Safety Engineering

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MODELLING AND EVALUATION OF THE EFFECTS OF HIGH BACK PRESSURE (HBP) ON REFINERY FLARE SYSTEM NETWORK

Safety and reliability of the flare system are often affected by High Back-Pressure (HBP). The primary aim of this study is to simulate a steady-state model of flare system using Aspen Flare System Analyzer and with the aid of real plant data generated from Kaduna Refining and Petrochemical Company (KRPC) Ltd, Nigeria. Three credible scenarios (normal operation/surplus fuel, cooling water failure and power failure) were considered. The results showed that the steady-state model of flare system for normal operation (Surplus Fuel), cooling failure and power failure scenario and the flare system meet performance requirements at a system back pressure of 1.01325 bar, except for cooling water failure scenario which showed the occurrence of high fluid velocity and momentum (rhoV²). Also, flare operation at normal back pressure, for all three scenarios does not exceed design and operational limits. The work recommends that KRPC managers should review options for reducing HBP particularly for cooling failure and power failure scenarios such that the back pressure would not exceed 10% of set pressure for the conventional valves.

Keywords: high back-pressure, safety engineering, flare system, relief valve, performance, Aspen Flare System Analyzer.

INTRODUCTION

Globally, the oil and gas industry is a critical sector of several economies and as such, ensuring the safety of the oil and gas facilities becomes paramount. For this reason, considerable effort has been focused, over the years on the prevention of major incidents. The oil and gas facilities are prone to challenges that can affect the effective operation and threaten process safety. Hence, the oil and gas industry has over the years emphasized process safety and asset integrity so as to prevent unplanned or emergency releases that could result in a major incident and threaten process safety. Process safety is a disciplined framework for managing the integrity of operating systems and processes, handling hazardous substances, and is achieved by applying good design principles, engineering, and operating and maintenance practices [1]. It entails the prevention and control of incidents that have the potential to release hazardous materials and energy such as the flare system in a refinery which can result in toxic exposures, fires, or explosions of facilities and could ultimately result in serious injuries, fatalities, property damage, lost production or environmental damage.

To mitigate the emergency or pressure build-up in the oil and gas facilities such as the refinery, a major safety requirement in oil and gas installations or facilities is a flare system which is usually installed to relieve pressure build-up that may occur during operation, shut down, start-up or due to power or process system failure or hazards associated with process emergencies. Therefore, the importance of flare system installation in several oil and gas facilities and as such, accurate design of the flare system plays a significant role in containing possible process safety hazards in the oil and gas facilities, particularly oil and gas offshore platforms [2,3]. This makes flaring a very important issue in the oil and gas industry.

Flaring is a high-temperature oxidation process used to burn combustible components, mostly hydrocarbons, of waste gases from industrial operations. Gas flaring is the combustion of associated gas produced with crude oil or from gas fields. Primarily gas flaring is employed for safety reasons. Hence, consideration of the release of gas to the atmosphere by flaring and venting becomes an essential practice in oil and gas production. Flaring is the controlled burning of natural gas produced in association with oil in the course of routine oil and gas production operations [1]. Venting is the controlled release of gases into the atmosphere in the course of oil and gas production operations. Solving the problem of this "nuisance" called venting while ensuring safe operation and minimizing undesirable venting, led to the introduction of flaring [4]. As such, one safety concern that frequently occurs in a flare system is the high back pressure, which is the sum of the superimposed and build-up back pressures [1, 5, 6].

However, the pressure that exists at the outlet of a pressure relief device is a result of the pressure in the discharge system [7]. In order to prevent dangerous bursts, explosions, and fires, pressure relief valves are designed and installed to bleed out excess liquid or vapor causing pressure build-up and as such, there are limits to the containable back pressure in the relief valves [8]. Effective and efficient flare system sizing must take into account the number of relief valves discharging into a common flare manifold or header, as the pressure drop

