A
Project Report
On

FLARE GAS RECOVERY UNIT

By
Hitesh Tripathi
R010206022
B.Tech. Applied Petroleum Engineering – Downstream
(2006-2010)

विद्यया शक्ति वशम्

COLLEGE OF ENGINEERING STUDIES
DEHRADUN - 248110
[Academic Session: 2009 – 2010]

A
Project Report
On
FLARE GAS RECOVERY UNIT

In partial fulfillment of requirements for the degree of

Bachelor of Technology
In
Applied Petroleum Engineering

SUBMITTED BY:
Hitesh Tripathi
R010206022
B.Tech. Applied Petroleum Engineering – Downstream
(2006-2010)

Under the Guidance of
Dr. Nityanand Choudhary

COLLEGE OF ENGINEERING STUDIES
DEHRADUN - 248110

[Academic Session: 2009 – 2010]

CERTIFICATE

This is to certify that the project entitled "Flare gas recovery unit" has been carried out by the following student under my guidance in partial fulfillment of the degree of Bachelor of Technology in Applied Petroleum Engineering of University of Petroleum and Energy Studies, Dehradun during the academic year 2009-2010 (Semester-VIII)

Name of Student:
Hitesh Tripathi

Mentor
(Dr. Nityanand Choudhary)
Date:
Place: Dehradun

PROJECT APPROVAL SHEEET

Following student has done the appropriate work related to the "Flare Gas Recovery Unit" in partial fulfillment for the award of Bachelor of Technology in Applied Petroleum Engineering of "University of Petroleum and Energy Studies, Dehradun" and is being submitted to College of Engineering Studies, Dehradun.

Name of Student:
Hitesh Tripathi

Mentor 14/5/2010
(Dr. Nityanand Choudhary)
Date:
Place: Dehradun

ACKNOWLEDGEMENT

I would like to sincerely thank, the management of UPES to provide me the opportunity to work on the project work on Flare Gas Recovery Unit.

I would like to give my sincerest thanks to Dr. Nityanand Choudhary, the mentor of the project, for his continuous guidance during the preparation of the project.

I also thank Mr. G. Sanjay Kumar who assisted me with the concepts of modeling & simulation involved with the project.

Finally I would like to thank all other person of UPES fraternity who directly or indirectly came out as helping hands in my project.

Hitesh Tripathi

B.Tech. A.P.E. (2006-2010)

Date:

Place: Dehradun

PAGE INDEX:

TABLE INDEX

FIGURE INDEX

ABSTRACT

With growing demand of fuel conservation and environmental concerns, it has become obligatory on part of refineries and petrochemical industries to provide more eco friendly means of emissions. Flaring of gases from these units, account for a large amount of greenhouse gas emissions, along with wastage of precious hydrocarbons which can be used as fuel. So a technique to recover the flare gases is a matter of utmost importance in present scenario.

The project, deals with the method by which flaring can be minimised by using 'Flare Gas Recovery Unit'.

The Flare Gas Recovery unit performs the basic operation of recovering the gas from the flare header and compressing it to boost the economical value of the gas, further the gas is passed through a separator to remove the associated liquids. The gas then is ready to be used for fuel purpose after proper treatment to remove unwanted components such as H_2S etc.

In the report, designing of different components for a FGRU have been discussed thoroughly. Accordingly a sample P&ID has been prepared of FGRU.

FGRU provides economical benefits to the plant where it has been installed, with a moderate investment for the setup and a short payback period.

FGRU's have been installed at various plants across India, viz.:

- Reliance refinery, Jamnagar
- IOCL refinery, Barauni
- IOCL refinery, Haldia
- ONGC gas processing complex, Hazira
- IOCL refinery, Guwahati
- CPCL refinery, Chennai
- HPCL Vishakh refinery, Vishakhapattnam

Case studies of few of the above mentioned establishment have been covered in the report.

Chapter 1:

Introduction:

Each year close to 150 billion cubic meters of gas is flared globally. This is equivalent to 1/3 of US gas consumption and 75% of global gas trade. Worldwide, final product costs of refinery operations are becoming proportionally more dependent on processing fuel costs, particularly in the current market, where reduced demand results in disruption of the optimum energy network through slack capacity. Therefore, to achieve the most cost-beneficial plant, the recovery of hydrocarbon gases discharged to the flare relief system is vital. Heaters and steam generation fuel provision by flare gas recovery leaves more in fuel processing and thus yield increment. Advantages are also obtained from reduced flaring pollution and extended tip life.

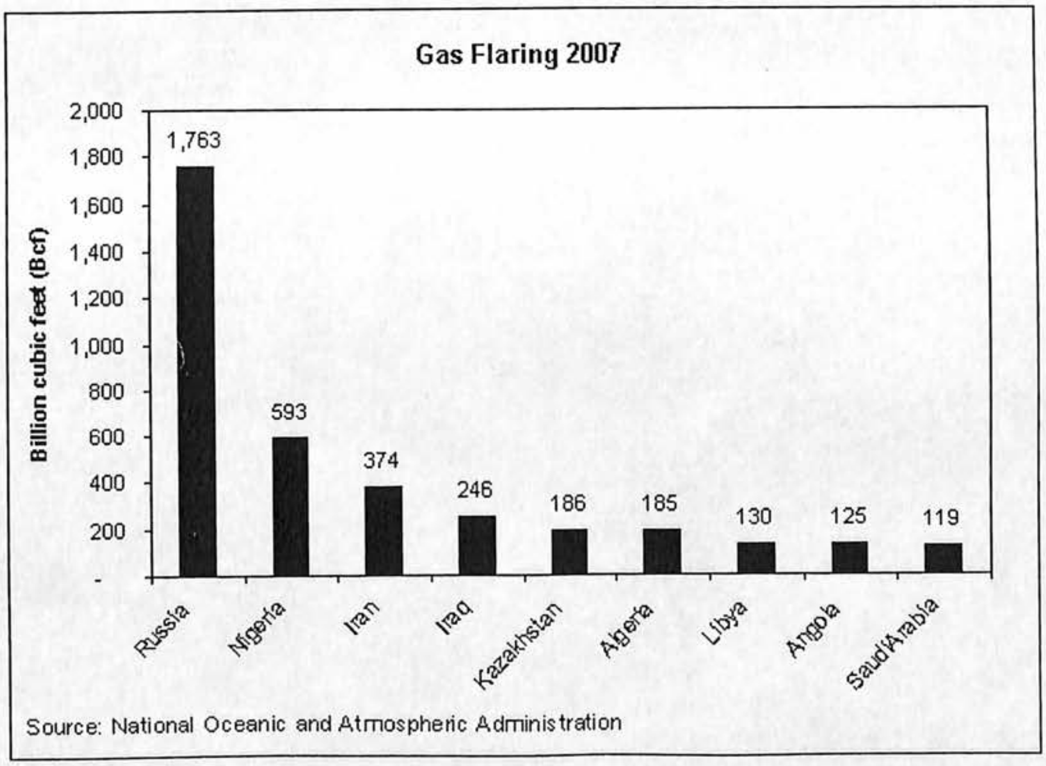


Fig. 1.1: Gas Flaring Nation wise Quantitative data (*Courtesy: http://www.eia.doe.gov/emeu/cabs/Nigeria/NaturalGas.html*)

An FGRU (Flare Gas Recovery Unit) is designed to capture waste gases that would normally go to the flare system. The FGRU is located upstream of the flare to capture some or all of the waste gases before they are flared. There are many potential benefits of an FGRU. The flare gas may have a substantial heating value and could be used as a fuel within the plant to reduce the amount of purchased fuel. In certain applications, it may be possible to use the recovered flare gas as feedstock or product instead of purchased fuel.

The FGRU reduces the continuous flare operation, which subsequently reduces the associated smoke, thermal radiation, noise and pollutant emissions associated with flaring. It also reduces the negative public attention drawn to the facility. Capturing waste gases may reduce odor levels. Reduced flaring also reduces steam consumption for steam-assisted flares and can extend the service life of the flare tips. In refineries with excess process-generated waste gas beyond fuel gas requirements, an FGRU can provide a means to scrub the hydrogen sulfide (H2S) before the clean gas is flared.

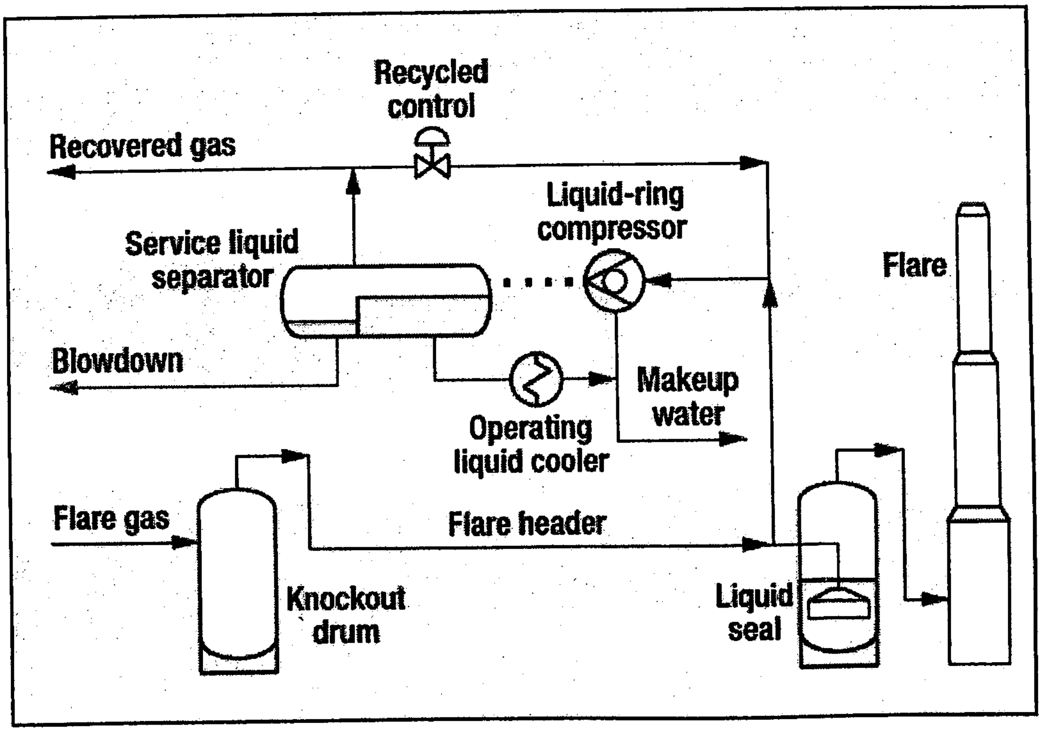


Fig. 1.2: Generalized flare gas recovery process schematic. *(Courtesy: Hydrocarbon Processing, June 2007 Issue, Gulf Publishing Co.)*

When the recovered flare gas is to be utilized as a fuel and the flow is less than or equal to the capacity of the FGRU, the flare gas will be recovered and directed to the refinery-fuel-gas header. During these periods, there will be little or no visible flame at the flare, although the flare pilot may be visible. When the flare-gas flow rate is greater than the capacity of the FGRU, the excess flare gas will flow through the liquid seal drum and to the flare tip where it will be combusted. From flaring rates just above the FGRU capacity to a maximum flaring episode, the liquid seal drum will promote smooth, safe operation of the flare tip. The FGRU system is operated at a slight positive pressure to prevent air infiltration into the system that could create a flammable mixture.

Need for Flare Gas Recovery:

Environmental Benefits:

Flaring and venting of gas from oil & gas wells and refineries is a significant source of greenhouse gas emissions. Its contribution to greenhouse gases has declined by three-quarters in absolute terms since a peak in the 1970s of approximately 110 million metric tons/year and now accounts for 0.5% of all anthropogenic carbon dioxide emissions.

Fig. 1.3: A protest rally against the flaring practice of Shell, Inc. at Ogonis, Nigeria
(*Courtesy: http://www.shellguilty.com/learn-more/climate-crimes/*)

The World Bank estimates that over 150 billion cubic meters of natural gas are flared or vented annually, an amount worth approximately 30.6 billion dollars, equivalent to 25 percent of the United States' gas consumption or 30 percent of the European Union's gas consumption per year. This flaring is highly concentrated: 10 countries account for 75% of emissions, and twenty for 90%. The largest flaring operations occur in the Niger Delta region of Nigeria. The leading contributors to gas flaring are (in declining order): Nigeria, Russia, Iran, Algeria, Mexico, Venezuela, Indonesia, and the United States. In spite of a ruling by the Federal High Court of Nigeria (that forbade flaring) in 2005, 43% of the gas retrieval was still being flared in 2006. It will be prohibited by law as of 2008. Russia has announced it will stop the practice of gas flaring as stated by Deputy Prime Minister Sergei Ivanov on Wednesday September 19, 2007. This step was, at least in part, a response to a recent report by the National Oceanic and Atmospheric Administration (NOAA) that concluded Russia's previous numbers may have been underestimated. The report, which used night time light pollution satellite imagery to estimate flaring, put the estimate for Russia at 50 billion cubic meters while the official numbers are 15 or 20 billion cubic meters. The number for Nigeria is 23 billion cubic meters.

Recovery of flare gas results in reduction of flaring or even zero flaring, which results in cutting off the emissions from flaring process.

Economic Benefits:

Worldwide, final product costs of refinery operations are becoming proportionally more dependent on processing fuel costs, particularly in the current market, where reduced demand results in disruption of the optimum energy network through slack capacity. Therefore, to achieve the most cost-beneficial plant, the recovery of hydrocarbon gases discharged to the flare relief system is vital. Heaters and steam generation fuel provision by flare gas recovery leaves more in fuel processing and thus yield increment.

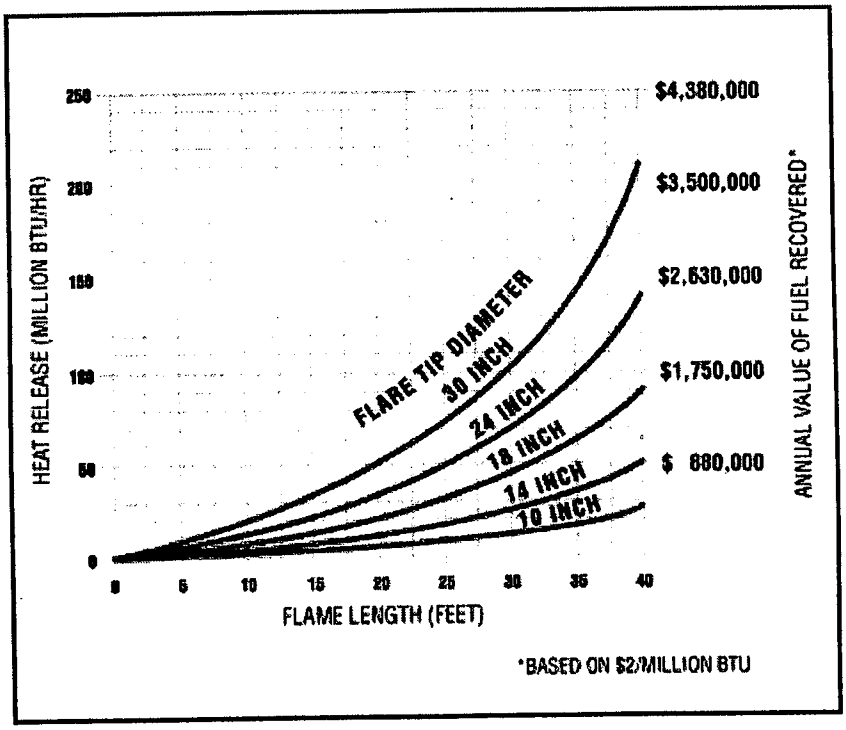


Fig. 1.4: <u>FGRU Payback Analysis Diagram</u> *(Courtesy: http://www.johnzink.com/products/fgr/html/fgr_jz_benefits.htm#payback)*

The chart above shows the estimated heat release associated with elevated flares based on the flame height. The heat release can then be correlated to a potential annual savings resulting from flare gas recovery by using the axis on the right.

Conservation of otherwise wasted hydrocarbons can dramatically reduce fuel gas costs. In one case a unit costing $1,300,000 paid for itself within the first year of operation. The end user credits the system with recovering over $30,000,000 in gas since installation.

This same facility was also able to cut usage of supplemental fuels and smoke suppression steam at the flare for additional savings

Some other economic benefits may be summed up as:

<u>Zero impact on safety relief system:</u>
When properly executed, flare gas recovery can be seamlessly integrated into existing flare systems without compromising performance or safety.

<u>Extended flare-tip life:</u>
Flare tips are exposed to extreme conditions, and therefore, have a limited lifespan. Life of a flare tip is related to the amount of usage, so a reduction in flare operation may extend the flare-tip life for years.

<u>Reduced steam consumption:</u>
Steam is frequently used to suppress smoke in flares. Recovering flare gas reduces the amount of flare gas for combustion and thus reduces the steam usage. A reduction in steam utility usually has an associated, measurable financial benefit.

Chapter 2:

Existing Flare Systems:

2.1) Purpose a Flare System:

In refineries and chemical plants, the primary purpose of flare system is to act as a safety device to protect vessels or pipes from over-pressuring due to unplanned upsets. This acts just like the spout on a tea kettle when it starts whistling as the water in it starts boiling. Whenever plant equipment items are over-pressured, the pressure relief valves on the equipment automatically release gases (and sometimes liquids as well) which are routed through large piping runs called flare headers to the flare stacks. The released gases and/or liquids are burned as they exit the flare stacks. The size and brightness of the resulting flame depends upon how much flammable material was released. Steam can be injected into the flame to reduce the formation of black smoke. The injected steam does however make the burning of gas sound louder, which can cause complaints from nearby residents. Compared to the emission of black smoke, it can be seen as a valid trade off. In more advanced flare tip designs, if the steam used is too wet it can freeze just below the tip, disrupting operations and causing the formation of large icicles. In order to keep the flare system functional, a small amount of gas is continuously burned, like a pilot light, so that the system is always ready for its primary purpose as an over-pressure safety system. The continuous gas source also helps diluted mixtures achieve complete combustion.

Fig.2.1: Gas flare at Star Refinery, Map Ta Phut, Thailand (*Courtesy: http://en.wikipedia.org/wiki/Gas_flare*)

2.2) Different Types of Flare System:

1) Utility Flares

Utility flares are one of the most common and basic flare designs.

Utility flares are employed in applications which do not require smokeless burning or in applications where smokeless flaring can be achieved without the use of an additional assist medium. Utility flares therefore, do not require auxiliary gas streams such as steam or air; two fluids normally used to improve smokeless capacity. These flares are typically accompanied by a Dynamic Seal in the base of the tip to reduce purge gas costs and prevent flashback. Additionally, the Flare Industries' Utility Tip incorporates a flame retention ring to eliminate flame lift off and provide stable, reliable combustion.

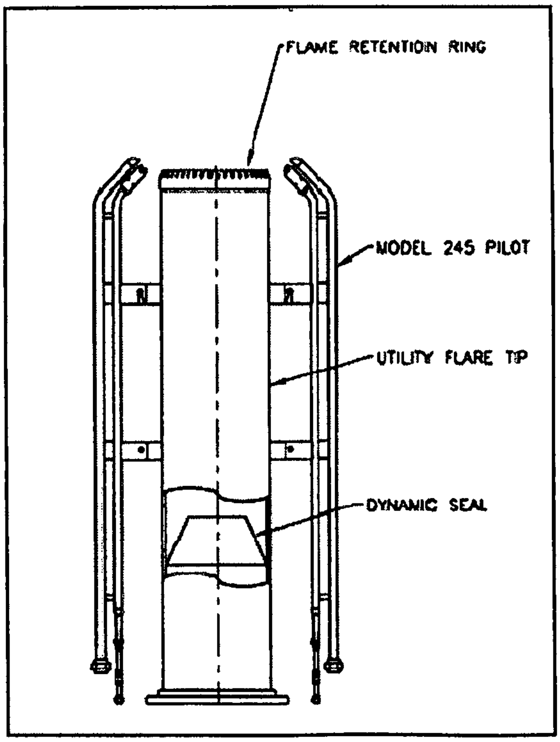


Fig. 2.2: Schematic Diagram of Utility Flare (*Courtesy: Flare Industries, Inc. Brochure*)

Design Features:

- High alloy material construction in the heat affected zone
- Flame retention ring to stabilize combustion
- Dynamic/Velocity seal to reduce purge gas expense and prevent flashback
- Wide range of diameters
- High alloy wind shield (optional)

Principal Applications:

- Petroleum refining
- Petroleum production
- Chemical processing
- Food processing
- Municipal waste disposal
- Bio-gas disposal
- Natural gas compression and production

2) Air Assist Flares

Air assist flares smokelessly dispose of heavier waste gases which have greater tendency to smoke. Air Assist flares can be employed at sites where steam may not be available.

Air flare systems are composed of two concentric risers and one or more blowers providing supplemental combustion air. A blower forces air into an outer air annulus where the process gas passes through an inner riser and upon reaching the flare tip, these two streams intermix. This air assist has three principle effects:

- High-pressure airflow causes turbulence in the waste stream which improves mixing and therefore enhances combustion efficiency.
- Additional air is induced into the waste gas providing the oxygen necessary for augmented smokeless capacity.
- Constant airflow creates a cooling effect for extended flare tip service life.

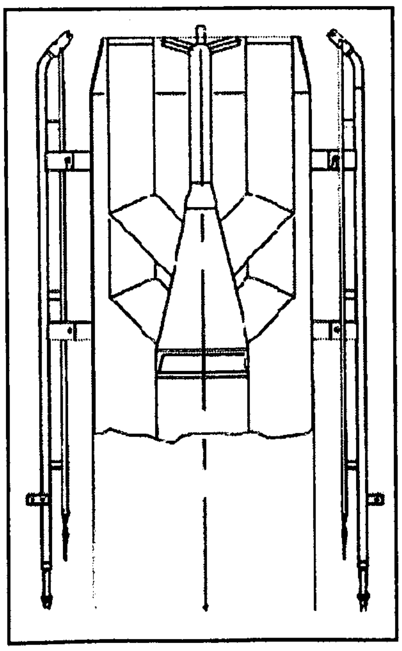


Fig. 2.3: Schematic Diagram of Air Assist Flare (*Courtesy: Flare Industries, Inc. Brochure*)

Design Feature:

- Large air/fuel boundary to increase smokeless capacity
- Dynamic/Velocity seal to reduce purge gas expenses and prevent flashback
- High alloy construction in the heat affected zone
- One or more blowers for greater smokeless range

Principal Applications:

- Petroleum refining
- Petroleum production
- Chemical processing
- Pipeline transportation
- Tank and barge loading facilities
- Natural gas compression and production

3) FirecatTM Recuperative Oxidizer

An exorbitant fuel cost is perhaps the most distressing concern when considering which type of thermal oxidizer to choose. One way to hedge this variable cost is to employ some form of heat or energy recovery. FirecatTM Recuperative Oxidizers employ shell and tube heat exchangers, boilers, or hot oil heaters to take advantage of the heat available in the flue gases. In this way, flue gases constantly heat oil, create steam, or preheat waste gases and combustion air, thereby reducing fuel gas consumption.

