High Back Pressure on Pressure Safety Valves (PSVs) in a Flare System

Developing the Simulation model, Identifying and analyzing the back-pressure build-up

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Acknowledgements

Abstract

Process safety is a disciplined framework for managing the integrity of operating systems and processes handling hazardous substances. It is achieved by applying good design principles, engineering, and operating and maintenance practices.

Flare systems play an important role in the safety of Oil and Gas installations by serving as outlets for emergency pressure relief in case of process upsets. Accurate and reliable estimation of system thermo-hydraulic parameters, especially system back-pressure is critical to the integrity of a flare system design. Accurate design of the flare system plays a key role in containing possible process safety hazards on the oil and gas installation, especially oil and gas offshore platforms. In order to enable uniformity and consistency, design guidelines and constraints are provided within the industry, both national and international standards – NORSOK, API and ISO – which serve as recommended practice in process and flare system design.

This thesis is focused on analyzing the back-pressure build-up in the high pressure flare system at Kollsnes gas processing plant. The relief scenario considered in this thesis is pool fire case in condensate system in Kollsnes gas processing plant. The simulation tool used to model the flare system in this case is Aspen Tech's Flare system analyzer (known as FLARENET), is a steady state simulation tool. The FLARENET model includes the pressure safety valves (PSV), downstream tail pipes, flare header, flare knock out drum and

flare stack. All the actual plant data are given as input to the model so as to get the more practical result.

After running the simulation model, it emerges that for a total relieving rate of 108.33 kg/sec (Vapor flow) in pool fire scenario, the back-pressure generated at some of the PSV's in the relief network is 10.6 Barg against their set pressure of 10 Barg. This raises serious process safety concern as the relieving rate from the PSVs is drastically reduced due to very high back-pressure, which in turn will increase the pressure inside the process equipment exposed to fire. This concern has been conveyed to the Kollsnes plant operations group.

To verify the results obtained from FLARENET simulation, I had undertaken actual plant verification. This was carried out in co-ordination with the Kollsnes plant operations group during September 2012, just before annual maintenance shutdown of the plant. The back-pressure results obtained as a result of controlled blow-down from the plant matched well with the FLARENET simulation results.

Further follow up tasks is being under taken by Statoil ASA to alleviate the back-pressure problem. This thesis suggests two options for solving the problems. Further evaluation of the suggestion and its implementation in the plant is going on in the company. This thesis also opens door for further research on high back-pressure in flare system and analyze the problem dynamically. This will reduce the conservative steady state assumptions and will have much wider industrial acceptability with respect to cost savings potential.

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List of Symbols

Symbol	Definition	Units
m	Mass	kg
ρ	Fluid density	kg/m^3
A	Cross-sectional area	m^2
$\dot{m}$	Mass flow rate	kg/s
p	Pressure	bara
T	Temperature	K
$\not z$	Compressibility factor	-
R	Gas constant	$m^3\ bar\ K^{-1}\ mol^{-1}$
u	Volume	m^3
$\not\forall$	Control volume	m^3
s	Entropy	$m^3\ bar\ K^{-1}$ or J/K
h	Specific enthalpy	$m^3\ bar\ kg^{-1}$ or
c_v	Constant volume specific heat capacity	J/kg/K
c_p	Constant pressure specific heat	J/kg/K
Q	Volumetric flow rate	m^3/s
U	Flow velocity	m/s
c	Speed of sound	m/s
g	Acceleration due to gravity	m/s^2
z	Elevation	m
M	Mach number	-
f	Fanning friction factor	-
L	Length	m
D	Inner diameter	m
γ	Specific heat ratio	-
U_{LS}	Superficial liquid velocity	m/s
U_{GS}	Superficial gas velocity	m/s
U_{mix}	Mixture velocity	m/s

x

List of Abbreviations

PSV   Pressure safety valve

HP   High pressure

LP   Low pressure

PSD   Process shutdown

ESD   Emergency shutdown

FLARENET   Aspen Flare system analyzer steady state software

KOD   Knock out drum

NGL   Natural gas liquid

DPC   Dew point control

KFGC Project   Kollsnes flash gas and condensate Project

EBV   Emergency blow down valve

API   American petroleum Institute

PCV   Pressure control valve

BDV   Blow-down valve

HSE   Health safety and environment

VLE   Vapor-liquid equilibrium

EOS   Equation of state

SRK   Soave-Redlich Kwong

PR   Peng-Robinson

PFD   Process flow diagram

MEG   Mono ethylene glycol

P&ID   Process & Instrumentation diagram

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Chapter 1

1. Introduction

1.1. General background

Across the global oil & gas industry, considerable effort has been focused on the prevention of major incidents. For the oil & gas industry the emphasis of process safety and asset integrity is to prevent unplanned releases which could result in a major incident. Process safety is a disciplined framework for managing the integrity of operating systems and processes handling hazardous substances. It is achieved by applying good design principles, engineering, and operating and maintenance practices. It deals with prevention and control of events that have potential to release hazardous materials and energy. Such incidents can result in toxic exposures, fires or explosions and could ultimately result in serious incidents including fatalities, injuries, property damage, lost production or environmental damage.

As a major safety requirement at oil and gas installations such as refineries and process facilities, a flare system is usually installed to relieve built up pressure that may occur during shut down, start up or due to process system failure, reducing other safety hazards associated with process emergencies.

Accurate design of the flare system plays a key role in containing possible process safety hazards on the oil and gas installation, especially oil and gas offshore platforms. In order to enable uniformity and consistency, design guidelines and constraints are provided within the industry, both national and international standards – NORSOK, API and ISO – which serve as recommended practice in process and flare system design.

Thermo-hydraulic modeling serves a key role in flare system design. It enables the estimation of the thermodynamic and hydraulic parameters such as pressure, temperature, velocity/mach, and other flow parameters required for building/modification of flare systems. There are several simulation tools used for flow simulation in the Oil and Gas industry. AspenTech's FLARENET (flare system analyzer) has found common use among many flare system design engineers as a steady state simulation tool. Accurate and reliable estimation of system thermo-hydraulic parameters, especially system back-pressure is critical to the integrity of a flare design.

The main goal of this project is to

- Build the FLARENET model of the section of the Kollsnes Gas Processing plant (situated north-east of Bergen, Norway).

- Run the simulation for over pressure scenario (pool fire in condensate system).

- Analyze the back-pressure build-up in the flare system.

- Discuss the impact of back-pressure on Pressure reliving devices (such as PSVs) and mitigating measures.

1.2.　　Flare System

Typically a flare system is categorized under process utility system.

The flare system is the single largest pipe network in an oil & gas/ gas processing plant. It serves as a relief system for depressurizing different process and production units in cases of shut down or unexpected cases of hazardous process emergencies, by collecting excess fluid through relief devices and a pipe network and disposing of it to the required outlet. The light hydrocarbons and other gases are released by combustion into the atmosphere while

the heavier hydrocarbon, liquids are let out through drains and are often pumped back into the separation system.

The descriptive figure 1.2 shows a typical high pressure flare system. The manifolds and process facilities can be critical channels for over pressure. They are thus usually tied to the flare via pressure relieving devices (such as PSVs, EBVs), to protect the system in case of pressure build-up.
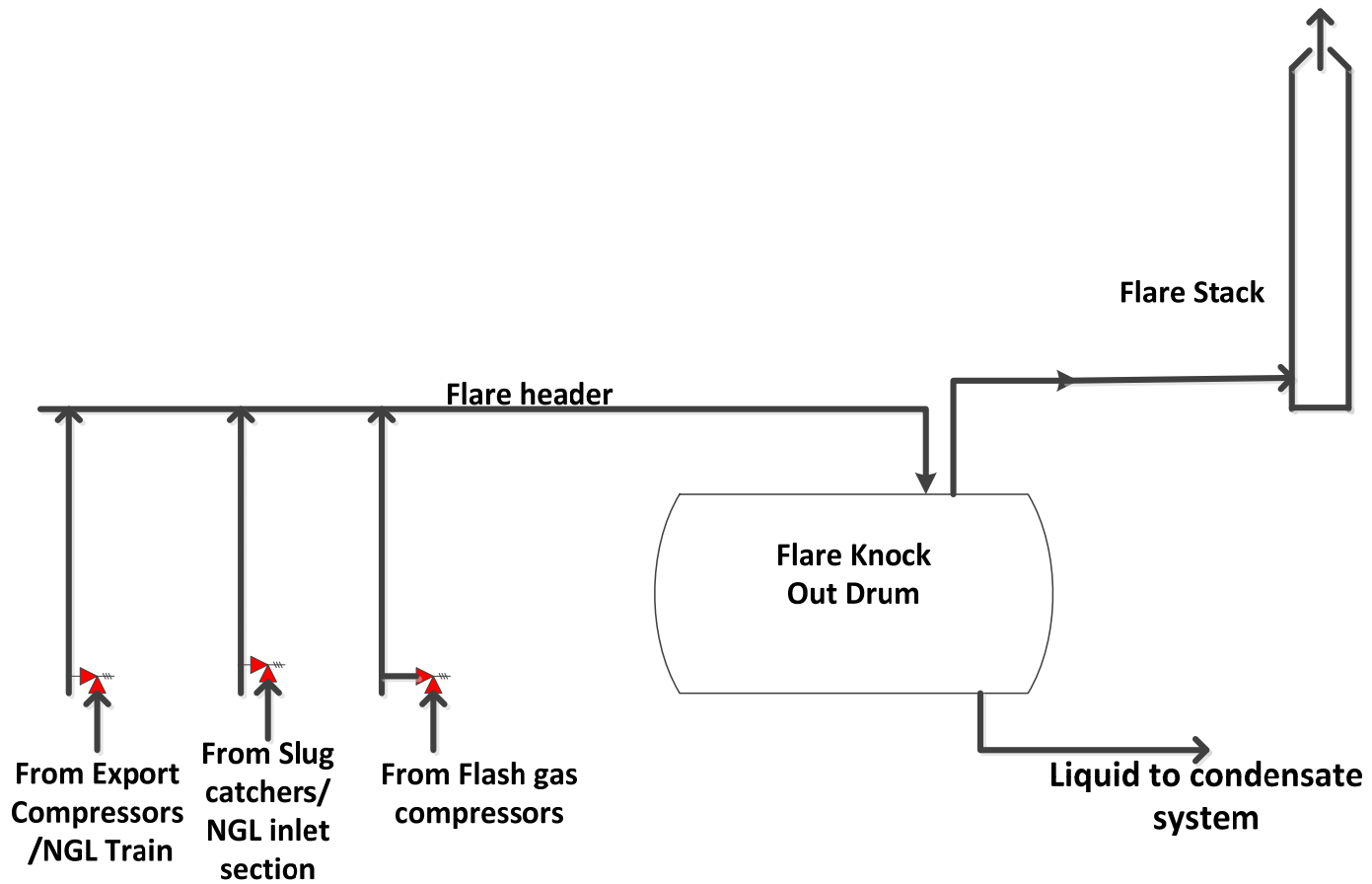
Figure 1.2: A typical Drawing showing components of a flare system

1.3.   Typical overpressure scenarios (Oil & Gas Industry focus)

Overpressure is the result of an unbalance or disruption of the normal flows of material and energy that causes the material or energy, or both, to build-up in some part of the system. Analysis of the causes and magnitudes of overpressure is, therefore, a special and complex study of material and energy balances in a process system. Pressure-relieving devices are installed to ensure that a process system or any of its components is not subjected to pressures that exceed the maximum allowable accumulated pressure.

- **Closed outlets on vessels**

The inadvertent closure of a manual block valve on the outlet of a pressure vessel while the equipment is on stream can expose the vessel to a pressure that exceeds the maximum allowable working pressure. If closure of an outlet-block valve can result in overpressure, a pressure-relief device is required

- **Operator error**

Wrong plant operation by the plant operator is considered a potential source of overpressure.

- **Inadvertent valve opening**

The inadvertent opening of any valve from a source of higher pressure, such as high-pressure steam or process fluids has the potential to expose the vessel and pipeline downstream to a pressure that exceeds the maximum allowable working pressure of the equipment and pipeline.

- **Check-valve leakage or failure**

Check valves are used to allow flow only in one direction. Most commonly they used in the discharge of a pump or compressor. In the event of a leakage/failure of check valve the flow of process fluid can occur in the other direction. This can result in exposing the upstream

equipment/pipelines to a pressure that exceeds the maximum allowable working pressure of the equipment/pipeline.

- **Utility failure**

In the event of loss of utilities like electricity, cooling water/ medium, Instrument air, steam, Inert gas it is possible to expose the part of a plant or whole plant to a pressure that exceeds the maximum allowable working pressure of the system.

- **Reflux failure**

The loss of reflux as a result of pump or instrument failure can cause overpressure in a column because of condenser flooding or loss of coolant in the fractionating process.

- **Abnormal heat input from reboilers**

Reboilers are designed with a specified heat input. When they are new or recently cleaned, additional heat input above the normal design can occur. In the event of a failure of temperature control, vapor generation can exceed the process system's ability to condense or otherwise absorb the build-up of pressure, which may include non-condensables caused by overheating.

- **Heat exchanger tube failure**

In shell-and-tube heat exchangers, the tubes are subject to failure from a number of causes, including thermal shock, vibration and corrosion. The result is the possibility that the high-pressure stream overpressures equipment on the low-pressure side of the exchanger.

- **Transient pressure surges**

Transient pressure surges due to water/steam/condensate induced hammering can cause the over pressure in the parts of process system.

- **Fire scenario**

In the event of an external fire, the process fluids inside the equipment/pipelines evaporate and have the potential to overpressure the equipment/pipeline.

- **Process changes / chemical reactions**

In some reactions and processes, loss of process control can result in a significant change in temperature and/or pressure. The result can cause over pressure in the reactor and connected systems.

- **Hydraulic expansion**

Hydraulic expansion is the increase in liquid volume caused by an increase in temperature can cause overpressure in the equipment/pipeline.

- **Entrance of volatile material into the system**

The entrance of water into hot oil is most common source of potential overpressure.

1.4. Reliefs to Flare Systems

A flare system consists of different relief units that handle depressurization for the different processes taking place on the platform/plant, to ensure safety of life and property on it. Typical sources of process relief are the production manifolds, compression system and separators where it is possible for pressure to build-up/overpressure.

The relief systems include; process relief, process flaring, blow-down etc.

- **Process relief**

Process relief involves pressure relief of a process unit in case of overpressure due to a process upset. In order to ensure process safety, pressure relief devices are connected to the vessels and units with a potential for overpressure.

The design basis of these pressure relief devices is dependent on the thermo-hydraulic conditions; pressure, and temperature of the vessel being relieved. These will be taken into account in order to determine the required relieving rate. The design pressure (set pressure) of the relief valve is usually set to a value at which it (the valve) opens to prevent pressure build-up above the vessel /pipeline design pressure.

- **Process Flaring**

Process flaring involves the controlled flaring or bleeding out of gas from a particular process unit or compressor, in case of pressure build-up above the acceptable limits. This is in order to allow for continued production, without causing a process upset from build-up of pressure. Pressure control valves (PCV or PV) are used for process flaring.

- **Blow down**

Blow down is the actual process of depressurizing a given process unit or section of a plant after shut down. A blow down valve (BDV) is used in this case. In the event of emergency (e.g. fire, gas leaks etc.)the EBVs are open after plant shut down. This serves as a safety measure against escalation of the fire into a full blown explosion.

In addition to these reliefs, in certain cases there are continuous purging of inert gas in the flare system so as to avoid oxygen ingress into flare the system.

1.5.   Components in Flare Network

The flare network is a connection of pipes that serve as the pathway for releases during a process relief. Discharged fluid from the relief valves are led through the flare network to a safe disposal point. The disposal system may be single device (connected to only a single relieving device), or multiple device disposal. Flare networks are normally multiple device disposal system due to the economic advantage it presents. The releases are disposed off to a vessel or point of lower pressure than the vessel being relieved. Gaseous releases are

disposed off or flared (combusted) to the atmosphere, while liquid/heavier releases are recycled back to the main process system. Below are the main components of a flare network.

- **Tail pipes**

The tailpipes are connected with the relieving device, PSV or PV, so they are the first contact line of the discharge/flare network. They are of comparably smaller diameters than the other branches of the flare network, and are designed to handle the maximum allowable back-pressure of the relieving device they are connected to. Flow velocities may be very high for tailpipes; they are designed for mach numbers of up to 0.7 mach

- **Flare Sub-Headers and Main Header**

Flare Headers serve as the collection point for releases coming from the different tailpipes. Depending on the size of the disposal system, system loads and back-pressure limitations, flare sub-headers may be required as intermediate lines connecting with the main header. Flare headers are of larger diameter than the other network pipes and are designed for mach number of up to 0,6. Flare headers are classified as high pressure or low pressure flare headers based on the pressure range of the incoming streams.

- **Knock-out Drum (KOD)**

The Knock-out Drum is a separation unit, usually a simple 2-phase separator. The heavy fluids like oil/condensate and water are lead out to drains and often pumped back into the separation system, while the lighter and gaseous components of the stream escape to the flare stack.

- **Flare Stack and Tip**

The flare stack is usually an elevated pipe pointing upwards. For offshore platforms, the size, positioning and orientation of the flare stack is a function of factors like personnel safety, wind direction, hydrocarbon dispersion and radiation heat from the burning flare. The flare stack is designed for velocities of up to 0.5 mach. Flare stack is connected to the flare tip, which serves as the burner for the combusted gases. For disposal to the atmosphere, the pressure downstream the flare tip is atmospheric. Flare tip design is very important; it influences the flare radiation, dispersion and back-pressure generated in the flare system.