from each relief valve discharge through the flare tip must not exceed the allowable relief valve back pressure for all system flow conditions. For conventional relief valves, the allowable back pressure is typically limited to about 10% of the minimum relief valve upstream set pressure [1, 8, 9]. Several studies have been reported on the impact of back pressure on pressure safety valves in flare systems [1, 2, 3, 5, 6, 9, 10, 11]. However, no studies have been in the relevant current extant literature on the effects of high back pressure (HBP) on the pressure safety valves of the KRPC flare system. It is in view of this that the study evaluates back-pressure,

noise, and flow characteristics due to process upsets within the flare network for normal operation, cooling water failure and power failure scenarios. The objectives of the study are to simulate a steady-state model of flare system using Aspen Flare System Analyzer for three scenarios (normal operation/surplus fuel, cooling water failure and power failure), analyze the effect of back-pressure build-up on the flare system, evaluate the effect of high back-pressure on pressure-relieving devices and to recommend mitigation measures against the effect of HBP on the flare system.
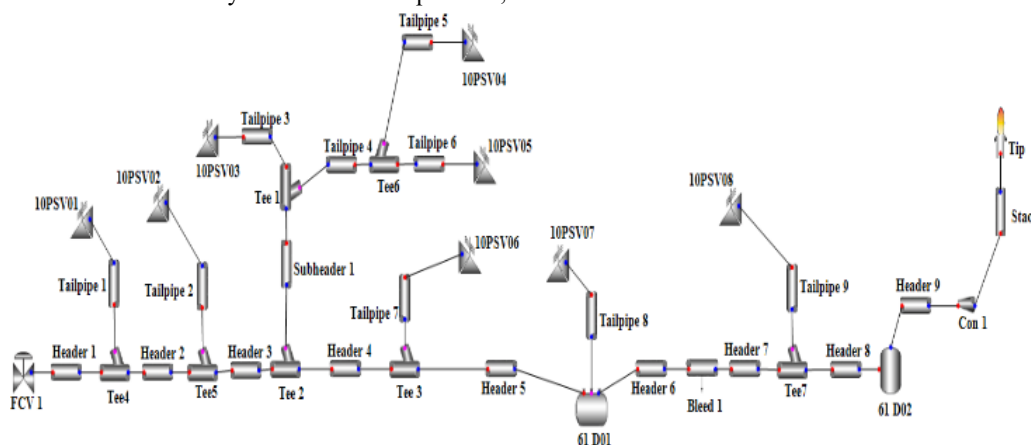

Figure 1: *Simulated model of flare system in Aspen FLARENET*

METHODOLOGY

The following data were collected from KRPC: composition of materials flowing through equipment and pipeline, a flow rate of materials passing through pipelines and equipment/pipeline conditions (phase, temperature, and pressure). This is followed by hazards identification, formulation of credible scenarios and articulation of the consequence modelling steps.

To formulate a structured approach to the identification of hazards, an understanding of contributory factors is essential. These factors include inventory analysis which was used in understanding the relative hazards and shortlisting of release scenarios. Initiating events Table 1: Collected pipe, tailpipe, header, sub-header and stack specification of KRPC flare system.

Assumptions
The following assumptions were made in the course of the modelling and simulation of the flare system using Aspen FLARENET:
1. The process is operating in steady-state condition.
2. Energy losses are assumed negligible.
3. Pressure losses in pipes are negligible

Simulation
Aspen Flare System Analyzer was used for the process simulation of the flare system network. This is because Aspen Flare System Analyzer provides reliable and comprehensive thermodynamic packages, a vast component library and advanced calculation techniques for flare system simulation. The procedure for the simulation mainly involves component selection, model

development by specifying pipes and relief valves sizes, operating conditions (temperature and pressure) as well as the scenario constraint specification for normal operation/surplus fuel scenario, cooling water failure scenario and power failure scenario. Figure 1 presents the simulated model of the flare system.