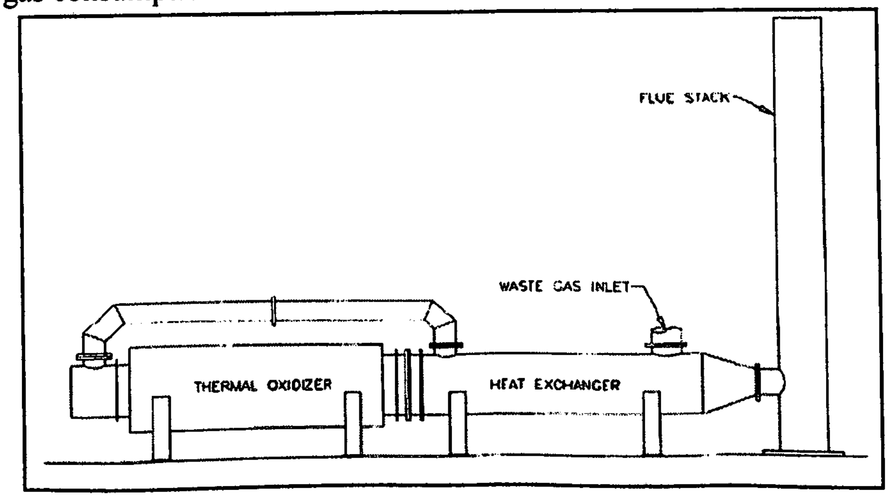


Fig. 2.4: Schematic Diagram of FirecatTM Recuperative Oxidizer

(Courtesy: Flare Industries, Inc. Brochure)

Design Feature:

- Gas/gas or gas/liquid heat exchanger
- Combustion or retention chamber
- PLC controlled
- Exhaust stack
- Refractory lined chambers for minimum heat loss

Principal Applications:

- Low BTU waste gases
- Petroleum refining
- Petroleum production
- Chemical processing

4) Steam Assist Flares

Steam assisted flares are designed to dispose of heavier waste gases which have a greater tendency to smoke. In order to prevent incomplete combustion, steam is injected into the waste stream using peripheral steam rings, center steam spargers, and/or inner induction tubes. The injection of steam has two principal effects:

- High-pressure steam flow causes turbulence in the waste stream which improves mixing and therefore improves combustion efficiency.
- Additional air is induced into the waste gas providing the oxygen necessary for augmented smokeless capacity.

Steam flares are typically used in applications where the customer has high-pressure steam available on site.

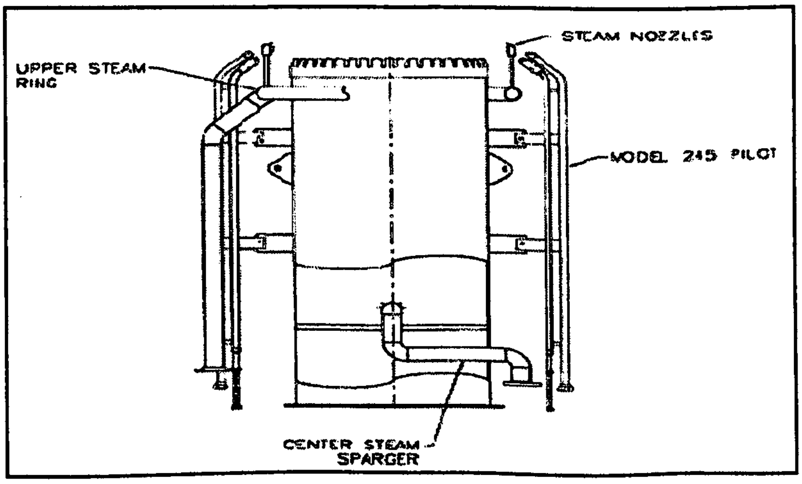


Fig. 2.5: Schematic Diagram of Steam Assist Flares
(Courtesy: Flare Industries, Inc. Brochure)

Design Feature:

- High pressure steam must be available
- High alloy material construction in the heat affected zone prevents induction tubes, rings, and spargers from warping and cracking
- Primary or secondary steam injection through:
  - Peripheral ring (SA Model)
  - Center sparger (SA & SAI Models)
  - Internal induction tubes (SAI Model)
- Flame Retention Ring to stabilize combustion
- Low noise design with the use of external noise muffler

Principal Application:

- Petrochemical processing
- Petroleum refining

5) <u>Sonic Flares:</u>

MACH 1 is the speed of sound. Flare Industries' cutting edge MACH-1 sonic flaring technology operates at this velocity in order to combust waste gas smokelessly. Sonic flares utilize multi-point exit nozzles to dispose of high pressure waste gas streams. The MACH-1 Sonic Flare Tip utilizes the pressure of the waste stream (creating sonic exit velocities) to create turbulent mixing and induce excess quantities of air for more complete combustion. Sonic flare tips emit reduced levels of radiation and can be placed at lower, less visible elevations. This advanced flaring technology is excellent for applications with high pressure waste gases and high capacity smokeless requirements.

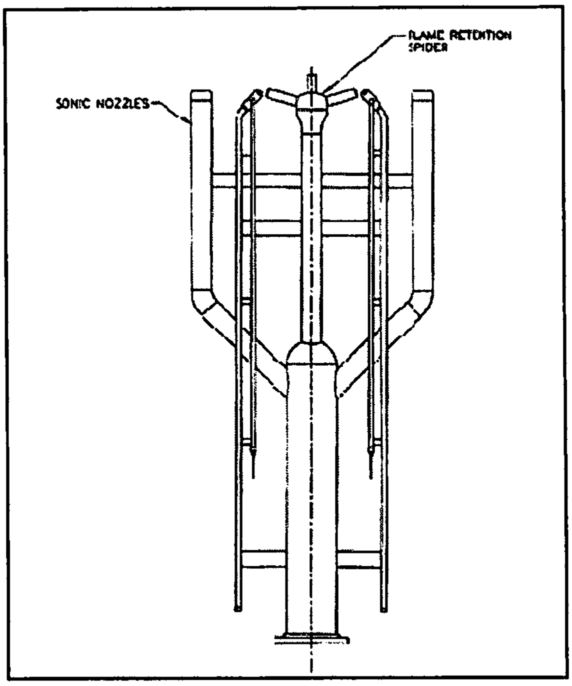


Fig. 2.6: Schematic Diagram of Sonic Flares
(Courtesy: Flare Industries, Inc. Brochure)

Design Features:

- Flow rates up to sonic velocity
- Flame stabilization from center spider burner
- Multiple arm design
- Single point ignition source
- Wide range of diameters
- High alloy construction in the heat affected zone

Principal Applications:

- Offshore production
- Pipeline transportation
- Petrochemical production
- Natural gas compression and production
- High pressure waste gas
- Steam or air assist is undesirable or unavailable

6) Enclosed Ground Flares:

The Enclosed Ground Flare destroys a process or waste stream, but does not maintain a constant temperature while doing so. This simplifies the control scheme allowing the overall system to be less expensive. The Enclosed Ground Flare has the following advantages: reduced flame visibility, minimal heat and noise, emissions sampling ease, and smokeless combustion. Flare Industries' Enclosed Ground Flare attains extremely high destruction efficiencies by assuring the appropriate residence time. Enclosed Ground Flares may require supplemental assist gas streams depending on whether the process stream can sustain combustion.

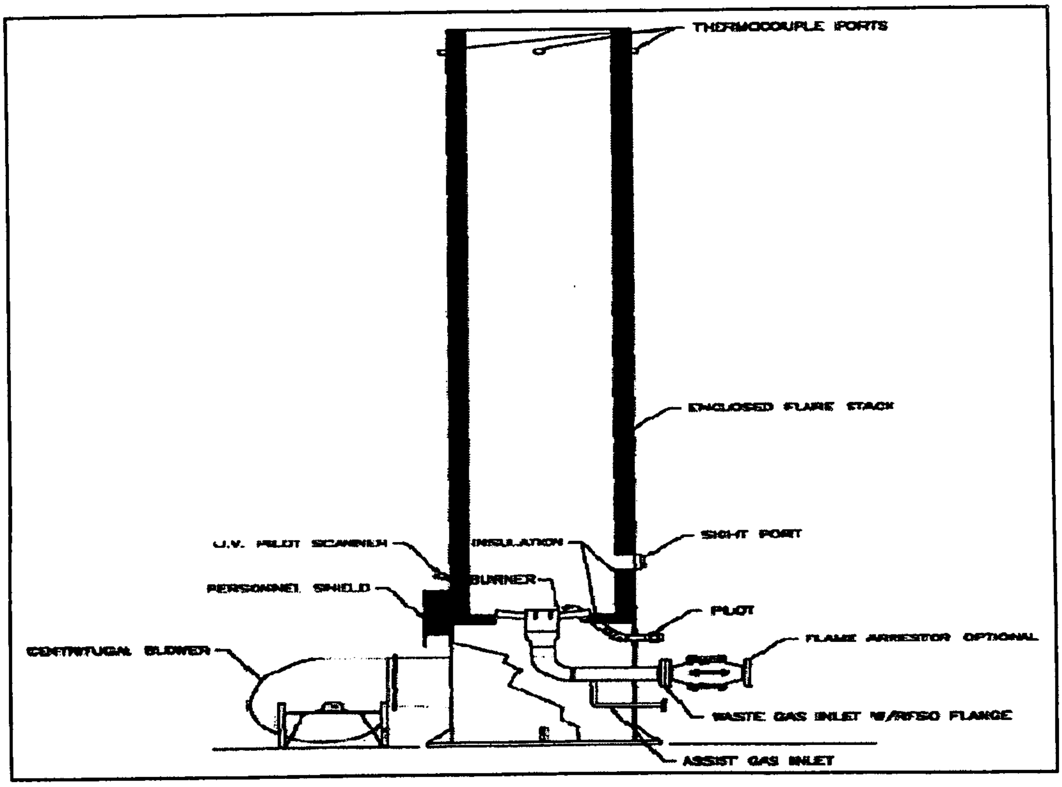


Fig. 2.7: Schematic Diagram of Enclosed Ground Flares (*Courtesy: Flare Industries, Inc. Brochure*)

Design Feature:

- Extremely high destruction efficiencies
- Flare Industries' high efficiency burner design
- Forced or natural draft designs available
- Fuel efficient pilot especially designed for enclosed flares
- Temperature monitoring
- Control schemes using industry standard PLC brands
- Burner longevity due to high alloy, chemical resistant construction

Principal Applications:

- Refineries
- Chemical plants
- Truck loading terminals

- Marine loading facilities
- Compressor station

Chapter 3:

FGRU Technical

Flare Gas Recovery Unit (FGRU) comprises of the following components:

- Flare Headers
- 2 Phase Separator (known as Knock Out Drum)
- Compressor (Liquid Ring or Liquid Jet)
- Operating Liquid for the Compressor
- 3 Phase Separator (to separate condensible/non-condensible HC vapors and operating liquid of compressor)
- Heat Exchanger to cool the operating liquid of compressor
- Control System
- Valves

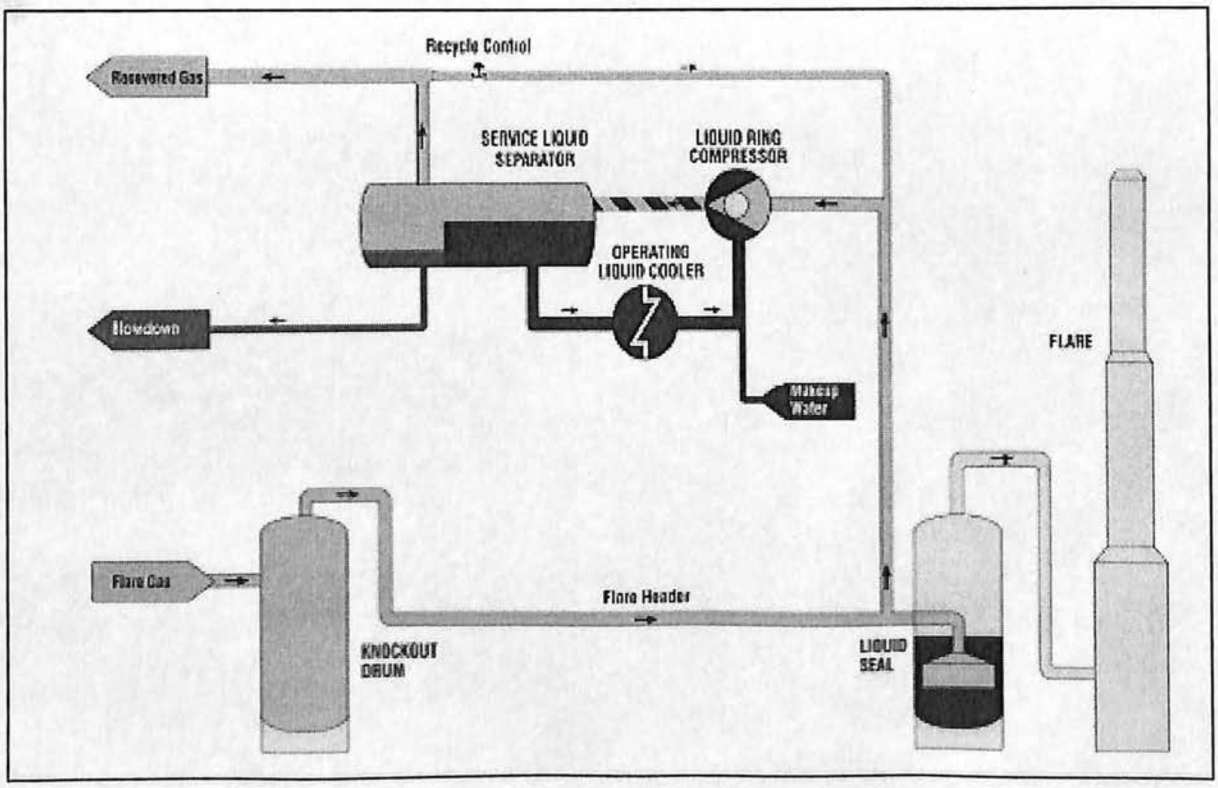


Fig 3.1: Process Flow Diagram of FGRU

(*Courtesy: Flare Gas Recovery: John Zink Co. White Paper*)

3.1) Explanation of PFD:

The basic processes used in the FGRU are compression and physical separation. The basic operations of the FGRU are:

- Process vent gases are recovered from the flare header.

- Gas compressors boost the pressure of this gas.

- Recovered gas is discharged to a service liquid separator.

- Separated gas may pass through a condenser where the easily condensed constituents may be returned as liquids feedstock while the components that do not easily condense are returned for use as fuel gas after scrubbing for contaminant removal, such as H2S.

Gas compression is performed by compressors selected for the specific application. For example, if a liquid-ring compressor is used, then separating recovered vapor phase from a mixed liquid is accomplished via a horizontal separator vessel. As flare gas flows into the header, an established hydrostatic head in the liquid seal drum will prevent flare gas from flowing to the flare.

This causes a slight increase of pressure in the flare gas header, but not enough to significantly affect the capacity of the overpressure protection devices in the refinery. When the flare-gas header pressure reaches the gas recovery initialization set point in a batch operation plant, the compression system will begin to compress the flare gas. The FGRU will start and stop with control signals from the PLC. In continuous-operation plants with varying flare loads, additional parallel compressors can be automatically staged on or off to augment the capacity of the base-load compressor as needed. Based on the inlet pressure of the flare gas header, fine-tuning of FGRU capacity control is by the spillback (recycle) of recovered gas from the service liquid separator back to the suction.

Discharge of the liquid-ring compressors will flow into the service liquid separator vessel where the gas and service liquid are disengaged and the compressed recovered flare gas is delivered to the facility fuel gas scrubbing and distribution system. The compressor service liquid, usually water, is used in the compressor as a seal between the rotor and the compressor case. The service liquid is separated from the recovered gas stream, cooled and re-circulated to the gas compressor train for reuse.

The gas processing capacity of the FGRU adjusts to maintain a positive pressure on the flare header upstream from the existing liquid seal drum. This positive pressure will ensure that air will not be drawn into either the flare system or the FGRU. If the volume of flare gas that is relieved into the flare system exceeds the capacity of the FGRU, the pressure in the flare header will increase until it exceeds the back-pressure exerted on the header by the liquid seal. In this event, excess gas volume will pass through the liquid seal drum and on to the flare where it will be burned. This will be the case when there is a rapid increase in flare gas flow due to an emergency release. Since the liquid seal serves as a backpressure control device for the FGRU, a properly designed deep-liquid seal is critical to the stable operation of the FGRU and flare. A deep-liquid seal, typically 30-in.of water is required to permit a suitable control range for the capacity control of the FGRU. As the flow transitions to the flare, this must be done with a very stable liquid level or else unstable flare header pressure could result, affecting FGRU control and proper flare operation.

If the volume of flare gas relieved into the flare header is less than the total capacity of the FGRU, the capacity of the FGRU adjusts to a turndown condition. This is accomplished by turning off compressors and/or by diverting discharged gas back to the turning off suction header through a recycle control valve.

Compressor speed can also be varied. Control of the FGRU is automated with minimal requirement for direct operator intervention.

3.2) Designing of FGRU for a particular unit:

The site analysis for designing & installation of a flare gas recovery unit will require the following data (Courtesy: FGRU Design Basis Information, Process Specification Form, John Zink Company)

- Flare System Data:
  - Number of Flare Equipments
  - Flare tip diameter
  - Flare design (maximum) flow rate
  - Flare smokeless flow rate
  - Flare Pressure drop from base to tip
  - Estimated suppression steam usage
  - Flare Header Line size
  - Whether KO Vessel installed or not
  - Liquid seal vessel installed or not
  - Liquid seal depth (If liquid seal vessel is installed)
  - Liquid seal fluid (If liquid seal vessel is installed)
- Site Conditions:
  - Elevation above sea level
  - Atmospheric pressure
  - Maximum ambient air temperature
  - Minimum ambient air temperature
  - Site design wind speed

- Feed Gas Properties
  - Heating Value (LHV)
  - Molecular Weight
  - Specific Gravity
- Operating Utilities:
  - Electrical power supply (60 Hz or 50 Hz)
  - For motors < 250 HP (480 VAC or 2300 VAC)
  - For motors > 250 HP (2300 VAC or 4160 VAC)
  - For control elements (120 VAC or 24 VDC)
  - Instrument air supply pressure
  - Service water supply pressure
  - Cooling water supply maximum temperature
  - Cooling water supply minimum temperature
  - Cooling water return maximum temperature
  - Cooling water return minimum temperature
- Economic Factors:
  - Value of electrical power (Rs/kWh)
  - Value of steam (per kg or per Lb)
  - Value of recovered gas or fuel (per kg or Lb or MMBtu or kJ)
  - Value of recovered gas as process feed (per kg or Lb or MMBtu or kJ)
- Design Basis:
  - Design (maximum) gas recovery rate
  - Feed temperature
  - Feed gas pressure
  - Recovered gas delivery temperature limit
  - Recovered gas minimum discharge pressure
  - Recovered gas intended use (fuel or process feed)
  - Control system platform

3.3) Designing of different components of FGRU:

- Pipeline
  - Number of segments
  - Length of segments
  - Diameter of segments
  - Material selection
- Separators
  - Length of separator
  - Diameter of separator

- Positioning of inlet/outlet openings
- Determination of height of liquid column and pressure of gas
- Other components involved
- Material Selection

- Compressor
  - Type
  - Power
- Control System
  - Type
  - Valves selection and positioning
  - LC & PC selection and positioning
  - Sensors
  - Platform

3.4) <u>Designing Principles of Pipelines:</u>

In this section a general guideline for determination of the following parameters used in designing the pipe layout in FGRU are discussed (Discussion is based on ANSI specifications on designing of pipelines):

- Equation representing the flow characteristics within the pipe
- Maximum allowable working pressure
- Maximum allowable flow velocity

1) Equation representing the flow characteristics within the pipe:

All fluid flow equations are derived from a basic energy balance which for a steady state system can be given as:

Change in internal energy + change in kinetic energy change in potential energy + work done on the fluid + heat energy added to the fluid –shaft work done by fluid on surroundings = 0

This can be represented in mathematical form as:

$dU + dv^2/2g_c + g/g_c\, dz + d(pv) + dQ - dw_s = 0$ ---- (3.1)

Where:

- U= internal energy ft-lb f/lbm
- v= fluid velocity, ft/sec
- z= elevation above a given datum plane , ft
- p= pressure , lbf/ft^2
- V= volume of a unit mass of the fluid,ft^3/lbm
- Q= heat energy added to the fluid ft-lbf/lbm

- w_s= shaft work done by the fluid on the surroundings

Equation (3.1) can be converted to a mechanical energy balance using the following thermodynamic relations:

$du + d(pv) = dh = Tds + Vdp$ ---- (3.2)

Where:

- h= specific fluid enthalpy, ft-lbf/lbm
- T= temperature ,°R
- s= specific fluid entropy, ft-lbf/lbm

now equation (3.1) becomes

$Tds + Vdp + dv^2/2g_c + g/g_c\, dz + dQ - dw_s = 0$ ---- (3.3)

For an ideal process $ds = -dQ/T$ ---- (3.4)

Since no process is ideal

$ds \geq -dQ/T$ ---- (3.5)

$Tds = -dQ + dl_w$ ---- (3.6)

l_w= lost work due to irreversibility

On further substitution to above equation we get

$-dQ + dl_w + Vdp + dv^2/2g_c + g/g_c\, dz + dQ - dw_s = 0$ ---- (3.7)

Neglecting the shaft work w_s and multiplying throughout by density ρ

$dp + \rho\, dv^2/2g_c + g/g_c\, \rho\, dz + \rho\, dl_w = 0$ ---- (3.8)

And it can also be written as

$\Delta p + \rho\, \Delta v^2/2g_c + g/g_c\, \rho\, \Delta z + \Delta p_f = 0$ ---- (3.9)

[Where Δp_f is pressure drop due to friction= $fv^2 l\, \rho/2g_c d$]

<u>Friction in pipe:</u>

The term l_w represents all energy losses resulting from irreversibility of the flowing stream.

- Friction losses
- Internal losses due to viscosity effects
- Losses due to roughness of the wall of the pipe

Friction factor f', defined as the ratio of the wall shear stress and the kinetic energy per unit volume and is used in computing the magnitude of the pressure drop due to friction.

$f' = \tau_w / (\rho v^2 / 2g_c)$ ---- (3.10)

For steady state flow in a uniform circular conduit such as pipe this results in well known 'Fanning equation':

$\Delta p_f = 2f'L \rho v^2 / g_c d$ ---- (3.11)
Where'd' is the inside pipe diameter.

Friction factor f' is called the Fanning friction factor. Usually, the Moody friction factor equal to 4f' is used.

In terms of the Moody friction factor f, the Fanning equation becomes:

$\Delta p_f = fL \rho v^2 / 2g_c d$ ---- (3.12)

head loss in terms of height of liquid flowing thus obtained is:

$h_{fs} = 4fLv^2 / 2g_c d$ ---- (3.13)

Pipe Roughness:

- Absolute roughness ε of a pipe wall is defined as the mean protruding height of relatively uniformly distributed and sized, tightly packed sand grains that would give the same pressure gradient behavior as the actual pipe wall.
- Relative roughness is the ratio of the absolute roughness to the diameter of the pipe. Relative roughness= ε/d

<u>For smooth pipes</u>:

- $f = 0.5676 N_{Re}^{-0.3192}$ for intermediate flow
- $f = 16 \log (N_{Re} f^{0.5} / 0.7063)$ for partially turbulent flow
- $f^{0.5} = 2 \log (N_{Re} f^{0.5} / 0.628)$ for fully turbulent flow
- $f = 0.3614 N_{Re}^{-0.25}$ for N_{Re} up to 10^5

<u>For rough pipes</u>:

- $f^{-0.5} = -2 \log [\varepsilon/(3.7d) + 0.628/(N_{Re} f^{0.5})]$

<u>For very rough pipes</u>:

- $f^{-0.5} = -2 \log \varepsilon/(3.7d)$

2) Allowable working pressure for pipes:

To achieve higher throughputs a pipe can operate at high pressure which is limited by the maximum stress the pipe can handle. The maximum allowable internal working pressure can be determined using ANSI specification:

$$p_{max}=2(t-c)SE/d_o-2(t-c)Y \text{ ---- } (3.14)$$

Where

- p_{max}=maximum allowable internal pressure, psig
- t= pipe thickness
- c=sum of mechanical allowances (thread and groove depth), corrosion, erosion etc.
- S= allowable stress for the pipe material, psi
- E=longitudinal weld joint factor
- d_o= outside diameter of the pipe, in.
- Y= temperature de-rating factor

3) Allowable flow velocity in pipes:

High flow velocities in pipes can cause pipe erosion problems, especially for gases that may have a flow velocity exceeding 70 ft/sec.