1.6.   Flare system Design requirements

In the design of a flare system several factors have to be taken into consideration; engineering, safety, economic and practical. A proper analysis of thermal and hydraulic loads resulting from various relief scenarios and process contingences are crucial to proper sizing of different relief devices and components of the flare network.

The minimum recommended information necessary to provide a complete pressure relief system is as follow:

- Information on relief system

- Protected equipment description

- Analysis of cause of system overpressure

- Design codes

- System normal operating condition

- System relieving condition

- Relief device selection/configuration

- Relief system required area

- Relieving-fluid disposal requirements

- Relief device physical installation

- Pressure relief valve inlet-line pressure drop

To ensure safe and reliable design, there are national and international standards that give guidelines on recommended practice for flare system design:

- NORSOK standard P-100

- NORSOK standard P-001

- NORSOK standard S-001

- API 521/ ISO 23251

- API 520

Chapter 2

2. Literature Survey

Process safety is a disciplined framework for managing the integrity of operating systems and processes that handle hazardous substances. It relies on good design principles, engineering, operating and maintenance practices. In recent years, major incidents in both the upstream and downstream industries have highlighted the importance of having these robust processes and systems in place.

2.1. Flare system's contribution for overall Process safety

Flare and disposal system plays an important role to prevent major incidents and it is part of process safety design of a plant. As seen in figure 2.1 the Swiss cheese model, hazards are prevented/contained by multiple protective barriers. Barriers may have weaknesses or 'holes'. When holes align hazard energy is released, resulting in the potential for harm Barriers may be physical engineered containment or behavioral controls dependent on people. Holes can be latent/incipient, or actively opened by people.
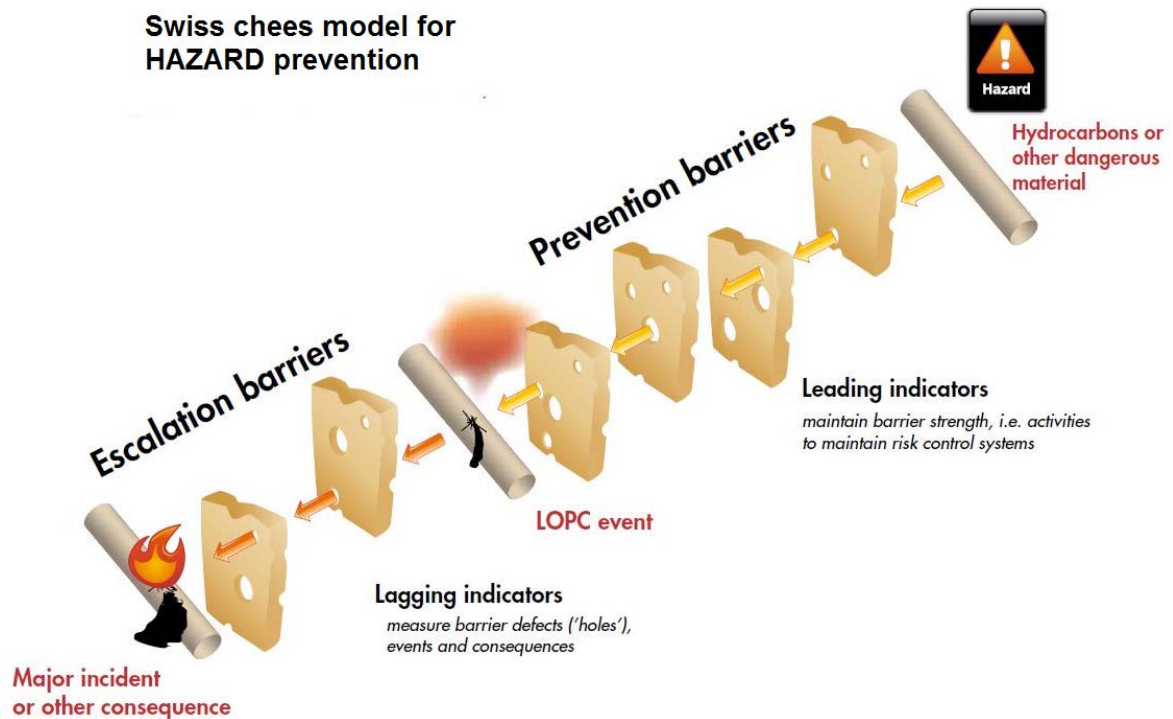
Figure 2.1: Swiss cheese model for HAZARD prevention (Based on the work of James Reason [27] [28])

Flare and disposal system is one of the major prevention barriers for the safety and integrity of the operating assets. API 521standard [1] and API 520 [2] has guidelines for proper design/rating of the flare system and its associated components.

2.2.   Challenges in modeling flare system

Proper design of the flare system for green field or brown field project holds key with respect to safety and cost impact. Too conservative design of various components in the flare s system will have adverse impact on the cost of whole project, at the same time improper design of the components could lead to unsafe operation leading to incidents.

The steady state simulation tool used in this thesis, FLARENET from Aspen Tech depends on the various process input parameters, over pressure scenario selection, physical properties and equations of state used in the model. The correct use of all these

variables comes from the experience. The user guide from Aspen Tech [6] has useful information for various assumptions and variable selection.

Quality check of the steady state FLARENET model is a challenge in most of the cases. Even though the model is built based on the actual plant data, isometrics and other steady state process conditions, in some cases the results obtained from the model could vary compared to the results from actual relieving condition in the plant. This could be due to the fact that dynamics of various conditions in actual relieving case compared to the steady state case used by FLARENET. This necessitates the need for dynamic modeling of flare system to get the comparable results.

Another aspect is getting quality data from the actual plant operation. Flaring from a plant does not take place in normal plant operations. The flaring of high pressure sources to flare system takes place in emergency conditions, plant startup/shut down cases. Happening of these events are not very frequent due to good process design, control and operations. Hence it remains a challenge to get the correct data from the on field instruments during these short emergency situations and sometimes also these data are not stored in the history.

2.3.   Flare system limitations in Oil & Gas industry

Flare, vent and blow down system are very critical systems in oil & gas plant. Initial system design for a typical topside facility is for maximum relief from the largest source for a particular relief scenario decided during design phase of the plant. As the time goes, subsequent modification projects, subsea tie-in to the existing topside facility makes flare system vulnerable. Some times each and individual project estimates the additional relief loads they will put into the existing flare system and compare with the available capacity in the flare system. In most of the cases the new sources (PSVs & EBVs) are added to the existing flare system without any modification or upgrade of current system.
Again, building a new flare system (which includes tail pipes, main header, KO drum and flare stack) requires heavy investment and typically in an offshore installation where there is restriction on total allowed weight on top side equipment makes it no feasible.

The guide line from Scandpower As [23] has very good information on risk assessment for new and expansion projects. The input from [19], considering new analysis for flare suggests various methods to be followed to reduce the expansion costs in flare system.

2.4.   Handling of Multi-phase flow of fluid in flare system

Many cases it is gaseous/vapor phase fluid goes through the flare system. In certain cases, the flow could be two phase with both liquid and gas phase present. Then, it necessitates a detail study of the flow regimes, velocities of different phases, reaction forces and change in fluid property along the flare header.

In this project not much focus is given for two phase flow in flare system as all the sources relieving during the fire scenario only relieve hydrocarbon gases. However multiphase dynamic fluid flow analysis software e.g. OLGA [25] and K-Spice [26] gives much detailed analysis of two phase flow, slug and hydrate formation behavior of fluid in the flare system.

Chapter 3

3. Theory for thermo-hydraulic modeling of flow in flare systems

3.1.　General Fluid Flow Equations

All flow problems are solved by applying one or more of the 3 conservation laws; the continuity equation, the energy balance equation, and the momentum balance equation. The general forms of these equations are referred to as the Navier Stokes equations. Appropriate assumptions and simplifications are applied to these general equations in order to solve specific flow problems. For flow in pipes, the following assumptions may apply

1. One dimensional flow in the axial direction is assumed

2. Steady state flow

The general conservation equations for one dimensional flow may be written as follows:

- **Continuity Equation**

Continuity equation for transient flow is given by

$$\rho_1 A_1 U_1 - \rho_2 A_2 U_2 = \Psi \frac{\partial}{\partial t} (\bar{\rho}_{CV}) \tag{3.1}$$

For steady state flow, $\frac{\partial}{\partial t} (\bar{\rho}_{CV}) = 0$. i.e.

$$\rho_1 A_1 U_1 - \rho_2 A_2 U_2 = 0$$

$$\Rightarrow \rho_1 A_1 U_1 = \rho_2 A_2 U_2 = \rho A U \tag{3.2}$$

$$\dot{m} = \text{mass flow rate} = \rho A U = constant \tag{3.3}$$

where: m = mass, ρ = fluid density, A = cross-sectional area, U= flow velocity,

CV = control volume

Index *1* and *2* refers to inlet and outlet of control volume respectively.

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- **Energy balance equation**

$$\sum_{i=inlets} m_i \left(e + \frac{U^2}{2} + gz + \frac{P}{\rho} \right)_i - \sum_{i=outlets} m_i \left(e + \frac{U^2}{2} + gz + \frac{P}{\rho} \right)_i + \frac{dq}{dt} - \frac{dw}{dt} = \frac{dE}{dt}$$

where $\frac{dE}{dt}$ is the accumulation of energy within the system.

(3.4)

For steady state flow accumulation is always equal to zero, therefore the energy balance

equation simplifies to the form

$$\sum_{i=inlets} m_i \left(e + \frac{U^2}{2} + gz + \frac{P}{\rho} \right)_i - \sum_{i=outlets} m_i \left(e + \frac{U^2}{2} + gz + \frac{P}{\rho} \right)_i + \frac{dq}{dt} - \frac{dw}{dt} = 0$$

(3.5)

where:

e = specific internal energy, P = pressure, g = gravitational constant, z = elevation,

q = heat, w = work

For gases, $e + P/\rho = h$ the specific enthalpy.

Thus the equation may be written as:

$$\sum_{i=inlets} m_i \left(h + \frac{U^2}{2} + gz \right)_i - \sum_{i=outlets} m_i \left(h + \frac{U^2}{2} + gz \right)_i + \frac{dq}{dt} - \frac{dw}{dt} = 0$$

(3.6)

The equation (3.8) may be further simplified depending on the type of thermodynamic

system assumed.

- **Momentum Balance equation**

From Newton's second law

$$\sum F = (\dot{m} U)_s = (\dot{m}U)_{cv} + (\dot{m}U)^{out}_{cv} - (\dot{m}U)^{in}_{cv} \tag{3.7}$$

For steady state flow there is no accumulation of momentum within the control volume,

$(\dot{m}U)_{cv} = 0$

So equation (3.10) becomes

$$\sum F = (\dot{m}U)^{out}_{cv} - (\dot{m}U)^{in}_{cv} \tag{3.8}$$

This equation (3.11) may be rewritten in polar co-ordinate form (r, Θ,z) as:

$$\sum F_z = (\dot{m}U_z)^{\text{out}} - (\dot{m}U_z)^{\text{in}} \tag{3.9}$$

$$\sum F_\Theta = (\dot{m}U_\theta)^{\text{out}} - (\dot{m}U_\theta)^{\text{in}} \tag{3.10}$$

$$\sum F_r = (\dot{m}U_r)^{\text{out}} - (\dot{m}U_r)^{\text{in}} \tag{3.11}$$

Here $\sum F$ is the sum of all forces acting on the fluid mass, including gravity forces, shear forces, and pressure forces. This can be shown using the Navier-Stokes equations.

3.2.   Thermodynamic relations used in simulations

A pipe network is also a thermodynamic system; therefore processes occurring in a pipe network during fluid flow may be described using equations of state, thermodynamic laws and relations. Important thermodynamic relations include; enthalpy, entropy, heat capacity.

- **The equations of State**

General equation of state:

$$f(p, v, T) = 0 \tag{3.12}$$

or

$$\frac{pv}{RT} = \frac{pv}{\rho RT} = z \tag{3.13}$$

where, z is the compressibility.

For a thermally perfect (ideal) gas, $z = 1$. Thus the equation of state for a thermally perfect gas becomes:

$$\frac{p}{\rho} = RT \text{ or } p = \rho RT \tag{3.14}$$

For a thermally imperfect (real) gas z is a function of temperature and pressure. There exist a number of equations of state for a thermally imperfect (real) gas, the most common of which are:

a) *Van der Waal's equation of state:*

$$P = \left(\frac{RT}{v-b}\right) - \left(\frac{a}{v^2}\right)$$ (3.15)

b) *SRK equation of state:*

$$P = \left(\frac{RT}{v-b}\right) - \left(\frac{a_c \alpha}{v(v+b)}\right)$$ (3.16)

where,

$a_c = f(P_c, T_c)$, $\alpha = (1+S[1-T_r^{\,0,5}])^2$, $S = 0,480+1,574\omega-0,176\omega^2$

c) *Peng-Robinson (PR) equation of state:*

$$P = \left(\frac{RT}{v-b}\right) - \left(\frac{a_c \alpha}{v(v+b)+b(v-b)}\right)$$ (3.17)

where,

$S = 0.37464+1.5422\omega-0.26992\omega^2$,

P = pressure, *T*= temperature, *R* = Universal gas constant, *υ* = volume, *a, b* = *f(P,T),*

ω = acentric factor

The Peng-Robinson EOS gives a more accurate estimation of the liquid phase density in VLE calculations.

- **Laws of thermodynamics**

The first law of thermodynamics:

It is a statement of the principle of conservation of energy.

de = dq + dw = dq – p dv (3.18)

The second law of thermodynamics:

It states that for a closed system (one in which neither heat nor work is exchanged with the surroundings) the entropy remains constant or increases but never decreases.

T ds = de + p dv = dq (3.19)

$$\Rightarrow ds = \frac{dq}{T} \tag{3.20}$$

where S = entropy

- **Other applicable thermodynamic relations**

Heat capacities:

Specific heat at constant volume c_v is given in equation (3.24)

$$c_v = \left(\frac{\partial e}{\partial T}\right)_v \tag{3.21}$$

Specific heat at constant pressure c_p is given in equation (3.25)

$$c_p = \left(\frac{\partial q}{\partial T}\right)_p \tag{3.22}$$

For an ideal gas

$$c_p = c_v + R \tag{3.23}$$

where $c_p / c_v = \gamma$ = ratio of specific heats at constant pressure to constant volume.

Specific enthalpy is given in equation (3.27)

$$h = e + p\,v \tag{3.24}$$

For an ideal gas

$$h = e + RT \tag{3.25}$$

Taking differentials on both sides of equation (3.28), we have

$$dh = de + R\,dT = c_v\,dT + R\,dT$$

$$\Rightarrow dh = (c_v + R)\,dT = c_p\,dT \tag{3.26}$$

3.3.   Different flow considerations

Depending on if the density/volume of a fluid is a function of temperature and pressure or

not, flow may be considered compressible or incompressible.

3.3.1. Incompressible flow

For steady state incompressible flow density is constant. This largely simplifies the

conservation laws, as compressibility effects are neglected. The conservation equations

take the form:

- **Continuity Equation**

$Q = AU = constant$ (3.27)

- **Energy Equation**

$$\left[\left(\frac{p}{\rho g}\right)+\left(\frac{U^2}{2g}\right)+z\right]_{in} = \left[\left(\frac{p}{\rho g}\right)+\left(\frac{U^2}{2g}\right)+z\right]_{out} + h_L \qquad (3.28)$$

where:

head loss $= h_L = \dfrac{\Delta p_0}{\rho g}$

- **Momentum Equation**

$$\sum F = \left(\rho Q U\right)_{out} - \left(\rho Q U\right)_{in} \qquad (3.29)$$

Here Q = volumetric flow rate

3.3.2. Compressible flow

Compressible flow is flow of gas, or vapor. Fluid properties such as density and volume are

a function of temperature and pressure. This strongly influences the flow behavior.

Appropriate equations of state and thermodynamic relations are used to characterize the

flow parameters/behavior.

For compressible flow, the energy equation takes the form

$$h_1 + \frac{U_1{}^2}{2} + q_H = h_2 + \frac{U_2{}^2}{2} \tag{3.30}$$

where q_H is heat gained or lost.

- **Sound velocity and mach number**

The speed of sound is defined as that speed at which an infinitesimal disturbance is propagated in a uniform medium initially at rest. It is assumed to be characterized by isentropic conditions.

Speed of sound is given in the equation (3.34)

$$c^2 = \frac{\gamma p}{\rho} = \gamma RT = \frac{\gamma R_0 T}{M_w} \tag{3.31}$$

γ = specific heat ratio, R = individual gas constant, R_0 = universal gas constant, M_w = molecular weight

The mach number, M is the ratio of the local velocity to the local speed of sound

$$M = \frac{U}{c} \tag{3.32}$$

When $M<1$, the flow is subsonic; when $M=1$, the flow is sonic; for $M>1$ the flow is said to be supersonic.

Mach number is a parameter strictly related with compressible flow. Mach number does not exist in incompressible flow ($M = 0$), because the speed of sound is considered infinite in this case.

Mach number serves as a valuable parameter in describing compressible flow. At low mach numbers, $M <= 0.3$ gas or vapor flow may be described with the assumption of incompressibility; with minimal error in the estimation of flow properties.

