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Simulation Modelling and Evaluation of the Effects of High Back Pressure (HBP) on the Refinery Flare System Network

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Abstract

The efficient performance of the flare system often affected by backpressure. It was in view of this that the present study evaluates backpressure, noise, and flow characteristics due to process upsets within the flare network. The primary objectives of the study were to simulate a steady state model of flare system using Aspen Flare System Analyzer with the aid of plant data generate from KRPC flare system for three scenarios (normal operation/surplus fuel, cooling water failure and power failure), analyse the effect of high back-pressure (HBP) build-up on flare system and to recommend mitigation measures against the effect of HBP on the flare system. This study showed that the steady state model of flare system was successfully simulated for normal operation (Surplus Fuel), cooling failure and power failure scenario and the flare system meets operational requirement for normal flare operation and power failure scenario at a system back pressure of 1.01325 bar, except for cooling water failure scenario which show the occurrence of high fluid velocity and momentum (rhoV2). Also, flare operation at normal backpressure, for all three scenarios do not exceed design and operational limits. The study found that at normal operation and cooling water failure, the performance of few relief valves were affected at high back pressure of 5 bar while the performance of several relief valves were affected for power failure scenario at high backpressure of 5 bar and could potentially result in instability and significant reduction in flow capacity across the flare header and turbulence flow or induced vibration in the PRVs, jeopardizing the safety of the equipment which the valve is meant to protect. Furthermore, the flare unit manager and operator should review options for reducing high backpressure particularly for cooling failure and power failure scenario such that the backpressure 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 backpressure to prolong life span of the flare system.

Keywords*: Backpressure, Flare system, Relief valve, Scenario, Performance and Aspen Flare System Analyzer*

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Background to the Study

Globally, the oil and gas industry are critical sector of the 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 effective operation and threatens process safety. Hence, the oil and gas industry have over the years emphasizes process safety and asset integrity so as to prevent unplanned or emergency releases which could result in a major incident and threatens 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 (Muktikanta, 2013). It entails the prevention and control of incidents that have 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. Hence 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 (Tharakan, 2013; Sotoodeh, 2019). 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 (Muktikanta, 2013). 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 to minimize undesirable venting, led to the introduction of flaring (OGP, 2000). 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 (Smith and Burgess, 2012; Muktikanta, 2013; Shahda, 2019).

However, the pressure that exists at the outlet of a pressure relief device is as a result of the pressure in the discharge system (Nicholas, 2013). 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 (American Petroleum Institute, 2014; Prakash, 2016). Effective and efficient flare system sizing must consider 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 backpressure for all system flow conditions. For conventional relief valves, the allowable backpressure is typically limited to about 10% of the minimum relief valve upstream set pressure (Muktikanta, 2013; American Petroleum Institute, 2014; Qassam *et al.*, 2014). Several studies have been reported on impact of back pressure on pressure safety valves in flare system (Smith and Burgess, 2012; Muktikanta, 2013; Tharakan, 2013; Qassam *et al.*, 2014; Prakash, 2016, Shahda, 2019; Sotoodeh, 2019; Jo *et al.*, 2020). However, no studies have been in 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 scenario. 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), analyse the effect of back-pressure build-up on the flare system, evaluate the effect of high back-pressure on pressure reliving devices and to recommend mitigation measures against the effect of HBP on the flare system

Methodology

Aspen Flare System Analyzer V.11 and Microsoft Excel 2016 software packages were used in the course of this study for the simulation and analysis of the flare system. The pipe data and flare gas composition used in this study was adopted from Kaduna Refinery and Petrochemical Company (KRPC) as presented in Table 1 for the tailpipes, headers, sub header and stack sizes as well as the flowrate of the relief valves used in this study.