The velocity at which erosion begins to occur is dependent upon the presence of solid particles, their shape etc.

$$v_e=C/\rho^{0.5} \text{ ---- } (3.15)$$

In most cases C is taken to be 100

If C and ρ are substituted then

$$v_e= 100(ZRT)^{0.5}/(28.97p\gamma_g)^{0.5} \text{ ---- } (3.16)$$

The gas flow rate at standard conditions for erosion to occur, $(q_e)_{sc}$, can be obtained as follows:

$$(q_e)_{sc} = 1{,}012.435\, d^2(p/\gamma_g ZT)^{0.5} \text{ ---- } (3.17)$$

3.5) Design of Separators:

This Design Standard Specification follows minimum requirements for the process design (including criteria for type selection) of gas (vapor)-liquid separators used in the production of the oil and/or gas, refineries and other gas processing and petrochemical plants according to API Spec. 12J "Specification for Oil and Gas Separators", 7th. Ed., Oct. 1989. For the purpose of this Standard, separation techniques are defined as, those operation, which isolate specific immiscible ingredients of a mixture mechanically, i.e., without a chemical reaction or a mass transfer process taking place.

Separators without mist extractors may be designed for gravity settling using Stokes' law equations. Typically the sizing is based upon removal of 150 micrometers and larger diameter droplets. For practical purposes, to be in safe side, use of the methods presented in the following sections is recommended.

3.5.1) Design flow rates

A separator may be incorporated in a process scheme for which there are different modes of operation. In this case, the separator design shall be based upon the operation mode with the severest conditions. For the gas/liquid separation in a knock-out drum or demister, the severest condition is that with the highest value of Q, where this is defined by:

$$Q = Q_v[\rho_v/(\rho_L - \rho_v)]^{0.5} \text{ m}^3/\text{s} \text{ ---- } (3.18)$$

Having identified the severest mode from the highest value of Q, it is then necessary to add on a margin to give the value on which the separator design shall be based. This value, Q_{max} should include margins for over design, safety or surging. It represents the 'flooding' condition.

The margin to be applied over the normal (process design) flow rate depends on the application. For oil processing, a margin of 15-25% is common; for oil production, margins up to 50% may be required.

3.5.2) Nature of the feed

The type of flow in feed pipe to the separator, transition from one flow regime to another, formation of droplets, foaming tendency of the liquid which may lead to carry over the liquid or carry through of gas and other factors such as existence of sands, rust, wax and other solids and cocking tendency of the liquid are points which should be Taken into account when fixing design conditions.

3.5.3) Liquid handling requirements

In checking the capacity of the separator to handle liquid, the following points should be considered.

1) <u>Degassing</u>

In order to prevent carry through of the gas bubbles into the liquid outlet stream in vertical vessels, the liquid velocity should satisfy the following requirement:

$Q_L/\pi r^2 < [(2.18 \times 10^{-2})/\gamma_L] \times [(\rho_L - \rho_v)/\rho_v]$ ---- (3.19)

Where γ_L, the liquid kinematic viscosity is in mm²/s or cSt.

Note:

Often 'liquid residence time' is used as a criterion for de-gassing. The method given here, based on Stokes' law is preferred.

2) <u>Control volume</u>

For de-gassing (and also to counter foam), the liquid velocity should be limited. When a liquid level is required in the separator, a certain liquid volume is necessary for control purposes.

a) Hold-Up time for control

The minimum requirement between LA (L) and LA (H) shown in Fig. 3.2, which should be applied in the absence of other overriding process considerations, is as follows:

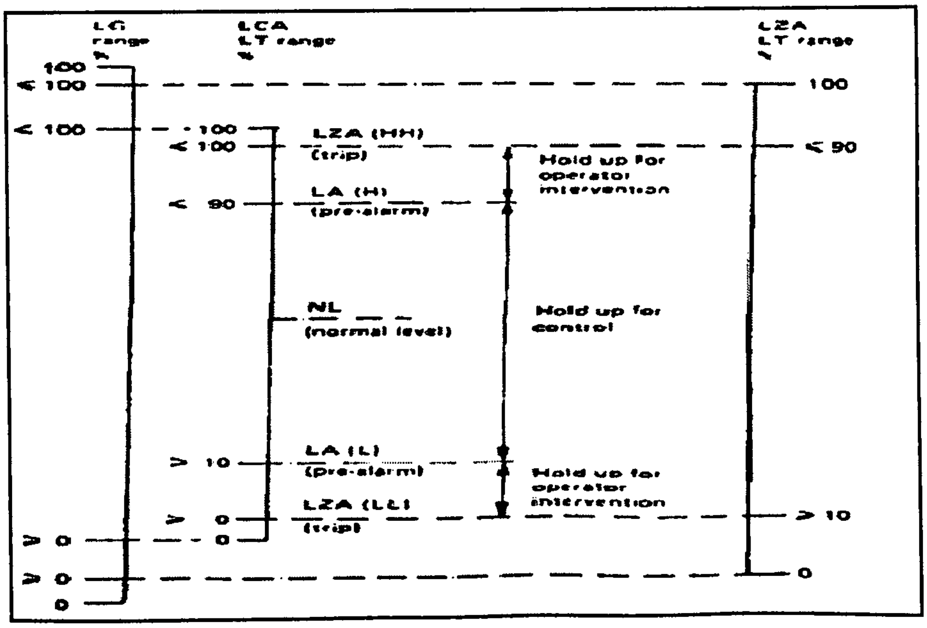


Fig. 3.2: <u>Liquid Level Control Terms</u> (*Courtesy: API Spec. 12J "Specification for Oil and Gas Separators", 7th. Ed., Oct. 1989*)

Legend for Fig. 3.2:

- H = High.
- HH = Very High
- L = Low
- LL = Very Low
- LA = Level Alarm.
- LG = Level Gage
- LT = Level Transmitter.
- LCA = Level Controller, Alarm Action.
- LZA = Level Controller, Trip Action.
- NL = Normal Level

Automatic control

4 minutes for product to storage

5 minutes for feed to a furnace

4 minutes for other applications

Manual control

20 minutes.

b) Hold-Up time for operator intervention

When operator action is necessary to avoid upsets or a shutdown of plant operation, a realistic estimate shall be made of the time required.

For inside plot separators a minimum hold-up of 5 minutes between pre-alarm and trip action is recommended.

For off plot separators, the time the operator needs to reach the equipment, should be added.

No hold-up is required for switches which do not directly affect plant operation, e.g., automatic starting of standby pump. The pre-alarm may then be omitted.

3.5.4) Liquid slugs

If the feed contains slugs of liquid, extra hold-up volume is required. In the absence of other information, the slug volume should be taken as 2-5 seconds of flow with the normal feed velocity and 100% liquid filling of the feed pipe.

The separator should be able to accommodate this slug volume between NL and LA (H) or between NL and LA (HH), depending on whether it is required for the arrival of a slug to sound the high-level alarm, or not. To increase the volume for accommodation of the slug the NL may be set closer to LA (L).

When slugs are expected in the feed, consideration should be given to strengthening the piping and feed inlet device, if one is to be fitted.

3.5.5) Separator design methods

Recommended methods for basic (process) design of conventional Gas-Liquid Separators are presented in the following sections. Although general references are available in literature.

Basically there are two separators used in the FGRU system (more than two separators may be used in the system depending upon the requirement but in the scope of this project two basic separators of the FGRU will be discussed):

- 2 phase separator: Known as Knock Out Drum (KOD) in context of present system, it is used to separate the liquid hydrocarbons from the vapors in the flare header. The purpose of this separator is to recover the liquids as useful product and also to reduce the load on the compressor involved in the FGRU. The feed received by it has a high vapor to liquid ratio.
- 3 phase separator: It is installed after the compressor in the flow of the system, where it separates the vapor, liquid hydrocarbons and operating liquid of the compressor which gets entrained along with the compressed vapors. The feed received by it has a low vapor to liquid ratio.

3.6) Knock Out Drum (2 phase separator) design:

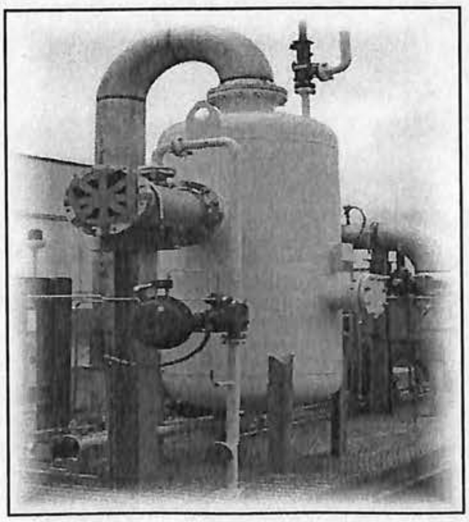


Fig. 3.3: A vertical Flare Knock Out Drum (*Courtesy: http://www.mrw-tech.com/images/pia_flares7.jpg*)

Flare KO drums are one type of gas/liquid separators which are used specifically for separation of liquids carried with gas streams flowing to the flares in oil, gas and petrochemical (OGP) plants.

The main difference between Flare K.O drums and other conventional gas/liquid separators lies in the size of the droplets to be separated, i.e., separation of 300, 600 micron (μm) droplets, fulfills the requirements of flare gas disengagement. Therefore usage of mist eliminating device is not usually necessary in Flare K.O drums except for cases where the results of calculations lead to an abnormally large drum size. In such cases, application of vane type or multicyclone separators may help to avoid employing an extremely large drum.

In this project the flare KO drum has been considered with mist extractor, the following data are according to this assumption

3.6.1) Design Specifications of Vertical knock-out drum with mist extractors

Most vertical separators that employ mist extractors are sized using equations that are derived from gravity settling equations. The most common equation used is the critical velocity equation:

$V_c = K[(\rho_L - \rho_v)/\rho_v]^{0.5}$ ---- (3.20)

Some typical values of the separator sizing factor, K, are given in Table 3.1. Note that this equation actually gives the size of the separation element (mist extractor), and does not size the actual separator containment vessel. That means the vessel may be selected larger than the element, (e.g., for surge requirements).

Table 3.1 (Typical K Factors for Sizing Wire Mesh Demisters)

Separator Type	**K. FACTOR m/s**
Horizontal (with vert. pad)	0.122 to 0.152
Spherical	0.061 to 0.107
Vertical or horizontal (with horiz. pad)	0.055 to 0.107
At atm. press.	0.107
At 2100 kPa	0.101
At 4100 kPa	0.091
At 6200 kPa	0.082
At 10300 kPa	0.064

Wet steam	0.076
Most vapors under vacuum	0.061
Salt and caustic evaporators	0.046

Notes:

1) K = 0.107 at 700 kPa - Subtract 0.003 for every 700 kPa above 700 kPa.

2) For glycol and amine solutions, multiply K by 0.6 to 0.8.

3) Typically use one-half of the above K values for approximate sizing of vertical separators without wire mesh demisters.

4) For compressor suction scrubbers and expander inlet separators multiply K by 0.7 - 0.8.

The following is a rough, but safe sizing method for vertical demister separators:

a) Diameter

The vessel diameter, Dv follows from:

$Q_{max}/[(\pi/4)D^2] \leq 0.105$ m/s ---- (3.21)

When a standard support ring for the demister mat is designed, then the width of the ring is considered to be negligible and Dv calculated from the above formula will be the vessel internal diameter.

Notes:

1) For viscous liquids, the maximum capacity of a horizontal demister mat is less.

For μg =100 cP the value 0.105 m/s is reduced by 10%.

For μg =1000 cP, the value 0.105 m/s is reduced by 20%..

2) Maximum capacity of the mat decreases as the rate of liquid fed to it increases. The above values apply to a lightly loaded mat, as encountered in most separators.

b) Height

Let h be the height of vessel required for liquid hold-up. Then the total vessel height (tangent to tangent) is:

H = h + dn + t + X + Y + 0.15 Dv ---- (3.22)

Where:

d_n = diameter of inlet nozzle

t = thickness of demister mat, usually 0.1 m

X = 0.3 Dv with a minimum of 0.3 m

Y = 0.45 Dv with a minimum of 0.9 m

c) Nozzles

1) Feed nozzle

When the vessel diameter is less than 0.8 m the feed nozzle should be fitted with a half-open pipe inlet device.

For vessel diameters of 0.8 m and greater, a vane-type inlet device is recommended. The diameter of the nozzle dn, may be taken equal to that of the feed pipe, but the following two criteria shall also be satisfied:

$\rho_m.V^2 \leq 6000$ kg / m.s^2 ---- (3.23)

$\rho_g.V^2_{g,in} \leq 3750$ kg / m.s^2 ---- (3.24)

Where:

ρm = (Mg + Ml)/(Qg + Ql) ---- (3.25)
(Mean density of mixture in the feed pipe)

Vm= (Qg+Q1) / $(\pi/4)d_L^2$ ---- (3.26)
(Velocity of mixture in the inlet nozzle)

2) Gas Outlet Nozzle

The diameter of the gas outlet nozzle should normally be taken equal to that of the outlet pipe, but the product ρg × Vg², out shall not exceed 3750 kg/m.s²

3) Liquid Outlet Nozzle

The diameter of the liquid outlet nozzle shall be chosen such that the velocity in it does not exceed 1 m/s, but should preferably be lower. The nozzle shall be equipped with a vortex breaker

d) Pressure drop

The pressure differential between inlet and vapor outlet is:

Pin - Pout = 8 × 10-4 × ρg × V2g,out kPa ---- (3.27)

In addition to the pressure drop mentioned above, it is sufficient for most purposes to assume that the extra pressure drop over the demister mat is equivalent to 10 mm of liquid.

e) Demister mat specifications

The mat shall be made of knitted wire formed to give the correct shape, and not cut so as to leave raw edges and loose pieces of wire which could become detached.

The wire mesh shall have a free volume > 97%, a wire surface area > 350 m^2/m^3 and a wire thickness$\geq$ 0.23 mm and $\leq$ 0.28 mm.

The thickness of 0.1 m for the mat is recommended. The wire mat shall be placed between two grids and shall be fastened in such a way that it cannot be compressed when being mounted.

3.7) Model of a typical KOD

Table 3.2 (Notations used in the calculations of KOD Model):

- F_0 = Feed flow rate (m^3/sec)
- F_L = Liquid exit flow rate (m^3/sec)
- F_v = Vapor exit flow rate (m^3/sec)
- T_0 = Feed Temperature (°C)
- T_v = Temperature of vapor (°C)
- T_L = Temperature of liquid (°C)
- y_o = Feed Composition (% mol) [Assuming feed contains only vapor phase]
- y_i = Vapor composition within the system (% mol)
- y_f = Composition of exit vapor stream (% mol)
- x_i = Liquid composition within the system (% mol)
- x_f = Composition of exit liquid stream (% mol)
- ρ_L' = Liquid density within the separator (kg/m^3)
- ρ_L = Density of exit liquid stream (kg/m^3)
- ρ_v' = Vapor density within the separator (kg/m^3)
- ρ_v = Density of exit vapor stream (kg/m^3)
- M = Mass (kg)
- M_v^{av} = Average molar mass of vapor (kg)
- h = height of liquid column (m)
- r = Radius of separator (m)
- D = Diameter of the separator (m)
- L = Vertical length of the separator (m)
- P = Pressure
- R = Gas constant
- V = Volume [Assuming the separator to be of perfectly cylindrical shape]

Forcing function in the system:

- Feed Rate (F_0)
- Feed Temperature (T_0)
- Feed Composition (y_0)

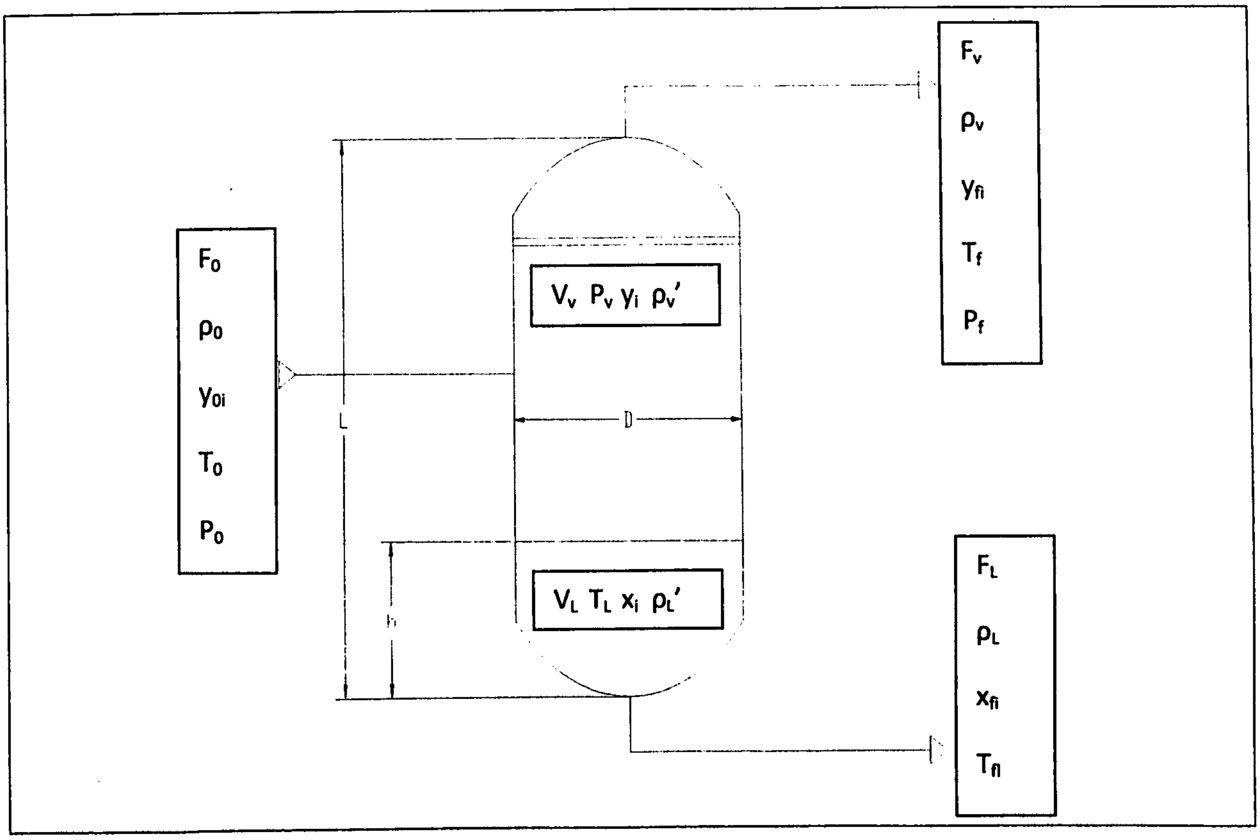


Fig. 3.4: Schematic diagram of Flare KOD

The density of the liquid in the tank ρ_L' will be a function of temperature and composition of the liquid i.e. $\rho_L' = f(x_j, T_L)$ ---- (3.28)

The function can be defined as:

w.r.t. x_j → term used will be $\rho l = \sum_{k=1}^{n} xj\rho j$

w.r.t. T → term used will be $V = V_0(1 + \beta \Delta T)$ [where V is volume at temperature T, V_0 is volume at temperature T_0, β is volumetric expansion coefficient of the collected liquid, $\Delta T = T - T_0$]

So $\rho_L' = M_L/V = M_L'/[V_0(1 + \beta\Delta T)]$ ---- (3.29)

Assuming isothermal process $\Delta T = 0$

So $\rho_L' = M_L/V$ [where $V = V_0$] ---- (3.30)

The density of vapor in tank will be a known function of temperature, pressure and composition i.e. $\rho_v' = (M_v^{av}.P)/RT_v$ ---- (3.31)

Outlet liquid flow rate will depend on the volume of liquid column V_L which will depend on height of liquid column 'h' i.e. $F_L = f(h)$ ---- (3.32)

Outlet gas flow rate will depend on the vapor pressure within the system i.e. $F_v = f(P_v)$ ----(3.33)

3.7.1) <u>Overall Continuity Equation:</u>

$dM/dt = \rho_0 F_0 - (\rho_v F_v + \rho_L F_L)$ ---- (3.34)

The mass within the system can be represented as

$V_L \rho_{L'} + V_v \rho_v'$ ---- (3.35)

$= V_L \rho_{L'} + (V - V_L)\rho v'$ ---- (3.36)

$V_L = \pi r^2 h$ ---- (3.37) [The volume data has been calculated assuming the separator to be perfectly cylindrical]

$V = \pi r^2 L$ ---- (3.38)

Substituting the values of eqn. 3.36, 3.37, 3.38 in equation 3.34 we get

$\pi r^2\, d[h.\rho_L' - (L-h)\rho_v']/dt = \rho_0 F_0 - (\rho_v F_v + \rho_L F_L)$ ---- (3.39)

Substituting the values of eqn 3.30, 3.31, 3.32, 3.33 in eqn. 3.39 we get

$\pi r^2\, d[h.\, f(x_j, T) - (L-h)\,(M_v^{av}.P)/RT]/dt = \rho_0 F_0 - (\rho_v\, f(P_v) + \rho_L\, f(h))$ ---- (3.40)

Assumptions:

For the function $F_v = f(P_v)$; design (i.e. maximum allowable) flow rate is assumed

For the function $F_L = f(h)$; design (i.e. maximum allowable) flow rate is assumed

Now for the calculation of ρ_L' and ρ_v' i.e. the density of vapor phase and liquid phase within the separator we will require the information on composition of both the phases (i.e. x_j and y_i).

The general input components of the feed are as follows:

(Courtesy: FGRU Design Basis Information, Process Specification Form, John Zink Company)

- Alkanes: C_1 to C_{10}
- Alkenes: C_2 to C_5
- Alkyne: C_2
- Napthenes: C_5 to C_7
- Aromatics: BTX and Styrene
- Others:
  - Methanol
  - Ethanol
  - H_2O
  - HCl
  - Cl_2
  - NH_3
  - SO_2
  - CO
  - CO_2
  - H_2S
  - H_2
  - O_2
  - N_2
  - He

Which accounts to a total of 32 components, it is beyond the scope of this project to prepare a simulation to find composition w.r.t. 32 components so the above components are to be grouped for creation of pseudo components:

Following similarities are considered while grouping the components:

- Molecular structure
- Phase state (i.e vapor or liquid at particular temperature)
- Solubility for a particular solvent (water in present case)

On the basis of above considerations following groups are prepared:

- Group 1 [Non Condensable HC]: Alkanes (C_1 to C_4), Alkenes (C_2 to C_4), Ethylene
- Group 2 [Condensable HC]: Alkanes (C_5 to C_{10}), Alkenes (C_5), Aromatics
- Group 3 [Water and water soluble components]: H_2O, Methanol, Ethanol, HCl, NH_3, SO_2, Cl_2
- Group 4 [Inorganic non-condensable & non-water soluble components]: H_2, N_2, O_2, He

So now a simulation to find the composition w.r.t. 4 components is to be determined (G_1, G_2, G_3, G_4)

Since G_1 and G_4 are considered to be non-condensible so it will be assumed (for further simplicity) that presence of the 2 mentioned groups are only in vapor phase, and have no component in the liquid phase.

