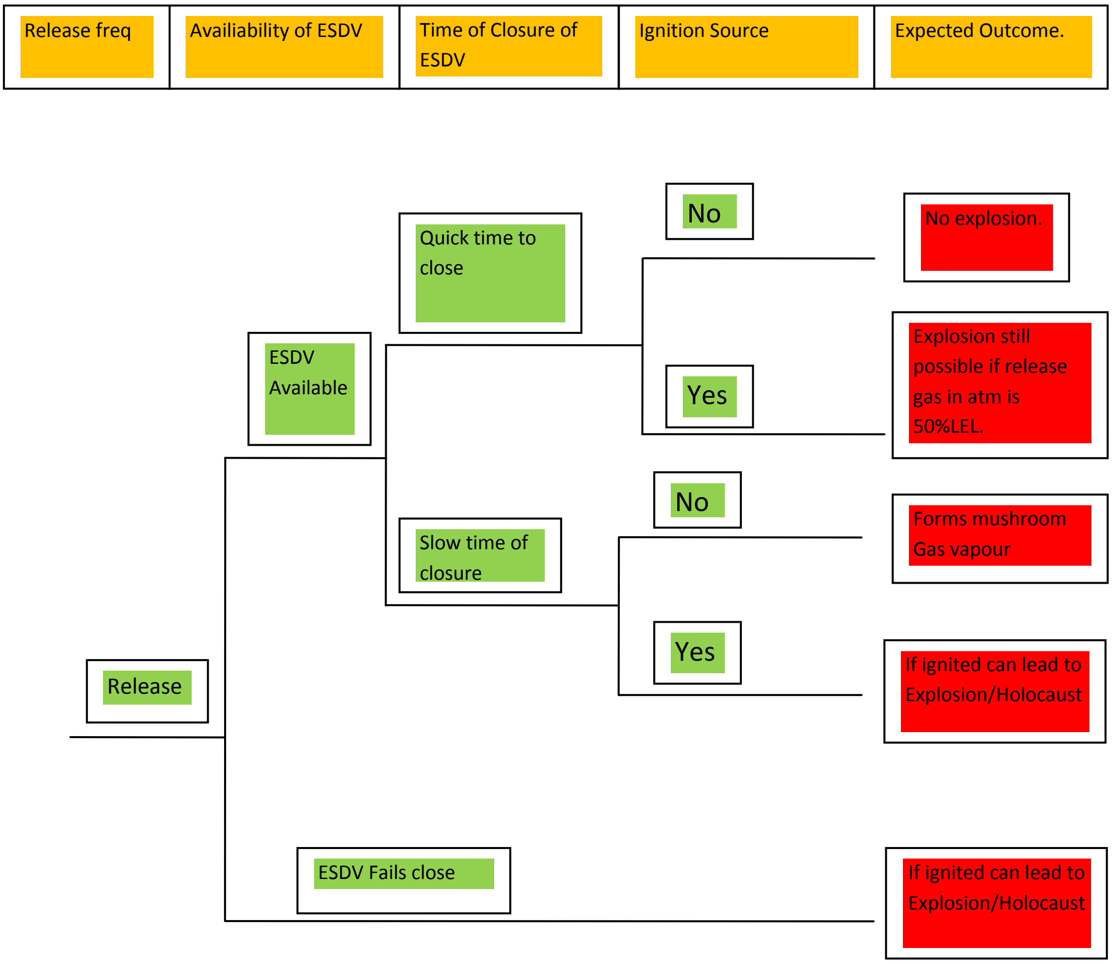


Figure.6.1: An Event Tree Showing resulting Consequences.

6.2 Cost Benefit Analysis of Using Fast Closing ESDV's

Cost Benefit Analysis CBA is used to assess risk reduction measures and demonstrates ALARP for a facility. CBA includes the determination of the Implied Cost of Averting a Fatality (ICAF). This involves the assessment benefits to personnel in terms of fatality risk reduction and also the determination of production deferment to determine the potential cost incurred following a major accident with or without risk reduction. The current benchmark adopted by HSE is a value of about £1,000,000 for ICAF **(45)**.

The ICAF expression relates the cost of measure, incremental change in risk ΔPLL and number of years of benefit as expressed in the equation (6.1).

$$ICAF = \frac{Cost\ of\ Measure}{\Delta PLL * No\ of\ Years\ of\ Benefit.} \qquad (6.1)$$

The incremental change in risk in some cases is taken as the value of potential loss of life caused by the probability of a certain event occurring, equation (6.2) briefly describes how PLL is determined**(46)**.

$PLL = \sum_{i,j} IR_{tot,k}\, n_{i,j}$ (6.2)

Where $n_{i,j}$ is the expected number of fatalities at location i produced by event j. and $IR_{tot,k}$ is the total individual risk to hypothectical member of population group k. These can be categorized as, $IR_{tot,office}$ inividual risk to personnels at office, $IR_{tot,operator}$ individual risk to operators and $IR_{tot,residence}$ individual risk to residence. Generally the equation that relates individual risk is given by**(46)**;

$IR_{tot,k} = \theta_k . \sum_i P_{ioc,i,k} . FOF_i$ (6.3) Where θ_k is the overall fraction of time that the hypothetical member of population of group k spends in an area of interest, $P_{ioc,i,k}$ the probability that the hypothetical member of group k is at location I and FOF_i is the frequqency of event outcome at the location i.

$FOF_i = \sum_j f_{eo,j} P_{fat,i.j} . P_{weather,j} . P_{direction,i.j}$ (6.4)

Where, $f_{eo,j}$ is the frequency of event outcome j, $P_{fat,i.j}$ is the probability of fatality at location I produced by event j and determined by using the hazard dosage value criterion (LD), $P_{weather,j}$ is the probability of weather conditions required to produce event outcome at j and $P_{direction,i.j}$ is the probability of event outcome j being directed at location i **(46)**.

The frequency of outcome is affected by several factors, one of which is the probability of event outcome from location j denoted by $f_{eo,j}$, created by the dispersion of gas from the full bore ruptured pipeline. This report is going to consider the probabilities from the release outcome of frequency of valve closing less than 6 seconds ($f_{< 6s}$) and frequency of valve closing greater than 6 seconds ($f_{>6s}$). Table 6.1 gives the description of both outcomes and the event tree in Figure.6.2, shows this description.

Table.6.1: Example of outcome of release rate with Valve's closure time.

Identifier	Description of Event	Probability of Outcome.
A	Closure time < 6 seconds for ESDV of nominal size 150mm	0.35
B	Closure time > 6 seconds for ESDV of nominal size 150mm	0.65

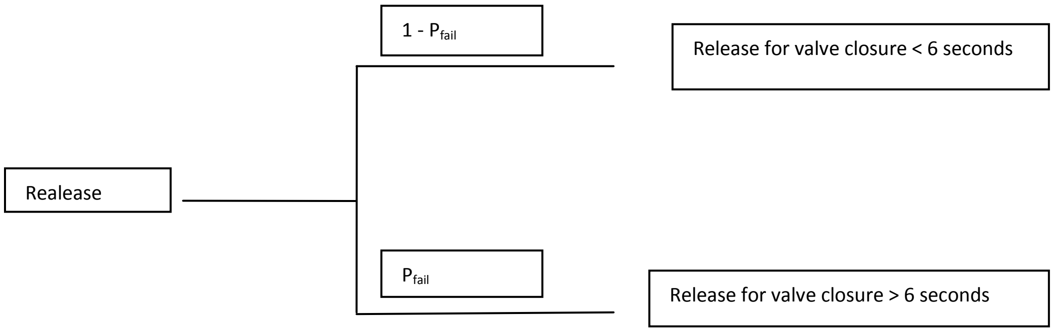


Figure.6.2: Event Tree showing Outcomes of Valve Closure time

The above outcomes can be used to determine the frequency of each category of release involving the expected closure time of the valve. It should be noted that if the valve fails to close at the expected time of closure it has partially failed to perform its function fully as the time elapsed will contribute to more release of inventory. The frequencies of both outcomes can be determined as;

$$f_{<6s} = f_{release}\ x\ (1 - P_{fail}) \quad (6.6)$$

$$f_{>6s} = f\ _{release} x\ P_{fail}\ , \quad (6.7)$$

Where $f_{<\,6s}$ is the frequency of release when the valve closes at a time less than 6 seconds and $f_{>6s}$ is the frequency when the valve closes at a time greater than 6 seconds.

This then is expressed in frequency categories F for both situations as,

$$F_{<6s} = \ F_{release}\ x\ \alpha_{success} \quad (6.8)$$

$$F_{>6s} = F_{release}\ x\ \alpha_{fail}\ \ , \quad (6.9)$$

Where $F_{<6s}$ is the frequqency category corresponding to $f_{<\,6s}$, $F_{>6s}$ the frequency category corresponding to $f_{>6s}$ and $\alpha_{success}$, α_{fail} are values corresponding to probability category for $(1 - P_{fail})$ and P_{fail} repectively. This can also be used for closing time of other valves with expected time of closure as t_{max}, hence the general representation of frequency categories can be expressed as,

`

$$F_{<t_{max}} = \ F_{release}\ x\ \alpha_{success} \quad (6.10)$$

$$F_{>t_{max}} = F_{release}\ x\ \alpha_{fail} \quad (6.11)$$

6.3 The Concept of ALARP in risk Analysis

Generally ALARP stands for as low as reasonably practicable and is a term used for setting an acceptable value for risk. The basic concept is that risk should be reduced to a reasonable level that is as low as possible without requiring excessive investment bringing in the concept of SFAIRP (so far as is reasonably practicable). The ALARP triangle is divided into three regions, unacceptable region, tolerable region and broadly accepted region.

The Alarp triangle shows the factor for gross disproportion varying between 1 at broadly acceptable region at 1 x 10^{-6}/yr individual risk and to 10 or more at the intolerable boundary of 1 x 10^{-3}/yr. Hence, the tolerable region could be taken between 2-5.

6.4 Calculating the ICAF

The ICAF is calculated using equations 6.1, to do this, the individual risk is determined by**(46)**;

$$IR_{tot,k} = m_{H,k}.10^{-7} + m_{G,k}.10^{-6} + m_{F,k}.10^{-5} + m_{E,k}.10^{-4}, \qquad (6.12)$$

Where $m_{x,k}$ is the number of event outcomes in category X for population k, $IR_{tot,k}$ is the total individual risk to hypothetical number of population goup k.

This model shall consider the individual risk category for valve closing less than the maximum time of closure (6 seconds) for a 150mm valve size.

$IR_{tot,operator}$ = 2 x 10^{-5} + 17 x 10^{-6} + 1.5 x 10^{-7} = 3.175 x 10^{-5}

$IR_{tot,office}$ = 2 x 10^{-6} + 5 x 10^{-7} = 2.5 x 10^{-6}

$IR_{tot,residence}$ = 3.5 x 10^{-7}

The different values of individual risk are then used to determine the potential loss of life PLL of using slow closing valves, using equation (6.2) and $n_{i,j}$as 10 numbers of people we obtain;

PLL = 4 x 10^{-4}

Also using the above PLL value to determine the values of ICAF with number of years of benefit of using the ESDV as 25 years as shown in Table.6.2.