Table 1: Collected pipe, tailpipe, header, sub-header and stack specification of KRPC flare system

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

Source: KRPC Flare System Data

Assumptions

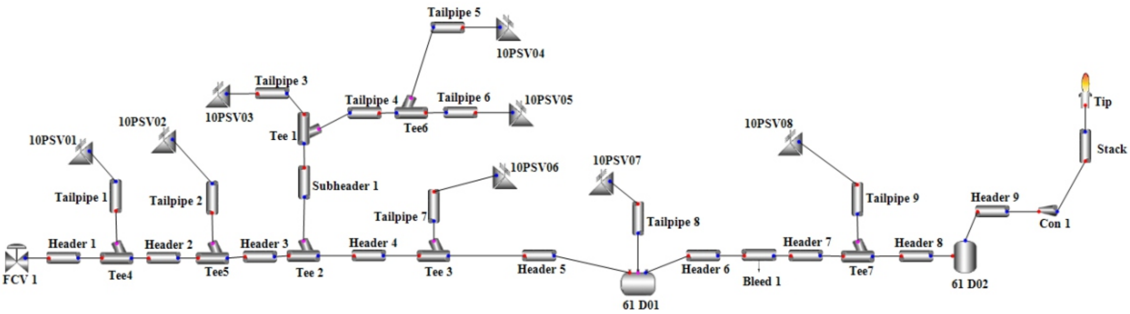
The following assumptions were made in the course of the modelling and simulation of the flare system using Aspen FLARENET.

1. The process is operating in steady state condition.
2. Energy losses are assumed negligible.
3. Pressure lose 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, 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 condition (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: Simulated model of flare system in Aspen FLARENET



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 backpressure on the model flare system in order to ensure the safe 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 to 4 presents the effect of normal backpressure at the three scenario of normal operation, cooling failure and power failure case considered in this study respectively.

Table 2: Effect of backpressure during normal operation scenario of the model KRPC's flare system

Name	Noise (dB)	Static Source Back Pressure (bar)	Upstream Static Pressure (bar)	Upstream Velocity (m/s)	Upstream Mach No.	Upstream Rho V2 (kg/m/s2)	Downstream Static Pressure (bar)
Header 4	0.0	–	1.12308	1.720	0.004	2	1.12307
Header 5	0.0	–	1.12307	1.720	0.004	2	1.12306
Header 6	0.0	–	1.12306	1.721	0.004	2	1.12304
Header 7	0.0	–	1.02304	0.618	0.001	0	1.02304
Header 9	0.0	–	1.02304	0.618	0.001	0	1.02304
Stack	0.0	–	1.02304	0.618	0.001	0	1.01875
Sub header 1	0.0	–	1.12309	0.000	0.000	0	1.12309
Tailpipe 4	0.0	–	1.12309	0.000	0.000	0	1.12309
Header 2	0.0	–	1.12312	1.720	0.004	2	1.12309
Header 3	0.0	–	1.12309	1.720	0.004	2	1.12308
Header 8	0.0	–	1.02304	0.618	0.001	0	1.02304
Tailpipe 9	0.0	1.02304	1.02304	0.000	0.000	0	1.02304
Tailpipe 7	0.0	1.12308	1.12308	0.000	0.000	0	1.12308
Tailpipe 3	0.0	1.12309	1.12309	0.000	0.000	0	1.12309
Tailpipe 6	0.0	1.12309	1.12309	0.000	0.000	0	1.12309
Tailpipe 5	0.0	1.12309	1.12309	0.000	0.000	0	1.12309
Tailpipe 2	0.0	1.12310	1.12310	0.000	0.000	0	1.12310
Header 1	0.0	1.12312	1.12312	1.720	0.004	2	1.12312
Tailpipe 1	0.0	1.12312	1.12312	0.000	0.000	0	1.12312
Tailpipe 8	0.0	1.12349	1.12349	0.000	0.000	0	1.12307

From table 2, it can be seen from the flare system model, that operation of the flare system at normal operation case does not violate the design constraint of the flare system. It can be seen that there is no noise generated as a result of the normal backpressure in the PRVs. This indicates that at normal operation, the flare system does not generate noise resulting from backpressure in the PRVs. This could be attributed to the low flowrate of the flared fluid (2332 kg/hr) at normal operation case of the modelled flare system.