So now it is evident that the components which may exist in both vapor and liquid phase are G_2 and G_3.

For the calculation of composition at different time, and simulating the system the following MATLAB™ script can be used for solving eqn. 3.40

3.7.2) <u>Algorithm for the script:</u>

- Take the required inputs viz.
    - T = System temperature in degree C
    - R = 8.314
    - tf = Simulation time for the system in seconds
    - dt = Time intervals
    - F0 = Feed flow rate (m^3/sec)
    - rho0 =Feed density kg/m^3
    - M1 = molar mass of G1
    - M2 = molar mass of G2
    - M3 = molar mass of G3
    - M4 = molar mass of G4
    - P1 = vapor pressure of G1 at temperature T
    - P2 = vapor pressure of G2 at temperature T
    - P3 = vapor pressure of G3 at temperature T
    - P4 = vapor pressure of G4 at temperature T
    - rho2 = density of condensed phase G2 at temperature T
    - rho3 = density of condensed phase G3 at temperature T
    - y1 = mole fraction of G1 in feed
    - y4 = mole fraction of G2 in feed
    - Pv = vapor pressure within the KOD at particular time t (regular input required which can be provided by a regular pressure monitoring device)
    - Fl = maximum allowable flow-rate for liquid
    - Fv = maximum allowable flow-rate for vapor
- Begin a loop for t=0 to t=tf, with an interval of dt
- At time t calculate the vapor composition (i.e. calculate the value of y3 and y4) by following simultaneous equations
    1) y2*P2 + y3*P3 = P – (y1*P1 + y4*P4)
    2) y2 + y3 = 1 – (y1 + y4)

    (Where the values of P1, P2, P3, P4, y1 and y4 are provided as inputs)

- From the obtained values as mentioned above calculate the average molar mass as $Mav = \sum_{k=1}^{4} ykMk$
- Calculate the vapor density as $\rho_v = M_{av}P_v/RT$
- Calculate mass of G2 in liquid as m2 = (F_0* ρ_0 *y02) – (Fv*rhov*y2)
- Calculate mass of G3 in liquid as m3 = (F_0* ρ_0 *y03) – (Fv*rhov*y3)
- Calculate total mass of liquid as mL = m2 + m3
- Take the input of liquid level as 'h' (input supplied by level monitor)
- Calculate liquid volume as $VL = \pi r^2 h$
- Calculate liquid density as $\rho_L = mL/VL$
- Call the function to solve differential equation mentioned in eqn. 3.40
- Store the value of M corresponding to t in an array
- End the loop
- Plot M vs. t

3.7.3) MATLAB™ script:

The following MATLAB™ script is prepared based on above mentioned algorithm.

```
% file name kod_cntn_call

% to simulate the overall continuity equation for Flare KOD

% code prepared by Kumar Pranav B.Tech. APE Downstream (2006-10) (UPES)

clear all; clc;

T = input ('System temperature in degree C');

R = 8.314;

tf = input ('Simulation time for the system in seconds');

dt = input ('Time intervals');

F0 = input ('Feed flow rate (m^3/sec)');

rho0 = input ('Feed density kg/m^3');

M1 = input ('molar mass of G1');

M2 = input ('molar mass of G2');

M3 = input ('molar mass of G3');

M4 = input ('molar mass of G4');
```

```
P1 = input ('vapor pressure of G1 at temperature' T);
P2 = input ('vapor pressure of G2 at temperature' T);
P3 = input ('vapor pressure of G3 at temperature' T);
P4 = input ('vapor pressure of G4 at temperature' T);
rho2 = input ('density of condensed phase G2');
rho3 = input ('density of condensed phase G3');
y01 = input ('mole fraction of G1 in feed');
y02 = input ('mole fraction of G2 in feed');
y03 = input ('mole fraction of G3 in feed');
y04 = input ('mole fraction of G4 in feed');
Fl = input ('maximum allowable flow-rate for liquid');
Fv = ('maximum allowable flow-rate for vapor');
for t=0:dt:tf
        dtspan = [t t+dt];
        M0 = F0*rho0;
        Pv = input ('pressure of system at time' t); % input supplied by pressure monitor
        A = [P2,P3;1,1];
        B = [(P-(y01*P1+y04*P4);(1-y01-y04)];
        C = A\B;
        y2 = C(1);
        y3 = C(2);
        Mav = y1*M1 + y2*M2 + y3*M3 + y4*M4;
        rhov = (Mav*Pv)/(R*T);
        m2 = (F0*rho0*y02) – (Fv*rhov*y2);
        m3 = (F0*rho0*y03) – (Fv*rhov*y3);
```

```
        mL = m2 + m3;
        h = input ('height of liquid in the KOD'); % input supplied by level monitor
        VL = pi*r^2*h;
        rhoL = mL/VL;
        [t,M] = ode45 (@ kod_cntn,dtspan,M0);
end;
plot (M,t);
xlabel ('Time');
ylabel ('Mass accumulation in KOD');
title ('Simulation for Flare KOD');
grid on;
```

Following code (which is to be placed in the same working directory as that of the call file mentioned above) is for the function file containing the differential equation which is called by the above mentioned code.

```
% file name kod_cntn
% Used to store function to be solved
function Mprime = kod_cntn (t, M,rho0, F0, rhov, Fv, rhol, Fl);
 Mprime = [rho0*F0 – (rhov*Fv + rhol*Fl)];
```

3.8) 3 Phase Separator design:

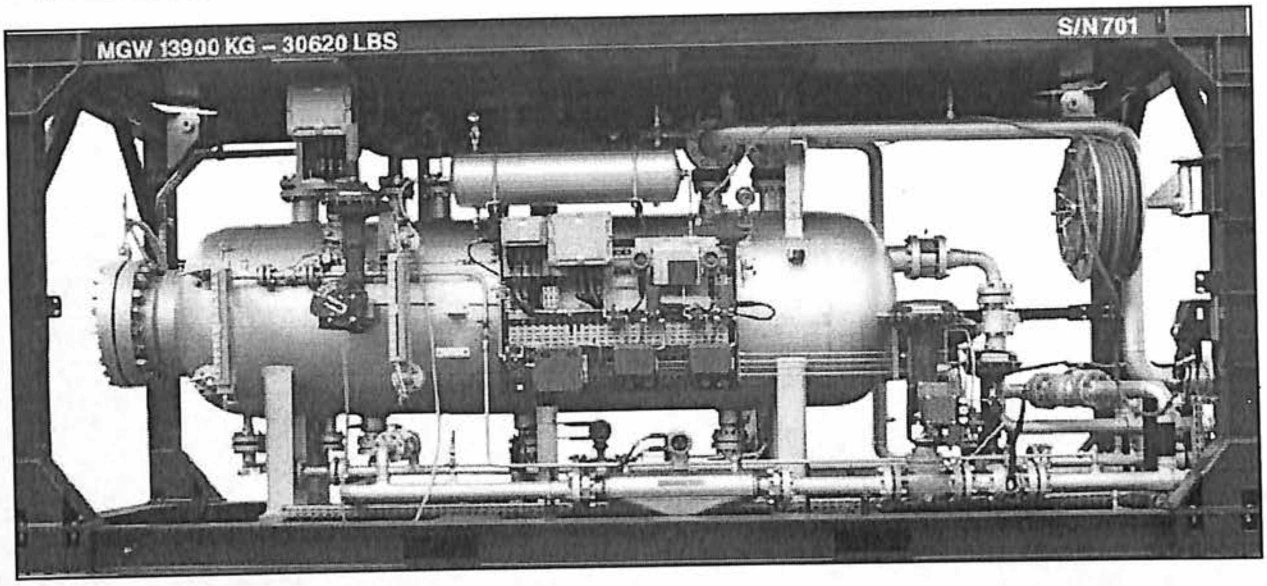


Fig 3.5: Horizontal 3 phase separator (*Courtesy: http://www.slb.com)*

Horizontal separators are practically used where large volumes of total fluids and large amount of dissolved gas are present with the liquid. They are also preferred where the vapor-liquid ratio is small or where three phase separation is required.

Separators can be any length, but the ratio of seam-to-seam length to the diameter of the vessel, Lv/Dv, is usually in the range of 2:1 to 4:1, the critical velocity within the three phase separator should be maintained as:

$V_C = K[(\rho_L - \rho_v)/\rho_v]^{0.5} (L_v/10)^{0.56}$ ---- (3.41)

K values given in Table 3.1 can be used for horizontal demister separators.

Note that the preferred orientation of mesh pad in horizontal separators is in the horizontal plane, and it is reported to be less efficient when installed in vertical position. But both designs are actually used due to specified applications.

The method presented in the following sections can be followed as a quick and safe method for basic design of horizontal demister separators.

1) Horizontal Mat

For sizing a horizontal separator with a horizontal mat, the equation and method presented for KOD can be used.

2) Vertical Mat

For a horizontal vessel fitted with a vertical mat, as shown in Fig. 3.7, the equation below can be applied:

$Q_{max}/A \leq 0.15$ ---- (3.42)

Where: A is taken above the LZA (HH) liquid level and Qmax is the process design value of Q plus a margin, (according to eqn. 3.1). Horizontal vessels are usually designed to be between about one third and one half-full of liquid.

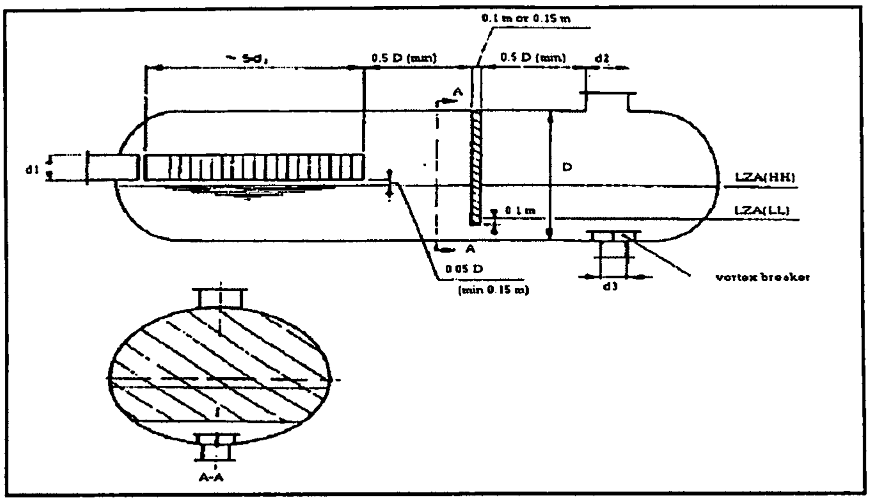


Fig. 3.6: A Horizontal Separator Fitted with Vertical Mat (*Courtesy: API Spec. 12J "Specification for Oil and Gas Separators", 7th. Ed., Oct. 1989*)

b) Nozzles

1) Feed nozzle, dn_1

The feed nozzle shall be fitted with a vane-type or another type of inlet device. The diameter of the nozzle,dn1, may be taken equal to that of the feed pipe but the following two criteria shall also be satisfied:

$\rho_m V^2 \leq 6000$ kg/ms^2 ---- (3.43)

$\rho_v V^2_{g,in} \leq 3750$ kg/ms^2 ---- (3.44)

The length of the vane type inlet nozzle should be taken equal to approximately 5 times the feed nozzle diameter.

2) Gas Outlet Nozzle, dn_2

For the gas outlet nozzle, the same method applies as for a vertical knock-out drum.

3) Liquid Outlet nozzle, dn_3

For the liquid outlet nozzle, the same method applies as for a vertical knock-out drum.

c) Pressure Drop

In addition to the pressure drop given in (eq. 3.27), it should be sufficient for most purposes to assume that the extra pressure drop over the demister is equivalent to 10 mm of liquid. There will be no additional pressure loss over the vane type inlet device.

Three-Phase vessel weir plates

The weir plate is a device which separates oil and water into two compartments.

Weir plates can be either fixed or adjustable. Fixed weir plates should be used in cases where the water content is constant. Adjustable weir plates are required when the water content is expected to increase.

Generally, the weir plate should always be 150 mm (minimum) above the oil/water interface. It can vary in height from the bottom inside shell wall to the top of the plate from 300 mm to the midpoint of the vessel.

Anti wave baffles

In large volume 3 phase separators it is sometimes necessary to install an anti wave baffle(s) to eliminate disturbances of oil/water interface. This is a partial cross sectional area plate with punched holes which act as a wave breaker while still letting liquid pass through.

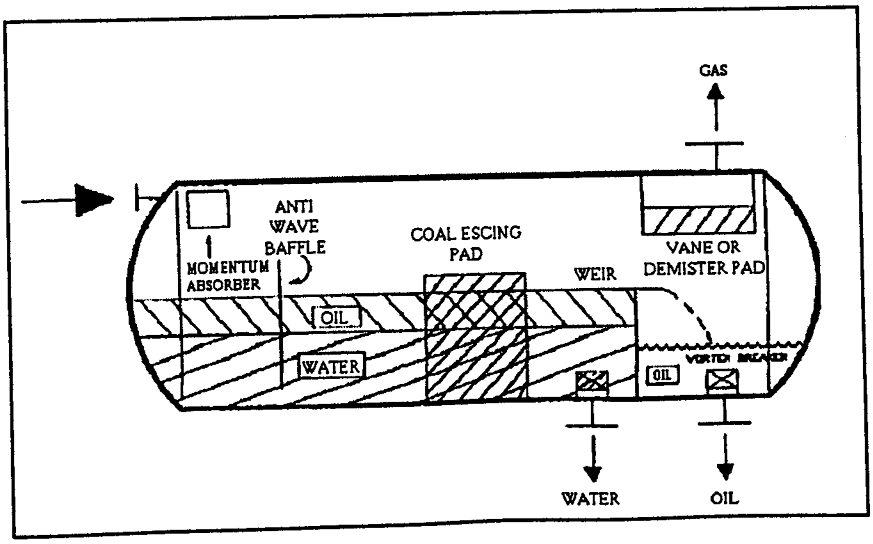


Fig. 3.7: Horizontal Oil/Gas/Water Separator (*Courtesy: API Spec. 12J "Specification for Oil and Gas Separators", 7th. Ed., Oct. 1989*)

3.9) Model for a typical 3-phase separator:

Table 3.3 (Notations used in the calculations of 3 phase separator model):

- F_0 = Feed flow rate (m^3/sec)
- F_L = Hydrocarbon liquid exit flow rate (m^3/sec)
- F_W = Operating liquid (water) exit flow rate (m^3/sec)
- F_v = Vapor exit flow rate (m^3/sec)
- T_0 = Feed Temperature (°C)
- T_v = Temperature of vapor (°C)
- T_L = Temperature of hydrocarbon liquid (°C)
- T_W = Temperature of operating liquid (water) (°C)
- y_o = Feed Composition (% mol) [Assuming feed contains only vapor phase]
- y_i = Vapor composition within the system (% mol)
- y_f = Composition of exit vapor stream (% mol)
- x_i = Hydrocarbon liquid composition within the system (% mol)
- x_f = Composition of exit hydrocarbon liquid stream (% mol)
- ρ_L' = Hydrocarbon liquid density within the separator (kg/m^3)
- ρ_L = Density of exit hydrocarbon liquid stream (kg/m^3)
- ρ_w = Density of operating liquid (water) [Assumption is made that water is in almost pure state so ρ_w = 1000 kg/m^3] (kg/m^3)
- ρ_v' = Vapor density within the separator (kg/m^3)
- ρ_v = Density of exit vapor stream (kg/m^3)
- M = Mass (kg)
- M_v^{av} = Average molar mass of vapor (kg)
- h_L = Height of hydrocarbon liquid column (m)
- h_w = Height of operating liquid (water) column (m)
- r = Radius of separator (m)
- D = Diameter of the separator (m)
- L = Horizontal length of the separator (m)
- L_W = Horizontal length of water section (m)
- P = Pressure
- R = Gas constant
- V = Volume [Assuming the separator to be of perfectly cylindrical shape]

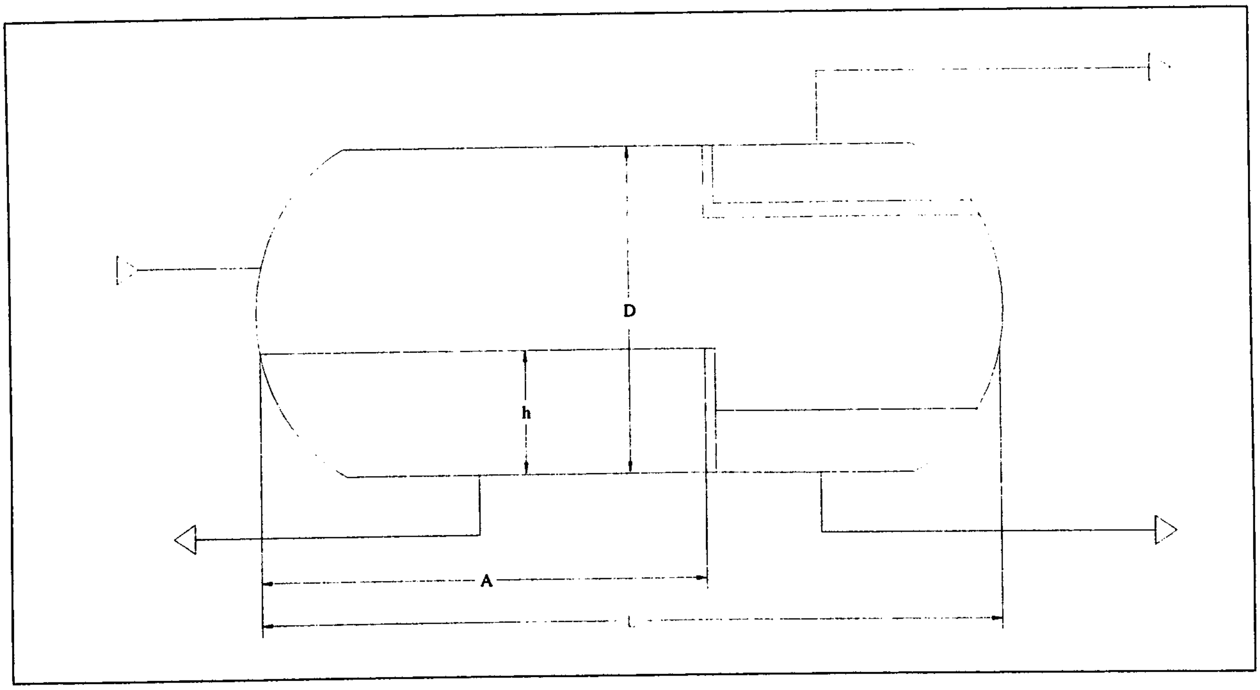


Fig 3.8: Schematic diagram of a 3 phase separator installed after the compressor

The density of the liquid in the tank ρ_L' and ρ_w' will be a function of temperature and composition of the liquid i.e.:

$\rho_L' = f(x_{Lj}, T_L)$ ---- (3.44)

$\rho_w' = f(x_{wj}, T_w)$ ---- (3.45)

The function can be defined as:

w.r.t. x_j → term used will be $\rho l = \sum_{k=1}^{n} xj\rho j$

w.r.t. T → term used will be $V_L = V_0(1 + \beta\Delta T)$ [where V is volume at temperature T, V_0 is volume at temperature T_0, β is volumetric expansion coefficient of the collected liquid, $\Delta T = T - T_0$]

So $\rho_L' = M_L/V_L = M_L'/[V_0(1 + \beta\Delta T)]$ ---- (3.46)

Assuming isothermal process $\Delta T = 0$

So $\rho_L' = M_L/V_L$ [where $V_L = V_0$] ---- (3.47)

Simmilar function will be used for ρ_w'.

$\rho_w' = M_w/V_w$ ---- (3.48)

The density of vapor in tank will be a known function of temperature, pressure and composition i.e. $\rho_v' = (M_v^{av}.P)/RT_v$ ---- (3.49)

Outlet liquid flow rate will depend on the volume of liquid column V_L which will depend on height of liquid column 'h' i.e. $F_L = f(h)$ ---- (3.50)

Outlet gas flow rate will depend on the vapor pressure within the system i.e. $F_v = f(P_v)$ ----(3.51)

3.9.1) Overall continuity equation:

$dM/dt = \rho_0 F_0 - (\rho_v F_v + \rho_L F_L + \rho_w F_w)$ ---- (3.52)

The mass within the system can be represented as

$V_L \rho_L' + V_v \rho_v' + V_w \rho_w$ ---- (3.53)

$= V_L \rho_L' + V_w \rho_w + (V - V_L - V_w)\rho v'$ ---- (3.54)

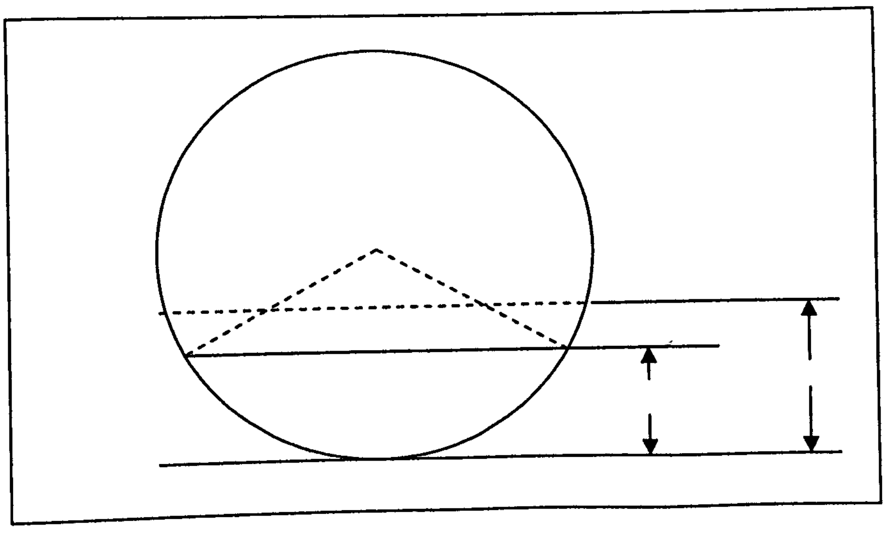


Fig 3.9: Cross section of a 3 phase separator

[The volume data has been calculated assuming the separator to be perfectly cylindrical]

$V_L = A_L (L - X)$ [Where A_L is area of segment of cross section of separator wetted by liquid hydrocarbon] ---- (3.55)

$A_L = r^2/2(\theta_l - \sin\theta_l)$ ---- (3.56)

Where $\theta_1 = 2\cos^{-1}[(H - h_L)/r]$ ---- (3.57)

$V_w = A_w X$ ---- (3.58)

$A_w = r^2/2(\theta_2 - \sin\theta_2)$ ---- (3.59)

Where $\theta_2 = 2\cos^{-1}[(H - h_w)/r]$ ---- (3.60)

$V = \pi r^2 L$ ---- (3.61)

Substituting the values of eqn. 3.54 to 3.61 in equation 3.52 we get

$d\,[r^2/2((2\cos^{-1}[(H - h_L)/r) - \sin(2\cos^{-1}[(H - h_L)/r))\rho_L' + V_v\rho_v' + V_w\rho_w\,]/dt = \rho_0 F_0 - (\,\rho_v F_v + \rho_L F_L + \rho_w F_w)$ [the value of V_w and V_v can also be shown as V_L has been done, whereas such display has been avoided for sake of simplicity] ---- (3.62)

Further F_v F_w F_L can also be displayed according to equations XXX, but following assumptions are made for the sake of simplicity.