Table.6.2: Showing ICAF values for Valves closing greater than maximum closure time.

Cost of Measure (£).	ICAF
1,000	100,000
10,000	1,000,000
100,000	10,000,000

The above values show that at a cost of £1000, the ICAF is less than the value stipulated for £1 million by HSE; hence the measure would clearly be reasonably practicable.

Similarly at a cost of £10,000 the ICAF is the statistical value and falls exactly in the range of 2-5 and is not considered grossly disproportionate and the measure will be practicable still.

At £1,000,000 the ICAF exceeds 10 times hence it is considered disproportionate to the benefit gained and not practicable.

Assuming a faster ESDV was used with time of closure lesser than the maximum time of closure (6 seconds) for this expected valve range, the IR was reduced by a factor of 10. Likewise the PLL by a factor of 10, so that the PLL now becomes 4 x $10^{-}3$ and the resulting ICAF is shown in Table.6.3,

Table.6.3: Showing ICAF values for valves closing less than the maximum closure time.

Cost of Measure (£).	ICAF
1000	10,000
10,000	100,000
100,000	1,000,000

The above values show the effect of reduction of risk by using quicker closing emergency valves in FBR conditions. The values of ICAF in Table.6.3 compared to that in Table.6.2 shows it is justifiable to use quicker ESDV valves, although most of the values used are hypothetical but the approach can be used to determine the CBA for using quicker closing ESDV valves in the risk reduction concept.

CHAPTER SEVEN

CONCLUSION AND RECOMMENDATION

7.1Conclusion.

The ESDV is a safety critical element and is one of the basic barriers needed to prevent major dangerous event such as explosion and fire either from happening of escalating beyond normal control system or human intervention. The time of closure is of great significance to curtail inventory loss during a FBR situation and thereby prevent the escalation of a dangerous event from happening at least reducing the probability of occurrence of such event to be below the unwanted threshold frequency.

The following were the conclusions deduced from this report for a 150mm/ 6inches ball valve model.

- The time of closure if very fast (faster than 6 seconds for 6 inch valve), will prevent excessive backflow of fluid through the ball valve port. This minimizing reverse fluid flow from contributing to the volumetric outflow from the rupture point of the downstream section of the valve resulted from the pressure surge pull at the rupture point of the pipeline.
- It is not possible to get an exact valve of 6 inches to close at 6 seconds closure time as this depends on the interaction of the speed/Torque of the actuator of the valve with the varying HCR parameters flowing across the valve.
- The time of closure of 1 seconds per inch diameter size of emergency shutdown valve presently used in the industries is not sufficient enough to stop inventory loss at least to the minimum in a FBR situation if compared to allowable leakage rates through valves as stipulated by API 14 series for SSV/SSSV and API 598 for metal seated valves.
- Pressure increase is the most significant variant HCR parameter that affects the time of closure of an ESDV.
- The cumulative volumetric outflow of gas during 6 seconds of closure time for a 6 inch valve is 6.688 m^3/s and depends on the prevailing conditions of initial pressure of 205bar and velocity of gas in pipe before rupture.
- The following HCR parameters (Pressure differential, volumetric flow rate, density), decreases across the valve with closure time.
- It is safer to use quicker closing ESDVs as this would reduce the level of risk and would be more cost effective compared to the cost incurred without risk reduction.

7.2 Recommendation

Based on the study the following recommendations could be taken into consideration by academicians, valve manufacturers, and process safety engineers.

- The model of this project can be used by Valve Manufacturers and Process Safety Engineers to determine methods of how to optimize ESDV closure time.
- The study should involve the use of more accurate results from real life empirical methods.
- The model can be considered for 3/multi-dimensional flow of fluids as this model is limited to gas flow only.
- The approach could be used to model time of closure of other SDV types, as this model only considered ball valves used for ESD procedures.
- The values of cumulative mass flow rate could be used to model the limiting volume of gas release rate and use it to quantify risk compared to the value of LEL.

REFERENCE

(1) APIWAT S. Pipeline Emergency Shutdown Valve (PESDV) Integrity Study: Case Study of UNOCAL Thailand Limited. 2007.

(2) BP International Limited (Engineering Practice Group). GS 130-6 Guidance for Specification 130-6 Actuators for shut-off valves. 1993;GS 130-6:1-24.

(3) Valvias. The history of the Valves. 2012; Available at: http://www.valvias.com/history.php. Accessed June/13, 2012.

(4) 1 - Definitions and abbreviations. In: Brian Nesbitt, editor. Handbook of Valves and Actuators Oxford: Butterworth-Heinemann; 2007. p. 1-41.

(5) Department of Energy FSC-6910. DOE-HDBK-1018/2-93 Fundamental Handbook Mechanical Science "Valve Functions And Basic Parts". 1993;2 (Valve Functions And Basic Parts):12/06/12.

(6) Smith P, Zappe RW. 3 - Manual Valves. Valve Selection Handbook (Fifth Edition) Burlington: Gulf Professional Publishing; 2004. p. 47-151.

(7) Anderson CN, Bosserman II BE, Morris CD, Cadrecha C, Lescovich JE, Taylor HW, et al. Chapter 5 - Valves. In: Garr M. Jones A2PE A2Robert L. Sanks A2Ph.D. A2PE A2George Tchobanoglous A2Ph.D. A2PE, Bayard E. Bosserman II P, editors. Pumping Station Design (Third Edition) Burlington: Butterworth-Heinemann; 2008. p. 5.1-5.32.

(8) Parisher RA, Rhea RA. Chapter 5 - Valves. Pipe Drafting and Design (Third Edition) Boston: Gulf Professional Publishing; 2012. p. 79-111.

(9) 3 - Isolating valves. In: Brian Nesbitt, editor. Handbook of Valves and Actuators Oxford: Butterworth-Heinemann; 2007. p. 81-130.

(10) Imgress Images. Images of Valves. Available at: https://www.google.co.uk/search?q=valves&hl=en&prmd=imvnsb&tbm=isch&tbo=u&source=univ&sa=X&ei=enrkT_eOHMah8gPg9cmjCg&ved=0CIgBELAE&biw=1280&bih=572. Accessed 06/21, 2012.

(11) 17 - Installation and maintenance. In: Brian Nesbitt, editor. Handbook of Valves and Actuators Oxford: Butterworth-Heinemann; 2007. p. 381-395.

(12) Global Supply line Pty Ltd. Australian pipe Line Valve (ANSI Valve Ratings, Standards and Design ASME B16.34). 2012; Available at: http://www.globalsupplyline.com.au/pdfs/catalogues/gsl/Valve-Selection-ASME.pdf. Accessed 06/17, 2012.

(13) HSE. The offshore Installations (Emergency Pipeline Valves) Regulation 1989 No: 1029. (No: 1029).

(14) Lundteigen MA, Rausand M. Partial stroke testing of process shutdown valves: How to determine the test coverage. J Loss Prev Process Ind 2008 11;21(6):579-588.

(15) Thomas k, Jörg K. Smart Valve positioners and their use in Safety Instrumented Systems. 2009(Industrial valves):41-47.

(16) John P. Assessment of valve Failures in Offshore Oil and Gas Sector. 2003;ISBN 07176 27802(HSE Research Report 162 prepared by TUV NEL Ltd):6-51.

(17) Nolan DP. 11 - Emergency Shutdown. Handbook of Fire and Explosion Protection Engineering Principles (Second Edition) Oxford: William Andrew Publishing; 2011. p. 119-126.

(18) Mahgerefteh H, Saha P, Economou IG. A Study of the Dynamic Response of Emergency Shutdown Valves Following Full Bore Rupture of Gas Pipelines. Process Saf Environ Prot 1997 11;75 (4):201-209.

(19) Fletcher I, Cox CS, Arden WJB, Doonan A. Modelling of a two-stage high-pressure gas reduction station. Appl Math Model 1996 10;20(10):741-749.

(20) Mehment S, Ebru M, Alpman K, Kucukada. Effect of the flow Conditions and Valve size on Butterfly valve Performance. Journal of Thermal Science and Technology 2010(ISSN 1300-3615):103-112.

(21) XuegS, Young CP. Numerical analysis of Butterfly Valve-Prediction of Flow Coefficient and Hydrodynamic Torque Coefficient. WCECS proceedings of the world congress on Engineering and Computer Science 2007.

(22) Mohamed SG, Ming Z, Duncan AM, David HA. A Review of Water Hammer Theory and Practice. ASME 2005;8(Applied Mechanics Reviews):49-76.

(23) Victor L. Streeter, E. Benjamin Wylie. Unsteady Flow (Description of the Water Hammer Phenomenon). In: Julienne V. Brown, Madelaine E, editors. Fluid Mechanics. 7th Ed. United State of America: McGraw-Hill Book Company; 1979. p. 479-516.

(24) P D Smith. Flow in Pipes and Pipe Networks. Basic Hydraulics Norwich, Norfolk England.: Butterworh & Co (Publishers) Ltd; 1982. p. 46-60.

(25) Bowman Conway Ann. Minimizing water Hammer Transients in a Series PipelineUniversity of Arizona; 1986.

(26) Thorley ARD, Tiley CH. Unsteady and transient flow of compressible fluids in pipelines—a review of theoretical and some experimental studies. Int J Heat Fluid Flow 1987 3;8(1):3-15.

(27) Ke SL, Ti HC. Transient analysis of isothermal gas flow in pipeline network. Chem Eng J 2000 2;76(2):169-177.

(28) Sylvester Denton Garfield. CFD Simulation of Highly Transient Flows.University College London; 2009.

(29) Oke A, Mahgerefteh H, Economou I, Rykov Y. A transient Outflow Model for Pipeline Rupture. Pergamon Chemical Engineering Science 2003;58:4591-4604.

(30) Dong Y, Gao H, Zhou J, Feng Y. Evaluation of Gas Release Rate Through Holes In Pipelines. Journal of Loss Prevention in the Process Industry 2002;15:423-428.

(31) Chaczykowski M. Transient flow in natural gas pipeline – The effect of pipeline thermal model. Appl Math Model 2010 4;34(4):1051-1067.

(32) Rank G, Nassir MA. Gas Dispersion Model. Journal Loss of Prevention In Process Industry 1991;14:151-159.

(33) Graham G, Dr. Jane HP. A Comparison of Inherent Risk Levels in ASME B31.8 and UK gas Pipeline Codes. 2006;IPC2006-10507.

(34) Amit SS. Safety and Environmental Concerns in Upstream oil." Technological Imperative for Exploration and Production of oil and Gas. Regional Training Institute Sivasagar ONGC 2009.

(35) Alison M, John H. Offshore Hydrocarbon Release 2001-2008 Research Report. HSE 2008;RR672:2-80.