Table 1: *Design specifications for some elements of the flare system network*

Name	Length (m)	Nominal Diameter	Relief Valves	Mass Flow (kg/hr)
Tailpipe 7	10	2 inch	10PSV03	1500
Header 1	10	32 inch	10PSV05	2000
Header 4	25	32 inch	10PSV07	2000
Header 5	20	32 inch	FCV 1	118680
Header 6	10	32 inch	10PSV01	67440
Header 7	15	54 inch	10PSV02	2000
Header 9	20	54 inch	10PSV04	1130
Stack	60.741	54 inch	10PSV06	1560
Subheader 1	15	6 inch	10PSV08	34580
Tailpipe 3	5	6 inch		
Tailpipe 4	5	6 inch		
Tailpipe 8	10	12 inch		
Tailpipe 1	20	32 inch		
Header 2	25	32 inch		
Tailpipe 2	5	4 inch		
Header 3	20	32 inch		
Tailpipe 6	10	6 inch		
Tailpipe 5	5	2 inch		
Header 8	20	54 inch		
Tailpipe 9	10	28 inch		
Tailpipe 9	10	28 inch		

Source: *KRPC Flare System Data*

RESULTS AND DISCUSSION
Effect of High Back-Pressure Build-Up on Flare System

The simulated flare system model was successfully done at normal operation, cooling failure and power failure case and used to test and analyse the effect of back pressure on the model flare system in order to ensure the safety and integrity of the whole asset. The effect of higher back pressure on the flare system as it is critical to the integrity of flare system design and operation which can affect either the set pressure or the capacity of a relief valve.

Table 2: *Effect of cooling water failure on back pressure during normal operation scenarios*

Name	1	2.	3.	4.	5.
Header 4	0.0	2.098	0.005	4	1.32080
Header 5	0.0	2.098	0.005	4	1.32079
Header 6	0.0	2.797	0.007	7	1.32073
Header 7	0.0	0.991	0.002	1	1.22072
Header 9	0.0	0.991	0.002	1	1.22070
Stack	0.0	0.991	0.002	1	1.21588
Subheader 1	34.3	52.776	0.119	2360	1.30891
Tailpipe 4	28.9	51.875	0.117	2319	1.35218
Header 2	0.0	0.000	0.000	0	1.32085
Header 3	0.0	0.000	0.000	0	1.32085
Header 8	0.0	0.991	0.002	1	1.22071
Tailpipe 9	0.0	0.000	0.000	0	1.22072
Tailpipe 7	0.0	4.596	0.011	21	1.32079
Tailpipe 3	0.0	0.000	0.000	0	1.32082
Tailpipe 6	0.0	0.000	0.000	0	1.32085
Tailpipe 5	0.0	0.000	0.000	0	1.32085
Tailpipe 2	0.0	0.000	0.000	0	1.32085
Header 1	0.0	0.000	0.000	0	1.35725
Tailpipe 1	0.0	0.000	0.000	0	1.36684
Tailpipe 8	31.7	51.322	0.116	2295	1.36454

Table Legend: 1. Noise (dB), 2. Upstream Velocity (m/s), 3 Upstream Mach No., 4. Upstream Rho V2 (kg/m/s^2), Downstream Static Pressure (bar)

Table 2 presents the effect of normal back pressure at the three scenarios of normal operation, a cooling failure and power failure case considered in this study respectively.

Also, Table 2 shows the effect of normal back pressure on the cooling water failure scenario of the model flare system. The operation of the KRPC's flare system at cooling water failure case shows that design violation occurred at Header 6, Header 7, Header 8 and Header 9 due to a slight increase in the flowing fluid momentum. This could be attributed to internal flow-induced forces across header 6 through to header 9 along with the flare system [2, 6, 12].

In the course of the simulation, it was observed that both upstream and downstream pressures were in the range of 1.31 and 1.38 bar.

From Table 2, it can be seen that the noise generated as a result of the normal back pressure in the PRVs is low. This indicates that in the cooling water failure scenario, the flare system does not generate excessive noise resulting from back pressure in the PRVs with less than 35 dB of noise across the few affected relief valves. However, there was no noise generated at the majority of the relief valve as well as FCV of the model flare system for the cooling water failure scenario. This could be attributed to the low momentum of the flowing fluid resulting from the low fluid velocity at the normal operation case of the model flare system.