Also, table 3 shows the effect of normal backpressure at cooling water failure scenario of the model flare system. The operation of the KRPC's flare system at cooling water failure case show that design violation occurred (Red colour) at Header 6, Header 7, Header 8 and Header 9 due to slight increase in the flowing fluid momentum (Table 4.2). This could be attributed to internal flow induced forces across header 6 through to header 9 along the flare system (Frederick, 2010; Tharakan, 2013; Shahda, 2019).

Table 3: Effect of cooling water failure on backpressure during normal operation scenario in KRPC's flare system

Name	Noise (dB)	Static Source Back Pressure (bar)	Upstream Static Pressure (bar)	Upstream Velocity (m/s)	Upstream Mach No.	Upstream Rho V2 (kg/m/s^2)	Downstream Static Pressure (bar)
Header 4	0.0	–	1.32082	2.098	0.005	4	1.32080
Header 5	0.0	–	1.32080	2.098	0.005	4	1.32079
Header 6	0.0	–	1.32076	2.797	0.007	7	1.32073
Header 7	0.0	–	1.22073	0.991	0.002	1	1.22072
Header 9	0.0	–	1.22071	0.991	0.002	1	1.22070
Stack	0.0	–	1.22070	0.991	0.002	1	1.21588
Subheader 1	34.3	–	1.33895	52.776	0.119	2360	1.30891
Tailpipe 4	28.9	–	1.36220	51.875	0.117	2319	1.35218
Header 2	0.0	–	1.32085	0.000	0.000	0	1.32085
Header 3	0.0	–	1.32085	0.000	0.000	0	1.32085
Header 8	0.0	–	1.22072	0.991	0.002	1	1.22071
Tailpipe 9	0.0	1.22072	1.22072	0.000	0.000	0	1.22072
Tailpipe 7	0.0	1.31808	1.32135	4.596	0.011	21	1.32079
Tailpipe 3	0.0	1.32082	1.32082	0.000	0.000	0	1.32082
Tailpipe 6	0.0	1.32085	1.32085	0.000	0.000	0	1.32085
Tailpipe 5	0.0	1.32085	1.32085	0.000	0.000	0	1.32085
Tailpipe 2	0.0	1.32085	1.32085	0.000	0.000	0	1.32085
Header 1	0.0	1.35725	1.35725	0.000	0.000	0	1.35725
Tailpipe 1	0.0	1.36684	1.36684	0.000	0.000	0	1.36684
Tailpipe 8	31.7	1.37687	1.37687	51.322	0.116	2295	1.36454

From 3, it can be seen that the noise generated as a result of the normal backpressure in the PRVs are low. This indicates that at cooling water failure scenario, the flare system does not generate excessive noise resulting from backpressure in the PRVs with less than 35 dB of noise across the few affected relief valves. However, there was no noise generated at majority of the relief valve as well as FCV of the model flare system for cooling water failure scenario (Table 3). This could be attributed to the low momentum of the flowing fluid resulting from low fluid velocity at normal operation case of the model flare system.

Table 4 shows the effect of normal backpressure at power failure case of the model flare system. Furthermore, operation of the flare system at power failure case show the occurrence of design violation (Red colour) at the Tailpipe. This violation occurred due to backpressures at the relief valve to the tailpipe exceeding the maximum allowable back pressure (MABP) in the relieving valve which is attributed to slight increase in pressure at the outlet of 10PSV07 which develops as a result of flow after the PRV opens (Jo *et al.*, 2020).

Table 4: Effect of power failure on backpressure during normal operation scenario in KRPC's flare system