(36) Andre MB, Davi BW, J. Christopher B. Allowable Leakage rates and Reliability of Safety and Pollution Prevention Equipment. Minerals Management Service U S Department of the Interior 1999;18-1298:1-23.

(37) SWI Valve Co Ltd. Procedure Manual API598 Testing for metal seated Gate/Globe and Check Valves. 2008;SW-P-25-01:1-6.

(38) Health and Safety Executive. Area Classification for secondary Release from low pressure Natural systems. 2008;RR630:1-181.

(39) Health and Safety laboratory. Outstanding Safety Questions concerning the use of Gas turbines for Power generation. Summary report. 2009; CM/04/09:1-9.

(40) Chiara V, Sandro M, Giuseppe M. Conceptual Model of CO_2 Release and Risk Assessment: a Review. The Italian Association of Chemical Engineering 2012;26 (1974-9791):12/07/2012.

(41) Tam VHY, Higgins RB. Simple transient release rate models for releases of pressurized liquid petroleum gas from pipelines. J Hazard Mater 1990;25 (1–2):193-203.

(42) Montiel H, Vílchez JA, Casal J, Arnaldos J. Mathematical modelling of accidental gas releases. J Hazard Mater 1998 4;59 (2–3):211-233.

(43) Haukaas T, Kiureghian AD. Strategies for finding the design point in nonlinear finite element reliability analysis. Prob Eng Mech 2006 4;21(2):133-147.

(44) Karamchandani A, Cornell CA. Sensitivity estimation within first and second order reliability methods. Struct Saf 1992 4;11(2):95-107.

(45) Jonkman, S. N, Van Gelder P.H.A.J.M, Vrijling J. k. An overview of quantitative risk measures for loss of life and economic damage. J. Hazard Mater 2003; 99(1): 1-30

(46) Health and Safety laboratory. A simple approach of estimating individual risk, a report document prepared by VECTRA Limited. 2003.

APPENDIX A

FORMULAR

<u>The calculation of Gas fluid density and Compressibility factor:</u>

From the Ideal gas equation;

$$PV = nRT \tag{1}$$

Where P = gas pressure, V is the volume occupied by gas in the pipe, n I the no of mole of the gas, r is a gas constant (8.314) and T is temperature in Kelvin (T = (273 + ^{0}C).

$$n = \frac{m}{M} \tag{2}$$

Where M is the molar mass of Natural gas in (kg/mol) and is the mass of the natural gas in kg.

Substituting equation (2) into (1) we obtain;

$$P = \frac{1}{M}\left(\frac{m}{v}\right)RT \tag{3}$$

Where $\rho = \frac{m}{v}$ in kg/m^3 and substituting into equation (3), we finally arrive at;

$$\rho_i = \frac{PM}{RT_i} \tag{4}$$

Relating equation (4) with varying temperature using general pressure/gay lussac's law

$$\frac{P_1}{T_1} = \frac{P_2}{T_2} \tag{5}$$

Since volume is constant all through representing the volume of gas contained in the 150mm pipe at a certain length L_k along the pipeline. The final temperature T_2 of the gas at certain final pressure of the gas in pipeline as valve closes at varying time intervals is thus obtained as;

$$T_2 = \frac{P_2}{P_1} * T_1 \tag{6A}$$

A more understandable version involving initial pressure P_i, final pressure P_{i+1}, initial gas temperature T_i and final temperature T_{i+1} was used for this model.

$$T_{i+1} = \frac{P_{i+1}}{P_i} * T_i \tag{6B}$$

Substituting equation (6) into equation (5) we obtain the density of the natural gas at varying temperature and pressure as the valve closes.

$$\rho_i = \frac{P_i M}{R\left(\frac{P_{i+1}}{P_i} * T_i\right)} \tag{7}$$

Where ρ_i is the density of natural gas at varying closure time interval of variant differential pressure and temperature considered for the gas flow for boundary conditions at rupture point?

The compressibility factor of the natural gas for this model was link with the ideal equation of equation (1).

$$P = \frac{\rho ZRT}{M} \quad (8)$$

Where Z is the compressibility factor, a better version used for this was;

$$P_i = \frac{\rho_i Z_i R\left(\frac{P_{i+1}}{P_i} * T_i\right)}{M} \quad (9)$$

Where Z_i in m^2/N was taken as the variant compressibility factor and varying density, pressure and temperature of the natural gas.

The celerity of gas can be calculated through the following equations.

For an ideal gas the celerity is given by;

$$c^2 = \frac{\frac{k}{\rho}}{1+\left(\frac{k}{E} * \frac{D}{e}\right)} \quad (10)$$

Where k is the compressibility modulus $(\frac{1}{Z})$ in N/m^2, c is called celerity or acoustic speed in (m/s), D is the diameter of the pipe and e is the Elastic Modulus. The non- ideal gas takes a different approach in this case celerity is expressed as the square root of the ratio of compressibility modulus to density of the gas as expressed in the equation below.

$$c = \sqrt{\frac{k}{\rho}} \quad (11)$$

Although the model derived the celerity directly from the fluid hammer equation, but celerity of natural gas can be gotten from the above expressions.

<u>The Relationship between Torque of the Actuator with differential pressure and flow rate across the ball valve port.</u>

There seem to be a relationship between the actual torques required by the actuator to close the valve from its fully open position at 90^0 to fully closed position at 0^0. Although it all depends on the type of actuator used, its power and efficiency rating of the motor which drives it. The project assumes that the power of the Actuator driven hydraulically this time by a fluid is equal to the product of the value of the differential pressure across the valve and volumetric flow rate across it or the Torque and the angular speed of the actautor.

$$T_m = \frac{D_m}{2\pi} \Delta P \quad (12)$$

Where T_m is the torque of the actuator, ΔP is the differential pressure of fluid used to drive actuator and in this model it is also assumed to be equal to the differential pressure across the valve and D_m is the diameter rating of the actuator which comes in sizes of the valve and maximum operating pressure(MA|OP).

$$\omega_m = \frac{2\pi}{D_m} , \tag{13}$$

Where ω_m is the angular speed of the actuator (rad/sec).

Hence the power P of the actuator is the product of the torque and angular speed.

$$P = \omega_m T_m \tag{14}$$

$$\omega_m T_m = Q\Delta P \tag{15}$$

$$T_m = \frac{Q\Delta P}{\omega_m} \tag{16}$$

Equation (16) was adopted in calculating the closing torque for this model where; $\omega_m = {}^{\theta}/_{\Delta t_{ci}}$, with θas the degree of closing and opening of the valve and Δt_{ci} the time of closure intervals.

Calculating the Time subsequent to Closure of the ESDV.

Time decay expressions were used for this model.

$$Q_{m_j} = Q_{m_{j_0}} exp^{-\alpha t} \tag{17}$$

$$t_{mj} = \frac{\ln\left\{\frac{Q_{m_{jo}}}{Q_{m_j}}\right\}}{-\alpha} , \tag{18}$$

Where Q_{m_j} is the final mass flow rate, $Q_{m_{j_0}}$ the initial mass flow rate, α is the decay constant and t_{mj} is the time subsequent to closure for mass flow rate.

$$\mathrm{Q} = Q_0 exp^{-\alpha t} \tag{19}$$

$$t_q = \frac{\ln\left\{\frac{Q_0}{Q}\right\}}{-\alpha} , \tag{20}$$

Where Q is the final volumetric outflow, Q_0 the initial volumetric outflow, α the decay constant and t_q the time subsequent to closure for volumetric outflow.

$$\mathrm{P} = P_0 exp^{-\alpha t} \tag{21}$$

$$t_p = \frac{\ln\left\{\frac{P_0}{P}\right\}}{-\alpha} , \tag{22}$$

Where P is the final temperature, P_0 initial temperature, α is the decay constant and t_p

is the time after closure for pressure drop.

APPENDIX B

The Relationship between Differential Pressure with other HCR Parameters.

Table B.1: The Relationship between differential Pressure with HCR Parameters.

ΔP(bar)	Degree of Opening (Θ)	Coefficient of Discharge C_d	Density (ρ) kg/m-^{3}	Q_i Flow rate across valve (m^3/s)
205.00	90	1.00	156.11	5.14599
138.79	80	0.90	117.34	4.34389
93.96	70	0.75	78.94	3.58174
63.61	60	0.58	53.02	2.74251
43.06	50	0.40	35.55	1.87391
29.15	40	0.30	23.80	1.39311
19.74	30	0.20	15.93	0.92073
13.36	20	0.13	10.66	0.59314
9.05	10	0.08	7.14	0.35970
6.12	5	0.04	4.79	0.17611
4.15	0	0.00	3.22	0