- **Adiabatic flow**

In adiabatic flow there is no heat transfer, $q_H = 0$. The energy balance equation (3.33) takes the form

$$h + \frac{U^2}{2} = constant \tag{3.33}$$

since for a perfect gas

$$h = c_p T$$

the energy equation (3.37) may be written as

$$c_p T + \frac{U^2}{2} = const$$

$$\Rightarrow c_p T_1 + \frac{U_1^2}{2} = c_p T_2 + \frac{U_2^2}{2} = c_p T_0 \tag{3.34}$$

Here T_0 is the stagnation temperature, the temperature at static conditions ($U = 0$). This holds for adiabatic flow with or without friction.

For adiabatic frictional flow (Fanno flow) in a constant area duct, the energy equation can be re-derived to give an expression for the pressure drop as

$$f \frac{L}{D} \frac{1}{2} \left(\frac{\dot{m}}{A}\right)^2 = - \int_1^2 \rho dp - \left(\frac{\dot{m}}{A}\right)^2 \ln\left(\frac{\rho_1}{\rho_2}\right) \tag{3.35}$$

In adiabatic frictional flow critical conditions occur at $M = 1$. The maximum flow speed which is the speed of sound is reached, and this occurs downstream of the pipe.

- **Isothermal flow**

Temperature, T is said approximately constant in isothermal flow. In this case the internal energy and enthalpy remain constant. The energy balance equation (3.33) takes the form:

$$\frac{U_1^2}{2} + q_H = \frac{U_2^2}{2} \tag{3.36}$$

For frictional flow in a pipe of uniform diameter, the energy balance equation may be re-derived to give an expression for the pressure drop for isothermal flow across a pipe of constant cross-section as given below in equation (3.41)

$$p_1{}^2 - p_2{}^2 = \frac{\dot{m}^2 RT}{A^2} \, [\, f \, \frac{L}{D} + 2 \, \ell n \left(\frac{p_1}{p_2} \right) \,] \tag{3.37}$$

In terms of mach number

$$\frac{M_1{}^2}{M_2{}^2} = 1 - \gamma M_1{}^2 [\, f \, \frac{L}{D} + 2 \, \ell n \left(\frac{M_2}{M_1} \right) \,] \tag{3.38}$$

Where

$$M_2/M_1 = p_1/p_2$$

There is a limiting factor on how large the velocity can get of

$$M = 1/\sqrt{\gamma}$$

The pressure drop equations are applicable for

$$M < 1/\sqrt{\gamma}$$
.

The above comparison between adiabatic flow and isothermal flow of air through a constant area duct, assuming the same initial values for each. Inspection of the results showed that at low pressure drops, $P_2/P_1 > 0.9$, showed very little difference. Thus adiabatic flow in a pipe may be analyzed as isothermal flow without introducing much error, for such pressure drop ranges.

- **Mach number relationship**

Pressure and Temperature variation in pipe flow can be expressed in relation to the mach number of the flow. Depending on the upstream and downstream mach numbers, the other flow parameters may be related as follows:

1) *Flow through a nozzle, convergent; divergent; convergent/divergent nozzles (Valves and Orifices)*

The general relationship relating the influence of cross-sectional area change on flow speed is given as

$$\frac{dU}{U} = -\frac{1}{\left(1-M^2\right)}\frac{dA}{A} \tag{3.39}$$

$$\frac{dM}{M} = -[1+\frac{(\gamma-1)M^2}{2}]/(1-M^2)\left(\frac{dA}{A}\right) \tag{3.40}$$

These relations shows that

a) At subsonic speeds, $0 \leq M < 1$, an increase in area gives rise to a decrease in flow velocity and mach number, and vice versa.

b) At supersonic speeds, *M>1,* an increase in area gives rise to an increase in velocity and mach number; and a decrease in area gives rise to a decrease in velocity and Mach number.

c) At sonic velocity, *M=1*, the denominator $(1-M^2)$ is zero. This means that for the axial change in velocity and mach number (*dU/dx and dM/dx*) not to become infinite, the axial change in cross-sectional area (*dA/dx*) must be zero; i.e. cross-sectional area must be constant at *M=1.*

From the analysis above, it can be stated that an initially subsonic flow through a convergent - divergent nozzle will remain subsonic if it does not turn sonic at the throat.

2) *Flow through a constant area duct (pipe segments)*

Normal shock waves: The following relationship for adiabatic flow through a duct of constant cross-sectional area, in which discontinuity of flow properties exist due to the presence of a normal shock wave.

The conditions on either side of the discontinuity may be related by applying the principles of conservation of continuity, momentum, and energy as below

$$\rho_1 U_1 = \rho_2 U_2 \tag{3.41}$$

$$p_1 + \rho_1 U_1^2 = p_2 + \rho_2 U_2^2 \tag{3.42}$$

$$h_1 + \frac{U_1^2}{2} = h_2 + \frac{U_2^2}{2} = h_0 \tag{3.43}$$

Writing these equations for a perfect gas, for which $h = C_P T$; the energy equation then shows that the total temperature, T_0 remains constant across a normal shock wave.

Using the relations for a perfect gas, and the definition of mach number, the conservation equations take the form

$$\frac{T_1}{T_2} = \left(\frac{p_1}{p_2}\right)^2 \left(\frac{M_1}{M_2}\right)^2 \tag{3.44}$$

$$\left(\frac{p_1}{p_2}\right) = \frac{1 + \gamma M_2^2}{1 + \gamma M_1^2} \tag{3.45}$$

And

$$\frac{T_1}{T_2} = \frac{1 + ((\gamma - 1)/2)M_2^2}{1 + ((\gamma - 1)/2)M_1^2} \tag{3.46}$$

Eliminating temperature and pressure from these 3 relationships and solving for M_2 in terms of M_1, we have

$$M_2 = \left[\frac{2 + (\gamma - 1)M_1^{\,2}}{2\gamma M_1^{\,2} - (\gamma - 1)} \right]^{0.5}$$

(3.47)

In practice it is seen that that the condition; if $M_1 > 1$, then $M_2 < 1$ holds, while for $M_1 < 1$, M_2 is limited to a maximum value of 1.

It is said that M_1 can have any value in the range $0 \le M_1 \le \infty$. Inspection of the equation above shows that the minimum value of M_2 is $((\gamma - 1)/2\gamma)^{0.5}$ corresponding to $M_1 = \infty$. So the possible range of M_2 is $((\gamma - 1)/2\gamma)^{0.5} \le M_2 \le 1$.

Based on the equations above, pressure, temperature and density ratio relationships across a normal shock in terms of M_1 or M_2 may be written, results which may be summarized as

a) *M, U, P₀* decrease;

b) *T₀* remains constant;

c) *P, T, ρ, S*, and *a* increase

when the flow passes through a shock wave.

Stagnation properties

A relationship between stagnation properties (at zero velocity) and static properties may be expresses in terms of mach number

$$\frac{T_0}{T} = 1 + \frac{(\gamma - 1)M^2}{2}$$

(3.48)

$$\frac{p_0}{p} = \left(1 + ((\gamma - 1)/2)M^2\right)^{\gamma/(\gamma - 1)}$$

(3.49)

- **Pressure drop & Friction factor models for multi-phase flow**

Mixed flow of oil, gas, and water is common in oil and gas installations. Pressure drop and flow behavior in multi-phase flow strongly differs from single phase flow, and thus cannot be well defined by single phase flow models. Multi-phase flow is associated with higher pressure drops; flow regimes are strongly influenced by pipe dimension and inclination, and flow-rate of the different phases. There are a number of multi-phase flow pressure drop and friction factor correlations and models available today. Some of them are listed below

- The Beggs and Brill model

- The Lockhart-Martinelli correlation

- The Taitel and Dukler model

- The BTD model for vertical upward flow

- Oresweski model for vertical flow

None of these models is thought to be universal, covering all flow regimes and fluid properties encountered in multi-phase flow. These multi-phase flow pressure drop correlations are used in numerical simulators. A number of them are available for use in FLARENET. A brief description of the Beggs and Brill model is presented below.

The Beggs and Brill Pressure drop model

H. D. Beggs and J. P. Brill developed pressure drop correlations for 2-phase (gas/liquid) flow using air and water. The parameters studied and their range include

1. Gas flow rates of (0 to 300Mscf/D), liquid flow rates of (0 to 30 gal/min)

2. Pipe diameter of (1 to 1.5 inch)

3. Inclinations angles of (-90o to +90o) from the horizontal

The 2-phase flow regimes were divided into 4 groups, limited within ranges for certain derived parameters.

- Segregated flow

$$\lambda_L < 0.01 \ and \ N_{FR} < L_1$$
$$Or \ \lambda_L \geq 0.01 \ and \ N_{FR} < L_2$$

- Transitional flow

$$0.01 \leq \lambda_L \ and \ L_2 \leq N_{FR} \leq L_3$$

- Intermittent flow

$$0.01 \leq \lambda_L < 0.4 \ and \ L_3 < N_{FR} \leq L_1$$
$$Or \ \lambda_L \geq 0.4 \ and \ L_3 < N_{FR} \leq L_4$$

- Distributed flow

$$\lambda_L < 0.4 \ and \ N_{FR} \geq L_1$$
$$Or \ \lambda_L \geq 0.4 \ and \ N_{FR} \geq L_4$$

Where:

$$N_{FR} = \frac{U_{mix}^2}{gD}, Froude \ number$$

$$\lambda_L = \frac{U_{LS}}{U_{GS}}, input \ liquid \ content$$

$$L_1 = 316 * \lambda_L^{0.302}$$

$$L_2 = 9.52 * 10^{-4} * \lambda_L^{-2.4684}$$

$$L_3 = 0.1 * \lambda_L^{-1.4516}$$

$$L_4 = 0.5 * \lambda_L^{-6.738}$$

It is noteworthy that this correlation is not limited by inclination. It is applicable to horizontal, inclined and vertical 2-phase gas-liquid flow in pipes.

The Beggs and Brill (homogeneous) model is the recommended pressure drop model for use in FLARENET for cases of multi-phase flow.

- **Speed of Sound in Multi-phase (gas-liquid) flow**

For cases with gas-liquid flow (partial condensation of gas or vaporization of liquid phase) the speed of sound and thus Mach number will be strongly affected. Speed of sound lies in the range of 300m/s in gas, and over 1000m/s in liquid. But for gas-liquid flow the speed of sound depends on the flow regime, and phase fraction. Below is a figure 3.1 taken from [29] showing the effect gas-liquid flow on the speed of sound for water (c = 1500 m/s) and gas (c = 344m/s). Two extreme gas-liquid flow regimes are considered; stratified flow and homogenized flow.

For stratified flow speed of sound is given as

$$c_S = \left[\frac{\frac{\epsilon_G}{\rho_G} + \frac{\epsilon_L}{\rho_L}}{\frac{\epsilon_G}{\rho_G c_G^2} + \frac{\epsilon_L}{\rho_L c_L^2}} \right]^{1/2}$$

$$(3.50)$$

where: ϵ_G and ϵ_L are gas and liquid phase fractions,

c_G and c_L are sound speed in gas and liquid,

ρ_G and ρ_L are gas and liquid phase densities

In homogenized (dispersed) flow speed of sound is given as

$$c_H = \left[(\epsilon_G * \rho_G + \epsilon_L * \rho_L) * \left(\frac{\epsilon_G}{\rho_G c_G^2} + \frac{\epsilon_L}{\rho_L c_L^2} \right) \right]^{-1/2}$$
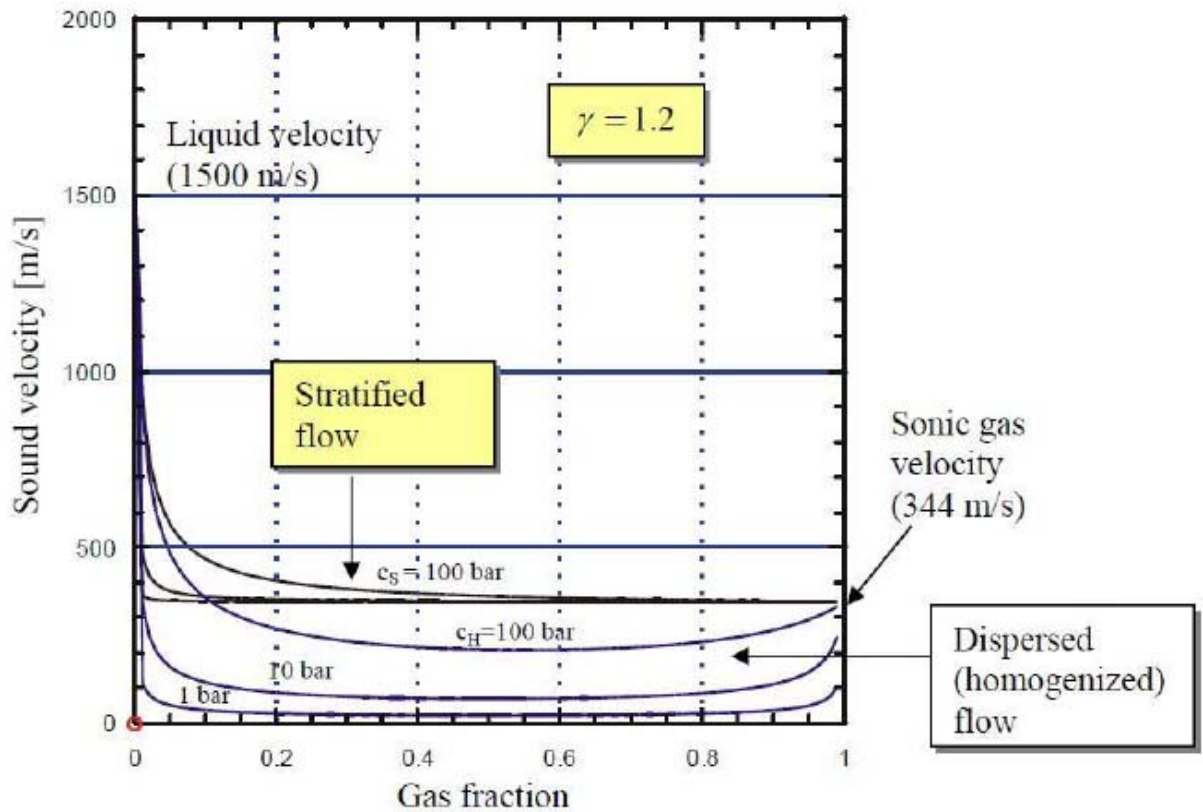
$$(3.51)$$

Figure 3.1: Sonic velocity in gas-liquid flow, for stratified (black line) and homogenized (dispersed)(blue line) flow. Plots are shown for pressures of 1, 10 and 100 bar [29].

3.4　Other pressure loss in fluid flow

There are additional pressure losses in fluid flow due to inline fittings like Tees, bends, expansion/contractions etc.Considering flow through a Tee joint as described below:
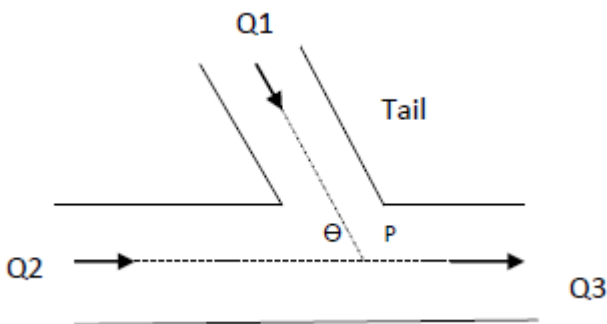

Fig: 3.2: Fluid flow through a Tee

We shall consider combining or mixing flow, which is typical for a flare network.

Continuity equation:

Q1+ Q2 = Q3 (3.52)

Energy Balance:

$$\left(p + \frac{1}{2}\rho U^2 + \rho gz\right)_{in} - \left(p + \frac{1}{2}\rho U^2 + \rho gz\right)_{out} = \Delta p_{in-out}$$

(3.53)

Where Δp_{in-out} is the loss in total pressure.

Momentum Balance:

Let's say the piezometric is given as

$$\hat{p} = p + \rho gz,$$

then:

$$(\hat{p}_1 + \rho_1 U_1^2 \cos\theta)A_1 + (\hat{p}_2 + \rho_2 U_2^2)A_2 = (\hat{p}_3 + \rho_3 U_3^2)A_3$$

(3.54)

When two flows meet at a junction, there is an additional loss in pressure due to:

1) Obstruction to flow caused by the junction

2) The formation of eddies as a result of mixing of the 2 streams

To account for the pressure loss across Tees/junctions/branches, restrictions and bends, pressure loss coefficients and resistance coefficients are used.

3.4.1 Pressure loss coefficients

The pressure loss coefficient is determined separately for each incoming stream in relation to the outgoing stream and is given as:

$$K_{13} = \frac{\Delta p_{13}}{\frac{1}{2}\rho U_3^2}$$

(3.55)

$$K_{23} = \frac{\Delta p_{23}}{\frac{1}{2}\rho U_3^2}$$

(3.56)

The loss coefficients have been defined using the total pressure drop across the branches and the dynamic pressure in the branch with the combined flow.

By solving simultaneously the continuity equation, energy balance equation and momentum balance equation, we get an expression for K as a quadratic function of $Q1/Q3$, dependent on the ratio $A3/A1$ and on the angle.

In line with this loss coefficients were experimentally obtained, and empirical correlations were developed to match the experimental data. Among these are correlations by Gardel (1957) and Miller (1971). The experiments were conducted under turbulent flow conditions in the range of (Re) = 105.