Name	Noise (dB)	Static Source Back Pressure (bar)	Upstream Static Pressure (bar)	Upstream Velocity (m/s)	Upstream Mach No.	Upstream Rho V2 (kg/m/s2)	Downstream Static Pressure (bar)
Header 4	(dB)"	–	8.26482	20.000	0.045	2253	8.26074
Header 5	28.4	–	8.25826	20.183	0.045	2292	8.25495
Header 6	27.7	–	8.24645	20.400	0.046	2341	8.23711
Header 7	25.0	–	8.13711	6.770	0.015	254	8.13245
Header 9	0.0	–	8.12909	8.021	0.018	355	8.12672
Stack	5.2	–	8.12672	8.023	0.018	355	8.09249
Subheader 1	24.0	–	8.27967	8.653	0.025	597	8.26841
Tailpipe 4	2.2	–	8.28566	8.803	0.020	411	8.28393
Header 2	0.0	–	8.29417	19.391	0.044	2110	8.27657
Header 3	27.5	–	8.27418	19.651	0.044	2161	8.26752
Header 8	26.9	–	8.13154	8.018	0.018	355	8.12969
Tailpipe 9	5.2	8.13265	8.13265	4.706	0.011	119	8.13255
Tailpipe 7	0.0	8.25958	8.26102	1.217	0.003	9	8.25789
Tailpipe 3	0.0	8.27451	8.27817	12.362	0.028	836	8.28169
Tailpipe 6	0.0	8.28414	8.28434	0.627	0.004	14	8.28423
Tailpipe 5	0.0	8.28888	8.28888	5.666	0.013	169	8.28796
Tailpipe 2	0.0	8.30525	8.30482	7.181	0.016	283	8.30525
Header 1	0.0	1.35725	1.35725	0.000	0.000	0	1.35725
Tailpipe 1	11.4	1.36684	1.36684	0.000	0.000	0	1.36684
Tailpipe 8	10.7	1.37687	1.37687	51.322	0.116	2295	1.36454

From table 4, it can be seen that the noise generated as a result of the normal backpressure in the PRVs are low. This indicates that at power failure case scenario, the flare system does not generate excessive noise resulting from backpressure 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 (Shahda, 2019).

Effect of back-pressure on the flare system Mach number

Another significant criterial 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 sub headers are expected not to exceed 0.6 Mach. As such, this study also examines the effect of back pressure on flare system. Table 2 present the effect of normal backpressure on the Mach number on the modelled flare system at the various relief valve for normal operation scenario. The maximum Mach number attained for all PSV's of the model flare system for normal operation scenario do not exceed 0.004 which is well below the maximum velocity for flare headers and sub headers shall which is expected not to exceed 0.6 Mach (NORSOK Standard, 1997). This could be 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 (Mukherjee, 2008; Muktikanta, 2013). Also, the low flow rate (2332 kg/hr) of the fluid also contribute to the low Mach number. This is significant as it helps to avoid pipe vibration and noise generation caused by excess velocity in the flare network.

Table 3 also presents the effect of normal backpressure on the Mach number at all relief valve 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 do not exceed 0.122 which is also well below the maximum velocity of 0.6 maximum Mach number for flare headers (NORSOK Standard, 1997; Muktikanta, 2013). 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 (Muktikanta, 2013). The low Mach number of 0.122 also enhance the avoidance of pipe vibration and noise generation resulting from excess velocity in the flare network.

Table 4 presents the effect of normal backpressure on the Mach number at all relief valve of the model flare system for power failure scenario. The maximum Mach number attained for all PSV's of the model flare system for power failure scenario do not exceed 0.092 which is also well below 0.6 maximum Mach number for flare headers design (NORSOK Standard, 1997; Muktikanta, 2013). 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 (Muktikanta, 2013). 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.

Effect of back-pressure on the flare system momentum (ρV2)

Another vital criterial for efficient operation of flare system is the fluid momentum (ρV2) as potentially cause of high vibration and noise level associated with flare system with all flare lines designed to keep the ρV2 < 150000 – 200000 kg/ms^2. Figure 4.19 present the profile of the effect of normal backpressure on ρV2 in the flare system at the various relief valve of the model KRPC's flare system for normal operation scenario. From Table 2, it can be seen that the maximum ρV2 attained for all PSV's and headers of the model flare system for normal operation scenario do not exceed 2 $kg/m/s^2$ which is well below the maximum limit of ρV2 < 200000 $kg/m/s^2$ which is dependent on the fluid velocity. The significant of ρV2 is to limit or prevent turbulence or induced vibration of flare piping's which could resulting into noise, acoustic fatigue, pipe stress, erosion etc. (Frederick, 2010). Since the model flare system for normal operation scenario do not exceed 2 $kg/m/s^2$, normal backpressure does not have effect on the operation of the flare system.