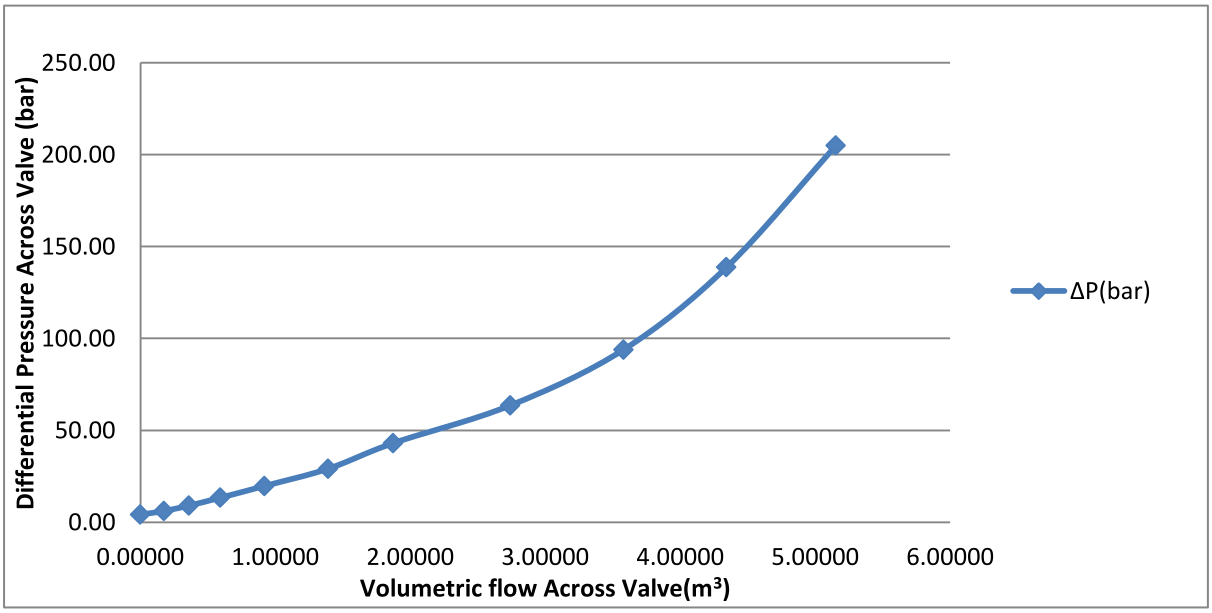


Figure.B.1: Graph of Differential Pressure vs. Volumetric flow

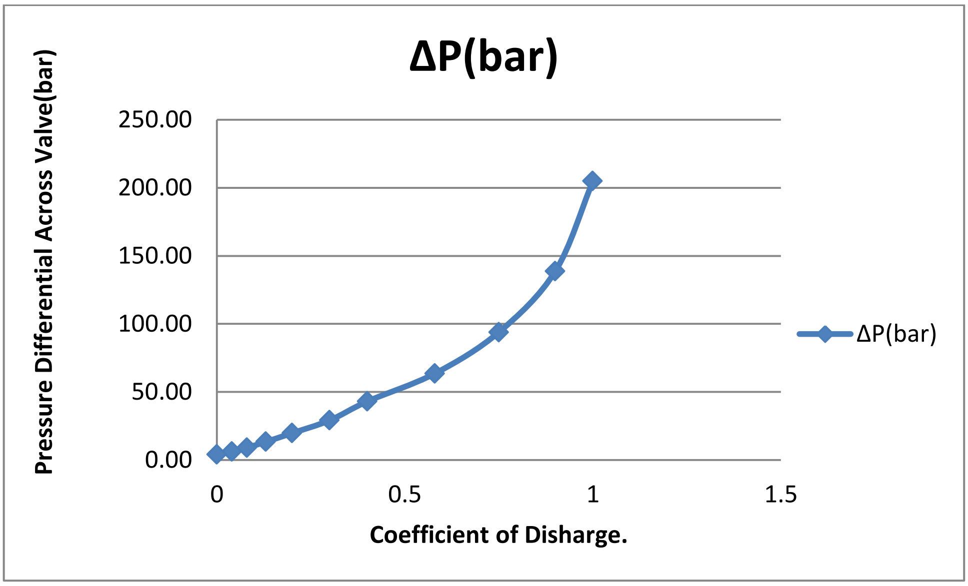


Figure. B.2: Graph of Differential Pressure vs. Coefficient of Discharge.

APPENDIX C

The Relationship of Graphs of Valves Opening Area with other HCR Parameters

Table.C.1: The Relationship of Valve Opening with HCR Parameters.

Area A_f (mm^2)	Coefficient of Discharge C_d	Q_i Flow rate across valve (m^3/s	ΔP(bar)
3180862.56	1.00	5.14599	156.11
3138112.33	0.90	4.34389	117.34
3095360.86	0.75	3.58174	78.94
3052607.75	0.58	2.74251	53.02
2967106.02	0.40	1.87391	35.55
2924373.70	0.30	1.39311	23.80
2881681.22	0.20	0.92073	15.93
2824809.61	0.13	0.59314	10.66
2753667.92	0.08	0.35970	7.14
2753667.92	0.04	0.17611	4.79
0	0	0	3.22

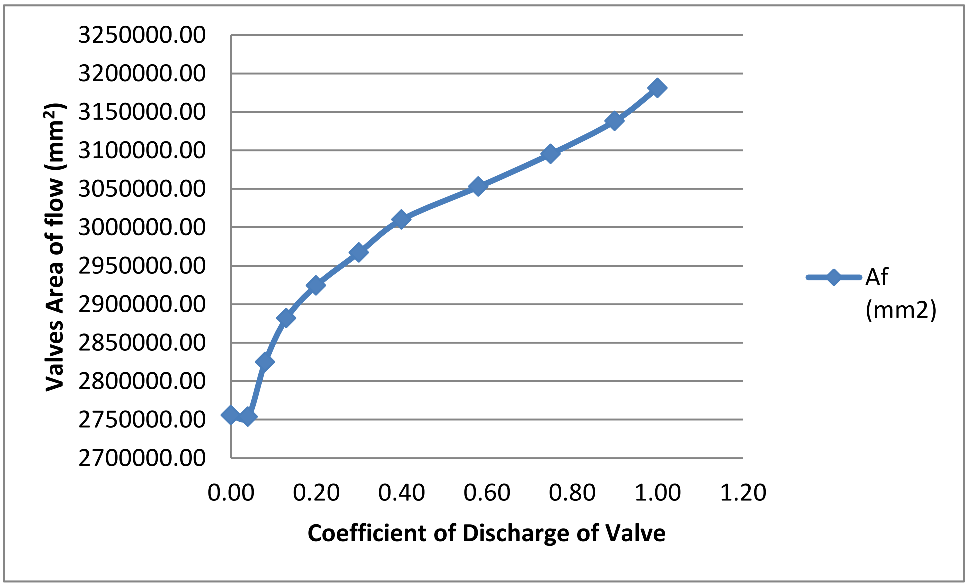


Figure.C.1: Graph of Valve Area of flow vs. Coefficient of Discharge.

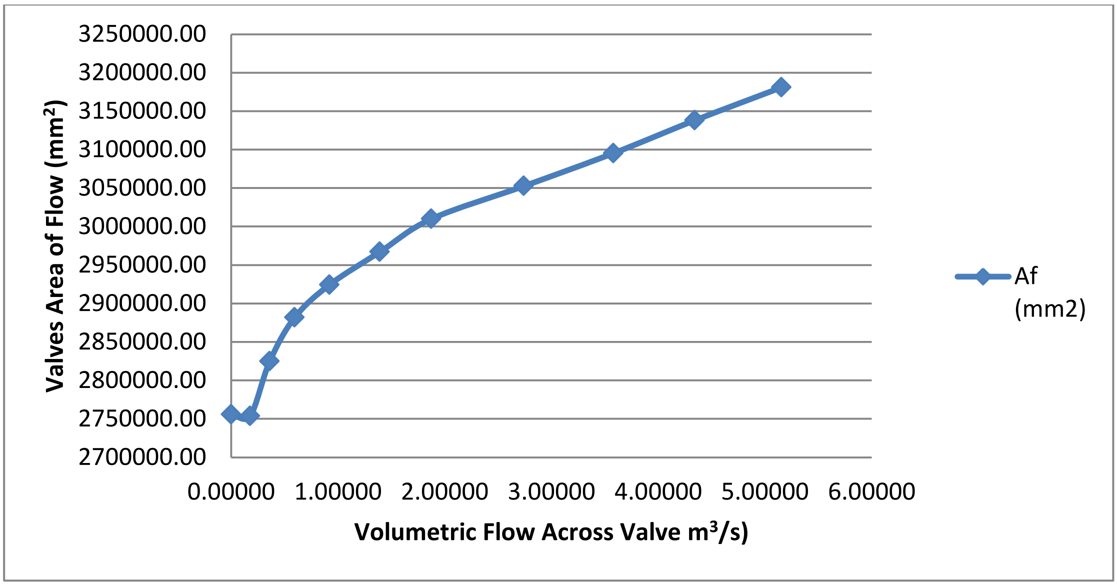


Figure.C.2: The Valve Area of Flow vs. Volumetric flow across valve.

APPENDIX D

The Relationships of Valves Opening/Closing Angle of Degree with other HCR Parameters.

Table.D.1: The Relationship of Degree of Opening with other HCR Parameters.

Degree of Opening (Θ)	Coefficient of Discharge C_d	Q_i Flow rate across valve (m^3/s	x(mm)
90	1.00	5.14599	0
80	0.90	4.34389	15
70	0.75	3.58174	30
60	0.58	2.74251	45
50	0.40	1.87391	60
40	0.30	1.39311	75
30	0.20	0.92073	90
20	0.13	0.59314	105
10	0.08	0.35970	120
5	0.04	0.17611	135
0	0	0	150

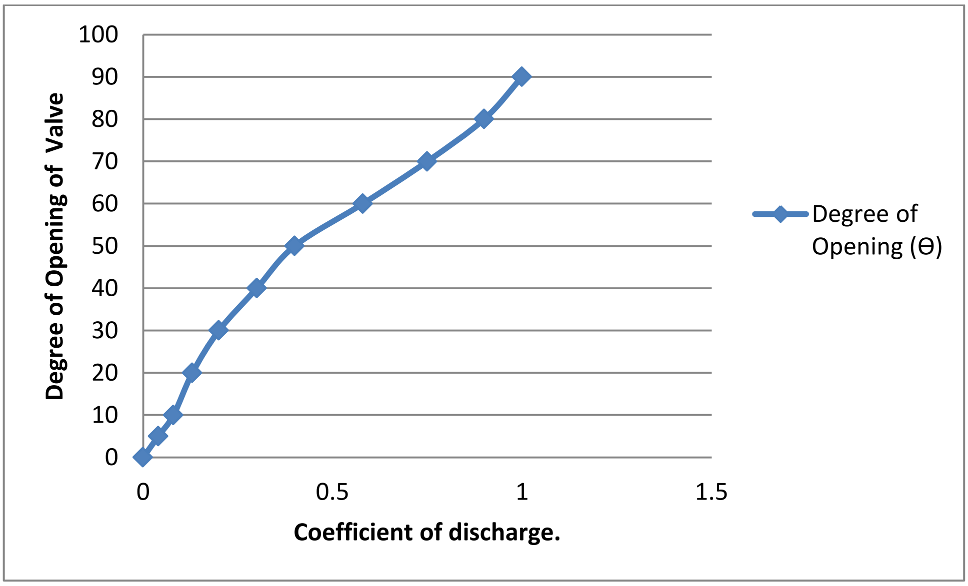


Figure.D.1: Graph of Degree of Opening vs. Coefficient of Discharge.

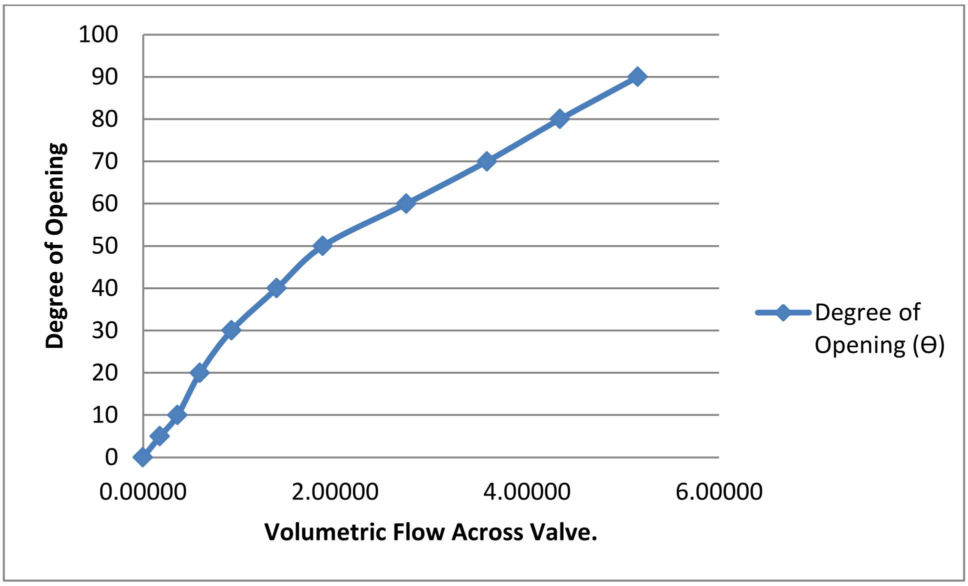


Figure.D.2: Graph of Degree of Opening vs. Volumetric Flow across Valve.