Assumptions:

For the function $F_v = f(P_v)$; design (i.e. maximum allowable) flow rate is assumed

For the function $F_L = f(h)$; design (i.e. maximum allowable) flow rate is assumed

For calculation of ρ_v', ρ_L', ρ_w' the composition of each phase i.e. vapor, liquid hydrocarbon and water will be required. Preliminarily it will require the feed composition.

Considering the feed composition of KOD we have:

(Courtesy: FGRU Design Basis Information, Process Specification Form, John Zink Company)

- Alkanes: C_1 to C_{10}
- Alkenes: C_2 to C_5
- Alkyne: C_2
- Napthenes: C_5 to C_7
- Aromatics: BTX and Styrene
- Others:
    - Methanol
    - Ethanol
    - H_2O
    - HCl
    - Cl_2
    - NH_3
    - SO_2

- CO
- CO_2
- H_2S
- H_2
- O_2
- N_2
- He

The difference from KOD feed is that G_3 will be at lower mole percentage, as most of it is assumed to have been removed in the KOD, and G_3 will be at a much higher mole percentage due to high amount of water that is entrained from the liquid ring compressor.

Other than the 2 above mentioned differences, other calculations required for simulation will be similar to that of KOD.

Grouping of the components to form pseudo components is done in the same way as it has been done for KOD.

So for 3 phase separator we have to find composition w.r.t. G_2 and G_3 in vapor (i.e. y_i, x_{Li}, x_{wi})

3.9.2) <u>Algorithm for the script:</u>

Following algorithm will be used for the purpose:

- Take the required inputs viz.
    - T = System temperature in degree C
    - R = 8.314
    - tf = Simulation time for the system in seconds
    - dt = Time intervals
    - F0 = Feed flow rate (m^3/sec)
    - rho0 =Feed density kg/m^3
    - M1 = molar mass of G1
    - M2 = molar mass of G2
    - M3 = molar mass of G3
    - M4 = molar mass of G4
    - P1 = vapor pressure of G1 at temperature T
    - P2 = vapor pressure of G2 at temperature T
    - P3 = vapor pressure of G3 at temperature T
    - P4 = vapor pressure of G4 at temperature T
    - rho2 = density of condensed phase G2 at temperature T
    - rho3 = density of condensed phase G3 at temperature T
    - y01 = mole fraction of G1 in feed
    - y02 = mole fraction of G2 in feed

- y03 = mole fraction of G3 in feed
- y04 = mole fraction of G4 in feed
- Pv = vapor pressure within the 3 phase seperator at particular time t (regular input required which can be provided by a regular pressure monitoring device)
- Fl = maximum allowable flow-rate for liquid
- Fv = maximum allowable flow-rate for vapor

- Begin a loop for t=0 to t=tf, with an interval of dt
- At time t calculate the vapor composition (i.e. calculate the value of y3 and y4) by following simultaneous equations
  3) y2*P2 + y3*P3 = P – (y1*P1 + y4*P4)
  4) y2 + y3 = 1 – (y1 + y4)
  (Where the values of P1, P2, P3, P4, y1 and y4 are provided as inputs)
- From the obtained values as mentioned above calculate the average molar mass as Mav = $\sum_{k=1}^{4} ykMk$
- Calculate the vapor density as $\rho_v = M_{av}P_v/RT$
- Take the liquid hydrocarbon density to be same as that of density of condensed G2 phase.
- Take the liquid water solution density to be same as that of density of condensed G3 phase
- Call the function to solve differential equation mentioned in eqn. 3.62
- Store the value of M corresponding to t in an array
- End the loop
- Plot M vs. t

3.9.3) MATLAB™ script:

On basis of above mentioned algorithm following MATLAB™ script has been written which will simulate the 3 phase separator, by using equation 3.62

```
% file name s3p_cntn_call

% to simulate the overall continuity equation for 3 phase separator

% code prepared by Kumar Pranav B.Tech. APE Downstream (2006-10) (UPES)

clear all; clc;

T = input ('System temperature in degree C');

R = 8.314;

tf = input ('Simulation time for the system in seconds');

dt = input ('Time intervals');
```

```
F0 = input ('Feed flow rate (m^3/sec)');
rho0 = input ('Feed density kg/m^3');
M1 = input ('molar mass of G1');
M2 = input ('molar mass of G2');
M3 = input ('molar mass of G3');
M4 = input ('molar mass of G4');
P1 = input ('vapor pressure of G1 at temperature' T);
P2 = input ('vapor pressure of G2 at temperature' T);
P3 = input ('vapor pressure of G3 at temperature' T);
P4 = input ('vapor pressure of G4 at temperature' T);
rho2 = input ('density of condensed phase G2');
rho3 = input ('density of condensed phase G3');
y01 = input ('mole fraction of G1 in feed');
y02 = input ('mole fraction of G2 in feed');
y03 = input ('mole fraction of G3 in feed');
y04 = input ('mole fraction of G4 in feed');
Fl = input ('maximum allowable flow-rate for liquid');
Fv = input ('maximum allowable flow-rate for vapor');
rhoL = input ('density of condensed G2 phase);
rhoW = input('density of condensed G3 phase);
for t=0:dt:tf
        dtspan = [t t+dt];
        M0 = F0*rho0;
        Pv = input ('pressure of system at time' t); % input supplied by pressure monitor
        A = [P2,P3;1,1];
```

```
        B = [(P-(y1*P1+y4*P4);(1-y1-y4)];
        C = A\B;
        y2 = C(1);
        y3 = C(2);
        Mav = y1*M1 + y2*M2 + y3*M3 + y4*M4;
        rhov = (Mav*Pv)/(R*T);
        [t,M] = ode45 (@ s3p_cntn,dtspan,M0);
end;
plot (M,t);
xlabel ('Time');
ylabel ('Mass accumulation in 3 Phase separator');
title ('Simulation for 3 Phase separator');
grid on;
```

Following code is for the function file containing the differential equation which is called by the above mentioned code.

```
% file name s3p_cntn
% Used to store function to be solved
function M = s3p_cntn (t, M,rho0, F0, rhov, Fv, rhol, Fl, rhow, Fw);
M = [rho0*F0 – (rhov*Fv + rhol*Fl + rhow*Fw)];
```

3.10) Compressor Selection for FGRU:

2 types of compressor may be used for the process:

- Liquid Ring Compressor
- Liquid Jet Compressor

3.10.1) Liquid Ring Compressor:

The rotor is positioned centrally in an oval-shaped body. Upon rotation, which proceeds without metal to metal contact, a ring of liquid is formed which moves with the rotor and follows the shape of the body. At the two points of the nearest proximity of the rotational axis and body, this completely fills the chambers of the rotor and as rotation proceeds, it follows the contour of the body and recedes again, leaving spaces to be filled by the incoming gas. These spaces are connected via the cone porting to the inlet of the compressor. As a result of the suction action thus created, gas is pulled into the compressor. As the rotation progresses, the liquid is forced back into the chambers, compressing the gas. This gas is forced out of the discharge port and then leaves the compressor via the outlet flange. The compressor is fed continuously with liquid which serves to seal the clearances between inlet and discharge port and remove the heat of compression. This liquid leaves the compressor together with the gas to be compressed and is separated from the gas in a discharge separator.

Liquid ring compressors are used both as single and double-acting design. In order to increase the suction capacity, machines are equipped with two-side flow impellers or double-impeller devices are used. According to their field of application, single and double-impeller compressors are known as single-acting machines and double acting compressors. The method of calculating the basic design values of a liquid ring machine is the same for both the vacuum pump and the compressor. Depending on the machine design and size, the optimal operation range of a vacuum pump lies at a circumferential impeller speed of between approx. 17 m/s and 20 m/s, compressors reach their optimum between 25 m/s and 30 m/s. Depending on the existing pressure ratio, there is a difference in the geometry of the port plate. Single-acting liquid ring compressors are manufactured in single-stage design for suction capacities of max. 10000 m3/h at a compression pressure of about 2.5 bar. Two-stage machines are available as single-acting versions for volume flow rates of max. ca. 1200 m3/h at discharge pressures of max. approx. 8 bar. Double-acting machines in single-impeller versions allow suction flows of max. 2500 m3/h at a compression pressure of approx. 3.3 bar. Higher compression pressures can be obtained by the series connection of multiple-stage compressors. For the compression based on higher suction pressures double-acting compressors are preferably used.

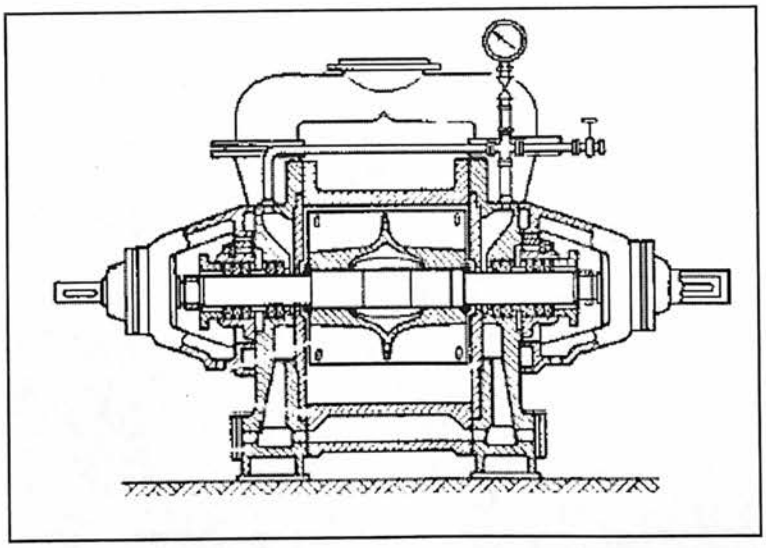


Fig. 3.10: Liquid ring compressor, single-stage, with double impeller (*Courtesy: H. Bannwarth; Liquid Ring Vacuum Pumps, Compressors and Systems*)

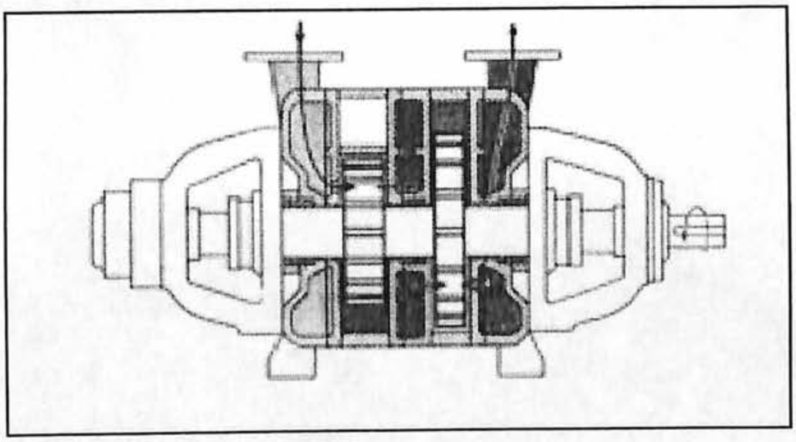


Fig. 3.11: Liquid ring compressor two-stage (*Courtesy: H. Bannwarth; Liquid Ring Vacuum Pumps, Compressors and Systems*)

Advantages of Liquid Ring Compressor:

- Virtually no gas temperature rise
- Low wear
- Reduced maintenance costs
- Reduced operation downtime
- Investment cost savings
- High operation safety
- Low noise
- Environmentally friendly operation

3.10.2) Liquid Jet Compressor:

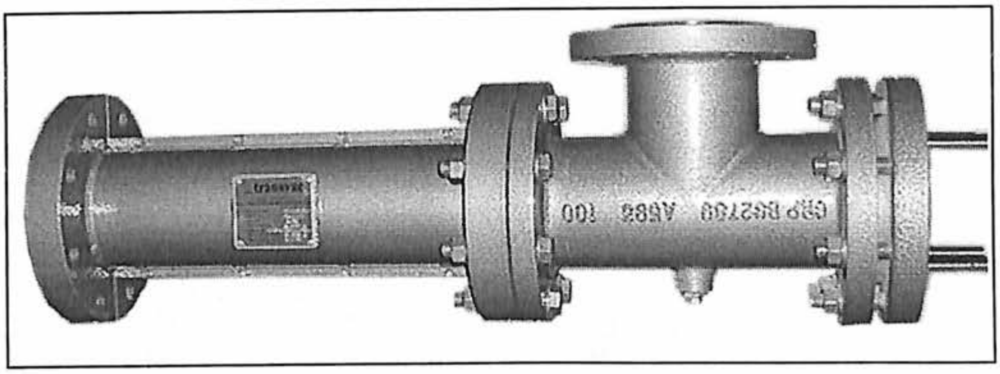


Fig. 3.12: A liquid Jet Compressor (*Courtesy: http://www.transvac.co.uk/webbrochures/Liquid_Jet_Compressors.pdf*)

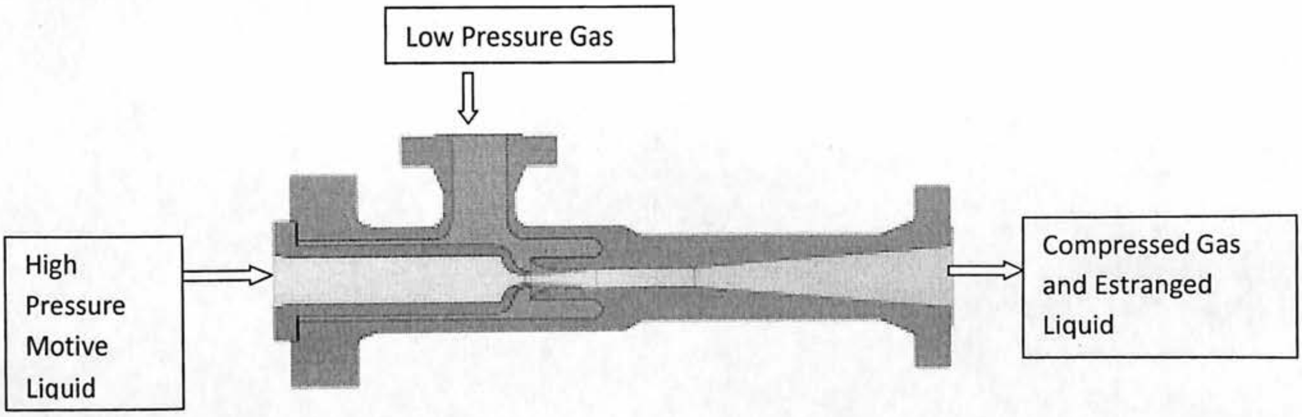


Fig. 3.13: Cross sectional working view of Liquid Jet Compressor (*Courtesy: Transvac datasheet on Flare Gas Recovery*)

In operation a high velocity jet of pressurized liquid discharged from the motive nozzle produces a region of low pressure in the suction chamber to entrain the secondary gas. The two streams then thoroughly mix in the throat before the resulting mixture flows through the diverging cone to regain pressure in order to overcome system discharge heads.

Advantage of Liquid Jet Compressor:

- Simple to operate and install
- Reliable with no moving parts
- Inline mixing of liquid and gas
- Virtually silent operation

- Minimum maintenance
- Suitable for hazard areas

3.10.3)Comparison of the 2 compressor types

Liquid jet compressor requires a high pressure motive fluid, for the purpose of which a pump needs to be installed to increase the pressure of the motive fluid (as shown in fig.3.14). As a general specification; for compression of 1 atms pressure of gas to 7 atms, at least 16 atms pressure of motive fluid is required, which increases the cost of electricity consumption (1.5 to 2 times than liquid ring compressor). Whereas is liquid ring compressor the process takes place in a single compressor without the need of installation of a separate pumping system.

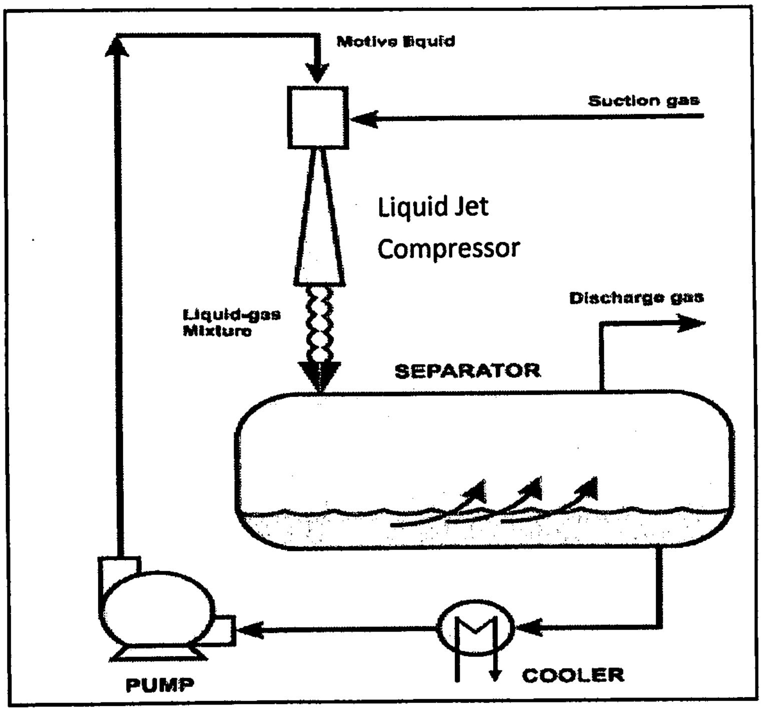


Fig. 3.14: Process Flow Diagram for Liquid Jet Compressor (*Courtesy: Hijet International; Brochure on Hijector Compressor*)

Liquid Jet compressors become useful when a high pressure motive fluid is present by default in the system, such as near production wells. The functioning of such a system is shown in fig. 3.15. Otherwise, where a high pressure motive fluid is not present then in such case liquid ring compressor is more useful.

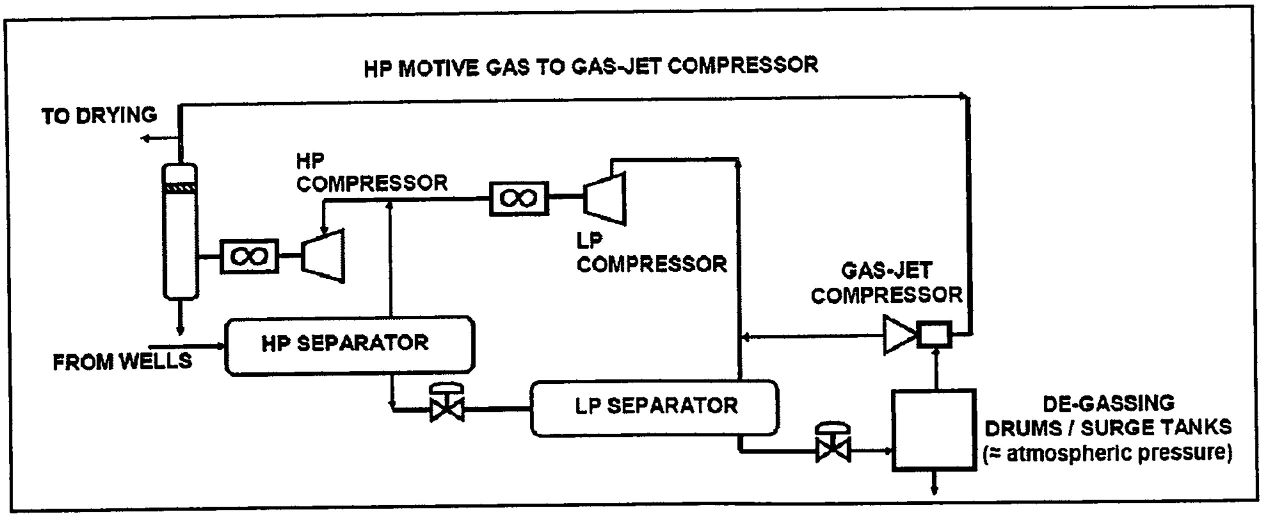


Fig. 3.15: Depiction of gas jet compressor usage at a production layout; similar operation will take place for liquid jet compressor, the difference being in motive fluid (*Courtesy: Transvac datasheet on Flare Gas Recovery*)

3.11) Design of Compressor:

Once the choice of the compressor is made, next step required is to design the compressor to suite the plant requirements. Compressor design involves only the determination of compressor capacity and power requirements for a given application, in order to select the type and size of compressor required.

As seen in the comparison of the 2 types of compressors, we see that the liquid ring compressor is more suitable for refineries and petrochemical plants. So in this section, designing of a liquid ring compressor will be dealt with. Liquid ring compressor works on the principle of centrifugal compressor, and due to the presence of liquid seal, the compression process is isothermal (as the heat released during the compression is absorbed by the liquid seal, and so the temperature of the gas being compressed remains constant). So the design of isothermal centrifugal compression will suffice for the liquid ring compression.

An analytic expression for the ideal horse power IHP is as below

$IHP= [3.0303\, q_{sc}\, p_{sc}\, T_1\ (Z_1+Z_2)/\ 2\, Z_1 T_{sc}]\ [(n/n-)[r^{(n-1)/n}-1]$ ---- (3.63)

For centrifugal compressors, the theoretical work required for compression is represented by the polytropic head hp,

$h_p= [1545\, T_1\ (Z_1+Z_2)/\ 2\, Z_1 M]\ [(n/n-1)[r^{(n-1)/n}-1]$ ---- (3.63)

Thus

$IHP= m\, h_p/33000$ ---- (3.64)

$GHP= m\, h_p/33000\eta_p$ ---- (3.65)

Centrifugal compressor performance is highly dependent upon speed.

The capacity varies directly as the speed, S, the head developed varies as the square of the speed, and the required horse power varies as the cube of the speed:

- $q \alpha S$
- $h_p \alpha S^2$
- $BHP \alpha S^3$

Compressor speed can be estimated as a function of the intake volume.