For flow through 90°-junctions, with A1=A2=A3 and q=Q1/Q3; Gardel (1957) gives the following correlating equations

$$K_{13} = -0.92(1-q)^2 + q(1-q) + 1.2q^2$$

(3.57)

and

$$K_{23} = 0.03(1-q)^2 + q - 0.38q^2$$

(3.58)

Miller's (1971) experimental data best fit the empirical relations given by Ito and Imai (1973)

$$K_{13} = 1.09 - 0.53(1-q) - 1.48(1-q)^2$$

(3.59)

and

$$K_{23} = 0.045 + 1.38q - 0.90q^2$$

(3.60)

Influence of geometric parameters

Taking into account the influence of inclination, θ , and cross-sectional area ratio A1/A3 (given A2=A3), and the radius ρ, of a fillet used by Gardel to fair the tail limb 1, into the main. A group of tests were run with θ =90 DEGC, and varying A1/A3 in the range 0.4<A1/A3<1; for A1=A2=A3 and vary in the range 45 DEGC< θ <135 DEGC; and for r, varied in the range 0.02<r<0.12, where r=ρ/D3.

The empirical equations derived by Gardel to fit the results from these experiments were:

$$K_{13} = -0.92(1-q)^2 - q^2\left[\left(1.2 - r^{\frac{1}{2}}\right)\left(\frac{cos\theta}{a} - 1\right) + 0.8\left(1 - \frac{1}{a^2}\right) - \left(\frac{1}{a} - 1\right)cos\theta\right]$$
$$+ (2-a)(1-q)q,$$

$$K_{23} = 0.03(1-q)^2 - q^2\left[1 + \left(1.62 - r^{\frac{1}{2}}\right)\left(\frac{cos\theta}{a} - 1\right) - 0.38(1-a)\right] + (2-a)(1-q)q$$

$$(3.61)$$

Where

$$a = \frac{A_1}{A_3}$$

3.4.2 Resistance coefficients

For fluid flow through bends and restrictions like valves and fittings, there also is additional pressure loss due to one or more of the following reasons:

1) Changes in direction of flow path

2) Obstructions in flow path

3) Sudden or gradual changes in the cross-section and shape of flow path

4) Loss due to curvature (for bends)

5) Excess loss in the downstream tangent (for bends)

We know, the velocity in a pipe is obtained at the expense of static head, and decrease in static head due to velocity is,

$$h_L = \frac{U^2}{2g}$$

(3.62)

which is also defined as he "velocity head". Flow through a restriction similarly causes a reduction in static head that may be expressed in terms of the velocity head. In this case,

$$h_L = K\frac{U^2}{2g}$$

(3.63)

where K is the resistance coefficient; defined as the number of velocity heads lost due to a restriction. The resistance coefficient is considered as being independent of friction factor or Reynolds number, and may be treated as a constant for any given restriction in a piping system under all conditions of flow.

If the formula for h_L above in equation (3.63) is compared with that for a strait pipe,

$$h_L = \left(f\frac{L}{D}\right)\frac{U^2}{2g}$$

(3.64)

then

$$K = \left(f\frac{L}{D}\right)$$

Where L/D is the equivalent length in pipe diameters of a straight pipe that will cause the same pressure drop as the given obstruction under the same flowing conditions.

In bends, the additional head loss may be split into 3 component part given as:

$$h_t = h_p + h_c + h_L$$

(3.65)

Where:

h_t = total loss, h_p = excess loss in downstream tangent, h_c = loss due to curvature

h_L = loss in bend due to length

Losses due to curvature and downstream tangent can be summed to give a quantity $h_b = h_p + h_c$ that can be expressed as a function of velocity head in the formula:

$$h_b = K_b \frac{U^2}{2g}$$

(3.66)

Where:

K_b is the bend coefficient.

Taking the additional losses into consideration, the energy balance equation (3.53) for fluid flow through a pipe with bends and restrictions may be written as follows:

$$\frac{p_{in} - p_{out}}{\rho g} + \frac{U_{in}^2 - U_{out}^2}{2g} + z_{in} - z_{out} = h_L + h_t$$

(3.67)

And

$h = h_L + h_t$

where:

h = total head loss, h_L = loss due to pipe length, h_t = additional loss due to restriction

then

$$h = \left(f\frac{L}{D} + K + K_b\right)\frac{U^2}{2g}$$

(3.68)

U is the flow velocity (usually downstream) through the restriction.

Several experiments have been conducted for the evaluation of K and K_b for different restriction types; values which can be found in standard tables and charts.

We see that pressure loss coefficients and resistance coefficients are derived from the same expression. Therefore correctly estimated resistance coefficients should give the same value for pressure loss as the pressure loss coefficients used in tee correlations.

Additional equations used in the simulation program are mentioned in Appendix D.

Chapter 4

4. Steps followed in building the flare system analyzer (FLARENET) model

Building the FLARENET model is a step-by-step approach as described below. The

FLARENET model built in the thesis is for a section/part (Condensate system) of the whole

Kollsnes gas processing plant. The process flow diagram (PFD) of the condensate system

is attached in Appendix B.2. Figure B.1 in Appendix B.1 shows the important process

systems in the entire Kollsnes plant.

4.1. Data requirements

Before starting to build the computer model of the flare header system,

all the data that will determine the system are defined first. In this model all the data's are

collected from the database of Kollsnes Gas processing plant and used to build the model.

4.1.1. Pipe Segment and Geometry

Data's given as inputs to the FLARENET model are shown in Table 4.1.

DATA	DESCRIPTION
Connectivity	Prepared a simple system sketch defining the connectivity of pipe segments to different nodes.
Pipe Length and associated fittings for each pipe segment	Taken from existing Isometric (ISO) drawing of Kollsnes plant.
Diameter and pipe schedule for each pipe segment	Taken from the flare system process & instrumentation diagram (P&ID) and ISO drawings.

Table 4.1: Pipe segment and geometry

The following diagram, Figure 4.1 shows the connectivity of the system used in this project.
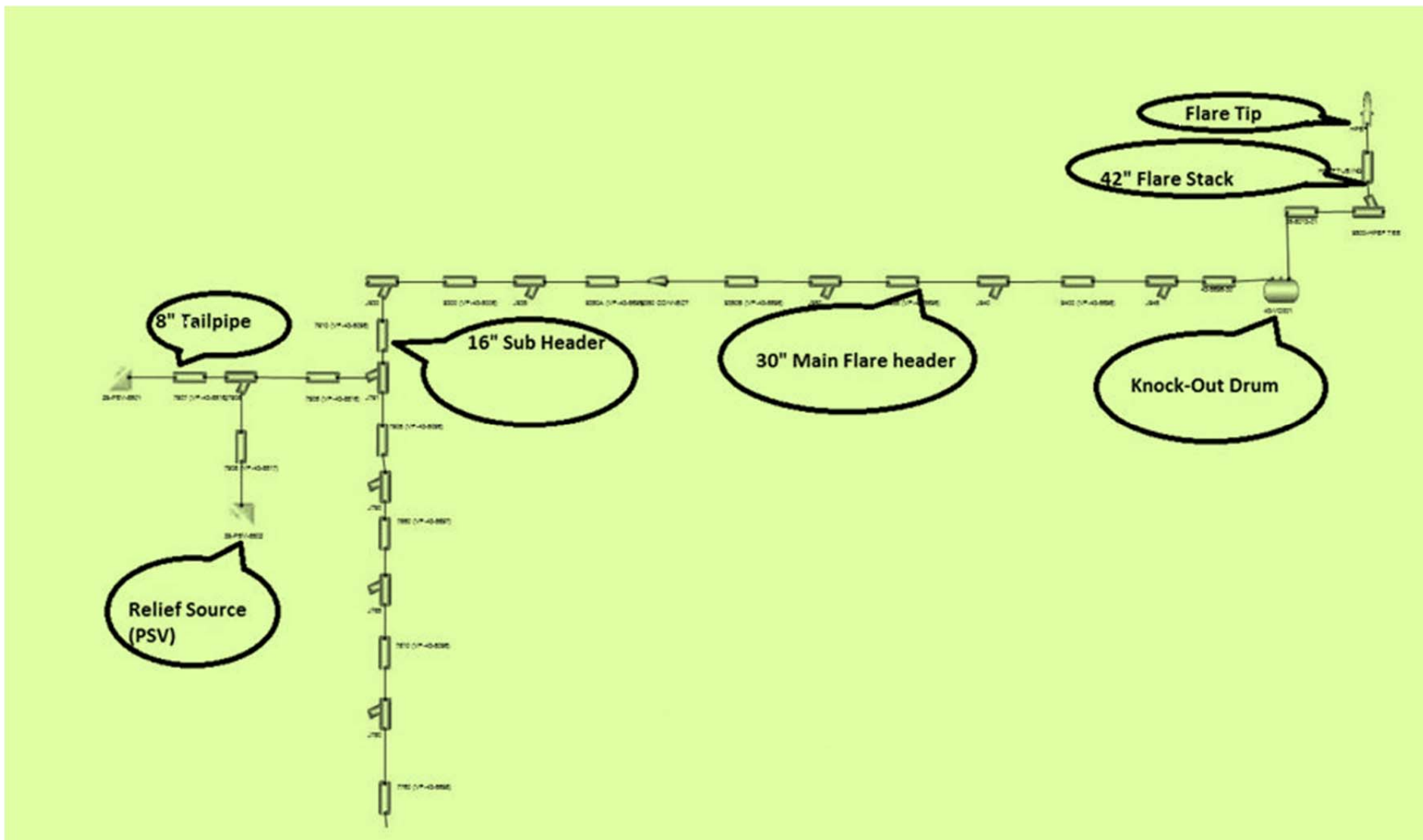
Figure 4.1: Details of Flare network model in FLARENET

The piping datas are given as input to FLARENET as shown in Table 4.2 for some selected

pipe segments.

Name	7040 (VF-43-5698)	7060 (VF-43-5698)	7070 (VF-43-5698)	7100 (VF-43-5647)	7110 (VF-43-5698)	7120 (VF-43-5698)
Location	PF-003-20	PF-003-20	PF-003-20	PE-106-01	PF-003-20	PF-003-20
UpstreamNode	J705	J704	J706	29-PSV-6080	J710	J712
DownstreamNode	J704	J706	J710	J710	J712	J715
Ignored	No	No	No	No	No	No
Tailpipe	No	No	No	Yes	No	No
Length(m)	0.45	26.75	66.4	18.80	7.38	3.7
ElevationChange(m)	0	0	0	-3230	0	0
Material	Stainless Steel	Stainless Steel	Stainless Steel	Stainless Steel	Stainless Steel	Stainless Steel
Roughness(mm)	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254
ThermalConductivity(W/m-K)	16.29	16.29	16.29	16.29	16.29	16.29
InternalDiameter(mm)	396.84	396.84	396.84	206.4	396.84	396.84
WallThickness(mm)	4.78	4.78	4.78	6.35	4.78	4.78

Table 4.2: Input piping data to FLARENET

The flare tip used in the simulation is not a pipe segment. It is specified as a node that

represents a zero length piece of pipe segment. The fitting loss for the flare tip is taken from

the manufacturer's specification. A pressure drop Vs Flow correlation is fed into the

FLARENET as shown in Table 4.3.

Data point	Mass flow rate, (kg/s)	Static pressure drop, (Bar)
1	13.9	0.6
2	27.8	0.7
3	55.6	0.85
4	111.1	1.2
5	166.7	1.4
6	222.2	1.6
7	250	1.7
8	277.8	1.95
9	305.6	2.25
10	333.3	2.55
11	361.1	2.8
12	3	3.15

Table 4.3: Flare tip curve data

4.1.2. Relief Source Data

Following datas are specified for the relief sources such as PSV.

DATA	DESCRIPTION
Flow and Composition	Flow refers to the quantity of fluid that the Source valve must pass as a consequence of the plant upset condition. Rated Flow refers to the quantity of fluid that the source valve will pass due to its physical construction. Rated Flow must always be greater than or equal to Flow. This is taken from the process datasheet.
Maximum Allowable Back-Pressure (MABP)	This is the maximum pressure that can exist at the outlet of the device (source) without affecting its capacity. This is taken from the process datasheet.
Downstream temperature	This temperature is used as the pressure independent temperature at which the source enters the network. This temperature is used when ideal gas enthalpies are used to calculate the heat balance, or as an initial guess when any other enthalpy method is used.
Upstream pressure and temperature	Relief source set pressure is used as upstream pressure.
Discharge flange size	Taken from the relief valve datasheet.

Table 4.4: Relief source data specification

Table 4.5 shows relief source (PSV) data input into the FLARENET for some of the relief valves.

Name	29-PSV-6013/6014	29-PSV-6018/6019	29-PSV-6031/6032	29-PSV-6038/6039
Location	PE-105-02	PE-105-03	PE-105-07	PE-105-01
OutletPipe	7500 (VF-43-5461)	7450 (VF-43-5471)	7400 (VF-43-5593)	7300 (VF-43-5589)
Type	Relief Valve	Relief Valve	Relief Valve	Relief Valve
Ignored	No	No	No	No
InletPressure(bar)	34	12	12.55	12.55
Inlet Temp.Spec.(C)	63	32	215	215
AllowableBackpressure(bar)	13.01	5.01	5.21	5.21
OutletTemperature(C)	15	15	15	15
MassFlow(kg/hr)	5162.4	6602	1604.6	1604.6
Rated MassFlow(kg/hr)	5162.4	6602	1604.6	1604.6
Valves	1	1	1	1
Relief ValveType	Balanced	Balanced	Balanced	Balanced

Table 4.5: Relief source data input to FLARENET

Additional input conditions for PSVs are given in Table C.1 in Appendix C.

4.1.3. Fluid Composition

The components are created in the FLARENET file using component manager.

The composition of fluid being relieved from PSVs is copied from the HYSYS simulation file into the FLARENET.The composition of fluid from the relief/control valves can be defined in FLARENET in three different basis

- Composition based on Molecular weight

- Composition based on mole fraction

- Composition based on mass fraction.

4.2.   Building The Flare Pipe Network

As all the scenarios have common pipe network, the flare pipe network model is built via the process flow sheet. The desired objects for the network are added from the available palette in the FLARENET flow sheet.
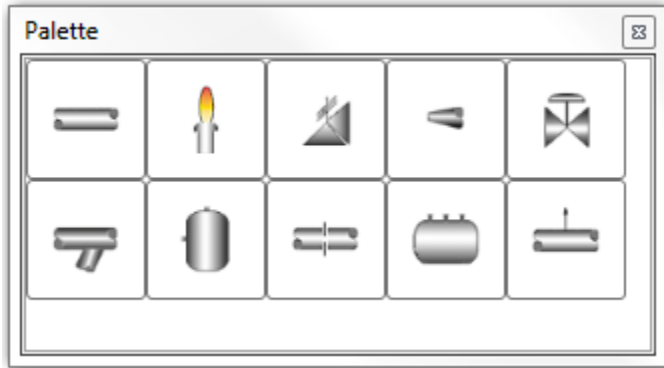
Figure 4.2: FLARENET palette

The details of each palette are entered in FLARENET as described in chapter 4.1.1 and 4.1.2. However the details of flare knockout drum (KOD), flare tip, blow down valves are taken from vendor supplied process datasheets.

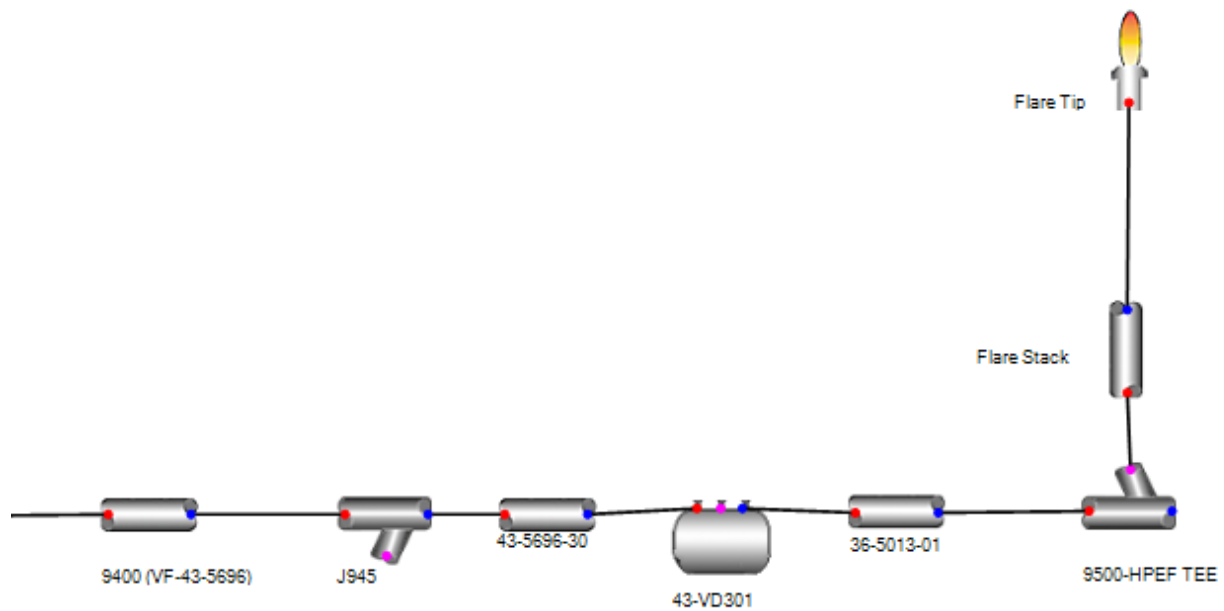A portion of the flare pipe network in FLARENET looks as shown in the Figure 4.3.