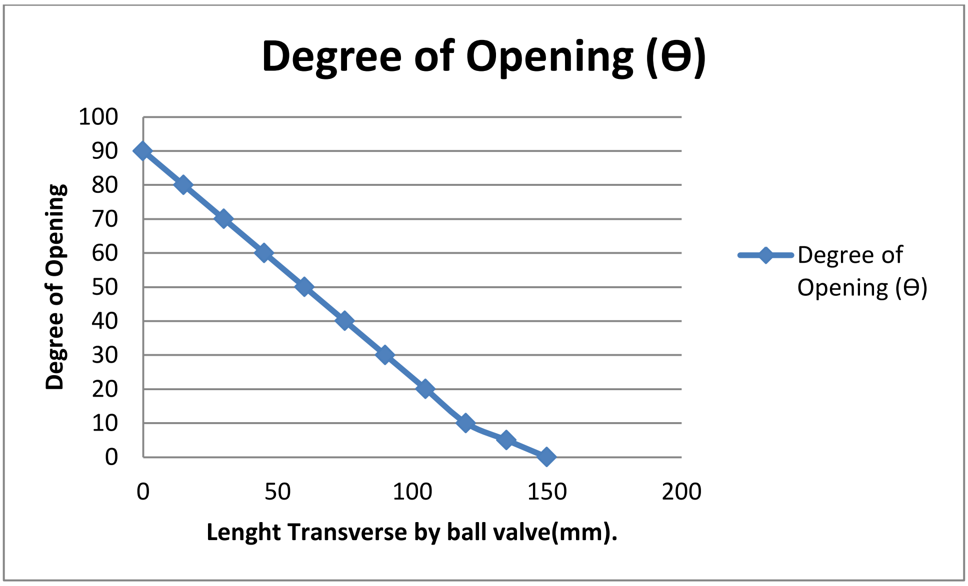


Figure.D.3: Graph of Degree of Opening vs. Length Transverse by Valve.

APPENDIX E

The Relationship of Compressibility factor with other HCR Parameters.

Table.E.1: The Relationship of Compressibility Factor with HCR Parameters.

Compressibility Factor(Z)(m^2/N)	Density (ρ) kg/m-3	ΔP(bar)
1.000024056	156.11	205.00
0.900698539	117.34	138.79
0.906329087	78.94	93.96
0.913568357	53.02	63.61
0.922424582	35.55	43.06
0.932623004	23.80	29.15
0.943580259	15.93	19.74
0.964632261	10.66	13.36
0.973383943	7.14	9.05
0.973383943	4.79	6.12
0.980511184	3.22	4.15

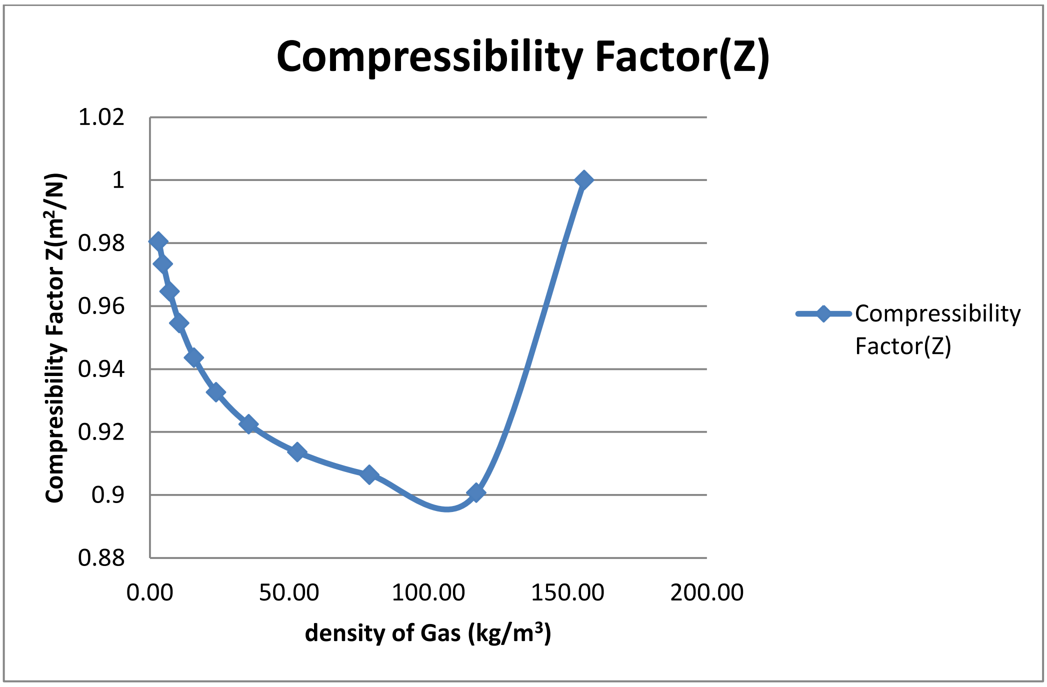


Figure.E.1: Graph of Compressibility factor vs. Density of Natural gas.

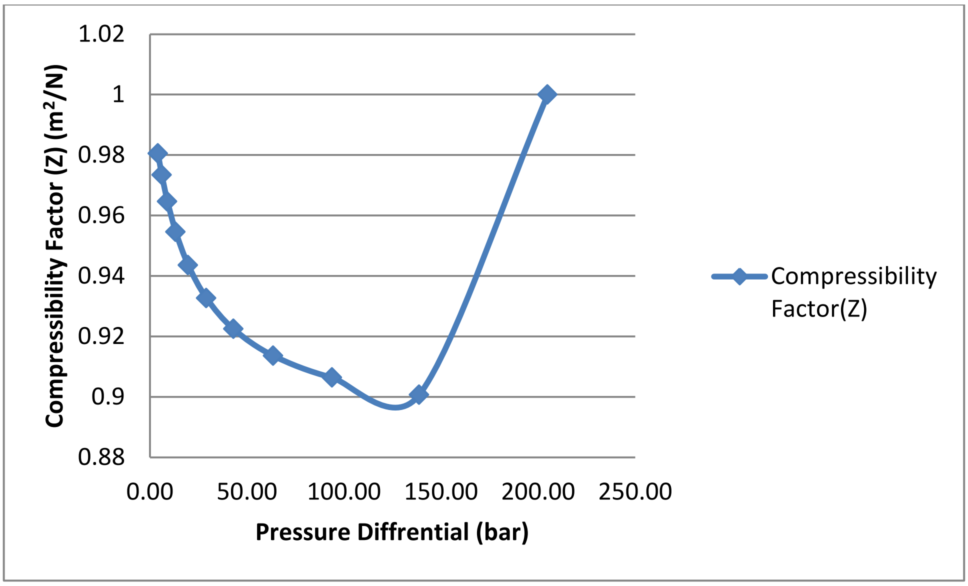


Figure.E.2: Graph of Compressibility factor vs. Pressure Differential across Valve.

APPENDIX F

The Relationship of Celerity with other HCR Parameters

Table.F.1: The Relationship of Celerity with HCR Parameters.

Celerity c(m/s) * E 02	Pressure Differential @ valve ΔP(bar)	Density (ρ) kg/m-3	Compressibility Factor(Z) (m2/N)	∑(tci) Δt (s)
0.81	205	156.11	1.000024056	0.00
0.85	138.79	117.34	0.900698539	0.68
1.03	93.96	78.94	0.906329087	1.35
1.34	63.61	53.02	0.913568357	2.03
1.95	43.06	35.55	0.922424582	2.71
2.61	29.15	23.80	0.932623004	3.39
3.94	19.74	15.93	0.943580259	4.06
6.09	13.36	10.66	0.954509636	4.74
9.95	9.05	7.14	0.964632261	5.42
19.99	6.12	4.79	0.973383943	6.09
0	4.15	3.22	0.980511184	6.43

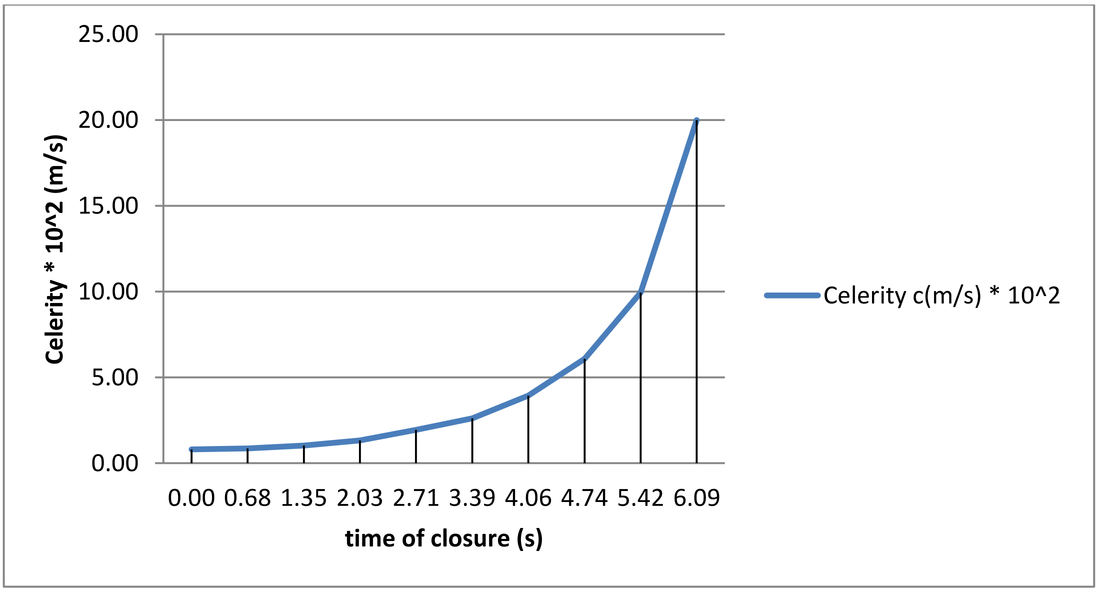


Figure.F.1: Graph of Celerity vs. time of closure of the Valve.