From table 3, it can be seen that the maximum ρV2 attained for all PSV's and headers of the model flare system for cooling failure scenario do not exceed 2500 $kg/m/s^2$ which is well below the maximum limit of ρV2 < 200000 $kg/m/s^2$ (Frederick, 2010). This value for the flare system is reasonable as it helps limit or prevent turbulence or induced vibration in the flare network which could resulting into noise, acoustic fatigue, pipe stress, erosion etc. Normal backpressure does not have significant effect on the ρV2 of the flare system for cooling failure scenario.

From Table 4, it can be seen that the maximum ρV2 attained for all PSV's and headers of the model flare system for power failure scenario do not exceed 8000 $kg/m/s^2$ which is also, well below the maximum limit of $\rho V2 < 200000$ $kg/m/s^2$ (Frederick, 2010). This value for the KRPC's flare system is in reasonable agreement with the maximum limit. The ρV2 value for power failure scenario of the flare system aide in limiting or preventing turbulence or induced vibration in the flare network which often result into noise, acoustic fatigue, pipe stress, erosion etc. Normal backpressure does not have significant effect on the ρV2 of the flare system for power failure scenario. Therefore, design or normal backpressure of the flare system, for all three-case scenario of normal operation, cooling failure and power failure do not exceed design limits.

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

The impact of high backpressure on PSVs of the model flare system was further investigated at a high backpressure of 5 bar deviation from normal backpressure 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 5 to 7 presents the effect of high backpressure at the three scenario of normal operation, cooling failure and power failure case considered in this study respectively.

Table 5: Effect of high backpressure on the model flare system for normal operation scenario

Name	Noise (dB)	Static Source Back Pressure (bar)	Upstream Static Pressure (bar)	Upstream Velocity (m/s)	Upstream Mach No.	Upstream Rho V2 (kg/m/s2)	Downstream Static Pressure (bar)
Tailpipe 7	0.0	5.12215	5.12215	0.000	0.000	0	5.12215
Header 1	0.0	5.12216	5.12216	0.377	0.001	1	5.12216
Header 4	0.0		5.12215	0.377	0.001	1	5.12215
Header 5	0.0		5.12215	0.377	0.001	1	5.12215
Header 6	0.0		5.12215	0.377	0.001	1	5.12214
Header 7	0.0		5.02214	0.126	0.000	0	5.02214
Header 9	0.0		5.02214	0.126	0.000	0	5.02214
Stack	0.0		5.02214	0.126	0.000	0	5.00112
Subheader 1	0.0		5.12215	0.000	0.000	0	5.12215
Tailpipe 3	0.0	5.12215	5.12215	0.000	0.000	0	5.12215
Tailpipe 4	0.0		5.12215	0.000	0.000	0	5.12215
Tailpipe 8	0.0	5.12407	5.12407	0.000	0.000	0	5.12215
Tailpipe 1	0.0	5.12216	5.12216	0.000	0.000	0	5.12216
Header 2	0.0		5.12216	0.377	0.001	1	5.12216
Tailpipe 2	0.0	5.12216	5.12216	0.000	0.000	0	5.12216
Header 3	0.0		5.12216	0.377	0.001	1	5.12215
Tailpipe 6	0.0	5.12215	5.12215	0.000	0.000	0	5.12215
Tailpipe 5	0.0	5.12215	5.12215	0.000	0.000	0	5.12215
Header 8	0.0		5.02214	0.126	0.000	0	5.02214
Tailpipe 9	0.0	5.02214	5.02214	0.000	0.000	0	5.02214

From table 5, it can be seen from the flare system model, that high backpressure in the flare system at normal operation scenario results in high backpressure activities in the Tailpipe 1, Tailpipe 5 and Header 1. This is due to internal pressure development above the maximum allowable backpressure in the flow control valve (FCV) and few relief valves. This in turn affect 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 (American Petroleum Institute, 2014). The effect of high backpressure 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 backpressure exceeded the maximum allowable backpressure of the flare system resulting from 10PSV05, 10PSV07 relief valve and FCV. This indicates that at normal operation scenario, high back pressure would affect the performance of the flare system relief valves and flow through the flare header (Frederick, 2010; Tharakan, 2013). Hence, excessive backpressure at a pressure relief valve affects the performance of that valve which could potentially results in instability and significantly 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 backpressure and for normal operation scenario, the flare system does not generate noise resulting from backpressure in the PRVs.