Furthermore, the operation of the flare system at the power failure case shows the occurrence of design violation at the Tailpipe. This violation occurred due to back pressures at the relief valve to the tailpipe exceeding the Maximum Allowable Back Pressure (MABP) in the relieving valve which is attributed to a slight increase in pressure at the outlet of 10PSV07 which develops as a result of flow after the PRV opens [11].

It was also found that the noise generated as a result of the normal back pressure in the PRVs is low. This indicates that in the power failure case scenario, the flare system does not generate excessive noise resulting from back pressure in the PRVs with less than 30 dB of noise across all relief valves and FCV of the model flare system. This could be attributed to the low momentum of the flowing fluid resulting from low fluid velocity in the model flare system [6].

Another significant criterion for efficient operation of flare system is the Mach number which is a function of fluid velocity and the maximum velocity for flare headers and subheaders are expected not to exceed 0.6 Mach. As such, this study also examines the effect of back pressure on the flare system.

Table 2 also presents the effect of normal back-pressure on the Mach number at all relief valves of the model flare system for cooling water failure scenario. The maximum Mach number attained for all PSV's of the model flare system for cooling water failure scenario does not exceed 0.122 which is also well below the maximum velocity of 0.6 maximum Mach number for flare headers [1, 13]. This is attributed to the fact that the flare headers are of larger diameter than the other network pipes and the flare network is designed to handle the designed back-pressure [1]. The low Mach number of 0.122 also enhances the avoidance of pipe vibration and noise generation resulting from excess velocity in the flare network.

The maximum Mach number attained for all PSV's of the model flare system for power failure scenario does not exceed 0.092 which is also well below 0.6 maximum Mach number for flare headers design [1, 13]. This is due to the larger diameter of the headers compared to the other network pipes and that the flare network is designed to handle the designed back-pressure [1]. The low Mach number of 0.092 also helps in avoiding pipe

vibration and noise generation resulting from excess velocity in the flare network. Therefore, all case scenarios are well below the maximum design Mach number of 0.6.

Impacts of High Back-Pressure on Pressure Relieving Devices of Flare System

The impact of high back pressure on PSVs of the model flare system was further investigated at high back pressure of 5 bar deviation from normal back pressure of 1.2 bar. The effect of higher back pressure on the flare system is critical to the integrity of flare system design and operation which could affect either the set pressure or the capacity of a relief valve. Table 3 presents the effect of high back pressure at the three scenarios of normal operation, a cooling failure and power failure case considered in this study respectively.

Maximum Allowable Back Pressure was exceeded for 10PSV05, 10PSV07 and FCV 1. It can be seen from the flare system model, that high back pressure in the flare system at normal operation scenario results in high back pressure activities in the Tailpipe 1, Tailpipe 5 and Header 1. This is due to internal pressure development above the maximum allowable back pressure in the flow control valve (FCV) and a few relief valves. This in turn affects the set pressure (the pressure at which the relief valve begins to open) and even the capacity (the maximum flow rate that the relief valve will relieve) of the affected relief valves in the flare system. The set pressure for a conventional relief valve increases directly with back pressure which can be compensated for constant back pressure by lowering the set pressure [8]. The effect of high back pressure experienced in FCV and relief valves result in variation in back pressure (is usually not constant) which is attributed to the affected relief valve or other relief valves relieving into the flare header. Also, it can be seen that the system back pressure exceeded the maximum allowable back pressure of the flare system resulting from 10PSV05, 10PSV07 relief valve and FCV. This indicates that a normal operation scenario, high back pressure would affect the performance of the flare system relief valves and flow through the flare header [2, 12]. Hence, excessive back pressure at a pressure relief valve affects the performance of that valve which could potentially result in instability and a significant reduction in flow capacity across the flare header, jeopardizing the safety of the equipment which the valve is meant to protect. However, it can be seen that at high back pressure and for normal operation scenarios, the flare system does not generate noise resulting from back pressure in the PRVs.