3.12) Overall Flow Stream Design of FGRU:

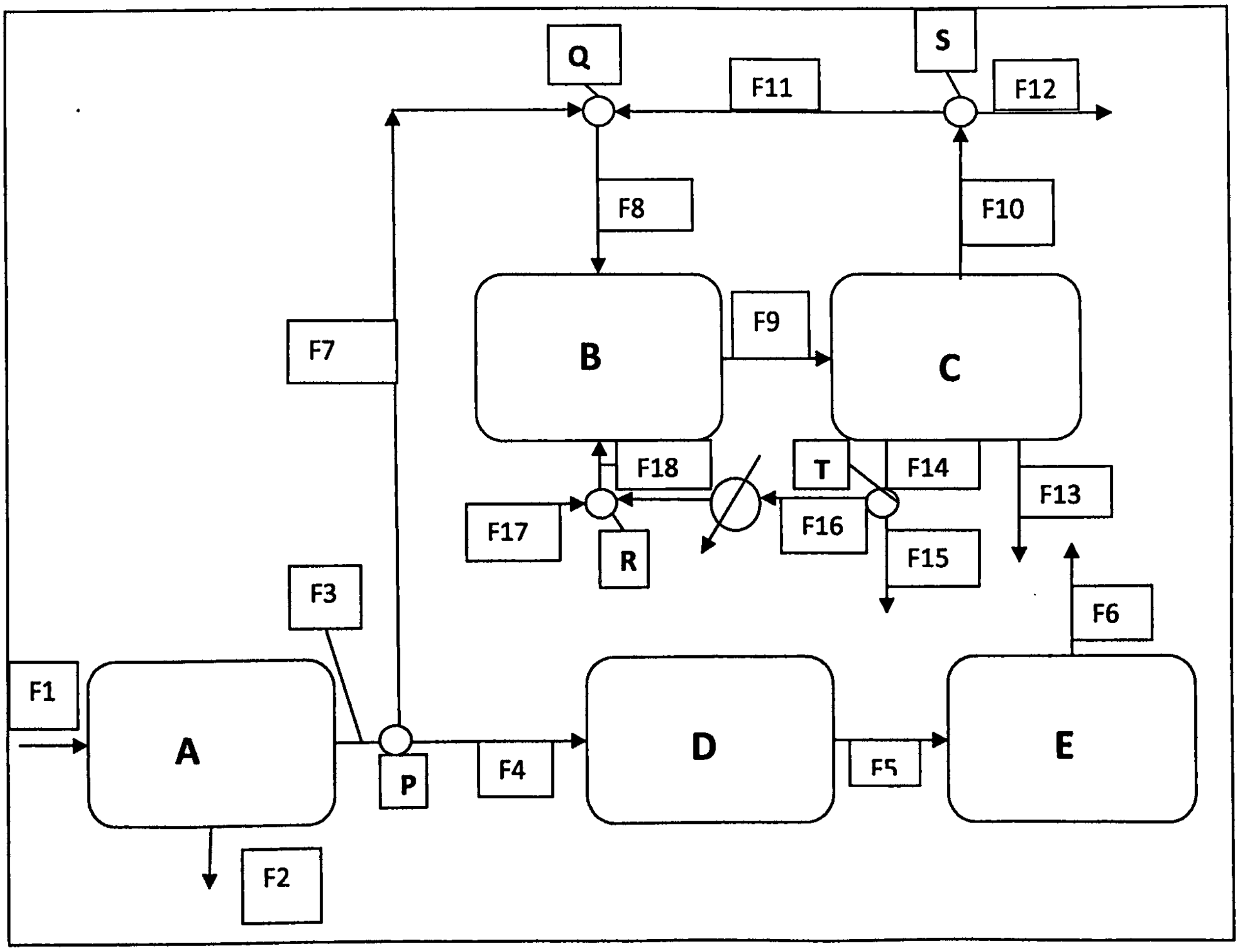


Fig 3.16: Block Flow Diagram of FGRU

Blocks in the Diagram:

A: Flare Knock Out Drum (KOD)

B: Liquid Ring Compressor

C: 3- Phase Separator

D: Liquid Seal Drum

E: Flare Stack

Table 3.4: Nodes in the Block Flow Diagram of FGRU

Node	Input	Output
P	F3	F4,F8
Q	F7,F12	F8
R	F16,F17	F18
S	F10	F11,F12
T	F14	F15, F16

Description of the streams:

- F1: Input to Flare KOD
- F2: Vapor output from Flare KOD
- F3: Liquid Output From Flare KOD
- F4: Flow towards Liquid Seal Drum
- F5: Output from Liquid Seal Drum
- F6: Gas being flared
- F7: Flow of gas towards FGRU
- F8: Flow of gas to compressor
- F9: Compressed Gas
- F10: Vapor exit from 3-phase separator
- F11: Part vapor recycled back to the process
- F12: Part of vapor recovered from the process
- F13: Liquid Hydrocarbon exit from 3-phase separator
- F14: Operating liquid exit from 3-phase separator
- F15: Part of operating liquid sent to effluent
- F16: Part of Operating liquid sent to recycle
- F17: Fresh operating liquid feed
- F18: Operating liquid entering the compressor

Input streams for the system = F1, F17

Output streams for the system = F3, F6, F12, F13, F15

Forming of mass balance for the system can be divided into two parts:

For the compressor operating liquid, where:

F17 = F15

For the FGR system, where:

F1 = F3 + F6 + F12 + F13

The recovery of the flare gas will be 100% when F6 = 0 (i.e. zero flaring), otherwise the efficiency of the recovery system will be calculated as:

Efficiency = (F1-F6)/F1 x 100

Mass balance at each node:

P: F3 = F4 + F8

Q: F7 + F12 = F8

R: F16 + F17 = F18

S: F10 = F11 + F12

T: F14 = F15 + F16

3.13) FGRU Control System:

Basically 2 types of control systems (depending on the type of flare system installed) can be used for FGRU, viz.

- Control system for flare without liquid seal drum
- Control system for flare with liquid seal drum present

3.13.1) FGRU Control System for flare without liquid seal drum:

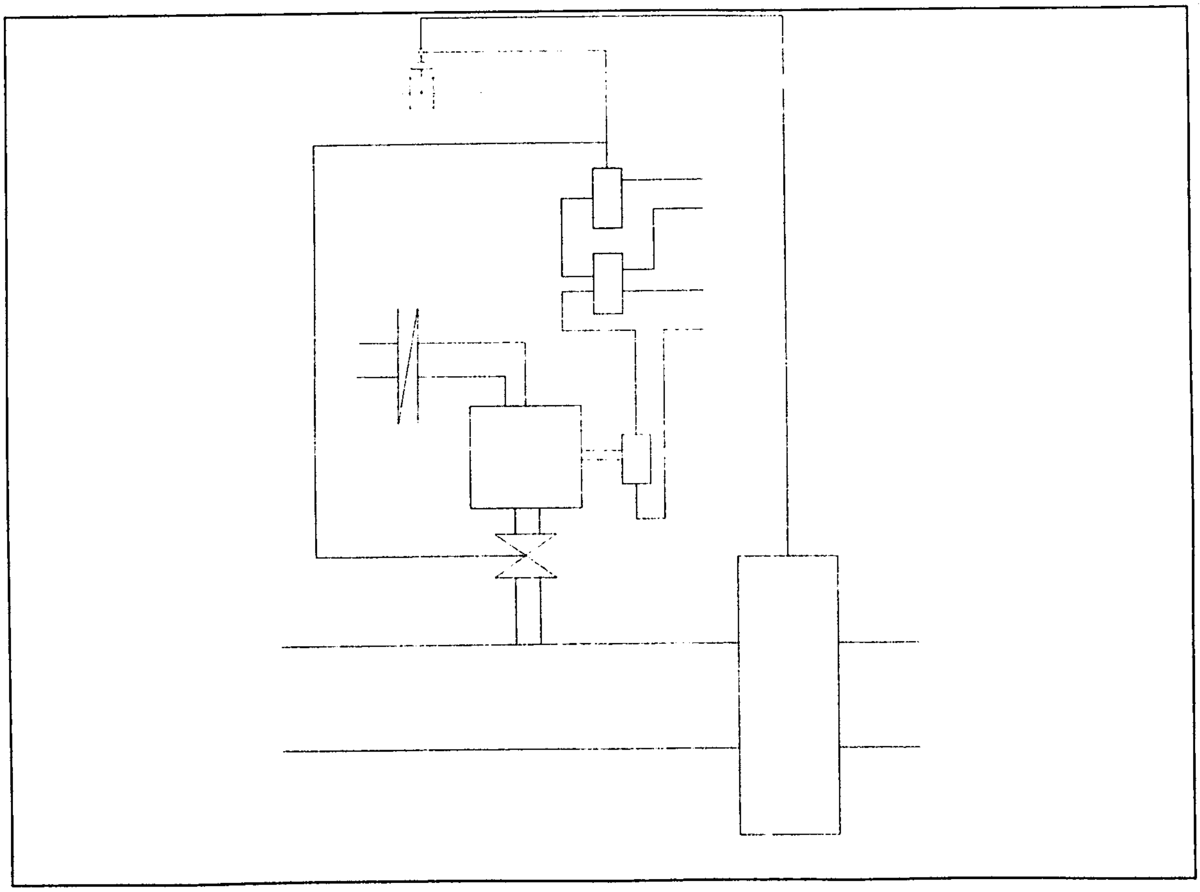


Fig. 3.17: Schematic Representation for FGRU Control System for Flare without Liquid Seal Drum (*Courtesy: Flare System Vapor Recovery: United States Patent 3915620; Inventor: Robert D. Reed*)

Description of the figure:

1) Represents the control system
2) Flare vapor flow system conduit
3) Vapor Flow within the system
4) Flow of vapor within the stack

5) Sensor system sensitive to flow rate of gases in conduit (2) and also pressure in (2) [The signal output is selected as function of pressure and flow rate]
6) Signal line which controls three operations:
    - Through line (7) controls valve (11) which initiates flow of steam to the flare stack to initiate proper combustion condition.
    - Through line (8) and line (9) to pressure control switch (10) which receives the electrical power over the lead (12) to control starting relay (13) which controls the power line (14) through leads (15), (16), (17) to supply power to the driving motor (18) which drives the compressor (19) through shaft (20) which takes in vapor from conduit (2) through conduit (21) and valve (22) and delivers compressed vapors through conduit (23) and check valve (24); conduit (25) carries the fuel gas for further processing. [Purpose of check valve (24) is to prevent any back flow of fuel gas]
    - Through line (25) controls valve (22) which is normally closed and opens on receiving signal from (5) through (25); control valve (22) allows additional flow of vapor from flare system to compressor (19) [A bypass is provided around control valve (22) with orifice (26) of appropriate size to maintain a selected minimum amount of gas into the compressor even though valve (22) is closed.

3.13.2) FGRU Control System for flare with liquid seal drum:

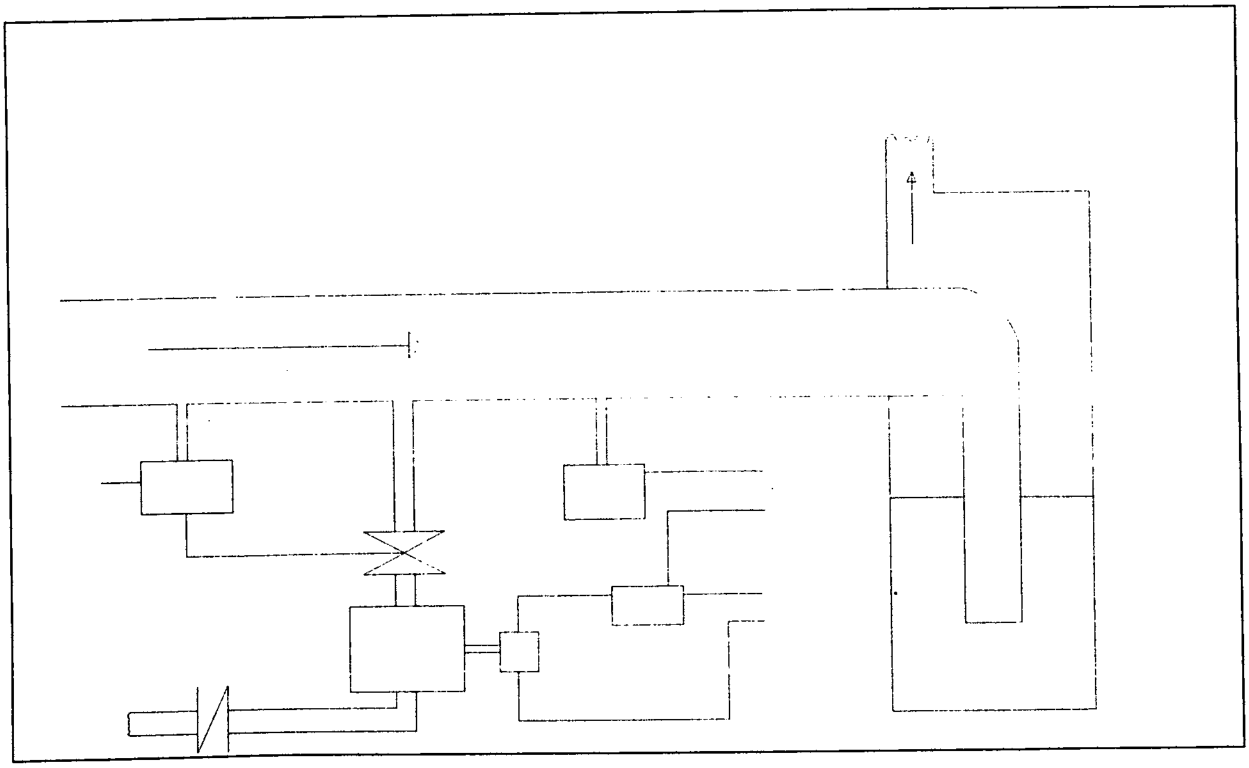


Fig. 3.18: Schematic Representation for FGRU Control System for Flare with Liquid Seal Drum (*Courtesy: Flare System Vapor Recovery: United States Patent 3915620; Inventor: Robert D. Reed*)

Description of figure:

1) Conduit carrying flare vapor
2) Vapor flow within the system
3) Vapor flow to the flare stack
4) Side conduit leading the vapor to the compressor (5) through control valve (6); the compressor compresses the gas up to required degree of compression and sends the fuel gas ahead through check valve (7). [Control valve (6) is provided with bypass having orifice (8)]
9) Pressure tap on conduit (1) leading to control means (10), which permits flow of fluid in (11) to pass through conduit (12) to the valve (6)
13) Chamber filled with water, where the conduit (1) is immersed. Depth of immersion or hydrostatic level through which the gases must pass is indicated by 'D'
    - Pressure in the conduit (1) is dictated by 'D'; and at static flow conditions is measured in terms of height of water column. Pressure in the conduit (1) must be greater than 'D'

- Due to the presence of water seal any intake of air is not possible within the system.

14) Conduit which transmits the pressure in conduit (1) [when it is equal to water header in water seal] to pressure switch (15) to deliver control power to relay (17) being supplied through power lead (16); on closing of the relay (17) power from power lead (18) is to motor (19) which transfers power to compressor (5) through shaft (20)

3.13.3) <u>Comparison of the above mentioned control systems:</u>

It is to be understood that greatest recovery of flare vapors is possible when the flare system includes a water seal between the point of vapor recovery and the flare. Pressure upstream of the water seal must rise to a condition greater than the depth of immersion of the tube pendant in the water of the seal in order to provide continuing vapor flow through the system to flare for discharge to atmospheric pressure. Thus all vapors moving from origin in the system upstream of the seal is recoverable since the water seal will not permit vapor flow in either direction until water-displacement pressure is present either upstream or downstream of the water seal. Withdrawal of vapor, by control is not possible until the pressure upstream of the water seal becomes substantially equal to immersion depth of the water seal and, by control, the rate of vapor withdrawal from the flare system increases upstream of the water seal as pressure there increases beyond the pressure required for the initial flow to the flare. Since initial compression option is not available until pressure upstream of the seal is approximately equal to water seal immersion normally and since the compressor is the source of energy for vapor with drawal when it is operating, no vapor can be withdrawn from the system when it is not operating but withdrawal can continue when pressure upstream of the seal is caused to be substantially equal to water seal immersion depth or greater by virtue of vapor flow equal to vapor withdrawal upstream of the point of vapor withdrawal and the compressor is operating by virtue of pressure control means.

When no water seal forms a part of flare system and in view of need for flow from the flare system to the flare to assure that no air will be drawn into the system by compressor operation, initial compressor operation, cannot, by control, occur until such time as flow to the flare exists in adequate quantity thus there is flare-burned loss of the quantity of vapor which moves from the system to the flare before the recovery can begin. As the initial compressor operation occurs, only a small quantity of vapors is withdrawn from the flare system until such time as the flare system flow increases.

All flare systems cannot include water seals for various reasons, thus two forms of vapor recovery systems are required because, as has been stated, any flare vapor movement must be from the flare system to the flare, to avoid indraft of air to the system and creation of explosion hazard. Where no water seal is present there must be a selected minimum flow of vapor to the flare before initial compressor operation for vapor recovery can begin. Vapor which moves to the flare are discharged to atmosphere for burning and is thus lost. The selected minimum flow to the flare can be in the order of 1.5 ft/sec but is not so limited when no water seal is part of the flare system.

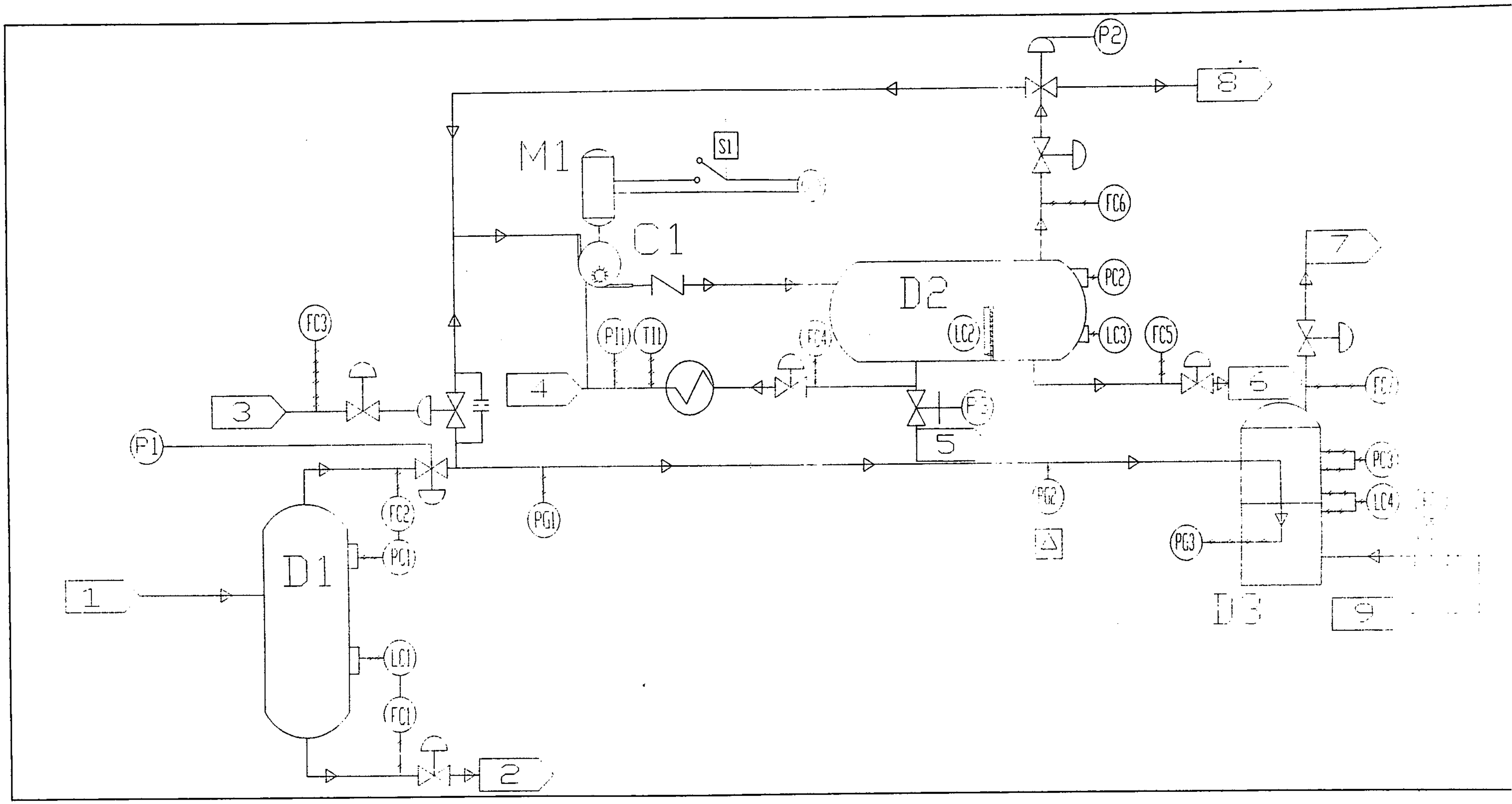
3.14) A Sample P&ID of FGRU:

On the basis of above mentioned models, and control systems a sample P&ID of FGRU has been prepared with help of Auto Cad 2006 of Auto Desk™ as follows:

Table 3.5 (Legends for notations used in P&ID):

Sl. No.	Symbol	Description	Remarks
1	1	Flow Stream Label	Flare gases received from plant utilities (from off plot)
2	2	Flow Stream Label	Liquid stream outlet of flare KOD (D1) (to off plot)
3	3	Flow Stream Label	Control fluid inlet (within plot)
4	4	Flow Stream Label	Fresh operating liquid inlet for liquid ring compressor (C1) (within plot)
5	5	Flow Stream Label	Part of operating liquid received from 3 phase separator (D2) being sent to effluent treatment (to off plot)
6	6	Flow Stream Label	Hydrocarbon liquid received from 3 phase separator (D2) being sent to blow down (to off plot)
7	7	Flow Stream Label	Gas being sent to flare stack (to off plot)
8	8	Flow Stream Label	Recovered flare gas being sent for treatment (to off plot)
9	FC 1	Flow Controller	Controls the liquid outlet rate from flare KOD (D1)
10	FC 2	Flow Controller	Controls the gas outlet rate from flare KOD (D1)
11	FC 3	Flow Controller	Controls the input of control fluid as in Flow Stream Label 3
12	FC 4	Flow Controller	Controls the operating liquid outlet rate from 3 phase separator (D2)
13	FC 5	Flow Controller	Controls the hydrocarbon liquid outlet from 3 phase separator (D2)
14	FC 6	Flow Controller	Controls the vapor outlet rate from 3 phase separator (D2)
15	FC 7	Flow Controller	Controls the vapor outlet rate from liquid seal drum (D3)
16	FC 8	Flow Controller	Controls the liquid seal inlet rate in Liquid Seal Drum (D3)
16	PC 1	Pressure Controller	Controls the vapor pressure within D1

17	PC 2	Pressure Controller	Controls the vapor pressure within D2
18	PC 3	Pressure Controller	Controls vapor pressure within D3
19	LC 1	Level Controller	Controls liquid level in D1
20	LC2	Level Controller	Controls operating liquid level in D2
21	LC 3	Level Controller	Controls liquid hydrocarbon level in D2
22	LC 4	Level Controller	Controls level of seal in D3
21	PI 1	Pressure Indicator	Indicates flowing pressure of recycled operating liquid stream
22	TI 1	Temperature Indicator	Indicates temperature of recycled operating liquid
23	PG 1	Pressure Monitor	Monitors pressure in flare header near recovery point
24	PG 2	Pressure Monitor	Monitors pressure in flare header near liquid seal drum
25	PG 3	Pressure Monitor	Monitors hydrostatic pressure in part of flare header dipped in liquid
26	P 1	Sampling Point	For analyzing gas composition of exit stream of D1
27	P 2	Sampling Point	For analyzing gas composition of exit stream of D2
28	P 3	Sampling Point	For analyzing operating liquid composition of exit stream of D2
29	S 1	Solenoid	Switches the motor (M1) on/off depending on signal received
30	M 1	Electrical Motor	Runs the compressor through a shaft
31	C 1	Liquid-Ring Compressor	
32	D 1	Tank	Flare knock out drum
33	D 2	Tank	3 phase separator
34	D 3	Tank	Liquid seal drum



D1
D2
D3
M1
C1
S1
1
2
3
4
5
6
7
8
9
P1
P2
FC1
FC2
FC3
FC4
FC5
FC6
LC1
LC2
LC3
LC4
PC1
PC2
PC3
PG1
PG2
PG3
PI1
TI1

Fig 3.19: <u>Sample P&ID of FGRU System</u>

3.15) FGRU Safety:

The principal potential safety risk involved in integrating a flare gas recovery system is from ingression of air into the flare header, which can be induced by the compressor suction. This could result in a flammable gas mixture being flashed off inside the system from flare pilots. It should be noted that the FGR unit does not interrupt the flare system and should be able to handle sudden increases in load. Therefore, no modification to the existing flare system will be attempted, but with two exceptions. The connections through which the compressors will take suction on the system and additional seal drums which will provide extra safety against air leakage into the flare system and allow the buildup of flare header pressure, during compressor shutdown or flare gas overload. Also, the compressor control system does not affect the flare system pressure and thus its design will be able to avoid low pressure suction in the flare system during normal operation. When the compressors are not functioning properly, automatic or annual shutdown should result. The flare system will operate as it does now with no compressors. Meanwhile, if the volume of flare gases relieved into the flare system exceeds the capacity of the FGR unit, the excess gases will flow to the flare stack. If this volume is less than the full capacity of the FGR unit, a spillback valve will divert the discharged gases back to the suction zone to keep the capacity of the flare gas recovery unit constant.
Other safeguards to the flare system against air leakage are:

- The fail-safe shutdown of the FGR unit compressors on low pressure in the flare system.
- The shutdown of the FGR unit compressors upon high inlet and/or outlet temperatures.
- Adequate purge connections in the downstream of the seal drum.
- Low flow switches in the purge line to the main flare header downstream of the seal drum, to cut in fuel gas as purge gas.