Figure 4.3: A portion of Flare pipe network from FLARENET

4.3.   Defining over Pressure Scenario

In this project "Fire scenario" in Condensate and Flash gas system (area A44) in the

Kollsnes gas processing plant is defined as the overpressure scenario. This scenario is

defined in the FLARENET model using Scenario manager.

In the scenario editor tab the sources (PSVs) that are relieving are de-selected in the model
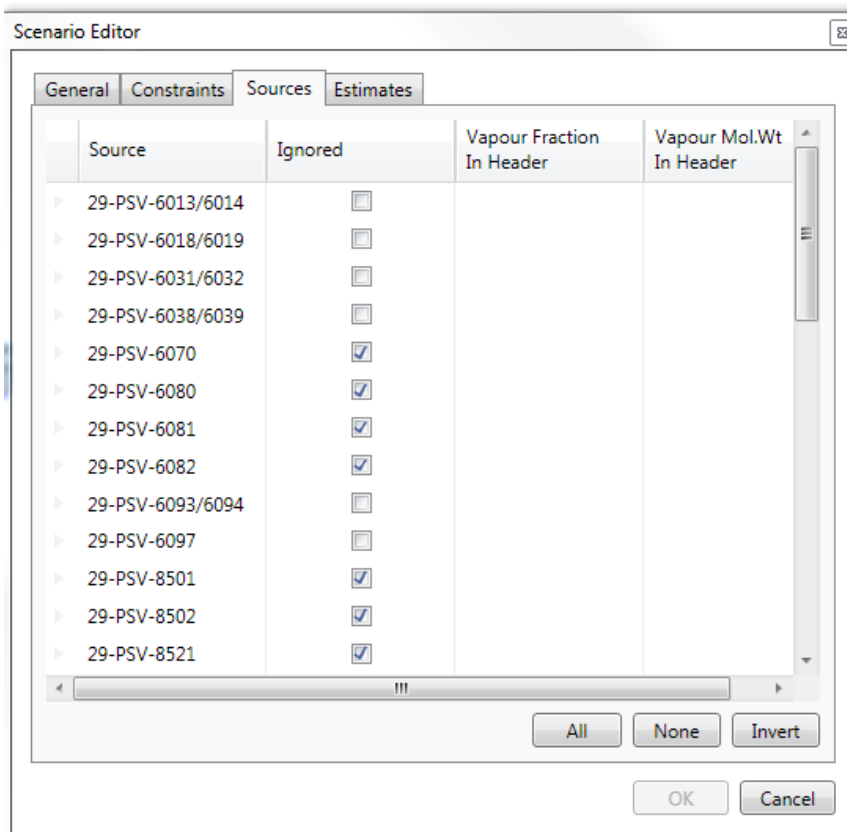
as shown Figure 4.4

Figure 4.4: Scenario editor for sources in FLARENET

The constraints are also specified in the scenario editor tab for maximum allowable Mach

number, Noise (dB) and Rho V^2.

4.4.   Defining The Relief Sources

As described in chap 4.3, after defining the scenario, the detail process conditions of

sources relieving are defined for PSVs as shown in Figure 4.5.

Figure 4.5: Relief valve conditions in FLARENET

In some cases, while simulating the blow down conditions the sources are modeled as

control valves (such as EBVs) and the conditions for those are specified in control valve

editor.

4.5. Model Check and Running Scenario

After entering all the relevant datas, the model check botton is pressed to see if there is any insufficient information about connectivity and ignored sources. All the mandatory fields need to be filled for the model to converge quickly. The model is set to run by pressing the run button. The detail options used for calculation are described in Appendix D.
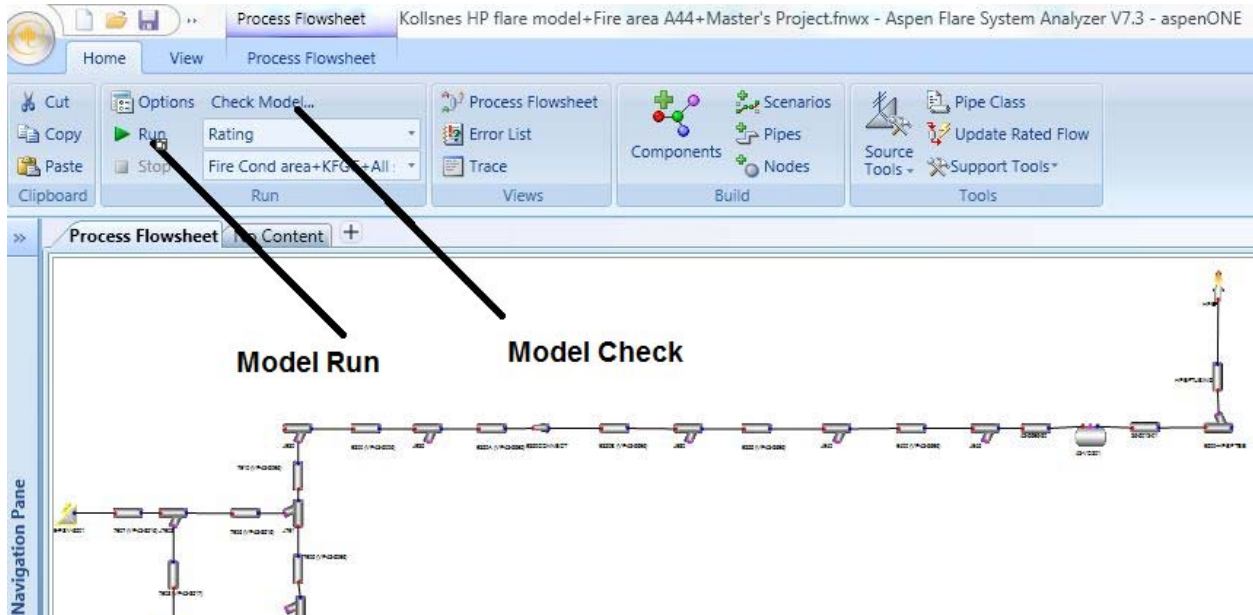

Figure 4.6: Pointer showing checking and running the FLARENET model

The complete FLARENET model is attached in the Appendix A (Schematic diagram FLARENET model). This model includes all the sources connected to high pressure flare system. However, based on the over- pressure scenario only some of the sources are relieving at once.

Chapter 5

5. Simulation run

As part of the Kollsnes Flare project, the task was to estimate the back-pressure in the fire area A44 (Condensate and flash gas system) in the event of a large pool fire in the whole area. The design case for the single fire area is" the Flare header should be sized in such a way that it can handle the fire relief load (From PSVs) form one fire area at a time" . This area comprises of different section with varying design pressures from 7-93 Barg.

In the steady state FLARENET simulations the back-pressure generated for a flow rate of 108.33 kg/sec (Estimated peak flow rate from the PSVs in fire area A44) is calculated by activating the PSVs in simulation process flow sheet. The PSVs open during this scenario are highlighted in the general arrangement drawing, Figure 5.1. The simulation is run until it converges.
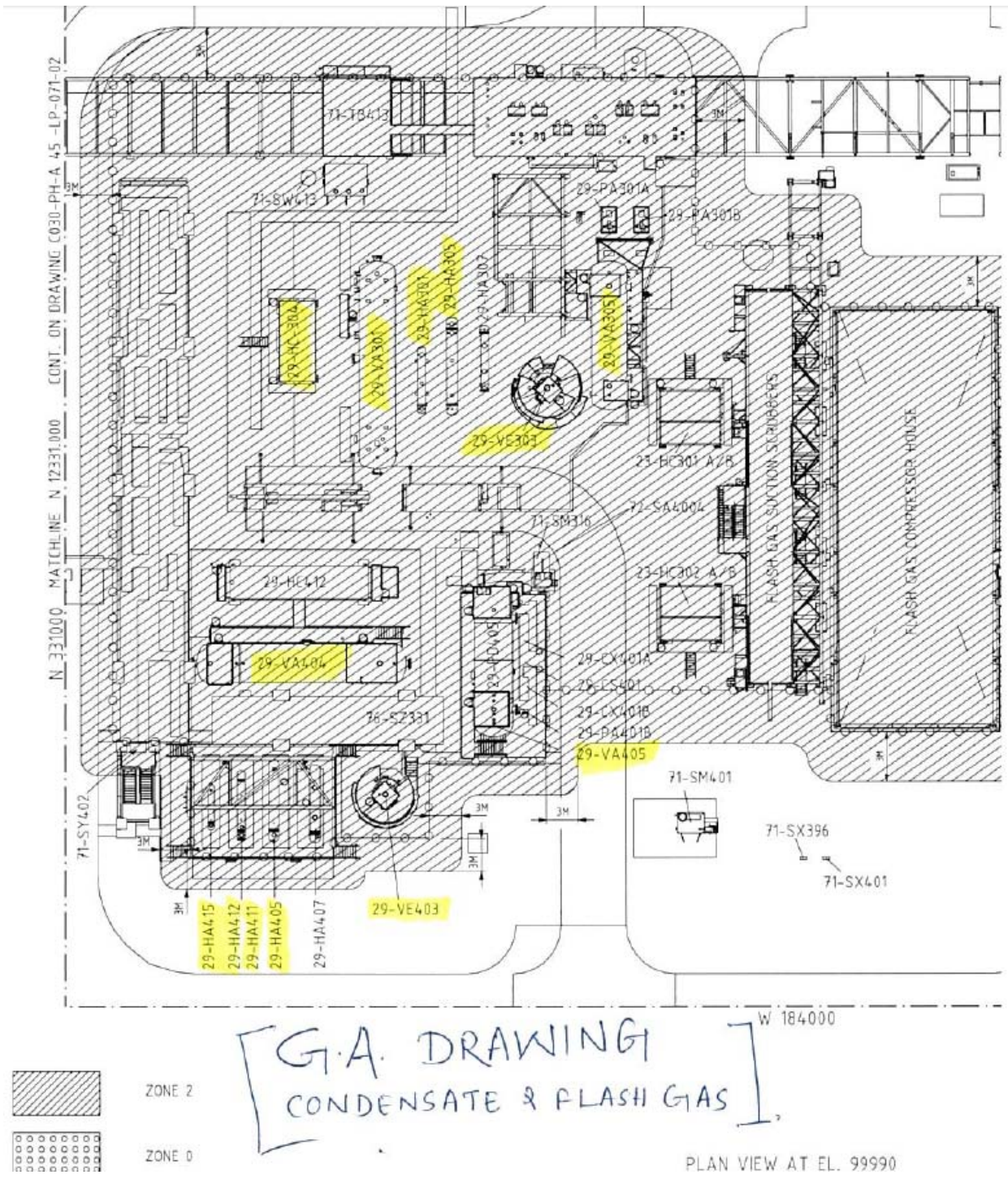
Figure 5.1: General arrangement drawing of condensate system Kollsnes plant

5.1.   Running the simulation for - Pool fire scenario

In the event of a pool fire scenario in the whole condensate and flash gas section, the
hydrocarbon present in the process equipment / pipelines will get heated and pressure
start to increase beyond their normal operating pressure. Following PSVs will open at
their respective set pressures to keep the pressure in the equipment below their design
pressures. The FLARENET simulation is run with making these PSVs active in the
simulation file with the relief flow rate as mentioned in the Table 5.1.

PSV Tag number	Flow rate, Kg/s	Set Pressure, Barg
29-PSV-6018/6019	18.33	10
29-PSV-6093/6094	8.61	10
29-PSV-6031/6032	4.44	10.5
29-PSV-6038/6039	4.44	10.5
29-PSV-6013/6014	14.33	30
29-PSV-6097	21.17	15
29-PSV-4070A/B	0.58	30
29-PSV-4501A/B	0.25	35
29-PSV-4503	1.22	10
29-PSV-4521/4522	0.64	10
29-PSV-4523/4524	1.39	35
29-PSV-4580A/B	29.11	10
29-PSV-4018A/B	1.72	10
29-PSV-4594A/B	2.08	10
Total	108.33	

Table 5.1: Process condition of active PSVs

5.2.   Printing the results/Output

The back-pressure build-up in the HP flare system is shown in the Figure 5.2. For the PSV
29PSV4522 the back-pressure is 11.2 Bara against the set pressure of 11 Bara.
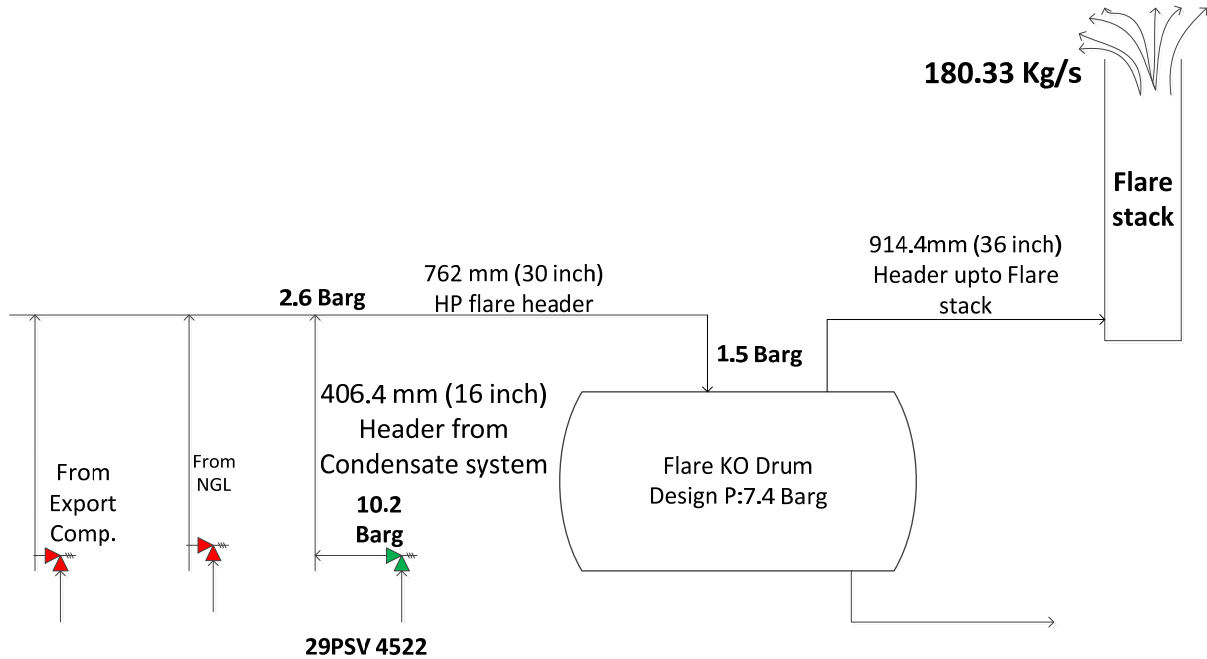
Figure 5.2: Steady state FLARENET simulation result for back-pressure build-up

Table 5.2 shows the back-pressure build-up for all the PSVs in the area.