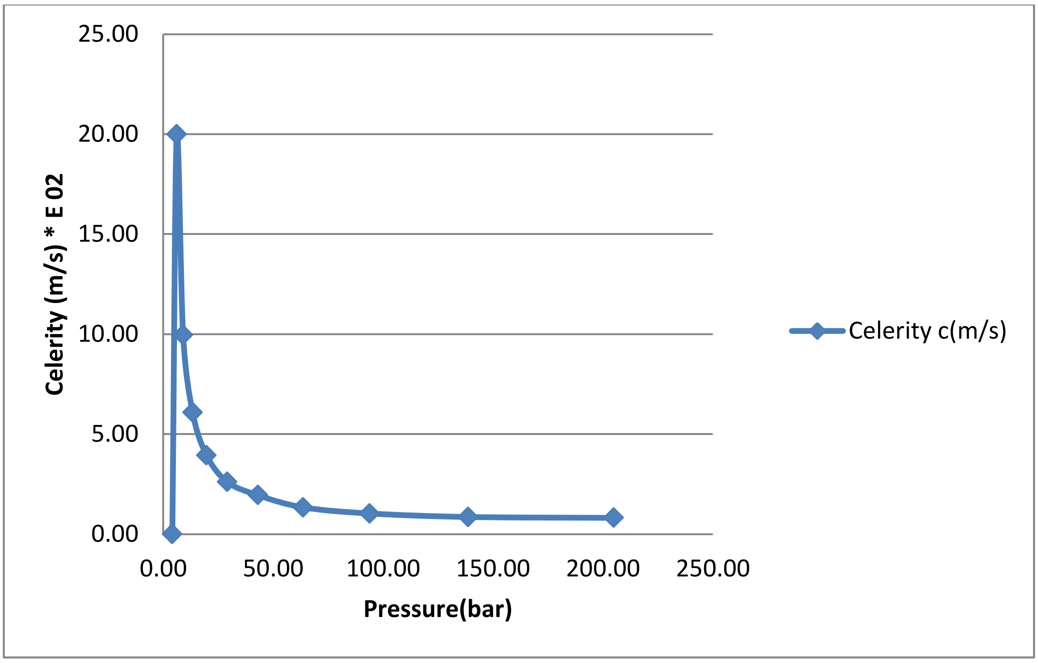


Figure.F.2: Graph of Celerity vs. Differential Pressure.

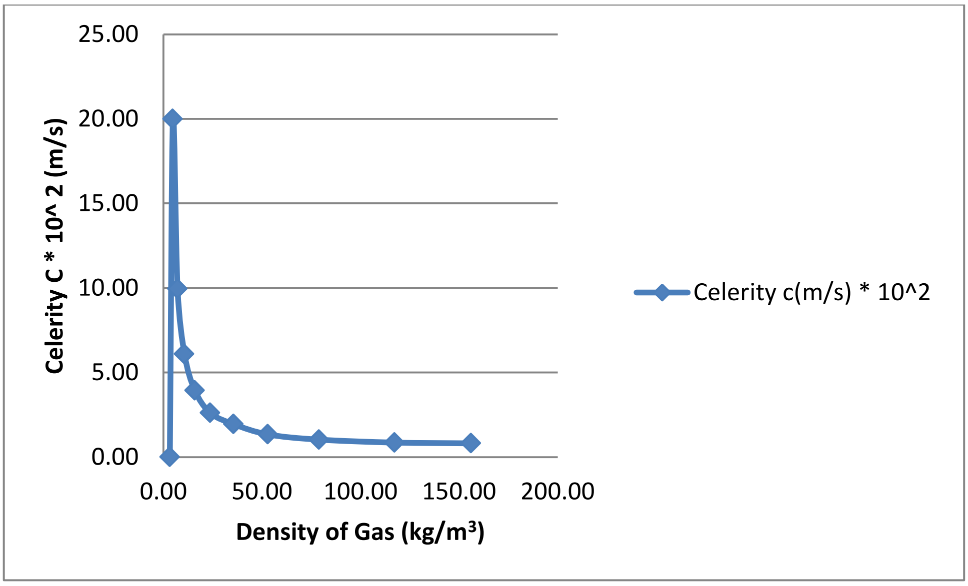


Figure.F.3: Graph of Celerity vs. Density of Gas.

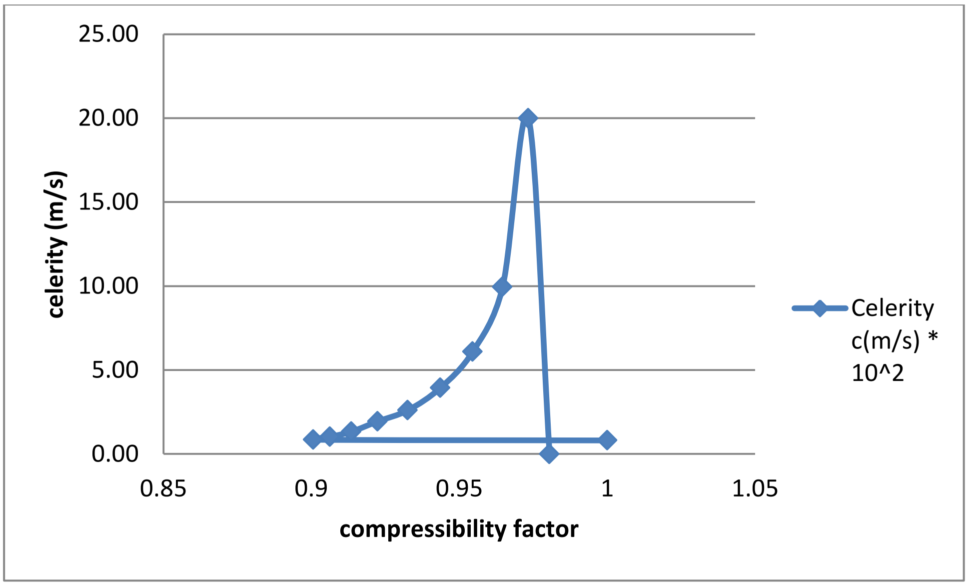


Figure.F.4: Graph of Celerity vs. Compressibility Factor.

APPENDIX G

The Relationship between Torque and other HCR Parameters.

Table. G.1: The Relationship of Torque with HCR Parameters.

Expected closing Torque (N/m^2)	Pressure Differential @ valve ΔP(bar)	C_d	Volumetric flow across Valve$Q_i(t)$ (m^3/s)
0	205.00	1.00	5.15499
56987202.41	138.79	0.90	4.34389
55669694.74	93.96	0.75	3.58174
37102740.5	63.61	0.58	2.74251
19070125.54	43.06	0.40	1.87391
9597954.31	29.15	0.30	1.39311
3865046.861	19.74	0.20	0.92073
1311070.731	13.36	0.13	0.59314
307579.4767	9.05	0.08	0.35970
57348.5095	6.12	0.04	0.17611
0	4.15	0	0

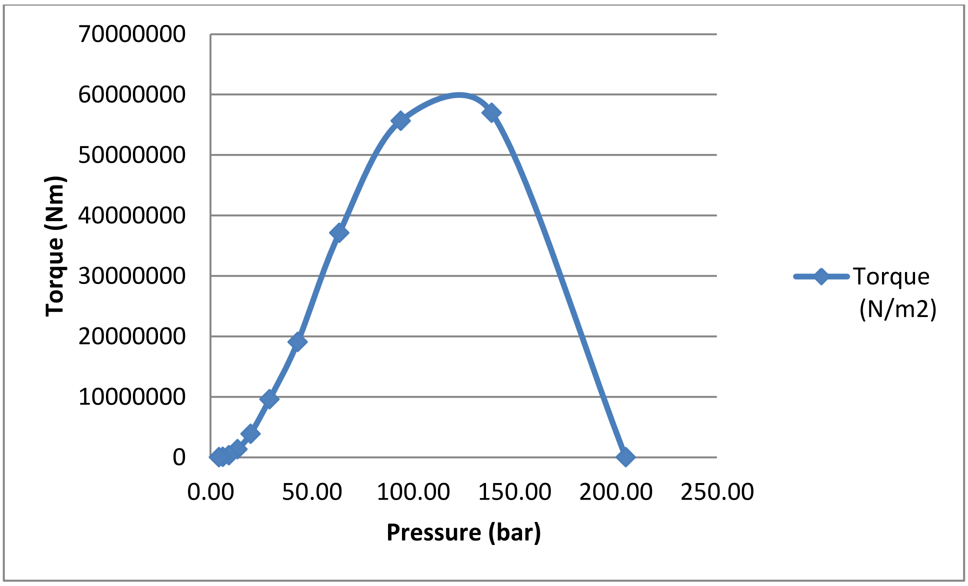


Figure.G.1: Graph of Torque vs. Pressure.

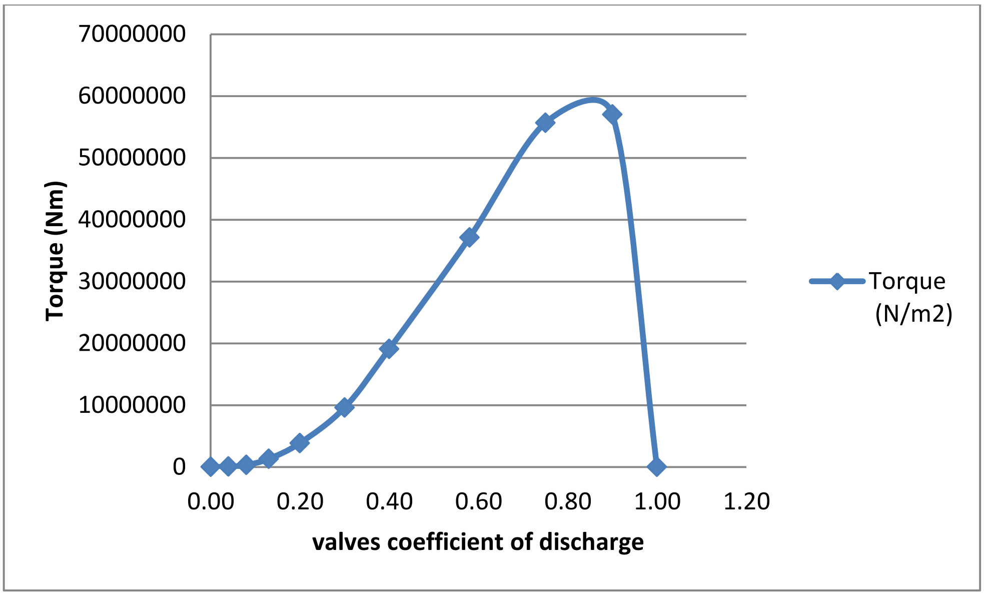


Figure.G.2: Graph of Torque vs. Coefficient of discharge (C_d).