From Table 3, it can be seen from the flare system model, that high back pressure in the flare system at cooling water failure scenario results in design violation at the Subheader, Tailpipe, relief valve and FCV. This resulted in an increase in the system velocity for the Subheader from 13.754 m/s to 13.774 m/s, Tailpipe 4 from 13.738 m/s to 13.745 m/s, Tailpipe 6 from 13.728 m/s to 13.736 m/s and excess fluid velocity of 13.7 m/s for 10PSV05 and 19.3 m/s for 10PSV07 relief valves for cooling water failure scenario. This high velocity in the relief valve 10PSV07 due to high back pressure resulted

in 1456 kg/m/s² momentum development in the model flare header. However, the momentum generated in 10PSV07 relief valves is well below the design maximum limit of $\rho V2 < 200000$ kg/m/s² [12], which is acceptable and helps to limit or prevent turbulence or induced vibration that could result in noise, acoustic fatigue, pipe stress, erosion, etc. in the flare network.

Table 3. *Effect of high back pressure on the model flare system for cooling water failure scenario*

Valve	Remark
10PSV05	Velocity Violation at Flange
10PSV07	Maximum Allowable Back Pressure Exceeded
10PSV07	Velocity Violation at Flange
10PSV07	RhoV2 Violation at Flange
FCV 1	Maximum Allowable Back Pressure Exceeded.

PSV: Pressure Safety Valve and FCV: Flow Control Valve

From Table 3, it can be seen that the system back pressure exceeded the MABP of the flare system resulting from the 10PSV07 relief valve (allowable back pressure of 5.12486 bar) and FCV (allowable back pressure of 5.0 bar). This indicates that in the cooling water failure scenario, high back pressure would affect the performance of the flare system relief valves and flow through the flare headers [2, 10, 12]. For this reason, excessive back pressure at a pressure relief valve could potentially lead to instability and a significant reduction in flow capacity across the flare header and could threaten the safety of the equipment which the valve is meant to protect [11]. Therefore, higher back pressure in the model flare system could result in turbulence or induced vibration in the PRVs.

It was also shown that the flare system model at high back pressure for power failure scenario results in design violation across all the relief valves and the control valve except for the 10PSV05. It can be seen that in the power failure scenario, the back pressure of the modelled flare system for all pressure relief valves except 10PSV05 exceeded the allowable back pressure for the power failure scenario. Also, it can be seen that the back pressure at the FCV exceeded allowable back pressure. The high flare system back pressure led to an increase in pressure at the outlet of the affected relief valves which develops as a result of flow after the pressure relief valves open [10]. This would significantly affect the performance of the relieving valve by reducing both its set pressure and its capacity leading to chatter (rapid opening and closing), which can damage the valve [1, 11].

Maximum allowable back pressure was exceeded for relief valves 01 to 08, including FCV. Also, it was observed that the impact of high back pressure on the model flare result in design and operation violation across the flare system (Table 3). It was also shown that the impact of high back pressure could affect the relief of hydrocarbon fluid to Tailpipe 1, Tailpipe 5, Tailpipe 3, Tailpipe 7, Tailpipe 8, Tailpipe 9, and Header 1 in the model KRPC's flare system for power failure scenario.

This violation occurred because the back pressures at almost all the relief valve and FCV control valves exceed the maximum allowable back pressure in the relieving valve. This is attributed to an increase in pressure at the outlet of the affected relieving valve which develops as a result of flow after the PRV opens [11, 14, 15], and also because many PSVs are relieving hydrocarbon fluid at the same time for power failure scenario.

Mitigation Measures against High Back Pressure On the Modelled Flare System

High back pressure operation in the flare system is a threat to the safety and efficiency of the flare system and could jeopardize the equipment integrity and safety. The effect of high back pressure on relief valve capacity is much more significant and could reduce the PRV's capacity by approximately 50%.

From the study, it was established that superimposed back pressure has an impact to the opening of the conventional relief valve and as such, the back pressure will result in additional spring force onto the affected relief valve's disk when in a closed position. To mitigate this challenge, the actual spring setting of the affected relief valves could be reduced by an amount equivalent to the amount of superimposed back pressure.