PSV Tag number	Flow rate, Kg/s	Set Pressure, Barg	Back Pressure result from simulations, Barg	Remarks
29-PSV-6018/6019	18.33	10	10.6	Back pressure higher than Set pressure
29-PSV-6093/6094	8.61	10	10.1	Back pressure higher than Set pressure
29-PSV-6031/6032	4.44	10.5	10	Back pressure higher than Set pressure
29-PSV-6038/6039	4.44	10.5	10.1	Back pressure higher than Set pressure
29-PSV-6013/6014	14.33	30	10.1	OK
29-PSV-6097	21.17	15	10.3	OK
29-PSV-4070A/B	0.58	30	10.2	OK
29-PSV-4501A/B	0.25	35	10.2	OK
29-PSV-4503	1.22	10	10.2	Back pressure higher than Set pressure
29-PSV-4521/4522	0.64	10	10.2	Back pressure higher than Set pressure
29-PSV-4523/4524	1.39	35	10.2	OK
29-PSV-4580A/B	29.11	10	10.4	Back pressure higher than Set pressure
29-PSV-4018A/B	1.72	10	10.2	Back pressure higher than Set pressure
29-PSV-4594A/B	2.08	10	10.2	Back pressure higher than Set pressure
Total	108.33			

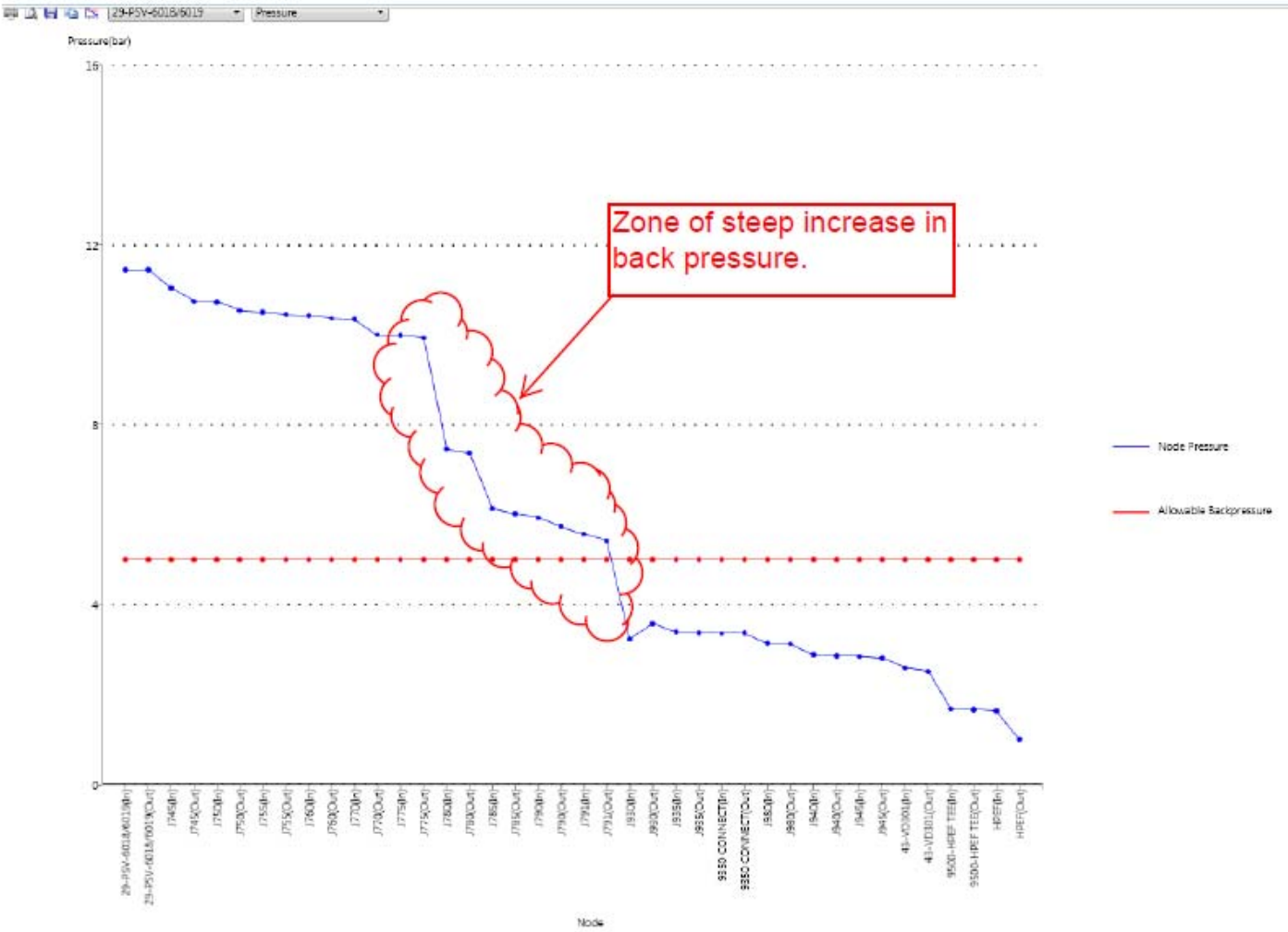Table 5.2: Back-pressure at the PSV downstream flange

Figure 5.3: Graphical representation of Back-pressure at different nodes in flare network.

The summary result for the 29-PSV-4018 after running the simulation is as shown in the figure 5.4.

Relief Valve Editor

| Connections | Conditions | Composition | Methods | Inlet Piping | Summary |

Property	Value
Mass flow(kg/hr)	6200,0
Rated flow(kg/hr)	6200,0
Molar flow(kgmole/hr)	308,63
Molecular weight	20,0887
Valve static pressure drop(bar)	0,74951
Valve total pressure drop(bar)	0,75170
Piping pressure drop(bar)	0,00000
Piping non recoverable pressure drop(bar)	0,00000

Property	UpStream	DownStream
Static pressure (bar)	11,99868	11,24916
Total pressure(bar)	12,00211	11,25040
Temperature (C)	18,30	17,84
Velocity(m/s)	8,159	5,1
Mach number		0,013
Rho V2 (kg/m/s2)		248

Figure 5.4: A typical simulation result at the PSV

Chapter 6

6. Verification of simulation results with actual plant data

During normal plant operation there is no flaring to high pressure flare system at Kollsnes gas processing plant. Hence it is difficult to obtain the actual plant data and compare it with the simulation results obtained from FLARENET simulations. I suggested the plant operation and maintenance department to carry out this test/verification during a planned plant shut down. The relief of hydrocarbon gases into the flare system will be done while depressurizing the dew point control (DPC) trains through a pressure control valve. The process parameters shall be noted during blow-down period with the help of existing flow/pressure transmitters/gauges or temporarily installed instruments.

6.1.   Set-up for plant verification

 During September 2012 there was planned total plant shutdown to carry out routine maintenance job around the equipments in the plant. In that period, it was possible to do the controlled hydrocarbon relief to the HP flare system through the pressure controllers in dew point control trains (DPC trains). The flow rate is measured using the online flow transmitter located downstream of flare knockout drum. The pressure is measured by the pressure transmitter on KO drum and another temporary pressure gauge at the condensate system node. Fig 6.1 shows the set-up done in the plant.

176.4 kg/sec

Nodes

Pressure Gauge

Flow
Transmitter

914.4 mm
(36 inch) Header
upto Flarestack

**Flare
stack**

Direction of increase in
Back pressure

Pressure
Transmitter

762 mm (30 inch) HP
flare header

Flare KO Drum
Design Pressure:
7.4 Barg

From Export
Compresors

From DPC
Train

**Condensate
system**

Indicates no flow in the
line

Indicates Flow in the line
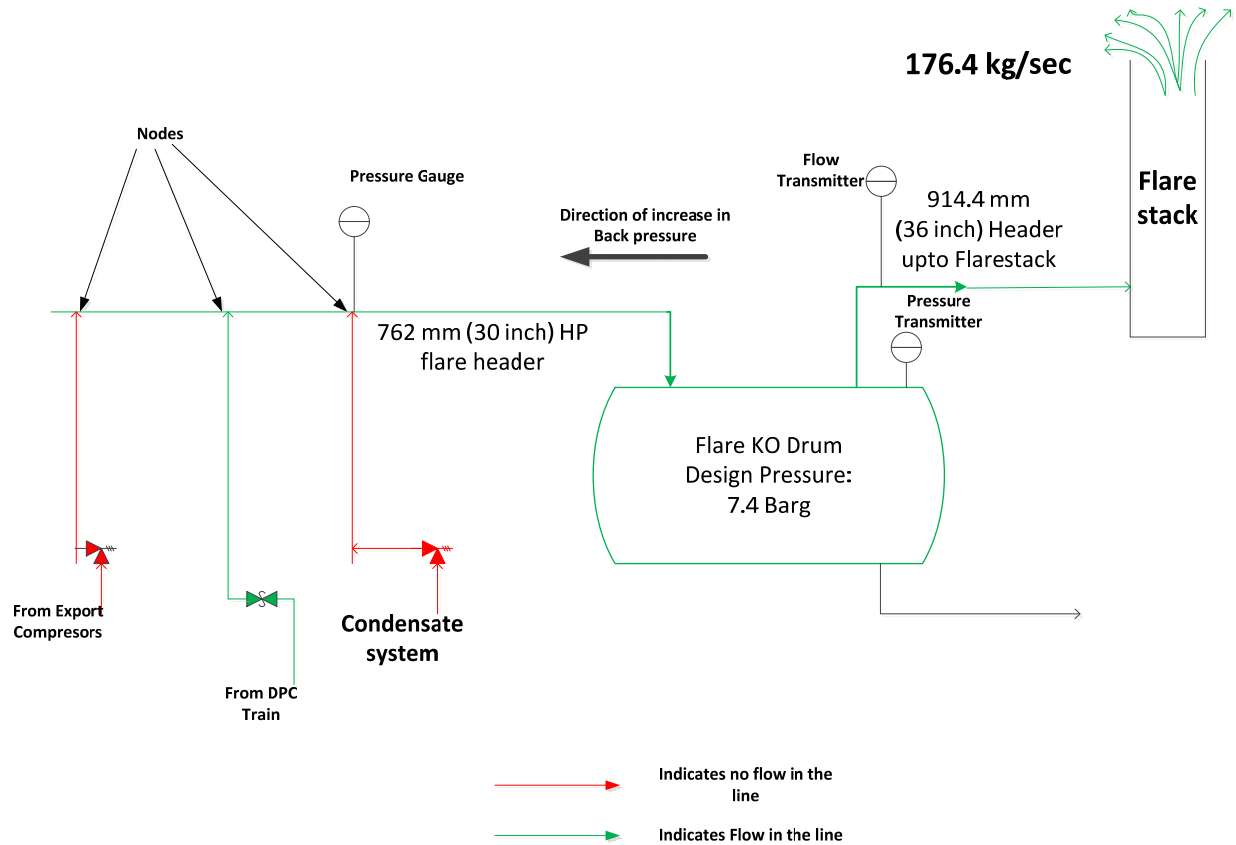
Figure 6.1: Set up for actual plant data verification

 Fig 6.2 shows the flow (in kg / sec) Vs de-pressurization time (in Sec) in the flare

system. A verification point is chosen for a flow rate of 176.4 kg/sec which is the most

stable region.

Hydrocarbon flow rate to flare Vs Time
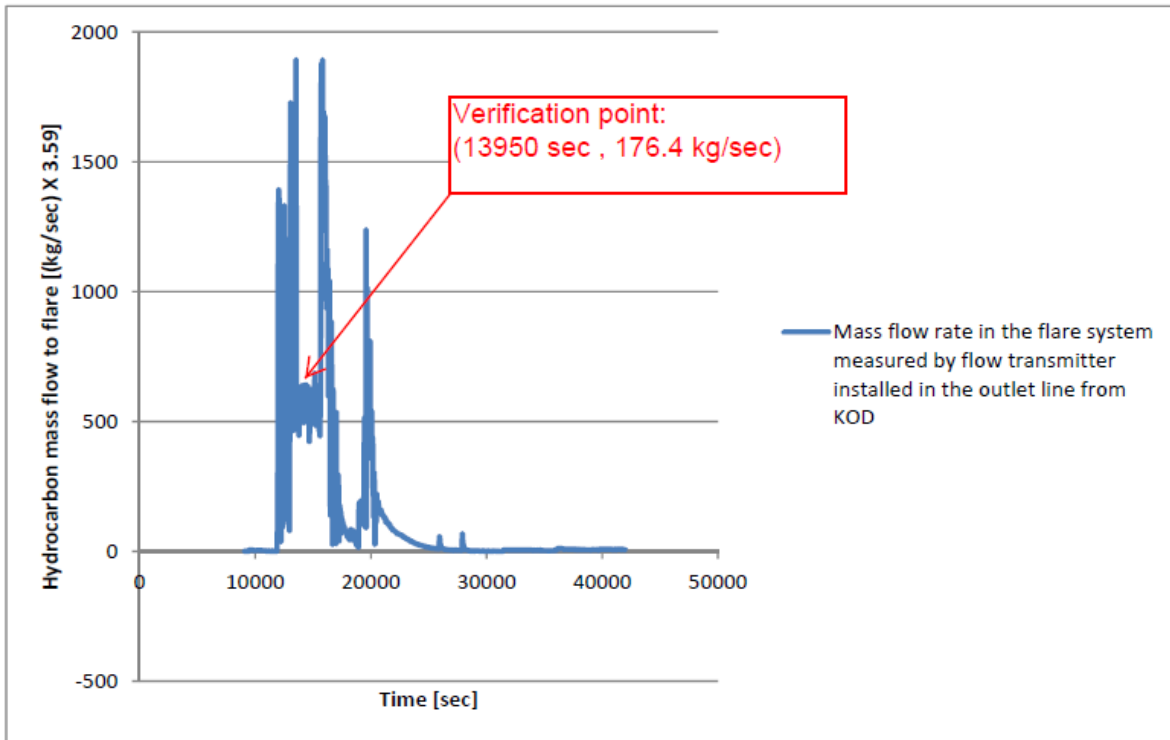
Figure 6.2: Flow measurement from plant
(Verification point is the point of steady flow to the HP flare system)

The back-pressure build-up due to the relief flow of 176.4 kg/sec is measured at two points in the flare system. The back pressure build up is plotted versus time in the Figure 6.3. The green curve represents the pressure build-up at flare KO drum and the violet one is the pressure build-up in the condensate system. As shown in the Figure 6.3, the pressure build- up in the condensate system is 4.5 Barg and at the KO drum is 3.0 Barg.
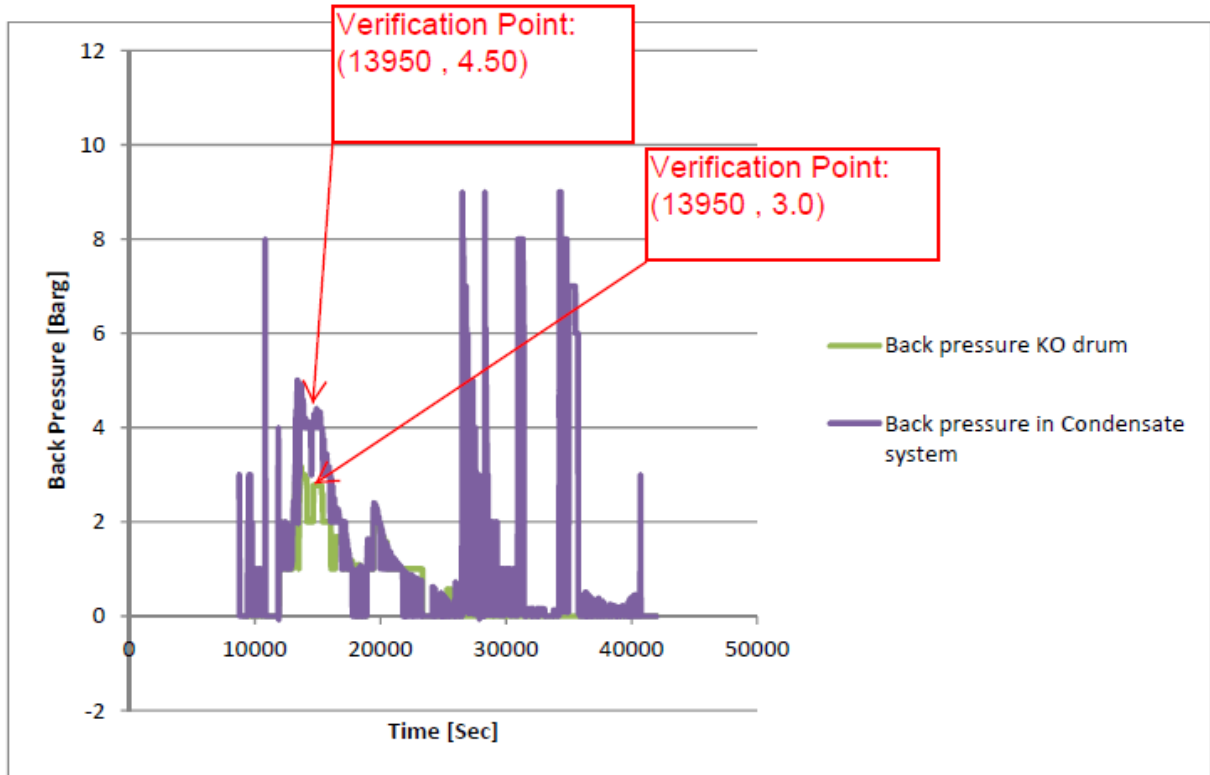
Figure 6.3: Back-pressure measurement from plant
(Verification point is the point of steady flow to the HP flare system)

FLARENET simulation is run for the relief case of 176.4 kg/sec from the pressure control valves in dew point control trains. Results from the FLARENET simulation is shown in the below Fig 6.4.
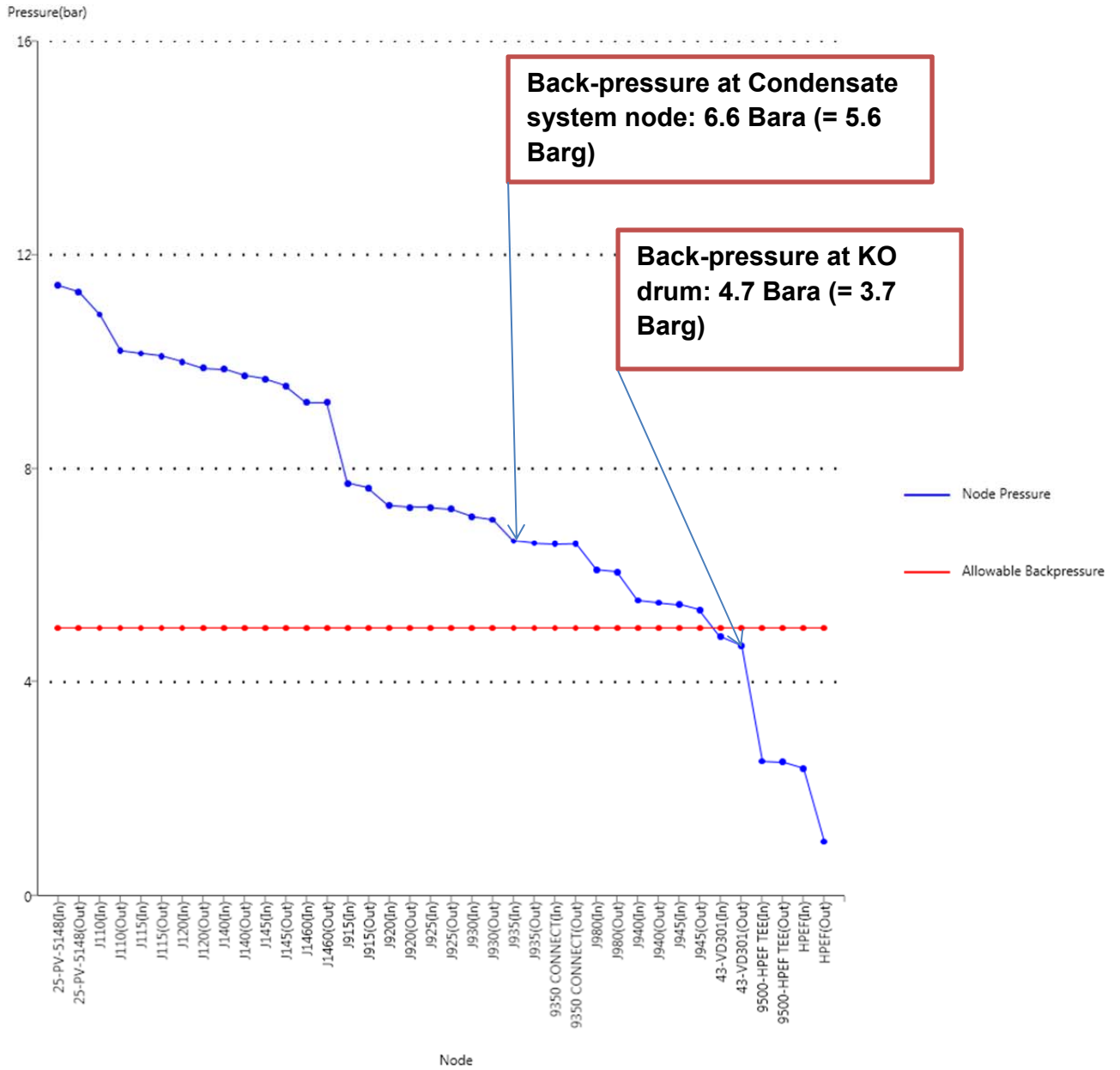
Figure 6.4: Back-pressure at different nodes from FLARENET

(Node is a junction point where a sub-header meets a main header)

The back-pressure result from the FLARENET shows the similar trend as in the plant de-

pressurization data (Ref.: Table 6.1).