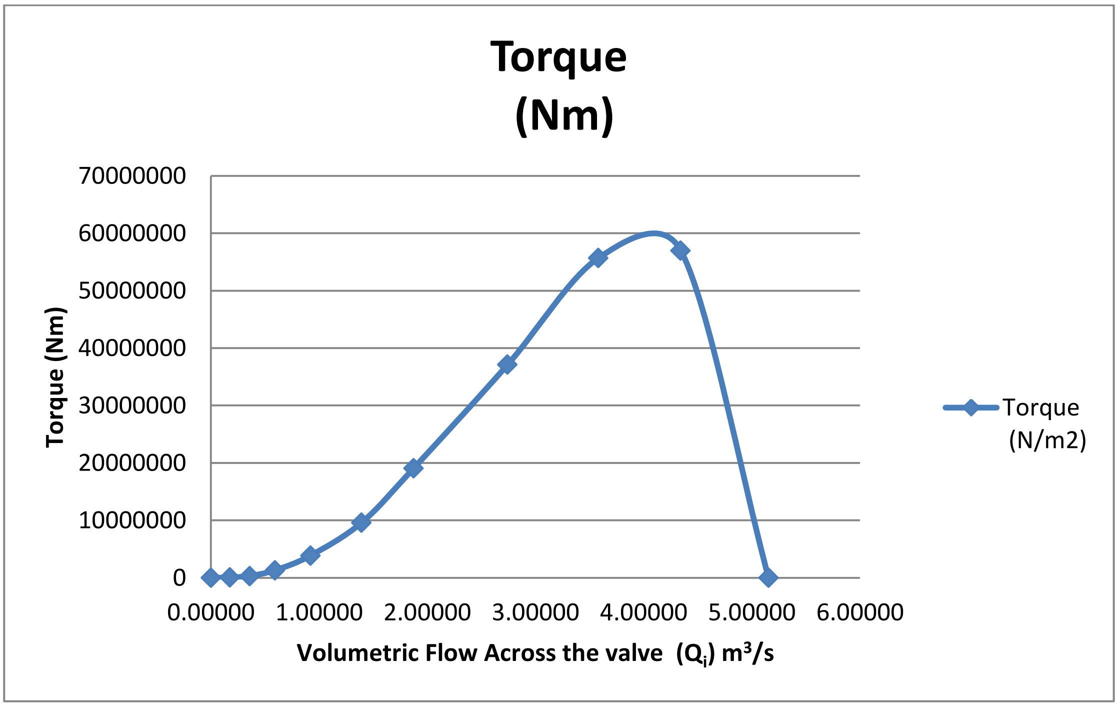


Figure.G.3: Graph of Torque vs. Volumetric Flow across the Valve.

APPENDIX H

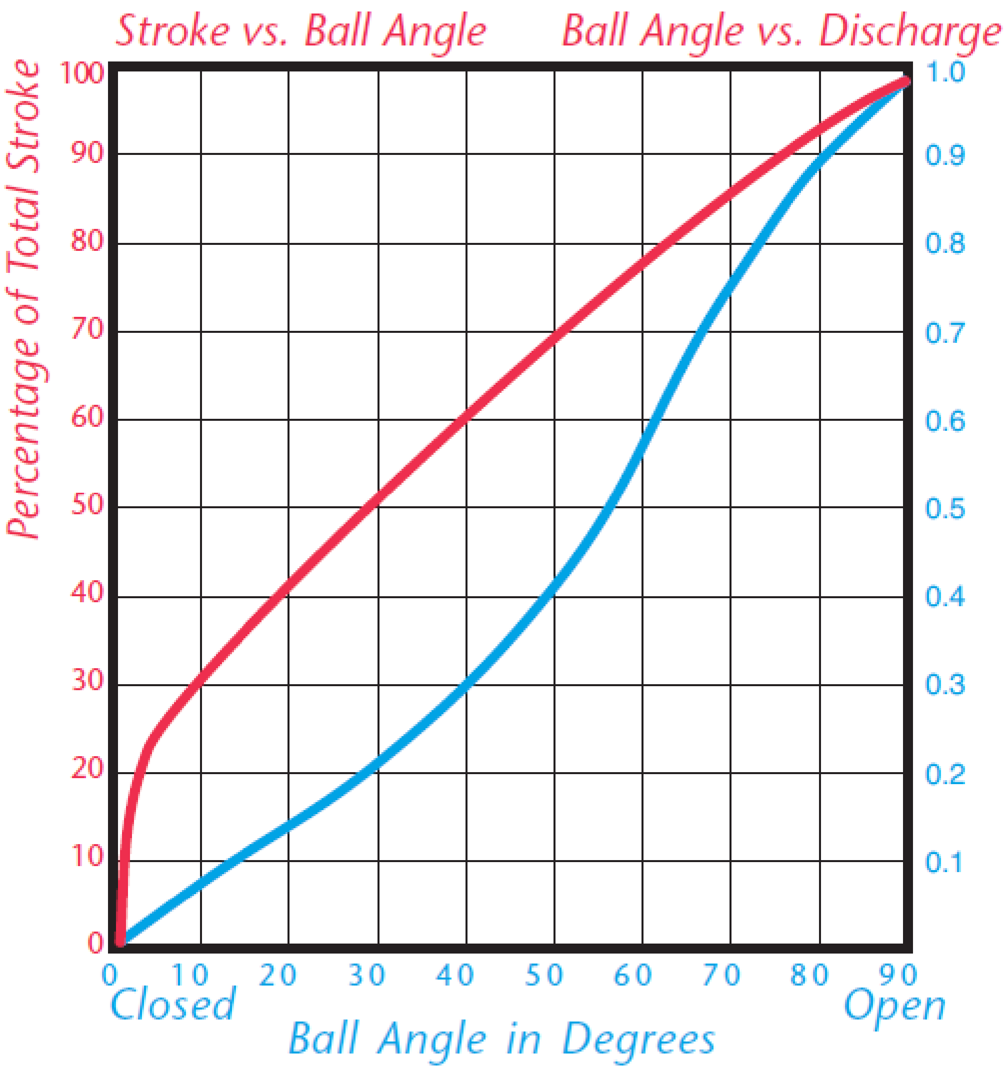


Figure.H.1: The Relationship between Ball Valves Opening/Closing angle vs. Coefficient of Discharge.

Table.H.1. Allowable leakage rates For SSV and SSSV (36).

Standard Reference	Application	Allowable Leakage Rates		Test Frequency
		Liquid (cc/min)	Gas (SCFM)	
Subsurface Safety Valves				
API 14A, Ninth Edition, 1994	Qualification	10	5	Not addressed
API 14B, Fourth Edition, 1994	Field	400	15	6 months
30 CFR Chapter 11 (250.124), 1996	Field	200	5	6 months
30 CFR Chapter 11 (250.804), 1998	Field	Not addressed	Not addressed	6 months
Surface and Underwater Safety Valves				
API 14C, 1994	Field	400	15	At least annually
API 6AV1, 1996	Qualification	0	0	Not addressed
API 14H, 1994	Field	400	15	Not addressed
30 CFR Chapter 11 (250.124), 1996	Field	0	0	Each month or 6 wks
30 CFR Chapter 11 (250.804), 1998	Field	0	0	Each month or 6 wks

APPENDIX I

HCR PARAMETERS & TIME OF CLOSURE SENSITIVIVTY DETERMINATION THROUGH FERUM PROGRAMME.

```
probdata.marg(1,:) = [1 314.52   5.52     314.52     0 0 0 0 0];
probdata.marg(2,:) = [1 415 10.16 415 0 0 0 0 0];
probdata.marg(3,:) = [1 6000000 1860000 6000000 0 0 0 0 0];

probdata.correlation = [0.4 0 0;
                        0   0.4 0;
                        0   0   0.4];

probdata.parameter = distribution_parameter(probdata.marg);

analysisopt.ig_max = 1000;
analysisopt.il_max = 10;
analysisopt.e1 = 0.001;
analysisopt.e2 = 0.001;
analysisopt.step_code = 0;
analysisopt.grad_flag = 'ddm';
analysisopt.sim_point = 'dspt';
analysisopt.stdv_sim = 1;
analysisopt.num_sim = 100000;
analysisopt.target_cov = 0.0125;

gfundata(1).evaluator = 'basic';
gfundata(1).type = 'expression';
gfundata(1).parameter = 'no';

gfundata(1).expression = '(1000*(x(1)*x(2))/x(3))-6';
gfundata(1).dgdq = {'(1000*x(2))/(x(3))';'(1000*x(1))/(x(3))';'-
(1000*x(1)*x(2))/(x(3)^2)'};

femodel = 0;
randomfield.mesh = 0;
```

##

RESULTS FROM RUNNING FORM RELIABILITY ANALYSIS

##

Number of iterations: 6

Time to complete the analysis: 0.047

Reliability index beta1: 3.7105

Failure probability pf1: 1.03407e-004

SENSITIVITIES OF THE RELIABILITY INDEX WITH RESPECT TO DISTRIBUTION PARAMETERS

----

var	mean	std dev	par1	par2	par3	par4
1	2.15079e-002	-9.47540e-003	2.15079e-002	-9.47540e-003	0.00000e+000	0.00000e+000
2	1.64233e-002	-1.01685e-002	1.64233e-002	-1.01685e-002	0.00000e+000	0.00000e+000
3	-5.26240e-007	-1.91125e-006	-5.26240e-007	-1.91125e-006	0.00000e+000	0.00000e+000

SENSITIVITIES of THE FAILURE PROBABILITY WITH RESPECT TO DISTRIBUTION PARAMETERS

----

var	mean	std dev	par1	par2	par3	par4
1	-8.78606e-006	3.87073e-006	-8.78606e-006	3.87073e-006	-0.00000e+000	-0.00000e+000
2	-6.70899e-006	4.15387e-006	-6.70899e-006	4.15387e-006	-0.00000e+000	-0.00000e+000
3	2.14971e-010	7.80753e-010	2.14971e-010	7.80753e-010	-0.00000e+000	-0.00000e+000

....

The following parameters are now available in your current workspace:

formresults.iter = Number of iterations

formresults.beta1 = Reliability index beta from FORM analysis

formresults.pf1 = Failure probability pf1

formresults.dsptu = Design point u_star

formresults.dsptx = Design point in original space formresults.alpha = Alpha vector

formresults.imptg = Importance vector gamma

formresults.gfcn = Recorded values of the limit-state function during search

formresults.stpsz = Recorded step size values during search

formresults.beta_sensi_thetaf = Beta sensitivities with respect to distribution parameters

formresults.pf_sensi_thetaf   = Probability of failure sensitivities with respect to distribution parameters

....

```
>> formresults.alpha

ans =

   -0.1187
   -0.1669
    0.9788

>> formresults.dsptu

ans =

   -0.4406
   -0.6192
    3.6319

>> formresults.dsptx
```

```
ans =

  1.0e+007 *

    0.0000    0.0000    1.2755

>> formresults.gfcn

ans =

   11.7543    4.0982    0.9008    0.0635    0.0003    0.0000

>> formresults.beta1

ans =

    3.7105

>> formresults.stpsz

ans =

     1     1     1     1     1

>>
```

APPENDIX J

THE MOELLING DATA OF TIME OF CLOSURE OF 150mm SHUTDOWN BALL VALVE FROM

The VBA programme in excel environment was used for the application to determine the time of closure of different ball valves sizes used for ESD procedures. As shown in Figure . J.1; the input values are R which stands for the radius of the ball valve, ΔP for maximum differential pressure across valve, T operating temperature/ fluid temperature, Molar mass of natural gas and Pi the expected downstream pressure. To run the programme you are required to enable the Macros programme and then input all these values after which the calculate button is pressed this automatically populates an excel table that shows how the HCR data relates to the time of closure, it also shows the plotted values or graphs of these data in other excel sheets.