For future maintenance and/or revamping of the flare system, the use of a larger size tailpipe could be considered to reduce back pressure or the use of a balance below type relief valve to overcome high back pressure. The flare unit manager and operator should review options for reducing high back pressure particularly for cooling failure and power failure scenario such that the back pressure would not exceed 10% of set pressure for the conventional valve and balanced or pilot valves may also be considered in the case of replacement of relief valves to mitigate high or excessive back pressure. Other possible remedies include making jump-overs to relieve local back pressure, replacing pipes and pressure safety valves (PSVs), running a parallel flare line, and relieving flare load to a different part of the flare system.

CONCLUSIONS

This study has demonstrated the modelling and evaluation of the effects of high back pressure (HBP) on the pressure safety valves of the KRPC flare system. The KRPC's flare system was modelled and simulated using Aspen Flare System Analyzer for three scenarios of normal operation (surplus fuel, cooling water failure and power failure).

Steady-state model of KRPC's flare system was successfully simulated using Aspen Flare System Analyzer software package for normal operation (Surplus Fuel), a cooling failure and power failure scenario with the aid of plant data generate from KRPC flare system. The simulated KRPC's flare system shows that the flare system meets the operational requirement for normal flare operation and power failure scenario at a system back pressure of 1.01325 bar, except for the cooling water failure scenario which shows the

occurrence of high fluid velocity and momentum (rhoV^2), which means there is a need to avoid the excessive occurrence of cooling water failure scenario in the KRPC's flare system to prolong the life span of the flare system.

The study showed that at normal operation and cooling water failure, the performance of 10PSV05 and 10PSV07 relief valves were affected at a high back pressure of 5 bar; however, in case of power failure scenario, the performances of 10PSV01, 10PSV02, 10PSV03, 10PSV04, 10PSV06, 10PSV07, 10PSV08 relief valves were affected at a high back pressure of 5 bar. This could potentially result in instability and a significant reduction in flow capacity across the flare header and turbulence flow or induced vibration in the PRVs, and jeopardize the safety of the equipment which the valve is meant to protect.

The KRPC's flare unit manager and operator should review options for reducing high back pressure particularly in case of cooling failure and power failure scenario such that the back pressure would not exceed 10% of set pressure for the conventional valve. In addition, balanced or pilot valves may be considered in the case of replacement of relief valves to mitigate high or excessive back pressure. From the study carried out, it is recommended that further study should be made on a predictive model for pollution dispersion of KRPC gas flaring system.

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MODELIRANJE I EVALUACIJA EFEKATA VISOKOG POVRATNOG PRITISKA NA SISTEMIMA BAKLJI U RAFINERIJI

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Rezime: *Visoki povratni pritisak često utiče na bezbednost i pouzdanost sistema baklji. Jedan od glavnih ciljeva ove studije je simulacija stabilnog modela sistema baklji uz upotrebu softvera Aspen Flare System Analyzer koji koristi podatke iz postrojenja kompanije za preradu nafte Kaduna Refining and Petrochemical Company (KRPC) Ltd, u gradu Kaduna u Nigeriji. U obzir su uzeta tri verodostojna scenarija (normalan rad/višak goriva, nestanak rashladne vode i nestanak struje). Rezultati su pokazali da pomenuti model stabilnog stanja sistema baklji za normalan rad (višak goriva), kao i scenario kvara sistema za hlađenje i nestanka struje u sistemu baklji ispunjavaju zahteve performansi ukoliko povratni pritisak iznosi 1,01325 bara, osim u slučaju nestanka rashladne vode kada dolazi do pojave velike brzine i momenta tečnosti (rhoV2). Takođe, rad baklji pri normalnom povratnom pritisku, za sva tri scenarija ne prelazi projektovane i operativne granične vrednosti. U radu su date preporuke na koji način rukovodioci pomenute kompanije (KRPC) mogu preispitati mogućnosti za smanjenje visokog povratnog pritiska, posebno u slučaju nestanka rashladne vode i nestanka struje, tako da povratni pritisak ne prelazi 10% pritiska u konvencionalnim ventilima.*

Ključne reči: visoki povratni pritisak, bezbednosno inženjerstvo, sistem baklji, ventil, performance, Aspen Flare System Analyzer.