Also, Table 6 shows the effect of high backpressure on the model flare system for cooling water failure scenario. From Table 6, it can be seen from the flare system model, that high backpressure in the flare system at cooling water failure scenario results in design violation at the Sub header, Tailpipe, relief valve and FCV. This resulted in increase in the system velocity in for the Sub header 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 $kg/m/s^2$ momentum development in the model flare header. However, the momentum generated in 10PSV07 relief valves is well below design maximum limit of $\rho V2 < 200000$ $kg/m/s^2$ (Frederick, 2010) which is acceptable and helps to limit or prevent turbulence or induced vibration that could resulting into noise, acoustic fatigue, pipe stress, erosion etc in the flare network.

Table 6: Effect of high backpressure on the model flare system for cooling water failure scenario

Name	Noise (dB)	Static Source Back Pressure (bar)	Upstream Static Pressure (bar)	Upstream Velocity (m/s)	Upstream Mach No.	Upstream Rho V2 (kg/m/s2)	Downstream Static Pressure (bar)
Tailpipe 7	0.0	5.12377	5.12377	0.000	0.000	0	5.12377
Header 1	0.0	5.12378	5.12378	0.000	0.000	0	5.12378
Header 4	0.0		5.12377	0.540	0.001	1	5.12377
Header 5	0.0		5.12377	0.540	0.001	1	5.12376
Header 6	0.0		5.12376	0.719	0.002	2	5.12375
Header 7	0.0		5.02375	0.240	0.001	0	5.02374
Header 9	0.0		5.02374	0.240	0.001	0	5.02374
Stack	0.0		5.02374	0.240	0.001	0	5.00385
Subheader 1	3.0		5.12835	13.754	0.031	615	5.12073
Tailpipe 3	0.0	5.13312	5.13312	0.000	0.000	0	5.13312
Tailpipe 4	0.0		5.13438	13.738	0.031	614	5.13178
Tailpipe 8	0.0	5.12486	5.12570	1.180	0.003	5	5.12376
Tailpipe 1	0.0	5.12378	5.12378	0.000	0.000	0	5.12378
Header 2	0.0		5.12378	0.000	0.000	0	5.12378
Tailpipe 2	0.0	5.12378	5.12378	0.000	0.000	0	5.12378
Header 3	0.0		5.12378	0.000	0.000	0	5.12378
Tailpipe 6	1.1	5.13823	5.13823	13.728	0.031	614	5.13500
Tailpipe 5	0.0	5.13561	5.13561	0.000	0.000	0	5.13561
Header 8	0.0		5.02374	0.240	0.001	0	5.02374
Tailpipe 9	0.0	5.02374	5.02374	0.000	0.000	0	5.02374

From table 6, it can be seen that the system backpressure exceeded the maximum allowable backpressure of the flare system resulting from 10PSV07 relief valve (allowable backpressure of 5.12486 bar) and FCV (allowable backpressure of 5.0 bar). This indicates that at cooling water failure scenario, high back pressure would affect the performance of the flare system relief valves and flow through the flare headers (Frederick, 2010; Tharakan, 2013; Prakash, 2016). Hence, excessive backpressure at a pressure relief valve could potentially leads to in instability and significantly reduction in flow capacity across the flare header and could threaten the safety of the equipment which the valve is meant to protect (Jo *et al.*, 2020). Therefore, higher backpressure in the model flare system could results turbulence or induced vibration in the PRVs.