	Hydrocarbon mass flow rate in flare system , kg/sec	Back-pressure at condensate system node , Barg	Back-pressure at Flare KOD , Barg
FLARENET simulations result	176.4	5.6	3.7
Plant verification result	176.4	4.5	3.0

Table 6.1: Comparison of results

However the values obtained from FLARENET simulations are on higher side. This is due to the fact that results obtained from FLARENET are conservative and used in plant design and expansion studies so as to give margins for operational flexibility.

Hence the trend for pressure build-up from FLARENET matches closely with the actual plant operational data.

6.2.   Analysis and Discussion of the verification results

It is evident from the result in chapter 5.2 that many PSVs will experience back-pressure higher than their set pressures. This has severe consequences for the process safety of the individual equipment the PSVs are protecting. The high back-pressure on the PSVs has various consequences:

- For the balanced bellow PSVs, the back-pressure above 50% of the PSV set pressure will dramatically reduce the PSV relieving capacity. This will result in pressure build-up in the individual equipment/pipeline due to the continuous vapour generation and may lead to explosion and fire.

- The back-pressure higher than design pressure of bellows will damage the PSV bellows.

From the figure 5.3, it shows the clouded part with steepest increase in back-pressure of 6.7 Bar. From the FLARENET model and actual plant data it seems that, this portion of the

pipe (length approximately: 453 meters) is of dimension 406.4 mm (16 inch). The velocity in this section of the pipeline is very high and in some parts it is 135m/s.

Further investigation on this issue shows that, the 406.4 mm (16 inch) pipeline from the condensate area was build when the plant was built and after wards a new condensate and flash gas compression facility was built in 1995. The PSV outlet from the new facility is also connected to the previously existing 406.4 mm (16 inch) line. As per the Kollsnes plant's existing design & operational philosophy, the whole condensate area (Both the new and old part) is considered as one fire area and the fire relief from PSVs in this area has to be accounted for.

Hence the existing branch pipe of 406.4 mm (16 inch) nominal diameter is too small to take the relief load of 108.33 kg/sec in fire scenario from the condensate area. Different options have been studied to mitigate the problems

- Base Case solution: Increasing the Nominal diameter of 406.4 mm (16 inch) branch pipeline.
- Alternative solution: Segregate the condensate system into two independent fire areas with PSV relief from each area connecting the main 762 mm (30 inch) HP flare header with two separate lines.

Chapter 7

7. Recommendations for model changes to alleviate high back-pressure

The following solutions as described in chapter 7.1 and 7.2 has been recommended based on the results from the FLARENET simulation and plant verification for the high back-pressure problem at Kollsnes plant.

7.1. Base case solution: Increasing the nominal diameter of 406.4 mm (16 inch) branch pipeline.

As it is evident that the majority of the pressure drop is in the 406.4 mm (16 inch) branch line. The current FLARENET model is changed by changing the size of the branch pipe to 609.6 mm (24 inch). The simulation is run after doing necessary changes with the suggested new data. The result from the simulation shows the Pressure build-up in the HP flare system, which is shown below in Fig 7.1.

108.33 kg/sec

Flare stack

914.4 mm (36 inch)
Header upto
Flarestack

762 mm (30 inch)
HP flare header

2.6 Barg

1.5 Barg

609.6 mm (24 inch)

Flare KO Drum
Design Pressure:
7.4 Barg

4.1 Barg

PSVs from Condensate Area

New Line

Existing line
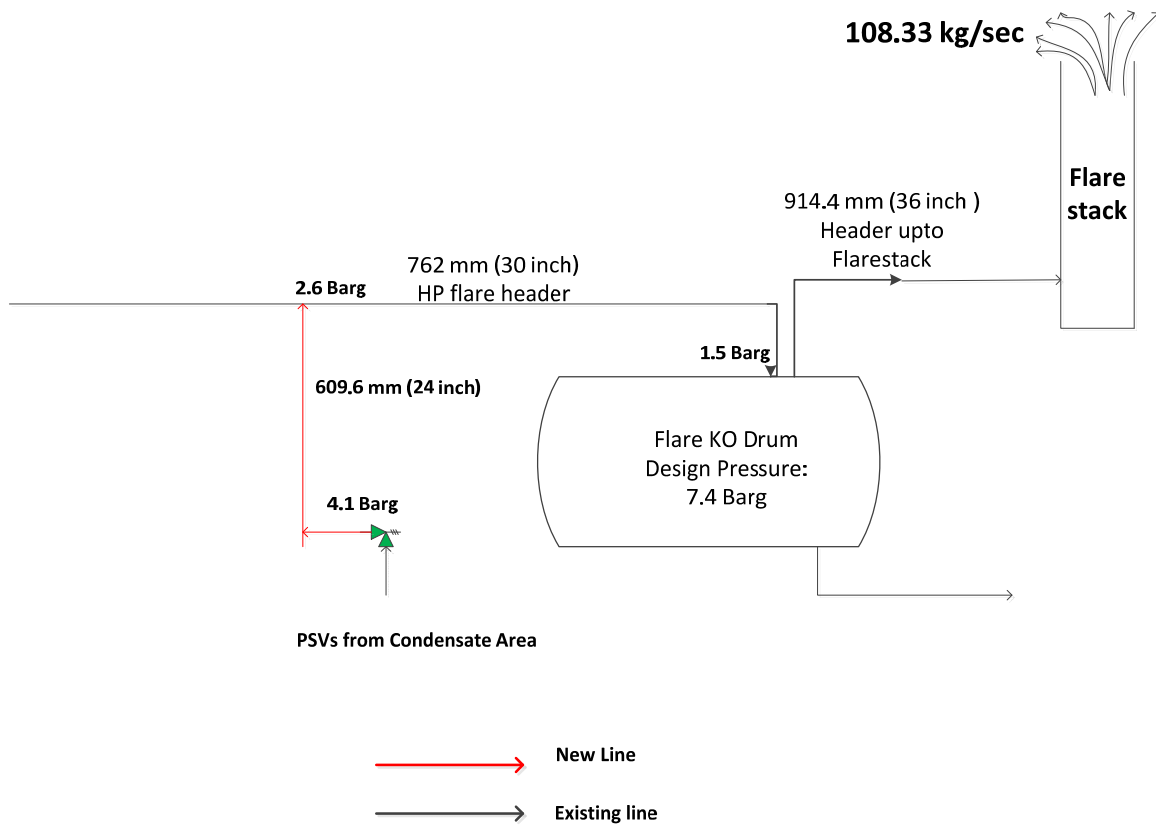
Figure 7.1: Base case solution for the back-pressure problem

Since the back-pressure calculated from FLARENET for the 609.6 mm (24inch) new line is within 50% of the set pressure of the low pressure PSVs (PSVs with set pressure below 15 Barg) , it is recommended to build a new 609.6 mm (24 inch) pipeline and connect it to the existing 762 mm (30 inch) main HP flare header. The length of the new 609.6 mm (24 inch) pipeline is approximately 453 meters, if it follows the routing of existing 406.4 mm (16 inch) line.

7.2. Alternative Solution: Segregation of condensate system into two independent fire areas

It is observed from the field survey undertaken by me for this project; there exists a small concrete wall between the old condensate facility (one area) and new KFGC facility (other area). Assuming that, this concrete wall separates the two areas physically (This is against the current safety strategy and fire area segregation philosophy of Kollsnes plant) and hydrocarbon leak/spillage from one area does not spread into the other which limits the fire/explosion in one area confined to that area itself, then this two sections can be treated as two separate fire areas.

FLARENET model is modified to segregate the areas. A new line of nominal diameter 508 mm (20 inch) is modelled and PSVs from old condensate system are connected to this.

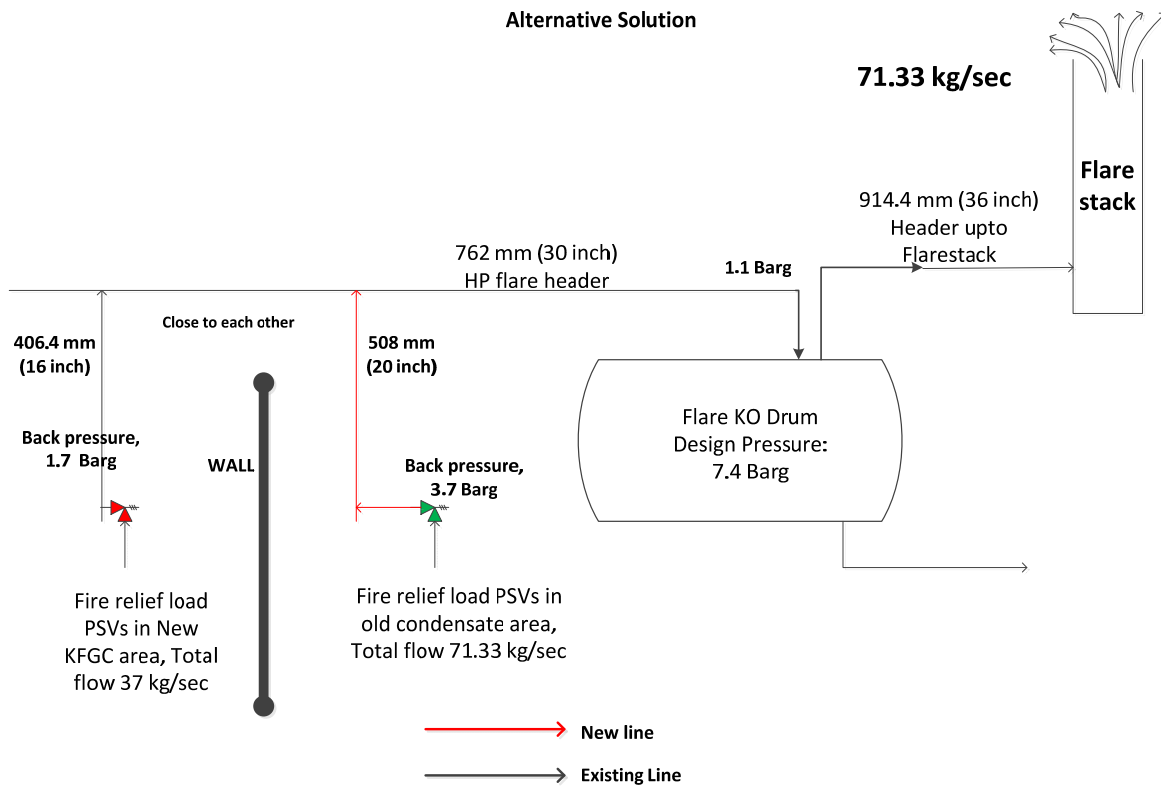Figure 7.2: Alternative solution for the back-pressure problem

The new simulation case is run for this scenario in FLARENET.
The peak relief rate from the PSVs in old part of the condensate facility is 71.33 kg/sec. This generates a total back-pressure of 3.7 Barg (obtained from simulation result) at the PSV downstream flange. This back- pressure is acceptable as it is below 50% of the PSV set pressure (= 10 Barg).

7.3.   Analysis and Discussion of the Solutions

Both the solutions described in chapter 7.1 and 7.2 will mitigate the high back-pressure at the PSVs. However, the solution with segregation of the whole area into two generates various other questions like:

- The process equipment's in the two sections are placed so close to each other that fire in one side will potentially be spread to the other part and vice versa.

- The division of whole area is against the current safety strategy and fire area segregation philosophy of the plant.

- The new KFGC plant does not have an independent access road, active and passive fire protections.

Based on these, it is improper to divide the whole area into two separate fire areas. The whole area is treated as one and the PSV relief from the whole area be accounted for.

Hence, the recommended solution for the plant is as described in Chap 7.1.This solution introduces new pipe lengths and its supports. This induces cost to do this modification project. It addresses the existing back pressure problem in the plant and also provides future opportunity for plant expansion in which some more PSVs can relieve flow through the new pipeline. This solution is simple and easy to execute and should be done in an over-all plant shutdown period.

Chapter 8

8. Conclusion and Further Discussion

8.1. Conclusion

The FLARENET model developed as part of this thesis gives very good result for design/rating/case-study of the flare system for various scenarios. The FLARENET model developed by me as part of this project can be further modified to simulate various other relieving scenarios as described in chapter 1.3. This can be done by activating the applicable relief devices and ignoring the others.

The summary of the results obtained from this thesis can be listed as follows:

- Back-pressure developed at the PSV downstream flanges due to the opening of PSVs from condensate system in pool fire scenario is too high. This will affect the relieving rate from the PSVs and may result in further pressure build-up in the process system. If the pressure rise continues in the process system, this can result in explosion and fire. This may result in loss of personnel, equipment, money and reputation for the company.

- The designing of flare system with respect to pipe sizes be such that it should be able to handle the necessary relief rate during various emergency scenarios which can generate maximum flow through the flare system.

- Addition of new sources (such as PSVs) to the existing flare system be evaluated properly looking at the all possible relief cases and in a global prospective considering its effect in the entire plant relief system.

- This thesis recommends that high back-pressure in the flare system at Kollsnes plant can be reduced to acceptable limits (set by various international standards and company's governing documents) by increasing the size of branch pipe in the flare network as described in chapter 7.1

- Relief of hydrocarbons/wastes to the environment has strongly been criticized now-a-days by the governments and other regulatory bodies. This introduces the concept of zero emission to the environment with the use of "closed flare system". Even though, the use of closed flare system prevents emission of gases to the environment but it increases the back-pressure in the flare system and to all the PSVS connected to the closed flare system. Hence this could be challenge for the Kollsnes plant, if in future the closed flare system is implemented. This concern has also been highlighted to the plant operation and maintenance management department.

8.2.   Further Discussion

Conventional flare header design techniques use peak relief flows in steady-state simulation to assess system capacities and determine back-pressures downstream of blow-down valves (BDVs) and pressure safety valves (PSVs), Mach number in the headers, and radiation at the flare tip. This steady-state assumption is highly conservative. While conservative approaches may be desirable in safety system design, they can nevertheless lead to gross overdesign throughout the system. Key areas of over design include:

Oversized flare header

Sizing the header for the sum of the maximum flows takes no account of effects such as:

• System packing, where the gas pressurizes the available volume in the flare

network.

• Potential for sequencing of flare events. For example, depressurization

initiated deliberately by an operator may be complete well before a fire

causes PSVs to lift. Steady-state peak flow analysis, on the other hand,

assumes that all events occur simultaneously.

Reducing the peak flows used as the design basis by judicious analysis can significantly

reduce pipe sizes and materials and fabrication costs, which can be substantial for large-

diameter headers. Reducing the size also creates knock-on savings related to the support

structure and flare stack size.

Oversized flare stack

The flare stack sizing depends on radiation emitted by the flame, which is a function of the

volumetric gas flow rate through the flare tip. Using unrealistically high flow rates

determined from peak flows results in an over-long stack, creating weight problems in

offshore facilities or adding stack support costs (or unnecessary additional header length) in

onshore facilities. Similarly, a lack of accurate temperature information leads to a wide span

between the minimum and maximum design temperatures used for gas arriving at the

stack, resulting in unrealistic allowances for thermal expansion and contraction.

Over-use of expensive alloys

Although flare system pipework may be in contact with gas at extremely low temperatures,

this typically occurs for a relatively short duration. The use of steady-state flows does not

consider the duration of such exposures to low temperature, which may result in very

conservative and expensive application of alloys. It can be argued that a good flare network design is one that minimizes capital expenditure while meeting all safety constraints. Overdesign should be avoided wherever possible.