Chapter 4:

FGRU Economical Analysis

4.1) Cost Analysis:

1. CAPEX Estimation of FGRU:

Implementation of an FGRU project will involve the following steps which comprise the capital expenditure (CAPEX) involved with the project:

Stage 1 -Engineering Study, Site Investigation & Process Engineering

Engineering Study involves:

- Identifying the use for Recovered Gas
- Review of the Existing Flare System
- Flare Header Flow and Positive Pressure
- Characterize Flare Gas Availability
- Evaluate Flare Gas Composition
- Select Gas Compressor Technology
- FGRU Design
- System Cost/Benefits Analysis
- FGRU Proposal

Site Investigation Requires collection of following Data: (*Courtesy: FGRU Design Basis Information, Process Specification Form, John Zink Company*)

- ❖ Flare System Data:
  - ➢ Number of Flare Equipments
  - ➢ Flare tip diameter
  - ➢ Flare design (maximum) flow rate
  - ➢ Flare smokeless flow rate
  - ➢ Flare Pressure drop from base to tip
  - ➢ Estimated suppression steam usage
  - ➢ Flare Header Line size
  - ➢ Whether KO Vessel installed or not
  - ➢ Liquid seal vessel installed or not
  - ➢ Liquid seal depth (If liquid seal vessel is installed)
  - ➢ Liquid seal fluid (If liquid seal vessel is installed)
- ❖ Site Conditions:

- Elevation above sea level
- Atmospheric pressure
- Maximum ambient air temperature
- Minimum ambient air temperature
- Site design wind speed

- Feed Gas Properties
  - Heating Value (LHV)
  - Molecular Weight
  - Specific Gravity
- Operating Utilities:
  - Electrical power supply (60 Hz or 50 Hz)
  - For motors < 250 HP (480 VAC or 2300 VAC)
  - For motors > 250 HP (2300 VAC or 4160 VAC)
  - For control elements (120 VAC or 24 VDC)
  - Instrument air supply pressure
  - Service water supply pressure
  - Cooling water supply maximum temperature
  - Cooling water supply minimum temperature
  - Cooling water return maximum temperature
  - Cooling water return minimum temperature
- Economic Factors:
  - Value of electrical power (Rs/kWh)
  - Value of steam (per kg or per Lb)
  - Value of recovered gas or fuel (per kg or Lb or MMBtu or kJ)
  - Value of recovered gas as process feed (per kg or Lb or MMBtu or kJ)
- Design Basis:
  - Design (maximum) gas recovery rate
  - Feed temperature
  - Feed gas pressure
  - Recovered gas delivery temperature limit
  - Recovered gas minimum discharge pressure
  - Control system platform

Stage 2 -Process/Mechanical Design Equipment Selection Procurement

Stage 3 -Fabrication & Assembly

[Stages 2 and 3 are in accordance to the details discussed in Chapter 3]

Stage 4 -Installation

Stage 5 -Commissioning Support & Operator Training

Ongoing -Service & Maintenance

[Stage 1 to 5 comprise the CAPEX whereas, ongoing stage is a part of OPEX (Operational Expenditure)]

2. **OPEX Estimation of FGRU**

Operational Expenditure (OPEX) in FGRU involves:

Unit Running Cost:

- Electricity Consumption By Compressor (Rs./kWh)
- Electricity Consumption by Control System (Rs./kWh)
- Lubrication Oil for Compressor (Rs./bbl)

Unit Maintenance Cost:

- Servicing and Operator's Wages

4.2) Payback Analysis:

Annual Recovery: R

Total Installation Cost (CAPEX): C

Annual OPEX: P

Payback = C/[R-P] years

Sample Analysis for Reliance Refineries, Jamnagar:

[*Data source: http://www.pcra.org/English/general/flaregas.htm*]

C = Rs. 10.08 Crore

R = Rs.14.5 Crore

P = Rs. 0.5 Crore

R – P = Rs. 14 Crore

Payback Period = 10.08/14 = 0.72 years = 9 months (Approximately)

Basis of Economics for Payback Analysis:

Fuel value: Rs/MMBtu [Which is used for valuation of flare gas recovered]

Cost of Electrical power: Rs/kWh [Which is used for estimation of OPEX]

Note: Above mentioned methods are guide for analyzing the economics of FGRU, whereas actual data can be found in Chapter 6 on "Case Studies of Present Application of FGRU in India".

4.3) Possible Barriers in Implementation of FGRU Project:

Demonstrated below are barriers that can prevent the FGRU project activity from being implemented and thus the emission reductions are additional to those that would have occurred in the absence of the project activity.

- **Investment barrier:** A financially more viable alternative to the project activity will lead to higher emissions.
- **Barrier due to prevailing practice:** Prevailing practice or existing regulatory or policy requirements will lead to implementation of a technology with higher emissions.
- **Technology barrier:** The project involves installation of a compressor which will take suction from the flare gas header.. Unlike refinery fuel gas, the flow rate, pressure of flare gas and the composition and hence the molecular weight of the gas is prone to wide fluctuations. Designing the compressor and the overall system thereof is more intimidating task.
  The flare gas composition is mostly hydrocarbons, hydrogen sulfide and hydrogen; as a result any mix of flare gas with air can prove to be highly explosive. This entails significant risks for the refinery, to address this; it is required to maintain always a positive suction pressure at around 150-200 mm water gauge. Any sudden flux in the suction pressure could result in significant amount of losses for the refinery. There is always a chance of liquid carry over and entrainment in the gas flare stream. Fluctuating heating value of flared gas is sufficiently high to maintain efficient and stable combustion, where viable, additional gas may be required to raise the heating value adequately. The overall tolerance level of the FGRS gets affected by the sudden gas and condensate surges. Since this system is an alternate measure for the safety system of the refinery, proper maintenance is very much required.

- **Operational barrier:** The quality and yield of the individual refinery products impacted the refinery margins. Smooth operation of the process units is required to maintain the quality and yield. Thus a disturbance in any of these units will adversely affect the refining margin which consequently spells out damaging losses for the whole refinery. The above disturbances and their associated effects centre on failure of the project activity; the following phenomena would impact the operational process.

  – **Compressor tripping** due to high liquid level in three phase separator is cited as an operational barrier.

  – **Liquid carry over in Fuel Gas Network** may take place due to malfunctioning of level controller in the three phase separator or due to condensation of hydrocarbons in the recovered flare gas header due to fluctuation of atmospheric temperature and conditions

- **Other barriers:** Flare Gas recovery is a high technology initiative and has very few technology suppliers worldwide.
  As an example IOCL Barauni had to go for three extensions for submission of proposal to its Global tender for procurement of FGRS package. In spite of such extensions, only one bid from an international vendor M/s Garo Dott was technically acceptable. Dependence on a single overseas vendor for such a technology intensive system is a barrier to project implementation and subsequent operations of FGRS with respect to availability of spare parts and technical expertise for maintenance.

In spite of the project activity facing a number of barriers set out above, it is implemented keeping in mind the additional environmental benefits like recovery of energy content in the waste gas which would otherwise be flared off into the atmosphere, GHG emission reduction, and the associated CDM benefits.

4.4) CONCLUSION

It is well known that there are many economical ways to achieve flaring minimization and gas conservation in oil and gas refineries. In order to find these ways, a comprehensive process evaluation of plants, especially units that produce flare gases, comprehensive monitoring of flow and composition of flare gases, investigation of existing flare systems and finding alternative choices for reusing flare gases has been carried out in various petroleum refineries, natural gas refineries and petrochemical plants across the world by various agencies. Based on these comprehensive process evaluation, various have alternatives been devised to reduce gas flaring.

Recovery of hydrocarbon gases discharged to the flare relief system is probably the most cost-beneficial plant retrofit available to the Oil & Gas refineries. Use of flare gas to provide fuel for process heaters and steam generation leaves more in fuel processing, thus increasing yields.

Chapter 5:

Latest Developments in FGRU Technology

5.1) Towards Zero Flaring

Zero flaring involves not operating the flare system during normal operations of the oil and gas installation whether onshore or offshore. Essentially the zero flare installation is designed to recover or recycle the waste gas generated during normal operations.

Zero flaring however, does not eliminate a flare system installation per se, but involves major changes in the design and operation philosophy of flare systems.

The following may be summarized for zero flaring concept:

a. Flare system is an essential safety part of any offshore or onshore oil and gas installation and is able to relieve gas from the process during upset or emergency conditions.
b. New installations should be designed for a normally 'not lit' flare utilizing latest technologies permitting recycle and recovery of waste gas during normal operations and efficient flare ignition systems preferably without flare pilots.
c. Existing flare installations should be modified to reduce/eliminate flaring considering the overall cost benefit analysis.
d. Zero flaring permits reduced CO_2 emissions thereby providing a mechanism to comply with the CO_2 emission regulations as legislated by the Kyoto Protocol.

The process is simple in that it relies on the closing of the flare by means of a fail-open, fast-opening valve, and a recovery system to take gas from the Knockout Drum to, for example, gas powered generators. The gas clearly has a useful destination as fuel gas, injection, or export. The economics of the system depend on items such as:

- Fuel Gas Requirements
- CO2 trading tariffs
- Environmental Pressure
- Flare Maintenance costs

The most immediate use for such systems is on platforms which are, or will be fuel gas deficient, as the gas burnt in the flare immediately could be used to replace alternative sources of fuel. Often there is a very good economic case for such development.

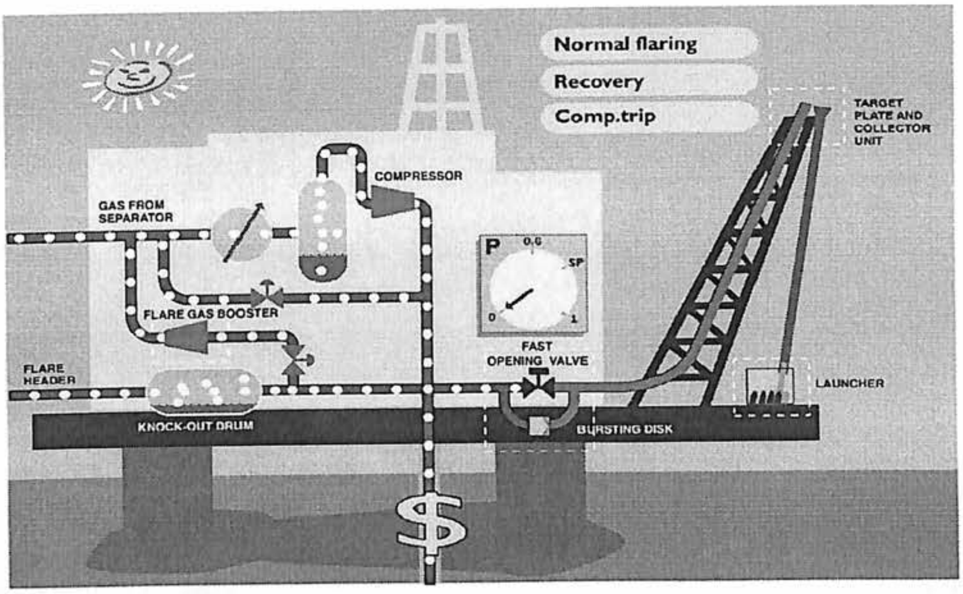


Fig. 5.1: Zero Flaring System (*Courtesy: Flaring Reduction and Gas Utilization; Global Forum*)

5.2) Ignition System for Zero Flaring:

Under ordinary circumstances (where flare gas recovery is not being used, or a partial flare gas recovery is taking place) a continuous ignition system has to be installed; which keeps a pilot flame continuously ignited. Whereas in a zero flaring system; a continuous ignition system will result in useless consumption of pilot gas. So a different ignition system needs to be installed, which will ignite only at a condition where gas is released in flare stack under emergency circumstances.

The ignition pellet is launched through a guide pipe to the flare tower (*as shown in Fig. 5.2*) when gas is released to the flare stack. The pellet bursts and generates a shower of sparks when exiting the guide pipe. The resulting shower of sparks is directed towards the flare tip and instantly ignites the gas cloud. The system is designed to operate for flare towers up to 2000 meters from the launching unit. The pellets are safe to handle and are stored in a magazine in the launching unit.

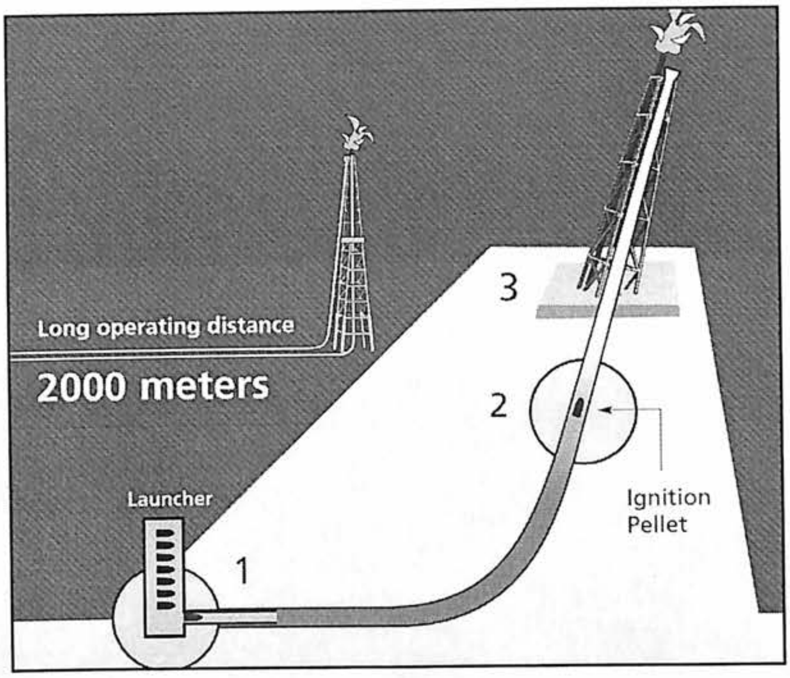


Fig. 5.2: Pellet Ignition System (*Courtesy: Hamworthy, Flare Gas Ignition*)

Some key features of above mentioned ignition system are:

- Long-range ignition pellet
- Armed by the launching pressure
- Ignite when emerged from guide pipe
- Independent of emerging velocity
- Will not ignite if exposed to fire

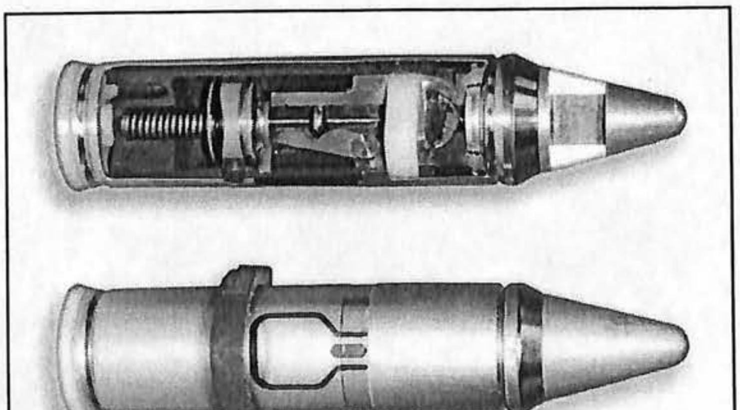


Fig. 5.3: Ignition pellet (*Courtesy: Hamworthy, Flare Gas Ignition*)

5.3) <u>Skid mounted FGRU:</u>

Setup of an FGRU requires installation of following equipments:

- Knock Out Drum (KOD)
- Compressor
- 3 Phase separator
- Heat Exchanger to reduce temperature of operating liquid of compressor
- Pumps (Optional)
- Pipes
- Valves and Control System

Individually carrying of these equipments and installing them is a tedious job, and covers a large area at installation site. So to avoid this FGRU manufacturing companies install all of the components on a platform (known as skid) which makes it easier to carry and install.

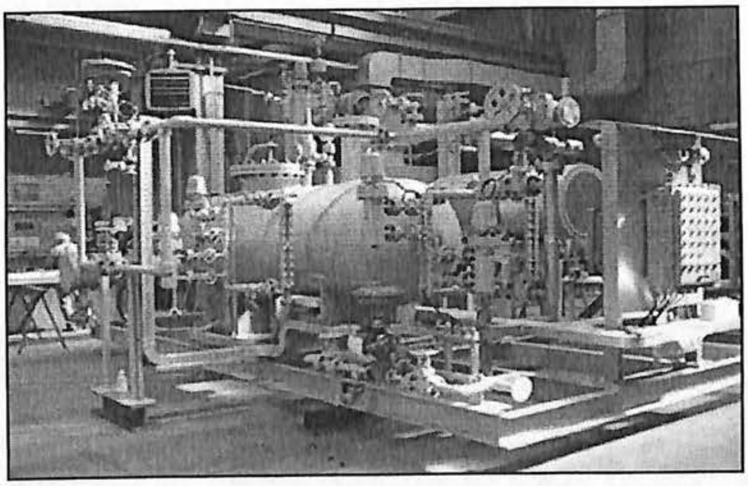


Fig. 5.4: A skid mounted FGRU (*Courtesy: Flare gas recovery with LRC: Gardener Denver*)

Chapter 6:

Case Studies of Present Applications of FGRU in India

In this section case studies of FGRU installation at following sites will be discussed:

- Reliance Refineries, Jamnagar, Gujarat (Reliance Industries Ltd.)
- Barauni Refinery, Barauni, Bihar (Indian Oil Corporation Ltd.)
- Hazira Gas Processing Complex, Hazira, Gujarat (Oil and Natural Gas Corporation)
- Haldia Refinery, Haldia, West Bengal (Indian Oil Corporation Ltd.)

Whereby the project has been completed at Reliance refinery, while is under completion and test run phase at other units (as on April, 2010)

6.1) Reliance Refineries, Jamnagar, Gujarat (Reliance Industries Ltd.)

Reliance refinery at Jamnagar is world's 3rd largest refinery and India's biggest refinery, implemented flare gas recovery system in Nov. 2003 with in-house design and limited help from Shell Global Solution Netherlands. This measure has reduced the quantity of hydrocarbon flaring from 53 to 10 Tons per day & controlled environmental pollution.

Process

At Jamnagar refinery complex, safety valve discharges and vents from all the process plants are connected to a closed flare system. There are four flare systems.

1. Main Flare System (Comprising of High & Low pressure headers)

2. Low Pressure Flare system.

3. Acid Gas Flare system.

4. Polypropylene plant flare system

Since inception Ultrasonic flow meters has been provided for measuring flare gas flows of each flare system near the flare stack upstream of water seal drums. In order to avoid stagnant areas and to keep positive pressure in the flare headers, fuel gas or nitrogen purge is used.

Technique of injection of measured quantities of nitrogen in the flare header of the individual plant and analysis of flare gases (before and after nitrogen injection) at plant battery limit was used to identify the flaring quantity (by nitrogen balance) from individual plant to reduce leakages.

With all these efforts the flare loss came to about 45 TPD. The flare loss from best performing pacesetting refineries was reported to be as low as 0.03%. The mandatory purging provided in the network alone constituted about 0.05% of the refinery input.

Methodology

At Reliance Jamnagar, the flare gas quantity is measured near the flare stacks and flow indications are available in the system. Average and peak load data was collected and studied for 6 months operation to establish flare gas recovery design flow rate under steady state operation.

It was observed that on an average 45 TPD of hydrocarbon was getting flared regularly, out of which approximately 14 TPD was coming from Rich Anime Flash Drums in VGO hydro-treaters as per design. Another proposal existed to recover and re-use these gases. Thus the average hydrocarbon flared was expected to reduce to 31TPD. Considering continuous purging of Nitrogen at various flare headers, total quantity of approximately 52 TPD was to be compressed and re-used. After commissioning of flare gas recovery system 21 TPD purge N2 will be replace by fuel gas. Hence a system for recovering 52 TPD of flare gases including purge gas was to be installed.

Flared fuel gas contains substantial quantity of H2S. Therefore a cost effective treatment system was required to remove H2S and make fuel gas suitable for firing in heaters & recover sulphur from H2S.

Modification

The following modifications were carried out.

1. Installed a skid mounted flare gas recovery system (All wetted parts shall be of SS 316L% the material should comply with NACE MR 0175 which is suitable for H2S, chlorine and organic sulphur) involving:

- A 20" tap off from the Main Flare header of 84" at downstream of knockout drums and upstream of liquid seal durms for the suction of Flare gas recovery compressors.
- A set of two Liquid ring compressors to compress the flare gas from 1.1 to 8.0 Kg/cm2 Abs with mechanical seal flushing system. A by-pass line for 100% re-circulation is provided. To meet the suction pressure requirements of these Compressors, flare gas header pressure need to be increased. This necessitated re-designing the water seal drums of the flare system & revalidating the safety release system of all the operating plants connected with this system.
- Discharge piping (6") from compressor discharge to separator inlet.
- Gas/liquid horizontal separator.
- 2" piping to discharge liquid hydrocarbon from separator bottom to OWS.
- 8" piping from separator outlet to Amine absorber inlet.
- A shell and tube water condenser to cool the liquid ring (water).

- Cooling water supply piping to the compressor from the exchanger and return piping from the compressor to the exchanger.

2. A Flare Gas Amine Absorber (12 valve type trays; Pressure 6.50 Kg/cm2 Abs; Temperature 40-450C; MOC-SS304)

3. 8" piping from Amine Absorber discharge to the Fuel gas header.

4. 4" piping from the Lean Amine header to the inlet of Flare Gas Amine Absorber.

5. 6" piping from the discharge of Flare Gas Amine Absorber to Rich Amine header.

Choice of Compressor

Liquid-ring compressor is preferred and most suitable over the other types (i.e reciprocating, screw, centrifugal etc.) available in the market for this service, since it ensures near isothermal compression and an intrinsically explosion-proof operation. It can handle a wide variation in flow rate, dirty gas, liquid slugs and solids. Liquid-ring compressors use a liquid (water) to form a seal in the shape of a ring between the outer ends of the impeller and compressor housing. The centrifugal force of the rotating impeller forces liquid to the outside wall forming a seal.