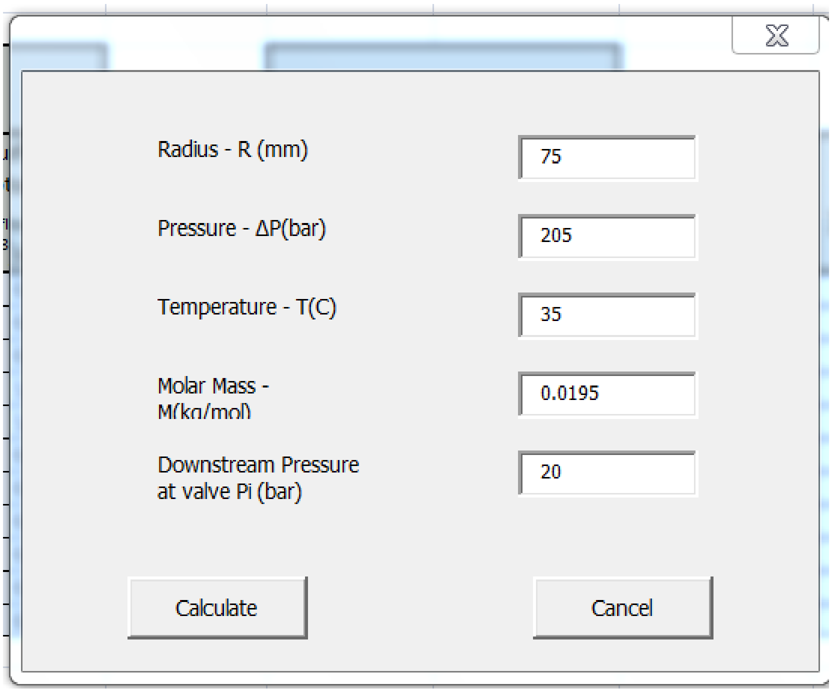


Figure.J.1: The input window form for Time of Closure Application.

Ball Valve Type : 150mm diameter (6 inches)

Fluid Natural Gas.

R (mm)=	75
ΔP_{max} (bar)=	205
T(^{0}C) =	35.000
M(kg/mol) =	0.0195
Pi (bar) =	5

Populate tables

DISTANCE TRANSVERSE BY VALVE

x(mm)	$\prod R^2 \bullet 2$	(R - (2R-x(t)/2)/360)	COS^{-1}(D)	E*C	(R-(2R-x(t)/2))	$\sqrt{[R^2\text{-}(R\text{-}(2R\text{-}x(t)/2)]^2}$	G*H	Valve Opening Area A_f(mm^2)	Degree of Opening (Θ)	C_d
0	35342.9	0	90.0000	3,180,862.56	0	75	0	3,180,862.56	90	1
15	35342.9	0.020833333	88.8063	3,138,672.01	7.5	74.62405778	559.6804334	3,138,112.33	80	0.9
30	35342.9	0.041666667	87.6120	3,096,463.13	15	73.48469228	1102.270384	3,095,360.86	70	0.75
45	35342.9	0.0625	86.4167	3,054,217.52	22.5	71.54544011	1609.772402	3,052,607.75	60	0.58
60	35342.9	0.083333333	85.2198	3,011,916.64	30	68.73863542	2062.159063	3,009,854.48	50	0.4
75	35342.9	0.104166667	84.0208	2,969,541.72	37.5	64.95190528	2435.696448	2,967,106.02	40	0.3
90	35342.9	0.125	82.8192	2,927,073.70	45	60	2700	2,924,373.70	30	0.2
105	35342.9	0.145833333	81.6145	2,884,493.16	52.5	53.56071321	2811.937444	2,881,681.22	20	0.13
120	35342.9	0.173611111	80.0022	2,827,509.61	60	45	2700	2,824,809.61	10	0.08
135	35342.9	0.208333333	77.9753	2,755,874.61	67.5	32.69174208	2206.69259	2,753,667.92	5	0.04
150	35342.9	0.208333333	77.9753	2,755,874.61	75	0	0	2,755,874.61	0	0

INVENTORY FOR CLOSURE TIME

Length transverse x(mm)	Density (ρ) kg/m-3	Internal Area of Pipe Apipe	Valve Opening Area A_f (mm^2)	Coefficient of Discharge C_d	PRESSURE DIFFRENTIAL ACROSS VALVE Downstream Pressure at valve P_i (bar)	Upstream Pressure at valve $P_{k(bar)}$	Pressure Diffrential @ valve ΔP(bar)	Volumetric flow across Valve $Q_i(t)$ (m^3/s)	Fluid velocity u(t)(m/s)	$\Delta u(t) = u_i - u_{i-1}$ (m/s)
0	156.11	17671.46	3180862.56	1.00	20.00	225.00	205.00	5.15499	1.62063	1.62063
15	117.34	17671.46	3138112.33	0.90	20.00	158.79	138.79	4.34389	1.38424	0.23639
30	78.94	17671.46	3095360.86	0.75	20.00	113.96	93.96	3.58174	1.15713	0.22711
45	53.02	17671.46	3052607.75	0.58	20.00	83.61	63.61	2.74251	0.89841	0.25872
60	35.55	17671.46	3009854.48	0.40	20.00	63.06	43.06	1.87391	0.62259	0.27582
75	23.80	17671.46	2967106.02	0.30	20.00	49.15	29.15	1.39311	0.46952	0.15307
90	15.93	17671.46	2924373.70	0.20	20.00	39.74	19.74	0.92073	0.31485	0.15467
105	10.66	17671.46	2881681.22	0.13	20.00	33.36	13.36	0.59314	0.20583	0.10901
120	7.14	17671.46	2824809.61	0.08	20.00	29.05	9.05	0.35970	0.12734	0.07850
135	4.79	17671.46	2753667.92	0.04	20.00	26.12	6.12	0.17611	0.06396	0.06338
150	3.22	17671.46	2755874.61	0.00	20.00	24.15	4.15	0	0	0.06396

INVENTORY OF FLOW AFTER RUPTURE					Time of closure						
mass flow rate @ Rupture Q_{mi}(kg/s)	volumetric flow @ rupture Q_{ij}(m^3/s)	Reverse flow Q_{rk}(m^3/s)	Total Outflow @ Rupture $Q_{outflow}$(t) (m^3/s)	Celerity c(m/s) * 10^2	time of closure Δt_{ci}(s)	$\sum(t_{ci})$ $= t_{ci} + t_{c(i-1)}$(s)	Cumulative $\sum Q_{outflow}$(m^3/s)	Cumulative $\sum Q_{outflow}$(SCFM)	Compressibility Factor(Z) (m^2/N)	Expected closing Torque (Nm)	Remarks
3.68632	0.0236143	0.000000	0.023614	0.81	0.00	0.00	0.023614	50.038802	1.000024056	0	Valve is fully Open
2.68483	0.0228812	0.434389	0.457270	0.85	0.68	0.68	0.480885	1018.994371	0.900698539	56987202.4	
1.86562	0.0236323	0.895434	0.919066	1.03	0.68	1.35	1.399951	2966.495747	0.906329087	55669694.7	
1.30962	0.0246998	1.151853	1.176552	1.34	0.68	2.03	2.576503	5459.610147	0.913568357	37102740.5	
0.93134	0.0261973	1.124347	1.150544	1.95	0.68	2.71	3.727047	7897.612774	0.922424582	19070125.5	
0.67283	0.0282644	0.975177	1.003441	2.61	0.68	3.39	4.730489	10023.905286	0.932623004	9597954.31	
0.49486	0.0310672	0.736581	0.767648	3.94	0.68	4.06	5.498136	11650.551111	0.943580259	3865046.86	
0.37094	0.0347965	0.516032	0.550829	6.09	0.68	4.74	6.048965	12817.757086	0.954509636	1311070.73	
0.28329	0.0396689	0.330922	0.370591	9.95	0.68	5.42	6.419556	13603.039644	0.964632261	307579.477	
0.22006	0.0459298	0.169069	0.214998	19.99	0.68	6.09	6.634555	14058.621190	0.973383943	57348.5095	
0.17344	0.0538624	0.000000	0.053862	0.00	0.34	6.43	6.688417	14172.755684	0.980511184	0	Valve is fullyclosed

INVENTORY AFTER VALVE CLOSURE												
						TIME SUBSEQUENT TO CLOSURE						
Radius Ratio D	Area Ratio A	time decay constant α	Q_{mj}/Q_{mj0}	$\Delta P/\Delta P_o$	Q/Q_o	$t_{mj}(s)$	$t_p(s)$	$t_{outflow}$ (s)	$Qj(m^3/s)$	Volumetric outflow after closure $Q_{outflow}(t)(m^3/s)$	$\sum\Delta P$ cumulative Pressure (bar)	ΔP Time decay Pressure (bar).
3	1	0.136345268	0.728321795	0.911111111	19.36408415	1.675552574	1.899474454	4.955984895	0.018791428	0.012014682	205.00	173.6628975
3	1	0.136345268	0.694876652	0.874043518	2.009897501	3.304096523	3.757414218	7.646633498	0.014582461	0.161207473	343.79	95.13010094
3	1	0.136345268	0.701976262	0.82449589	1.280160533	4.942805709	5.556995973	9.886183861	0.012045416	0.238751633	437.74	53.41838555
3	1	0.136345268	0.711149947	0.760791847	0.977894407	6.594498611	7.276165365	11.85639516	0.010050956	0.233639731	501.35	31.00296145
3	1	0.136345268	0.722432197	0.682858947	0.872145291	8.261931779	8.887263282	13.71216078	0.008492476	0.177399079	544.42	18.77271759
3	1	0.136345268	0.73549129	0.593114989	0.765015075	9.947280075	10.35746117	15.43686592	0.007281516	0.122296355	573.57	11.97434111
3	1	0.136345268	0.749586127	0.496693465	0.71755385	11.6516109	11.65024384	17.09752351	0.006343999	0.074601805	593.31	8.115960382
3	1	0.136345268	0.763697107	0.400517256	0.67278833	13.37459175	12.72781029	18.69376388	0.005617886	0.043060995	606.67	5.882863669
3	1	0.136345268	0.776802711	0.311440303	0.580149835	15.11458775	13.55382756	20.14185988	0.005051900	0.02378017	615.71	4.576274709
3	1	0.136345268	0.788155511	0.234427356	0.250524839	16.86909277	14.09578292	20.75022755	0.004604770	0.012697881	621.84	3.822750344
3	1	0.136345268	0	0.171709143	0	17	15	21	0.004	0.012	625.98	3.123468761