By making dynamic analyses using data that is mostly already available in some form, it is often possible to refine network designs to arrive at systems with a significantly lower capital cost while demonstrably meeting safety requirements. Similarly, it is often possible to find additional capacity during retrofits, thus removing the need for additional capital expenditures. However, further research on this could be done with respect to the real-time data on the relieving rate, time-interval for opening of various relief devices and back-pressure build- up in the flare network.

Chapter 9

9. Recommendations for further work

This thesis shows a typical example of Back-pressure build-up in a flare system and the problems associated with it. However there need to be done further study to completely eliminate the problem.

This thesis shows that how the flare system of an actual plant could be modeled using FLARENET steady state simulation tool which gives good indication of how to protect the safety and integrity of the equipment. This also helps to define the safe operating envelope of an Oil & Gas operating facility.

Further research/study in this aspect must be done on following things:

- Developing a dynamic model which gives real-time data on the pressure build-up in a flare system for the PSV relief or emergency Blow down cases. This should also include how the dynamics of flare system affected by the multiple relief from different PSVs. The result from the research will have wide industrial acceptance as this will lead to substantial financial savings with much better process design of the safety system in Oil & Gas industries.

- Developing the model of a process plant or part of it with hydrocarbon inventories in the equipment and pipelines. Applying the heat due to fire into different segments or to the whole section. Studying behavior of process fluid inside the vessel/pipeline. Analyzing the effect of increase in temperature/pressure on the metal pipes and process fluids due to different types of fire.

- Lastly, combining the aforesaid two models so as to build the complete plant model which includes both the processing facility and the flare relief system. This model can be extensively used in Oil & Gas and other downstream hydrocarbon industries in various studies related to process safety, De-bottlenecking and production optimization.

Appendices

Appendix A
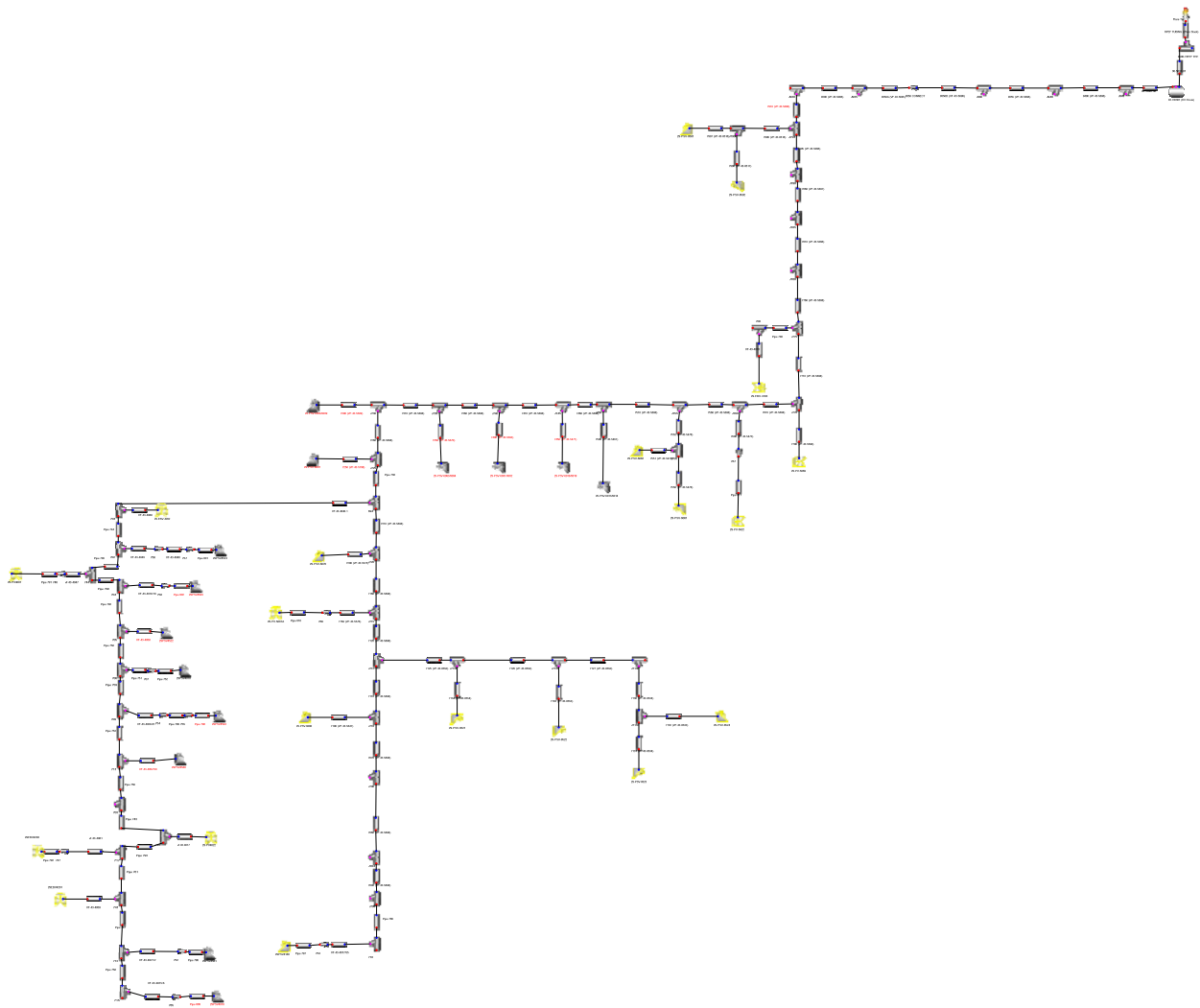
Schematic Diagram FLARENET model

Figure A.1: Schematic diagram FLARENET model

Appendix B

Block flow diagrams

B.1 Block flow diagram main process system

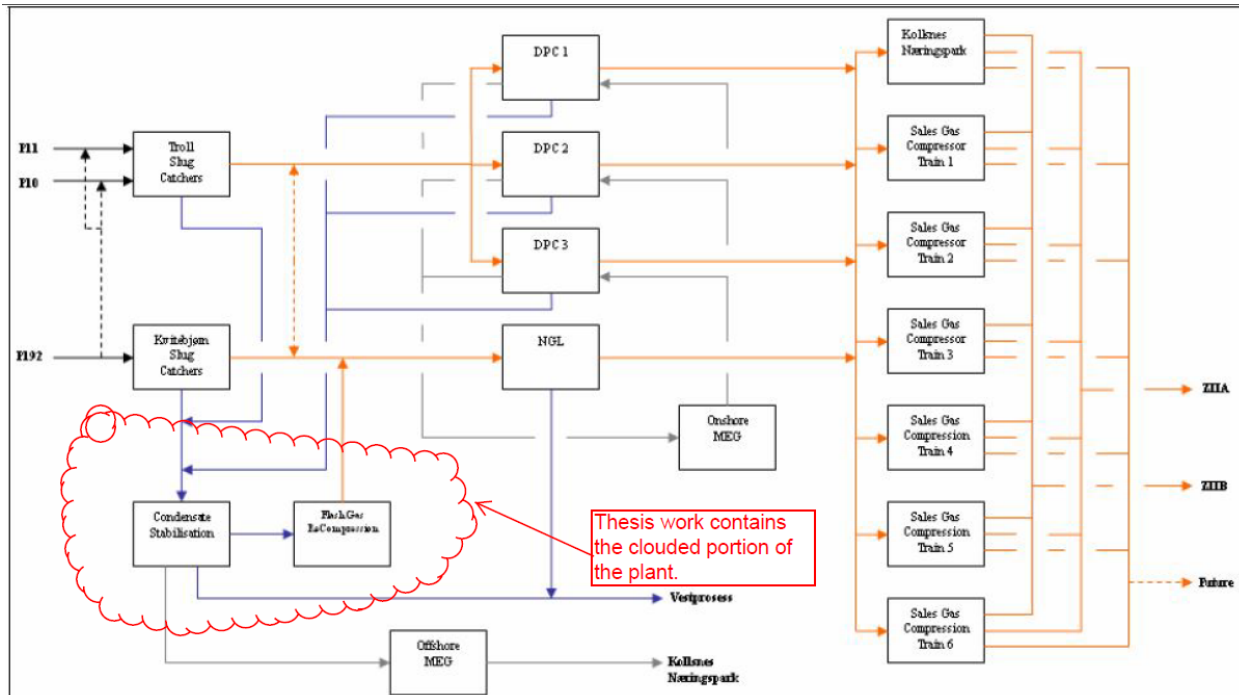Figure B.1: Kollsnes gas processing plant main process systems

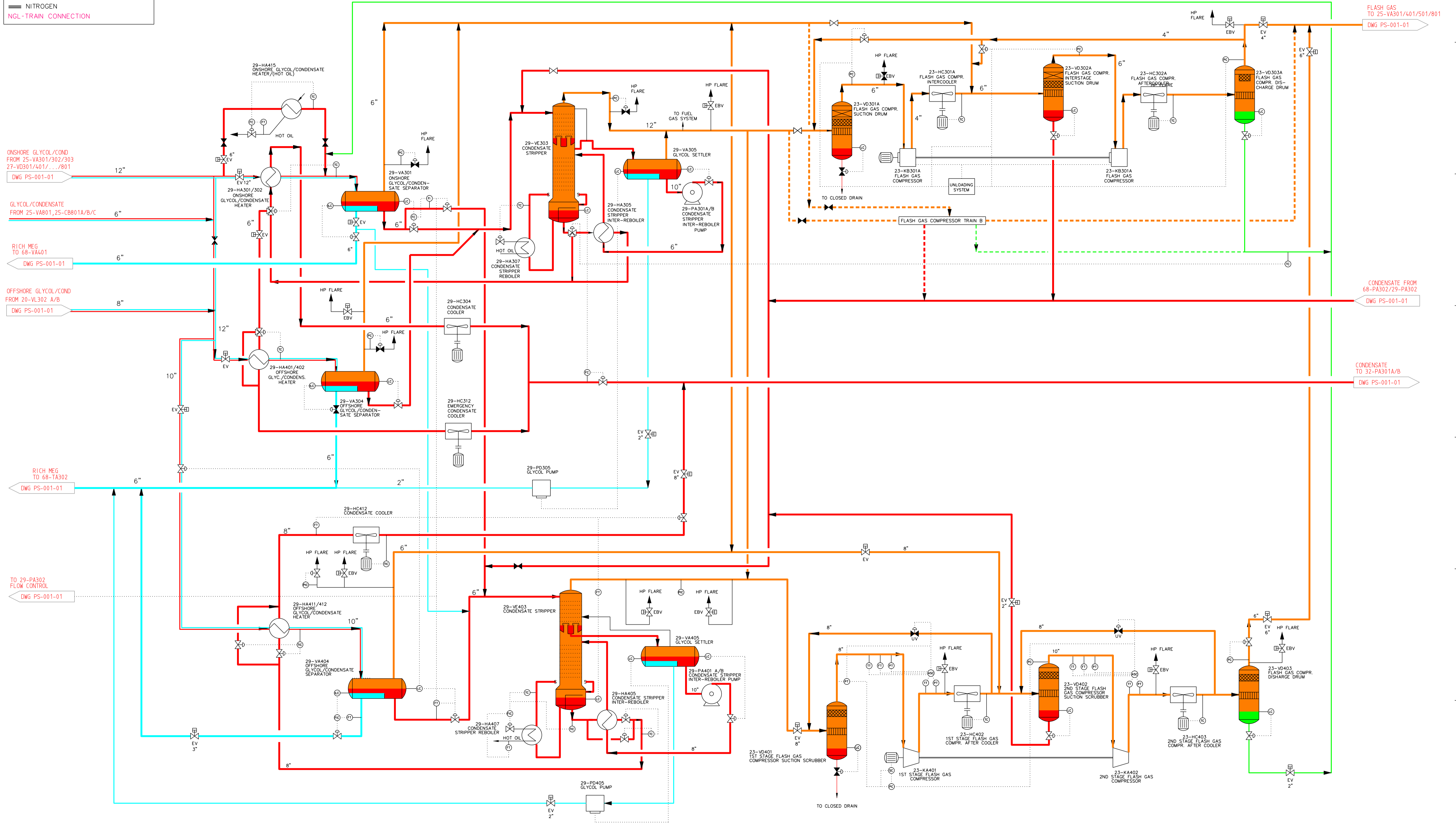**B.2 Process flow diagram condensate system**

Figure B.2: Process flow diagram condensate system

Appendix C

Input Conditions for PSVs

Following input process parameters has been used in the model for the PSVs active during

fire scenario.

PSV Tag number	Ignored (Yes/No)	Inlet Pressure (Bara)	Inlet Temperature (^{0}C)	Allowable Backpressure (Recommended by manufacturer) (Bara)	Rated Mass Flow (Kg/s)	Relief Valve Type
29-PSV-6013/6014	No	34	63	13	14.33	Balanced bellow
29-PSV-6018/6019	No	12	32	5	18.33	Balanced bellow
29-PSV-6031/6032	No	12.55	215	5.2	4.44	Balanced bellow
29-PSV-6038/6039	No	12.55	215	5.2	4.44	Balanced bellow
29-PSV-6093/6094	No	12	92	5	8.61	Balanced bellow
29-PSV-6097	No	17.5	234	7	21.17	Balanced bellow
29-PSV-4523/4524	No	43.35	295	15	1.39	Balanced bellow
29-PSV-4503	No	13.10	188	5	1.22	Balanced bellow
29-PSV-4521/4522	No	12	85	5	0.64	Balanced bellow
29-PSV-4070A/B	No	34	27	13	0.58	Balanced bellow
29-PSV-4594A/B	No	13.1	149	5	2.08	Balanced bellow
29-PSV-4580A/B	No	13.1	242	5	29.11	Balanced bellow
29-PSV-4501A/B	No	39.5	211	15	0.25	Balanced bellow
29-PSV-4018A/B	No	12	18.3	5	1.72	Balanced bellow

Table C.1: FLARENET Input conditions for PSVs

The details of the pipes and fittings have been given as input to the model as per actual

plant data.

Appendix D

FLARENET model calculation options used in simulation

Following options have been chosen prior to running the model as stated below.

D.1 General conditions

Atmospheric pressure: 1.0135 Bara

Ambient Temperature: 15 DEGC

External medium velocity: 10 m/s

System limit, Maximum possible velocity: 500 m/s

Source inlet velocity Basis: Inlet pipe velocity

Ignore source to pipe pressure loss in design mode active

Choked flow check active and use rated flow for tail pipes.

D.2 Methods used

- **Properties**

Overall VLE method: Soave-Redlich Kwong (SRK Equation 3.19)

Overall Enthalpy method: Soave Redlich Kwong (SRK Equation 3.19)

Sources outlet temperature estimation VLE method: Peng Robinson (Equation 3.20)

Sources outlet temperature estimation Enthalpy method: Peng Robinson (Equation 3.20)

- **Pressure drop equations**

Horizontal pipes: Isothermal Gas (Equation 3.41)

Inclined pipes: Isothermal gas (Equation 3.41)

Vertical pipes: Isothermal gas (Equation 3.41)

Friction factor method: Chen (Appendix 10.5.2)

Appendix E

Other Equations used in simulation

E.1 Navier-Stokes Equation in 3-D

- **Continuity Equation**

$$\frac{D\rho}{Dt} = \frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$$

It expresses the principle of conservation of matter. This is written for Cartesian coordinates

x, y, z, measured relative to a stationary frame of reference, with corresponding velocity

components u, v, and w.

- **Energy Equation**

$$\rho \frac{De}{Dt} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + \frac{p}{\rho}\frac{D\rho}{Dt} + \phi$$

This equation can be written in the form of enthalpy

$$h = e + \frac{p}{\rho}$$

which gives,

$$\frac{Dh}{Dt} = \frac{De}{Dt} + \frac{1}{\rho}\frac{Dp}{Dt} - \frac{p}{\rho^2}\frac{Dp}{Dt}$$

After substitution, we get

$$\rho \frac{Dh}{Dt} = \frac{Dp}{Dt} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + \phi$$

where Φ is dissipation function.

- **Momentum Equation**

$$\rho \frac{Du}{Dt} = \rho X + \frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z}$$

$$\rho \frac{Du}{Dt} = \rho Y + \frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z}$$

$$\rho \frac{Dw}{Dt} = \rho Z + \frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \tau_{zy}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z}$$

E.2 Chen's friction factor formula

$$\frac{1}{\sqrt{f}} = -2 \log_{10} \left[\left(\frac{(\varepsilon / D)}{3.7065} \right) - \frac{5.0452A}{Re} \right]$$

Where

$$A = \log_{10} \left(\frac{(\varepsilon / D)^{1.1098}}{2.8257} + \frac{5.8506}{Re^{0.8981}} \right)$$

f = Fannings friction factor

Re = Reynolds number

ε = Equivalent pipe roughness, ε = e/D = absolute pipe roughness/ID of pipe

This is friction factor for turbulent flow and flow in the flare network is considered to be turbulent.

Pressure drop from Dukler's method for single phase flow:

$$\Delta P_{total} = \Delta P_f + \Delta P_h + \Delta P_{acc}$$

$$\Delta P_{fl} = \frac{2 f \rho u^2 L}{gD}$$

$$\Delta P_{accl} = \frac{\rho}{2g}(u_2{}^2 - u_1{}^2)$$

where:

ΔP_f = Frictional pressure drop

ΔP_h = Hydrostatic pressure drop

ΔP_{acc} = Acceleration pressure drop

and

ρ = fluid density (average value, for gas flow)

u = fluid flow velocity

L= pipe length

G = gravitational constant

D = pipe inner diameter

ΔZ = elevation

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