As the operating fluid absorbs most of the heat of compression, there is minimal rise in recovered gas temperature during compression. The compressor doesn't require any after cooler. After separation of the compressor operating liquid from the gases, the operating liquid will get discharged from the separator and is cooled through a heat exchanger. Once the operating liquid is cooled, it returns to the compressor where it is re-used to create the compressor seal. No separate booster pump is required to move the operating fluid from the separator to the compressor. Due to presence of sour gases the quality of operating liquid needs to be strictly maintained to prevent acid build up and contamination of the operating fluid. Liquid bleed and fresh water make-up capabilities have been provided which will operate as necessary.

Flare Header Pressure Control

For safe operation of FGRS it is mandatory to eliminate the possibility of air being sucked into the flare gas system, since the composition is normally of hydrocarbons and hydrogen sulphide but also of hydrogen, what when mixed with air can be highly explosive. To avoid ingress of air into flare header, it is required to maintain always a positive suction pressure at around 150-200 mm water gauge (water seal level in drum needed adjustment) . In case of reduction of suction pressure, compressor spillback valve will open to recycle compressed gas back to compressor suction.

Seal Drum Modifications

Modifications to the existing seal drums were necessary to have a bandwidth for pressure control of the flare gas recovery system. The seal height has to be increased from existing 127 mm to

1000 mm. The increase in submerged portion of dip-legs was achieved by increasing the liquid level in the vessel by 873 mm.

Conclusion

The above modification called for an investment of Rs. 10.08 Cr and the savings achieved are Rs. 14.0 Cr./annum with a payback period of 9 months.

6.2) <u>Barauni Refinery, Barauni, Bihar (Indian Oil Corporation Ltd.)</u>

The project activity involves installation of a flare gas recovery system (FGRS) for recovery of process flare gas that was being traditionally flared off. The recovered flare gas will be used as fuel for meeting process heating requirements. Currently, the process heating requirements are being met by firing Fuel Gas (FG) and Internal Fuel Oil (IFO). Thermal energy generated from the recovered flare gas will directly displace equivalent amount of thermal energy that would have been generated by firing IFO, thereby leading to reduced IFO consumption and a reduction in the Greenhouse Gases that get emitted from combustion of IFO. The project activity leads to conservation of hydrocarbons that are otherwise wasted; this contributes to increasing the energy efficiency of the overall system.

In addition to the above, the project activity also results in a significant reduction of plant emissions. Flaring of hydrocarbons produces combustion by-products such as CO2, CO and NOx that are emitted to the atmosphere. When utilizing flare gas recovery, no such by-products are produced.

Project's contribution to Greenhouse Gas Emission Reduction:

At present, ,process heating requirements of IOCL's Barauni Refinery are being met through firing of Fuel Gas (FG) and Internal Fuel Oil (IFO). After implementation of the project activity, the recovered flare gas will be fired along with Fuel Gas and IFO, the resultant thermal energy generated from firing of the recovered flare gases will displace equivalent amount of thermal energy that would have been generated from firing of IFO. The reduction in IFO consumption will also lead to a reduction in emission of greenhouse gases that are emitted from combustion of IFO.

Project's contribution to Sustainable Development:

The contributions of this project activity towards sustainable development are provided below:

- Reduction in thermal energy losses by recovery of the gas that would otherwise have been flared

- Conservation of fuel oil, a non-renewable natural resource.
- Reduction in CO_2 emissions.
- Reductions in the emission of other harmful gaseous pollutants like SOx and sulphides. This results in ambient air quality improvement
- Creation of additional employment opportunities for skilled professionals.
- Enhancing the technical knowledge base of employees and personnel working on implementation and O&M of the project activity.

Technical description of the project activity

In refinery operations, flammable waste gases are vented from processing units during normal operation and process upset conditions. During normal operations, flare gas is generated at a high pressure; this gas is used as Fuel Gas in the refinery processes. During exigencies like process fluctuations, passing of flare related control valves/ pressure safety valves and depressurization of process equipments, flare gas generation is at a low pressure. These lower pressure flare gases are currently being flared off as mandated by the environment safety and operational requirements of refineries.

As a normal practice the waste gases are first collected in a piping header and then delivered to a Flare system where it is burnt off for safe disposal. The Flare system is a combustion device designed to safely and efficiently destroy the waste. The daily average flare loss is estimated to be at 10 MT/day. The thermal energy content of these gases gets wasted without yielding any useful output.

The project activity entails installation of a Flare Gas Recovery System (FGRS) in order to recover maximum low pressure off gas that is currently being flared off. The Flare Gas Recovery System (FGRS) will be a skid mounted packaged unit and will be installed between Flare Knock Out drum (KOD) and Flare stack. The FGRS comprise of two compressors, one of which will be working and other will be standby. The compressor will take suction from the above mentioned flare gas header upstream of the Liquid Seal Drum, compress the gas and cool it for reuse in the Refinery Fuel Gas system. The recovered gas will then be routed to a gas holder/vessel from where it will be discharged into the refinery fuel gas header based on pressure control and made available for use as fuel in the process furnace/burners. The skid mounted package unit consists of:

- Gas compressor – 2 No. (450 Nm^3/hr capacity) (One of which will be working and other will be standby. Normally one compressor will be operated. However, provision is kept for operation of both the compressors and pipeline capacity has been designed in such manner) having the following operating and design parameters
- Inlet pressure, kg/cm^2-g:
  Operating 0.2
  Design 3.5

- Inlet temperature, °C
  Operating 45
  Design 129
- Desired outlet pressure, kg/cm2-g
  Operating 5
- Desired outlet temperature, °C
  Operating 50
- Molecular wt.
  Normal 21
  Minimum 11
  Maximum 40
- Separator vessel
- Heat exchangers/cooler
- PLC based instrumentation

The above components are part of scope of supply of the global tender issued by IOCL Barauni. However after detail studies and expert recommendations, IOCL decided to use liquid ring compressor technology for recovery of refinery waste gas which has typically low pressure. This technology (API681) is proprietary and has very few suppliers available globally for oil and gas industry requirements. Subsequent to this decision, M/s Garo Dott. Ing. Roberto Gabioneta S.p.a has been selected through tendering processes as supplier of Flare Gas recovery system complete package. The first concrete communication in this regard was the fax of acceptance (FOA) to M/s Garo on 10th May 2008.

The recovered flare gas contains high heating value and its recovery will enable it to be used as a fuel for meeting the process heating requirements of the refinery. At present, this heat is generated by using FG and IFO. The use of recovered flare gas in the process furnaces would save IFO and contribute to GHG emission reductions.

The FGRS also reduces the continuous flare operation, which subsequently reduces the associated smoke, thermal radiation, noise and pollutant emissions associated with flaring. It may also reduce the odour levels.

Estimated amount of emission reductions over the chosen crediting period:

The estimated emission reductions over the 10 year fixed crediting period would be tCO2e as per details on annual emission reductions provided below:

Table 6.1: Annual Estimation of CO_2 emission reduction at Barauni Refinery:

Year	Annual estimation of emission reductions in tones of tCO2e
1st Year	11968
2nd Year	11968
3rd Year	11968
4th Year	11968
5th Year	11968
6th Year	11968
7th Year	11968
8th Year	11968
9th Year	11968
10th Year	11968
Total estimated reductions (tonnes of CO2 e)	119680
Total number of crediting years	10 years
Annual average over the crediting period of estimated reductions (tonnes of CO2 e)	11968

6.3) Hazira Gas Processing Complex (Oil and Natural Gas Corporation):

The project activity includes the "Zero Flare" scheme implemented at Hazira plant with an objective to reduce flaring of gas, by compressing the otherwise flared gas (which was sourced from various flare control valves, pressure safety valves, fuel gas purge points, seal purge gas released from compressors and expanders, tanks and other vessels) in order to put them back to the system and therefore recover the valuable hydrocarbons and reduce flaring to technical zero level. The intended objective was achieved which led to recovery and utilisation of otherwise flared tail gas to the tune of 0.02 million standard cubic meters per day (MMSCMD) from the gas processing plant at Hazira in order to achieve technical zero flaring.

The purpose of the project is to:

- Reduce the wastage of precious natural resources.
- Reduce the impact on the environment and safety of the locality / surrounding areas.
- Achieve zero hydrocarbon emissions.
- Utilize recovered gas to produce value added product(s) in addition to gas sales to consumers.

- Reduce the emissions of greenhouse gases (GHG)'s into the atmosphere

The scheme has therefore reduced the release of CO_2 emissions into the atmosphere and has positively contributed to the fuel requirement of the country by providing additional source of relatively cleaner fuel (gas). The project has promoted sustainable economic growth and enabled conservation of environment and natural resources such as coal/ oil and other fossil fuels.

The scheme has further resulted in enhanced production of acid gas (sulphur) and lean gas sales to consumers from the recovered gas. This has also facilitated reduced atmospheric pollution and conservation of non-renewable natural resources.

The HGPC is equipped with an integrated flare system consisting of three flares and integrated flare network which connects all the flare loads from process trains, cogeneration and storages spread across the complex to the flare system. The function of flare system is to safely dispose off flammable, toxic and corrosive vapours discharged by pressure relief devices of various units to less objectionable compounds by combustion. The flare network is kept continuously purged with fuel gas injected from the dead ends spread across the complex.

As described this flare network comprises two flare stacks (a) terminal flare and (b) elevated flare and (c) one box flare. Normally the elevated flare system is line. The flare system receives gas from:

Various flare control valves of all process units at Hazira Plant

- Pressure safety valves with their bypass valves to flare gas on all pressure vessels at Hazira Plant.
- Fuel gas purge points to keep the flare alive and to avoid air ingression at all dead ends of flare headers of all process units at Hazira Plant
- Seal purge gas released from various compressors and expanders, tanks and other vessels.

ONGC, Hazira did not stop with just reducing the gas-flared quantity by 65% but went on to achieve the objective of "Zero flare" wherein a task force was constituted which formulated the technical specifications for the flare gas recovery compressor which was implemented in January 2006.

Project's contribution to sustainable development:

The "Zero Flare" scheme has contributed to sustainable development in several ways by reducing the quantity of gas flared and recovering the same for better applications and protecting the environment.

The project helps in minimising environmental pollution due to emissions of CO2 and other air pollutants (SPM, SO2, NOx) otherwise released by flaring the gas in the atmosphere. The project activity has led to increased production of acid gas and lean gas, while conserving fossil fuels and reducing the GHGs.

The project has also contributed to local skilled employment opportunities by the way of implementing the flare gas recovery compressor at their plant. the operation and maintenance (O&M) of this unit would benefit the equipment suppliers (compressors, separator, KOD, valves, etc) and technical consultants for the project. The project positively benefits the people around the plants by reduced flaring related emissions and provides better occupational health and safety (OHS) at workplace.

The engineers at ONGC had to overcome many technological challenges to implement zero gas flaring project at the processing unit of Hazira Plant. ONGC believes that their endeavour in reducing wastage of precious natural resources will bolster India's continuous thrust towards a sustainable energy security.

Technology of project activity:

Fuel gas header was modified in GSP to reduce the tail gas being flared. Modification was done in the Fuel gas blanketing of Amine & Methanol tanks to reduce the gas being flared. The seating of existing ANSI class-IV leakage flare control valves were replaced with soft seats, resulting in tighter shut-offs and minimizing the technical flaring. Hydrocarbon liquid being collected in suction KOD of CFU off-gas compressor has been diverted to LPG column and minimizing the technical flaring. The work also involved installing a flare gas recovery compressor (FGRC) and laying of around 0.546 km length pipeline, for drawing flared gas from the flare header to the FGRC. The compressed gas is then led to the processing facilities within the same plant for producing acid gas and lean gas.

Flare Gas Recovery Compressor (FGRC) unit consists of-one flare gas recovery reciprocating compressor - skid mounted motor driven compressor package complete with electrical motors, auxiliaries, inter coolers, after coolers, separators, scrubbers, skid piping, pressure vessels, common suction knock out drum & discharge knock out drum with all requisite instruments, level switches, instrumentation and associated instruments, instrumentation, cabling, control systems etc and electrical items, electrical safeguarding systems, cabling, termination, earthing etc.

Table 6.2: Estimated amount of emission reductions over the chosen crediting period:

Year	**Emission Reduction (Tons of CO2e)**
2007-08	8,793
2008-09	8,793
2009-10	8,793
2010-11	8,793
2011-12	8,793
2012-13	8,793

2013-14	8,793
2014-15	8,793
2015-16	8,793
2016-17	8,793
Total estimated reductions (tonnes of CO2e)	87,930
Total number of crediting years	10
Annual average over the crediting period of estimated reductions (tonnes of CO2e)	8,793

6.4) Haldia Refinery, Haldia, West Bengal (Indian Oil Corporation Ltd.)

The purpose of the project activity is to recover low pressure off gas generated from the various process units of Indian Oil Corporation Limited, Haldia Refinery (IOCL, HR) which is presently directed to the flare to burn off at the flare tip and utilize it as one of the thermal energy sources for meeting process heating requirements. The project activity reduces fuel oill consumption, thereby contributing to reduction of CO2 emissions.

In IOCL, HR during normal operations high pressure (greater than 4.0 kg/cm2) off gas generated from various process units (such as distillation, cracking, reforming and other processes) is being routed to a fuel gas drum (called the refinery fuel gas drum), from where it is distributed to various process furnaces for consumption. The higher pressure of this gas allows its immediate use as a thermal energy source.

Low pressure off gas generated due to exigencies like process fluctuations, passing of flare related control valves and pressure safety valves and depressurization of process equipment is discharged to a flare knock out drum from where it is sent to the flare stack where it is burnt off for final disposal.

Sometimes, excess low pressure off gas generated due to the imbalance in generation and consumption of high pressure off gas is also routed to the flare stack in the same way. Hence the heat value of this gas is wasted to the atmosphere. The refinery employs a flare system

- To keep the relief system in readiness to ensure safe disposal of the refinery low pressure off gas generated due to exigencies from various process units and
- To maintain a positive pressure gradient within the system to avoid air ingress into the refinery internals.

At IOCL, Haldia Refinery, the heating requirements of the refinery processes are met in any one of the three ways –

(i) fuel oil firing in furnaces which operate only on fuel oil,

(ii) high pressure off-gas firing in furnaces which operate only on high pressure off-gas (hereafter referred to as 'refinery gas') and

(iii) dual fuel firing in furnaces2 which operate on fuel oil and refinery gas mix.

The project activity will reduce the consumption of fuel oil in the dual fuel fired furnaces replacing it with an equivalent amount of recovered waste gas that is flared.

The project activity positively contributes to sustainable development of India by conservation of a nonrenewable natural resource and through substantial reduction of Green House Gas (GHG) emission.

Table 6.3: Estimated amount of emission reductions over the chosen crediting period:

Year	**Estimation of annual emission reductions* (in tonnes of CO2 e)**
2008-09	15528
2009-10	15528
2010-11	15528
2011-12	15528
2012-13	15528
2013-14	15528
2014-15	15528
2015-16	15528
2016-17	15528
Total estimated reductions (tonnes of CO2 e)	155280
Total number of crediting years	10
Annual average of the estimated reductions over the crediting period (tCO2 e)	15528

Other than the above mentioned cases, some of the other installations of FGRU in India are as follows:

- Guwahati Refinery, Guwahati, Assam (Indian Oil Corporation Ltd.)
- Chennai Refinery, Chennai India (Chennai Petroleum Corporation Ltd)
- Visakh Refinery, Vishakhapattnam, Andhra Pradesh (HPCL)
- Uran Plant, Uran, Maharastra (Oil and Natural Gas Corporation)
- Kumchai Oil Field, Kumchai, Arunachal Pradesh (Oil India Ltd.)

References:

Books:

- McKetta , John J. (1985): Encyclopedia of Chemical Processing and Design; Marcel Dekker Inc, ISBN 0-8247-2491-7
- Beychok , Milton R. (2005): Fundamentals of Stack Gas Dispersion, Fourth edition; Self-published. ISBN 0-9644588-0-2
- Rice, Richard G. & Do, Duong D. (1995): Applied Mathematics and Modeling for Chemical Engineers; John Wiley & Sons, Inc., ISBN 0-471-30377-1
- Finlayson, Bruce A. (2006): Introduction To Chemical Engineering Computing; John Wiley & Sons, Inc, ISBN-10: 0-471-74062-4
- Bequtte, B. Wayne (1998): Process Dynamics Modeling, Analysis, and Simulation; Prentice Hall International Series in the Physical and Chemical Engineering Sciences, ISBN 0-13-206889-3
- Luyben,W.L. (1996): Process Modeling, Simulation, And Control For Chemical Engineers, Second Edition; McGraw-Hill Publishing Company, ISBN 6-67-639159-1
- Gary, James H. & Handwerk , Glenn E. (2001): Petroleum Refining Technology and Economics, Fourth Edition; Marcel Dekker Inc, ISBN: 0-8247-0482-7
- Treybal, Robert E. (1981): Mass Transfer Operations, Third Edition, McGraw –Hill Chemical Engineering Series, ISBN 0-07-066615-6
- Meyers, Robert A. (2004): Handbook of Petrochemicals Production Processes; McGraw-Hill Professional Publishing; ISBN 0-07-141042-2
- Meyers, Robert A. (1996): Handbook of Petroleum Refining Processes, Second Edition; McGraw-Hill Professional Publishing; ISBN 0-070-41796-2
- Morrison, Robert T. & Boyd, Robert N.(2005): Organic Chemistry, Sixth Edition; Pearson Prentice Hall; ISBN 81-7758-169-4
- Panneerselvam, R. (2009): Engineering Economics; PHI Learning Pvt. Ltd.; ISBN 978-81-203-1743-7
- Bannwarth, Helmut (2003): Liquid Ring Vacuum Pumps, Compressors and Systems: Conventional and Hermetic Design, Sixth Edition; John Wiley & Sons, Inc.; ISBN: 3-527-30385-5
- Holman, J.P. (1986): Heat Transfer; Mc-Graw Hill Book Co.; ISBN 0-07-029620-0
- Molar, Cleve B. (2004): Numerical Computing with MATLAB; Society for Industrial and Applied Mathematics; ISBN 978-0-898716-60-3

Articles, Journals and Research Papers:

- Innovative solutions for combustion and emissions challenges : Callidus Technologies by Honeywell
- Hydrocarbon Processing, January 2002 Issue, Pages 59-62: Gulf Publishing Co.
- Hydrocarbon Processing, May 2004 Issue, Pages 73-76: Gulf Publishing Co.
- Hydrocarbon Processing, June 2007 Issue, Pages 111-115: Gulf Publishing Co.
- Hydrocarbon Processing, June 2002 Issue, Pages 83-85: Gulf Publishing Co.
- Pressure Relieving and De-Pressurizing Systems: ANSI/API Standard 521 Fifth Edition, January 2007
- Flare Gas Recovery Systems: John Zink Co., LLC
- Heat Radiation from Flares: Selma E. Guigard (Principal Investigator); Warren B. Kindzierski (Co-Investigator); Environmental Engineering Program, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta
- Optimally Economic Design of Flare Systems: Hossein Shokouhmand, Shahab Hosseini; Proceedings of the World Congress on Engineering Vol II, July 2 - 4, 2008, London, U.K.
- Flare System Vapor Recovery: United States Patent 3915620; Inventor: Robert D. Reed; Assignee: John Zink Co. Tulsa, Okla.
- Liquid Seal for Recovering Flared Gas: United States Patent Application 2007/0144581; Inventor: Singh, Padam; Assignee: Oil & Natural Gas Corporation, Mumbai, India
- A Proposed Comprehensive Model for Elevated Flare Flames and Plumes: David Shore, Flaregas Corporation, AIChE 40th Loss Prevention Symposium, April 2006.
- Gas Flaring Emission Contributes to Global Warming: Lulea University of Technology (Sweden) and Institut National des Sciences Appliquées de Lyon (France)
- Flare Gas Recovery in Oil and Gas Refineries: O. Zadakbar, A. Vatani and K. Karimpour; Oil & Gas Science and Technology – Rev. IFP, Vol. 63 (2008), No. 6, pp. 705-711
- Gas Liquid Separator for Flare System: United States Patent 4035171; Inventor: Robert D. Reed & Robert E. Schwartz; Assignee: John Zink Co. Tulsa, Okla
- Apparatus for Recovery of Flared Condensible Vapors: United States Patent 4227897; Inventor: Robert D. Reed; Assignee: John Zink Co. Tulsa, Okla
- Safety System Intended in Particular to Eliminate Entrained or Codenesed Liquid, and to Limit Heat Radiation when Flaring or Dispersing Hydrocarbon Gases: United States Patent 4516932; Inventor: Gerard Chaudot; Assignee: Cabinet Brot, Paris, France
- Flare Gas Recovery Feasibility and Alternative Study Report Consolidated Compliance Order and Notice of Potential Penalty Enforcement Tracking No. AE-CN-08-0122, Murphy Oil USA, Inc.- Meraux Refinery

- Validation Report on Flare Gas Recovery system (FGRS) at Barauni Refinery of Indian Oil Corporation Limited; Report No. 2008-0468 Revision No. 03
- Guidelines for Oil & Gas Refineries on Effluent and Emission Standards(05.08.2008): Central Pollution and Control Board of India
- Climate change issues in Oil & Gas Sector: Ernst & Young
- Hijet™ Compression System for Flare Gas Recovery: Dr. George Georgiadis; Hijet International, Inc. Cyprus
- Jet Ejectors System & Methods: United States Patent Application 2008/0253901; Inventor: Mark T. Holtzapple, Gary P. Noyes and George A. Rabroker; Assignee: The Texas A&M University System, Highland Interests, Inc. and Star Rotor Corporation, TX US
- System and Method for Collecting and Increasing Pressure of Seal Leak Gas: United States Patent Application 2008/0251129; Inventor: Shawn D. Hoffart, Overland Park KS (US)
- API Spec. 12J "Specification for Oil and Gas Separators", 7th. Ed., Oct. 1989
- Design of Liquid-Jet Compressor Installations: V. N. Eliseev

Web Resources:

- http://www.pcra.org/English/general/flaregas.htm
- http://www.johnzink.com/products/fgr/html/fgr_jz.htm
- http://www.cheresources.com/invision/index.php?/?index
- http://en.citizendium.org/wiki?title=Vapor-liquid_separator&redirect=no
- http://en.citizendium.org/wiki/Flare_stack#The_purpose_of_flare_stacks
- *www.cogeneration.net/Flare_Gas_Recovery.htm*
- http://www.ramboll-oilgas.com/projects/viewproject.aspx?projectid=57F5330F-270F-48EE-9117-2D1BC223B5F8
- http://www.jccp.or.jp/english/technical/year/h19_08.html
- http://www.cogeneration.net/Flare_Gas_Recovery.htm
- http://www.tech-trade.no/Downloads/Ejectors,%20Eductors%20and%20Jet%20Pumps%20-%20Transvac/New%20Flare%20Gas%20Leaflet.pdf
- http://ogst.ifp.fr/articles/ogst/pdf/2008/06/ogst07116.pdf
- http://en.wikipedia.org/wiki/Gas_flare
- http://chemeng-processing.blogspot.com/2009/02/flare-gas-recovery.html
- http://www.freshpatents.com/Liquid-ring-compressor-dt20081023ptan20080260543.php
- http://www.scribd.com/doc/27118834/2009-June-29-MOUSA-Flare-Gas-Recovery-System-EDMS-42227489
- http://www.shellguilty.com/learn-more/climate-crimes/