Furthermore, table 7 shows the effect of high backpressure on the model flare system for power failure scenario. From table 7, it can be seen that the flare system model at high backpressure for power failure scenario results in design violation across all the relief valve and the control valve except for the 10PSV05. It can be seen that at power failure scenario, the backpressure of the modelled flare system for all pressure relief valve except 10PSV05 exceeded the allowable backpressure for power failure scenario. Also, it can be seen that the backpressure at the FCV exceeded allowable backpressure. The high flare system backpressure led to increase in pressure at the outlet of the affected relief valves which develops as a result of flow after the pressure relief valves opens (Prakash, 2016). This would significantly affect the performance of the relieving valves performance by reducing both its set pressure and its capacity leading to chatter (rapid opening and closing), which can damage the valve (Muktikanta, 2013; American Petroleum Institute, 2014; Jo *et al.*, 2020).

Table 7: Effect of high back pressure on model flare system relief and control valves

Relief Valve	**Remark**
10PSV01	Maximum allowable backpressure exceeded
10PSV02	Maximum allowable backpressure exceeded
10PSV03	Maximum allowable backpressure exceeded
10PSV04	Maximum allowable backpressure exceeded
10PSV06	Maximum allowable backpressure exceeded
10PSV07	Maximum allowable backpressure exceeded
10PSV08	Maximum allowable backpressure exceeded
FCV	Maximum allowable backpressure exceeded

Also, it was observed that the impact of high backpressure on the model flare result in design and operation violation across the flare system (Table 7). From Table 8, it can be seen that the impact of high backpressure affects the relieve of hydrocarbon fluid to Tailpipe 1, Tailpipe 5, Tailpipe 3, Tailpipe 7, Tailpipe 8, Tailpipe 9 and Header 1 (coloured red) in the model KRPC's flare system for power failure scenario. This violation occurred because the backpressures at almost all the relief valve and FCV control valve exceed the maximum allowable back pressure (MABP) in the relieving valve. This is attributed to increase in pressure at the outlet of the affected relieving valve which develops as a result of flow after the PRV opens (Jo *et al.*, 2020), and also because many PSVs are relieving hydrocarbon fluid at the same time for power failure scenario.

Table 8: Effect of high backpressure on the headers and tailpipes in the model flare system for power failure scenario

Name	Noise (dB)	Static Source Back Pressure (bar)	Upstream Static Pressure (bar)	Upstream Velocity (m/s)	Upstream Mach No.	Upstream Rho V2 (kg/m/s2)	Downstream Static Pressure (bar)
Tailpipe 7	16.7	10.75204	10.75204	28.131	0.063	5631	10.61447
Header 1	5.6	10.67158	10.67158	9.468	0.022	657	10.67110
Header 4	22.6		10.63990	15.515	0.035	1748	10.63674
Header 5	21.9		10.63482	15.652	0.035	1778	10.63225
Header 6	19.2		10.62523	15.812	0.036	1814	10.61800
Header 7	0.0		10.51800	5.230	0.012	197	10.51440
Header 9	0.0		10.51181	6.194	0.014	274	10.50997
Stack	18.3		10.50997	6.196	0.014	274	10.46641
Subheader 1	0.0		10.65177	6.713	0.020	463	10.64269
Tailpipe 3	0.0	10.65525	10.65540	0.469	0.003	10	10.65531
Tailpipe 4	0.0		10.65642	6.837	0.016	319	10.65507
Tailpipe 8	0.0	10.63744	10.63855	0.943	0.002	7	10.63453
Tailpipe 1	0.0	10.67128	10.67095	5.583	0.013	220	10.67128
Header 2	21.7		10.66267	15.064	0.034	1639	10.64901
Tailpipe 2	0.0	10.64741	10.65026	9.599	0.022	649	10.65299
Header 3	21.1		10.64716	15.252	0.034	1677	10.64200
Tailpipe 6	0.0	10.65892	10.65892	4.401	0.010	131	10.65821
Tailpipe 5	4.9	10.67927	10.68232	20.511	0.046	2974	10.65458
Header 8	0.0		10.51369	6.193	0.014	274	10.51226
Tailpipe 9	0.0	10.51456	10.51456	3.636	0.008	92	10.51447

It was also observed from table 8 that the backpressure developed exceeded the allowable backpressure in the 10PSV03 relief valve and the same for all other relief valve and FCV except 10PSV05 relief valve power failure scenario. High backpressure was also found to result in rise in fluid velocity and momentum (ρV2) along the flare tailpipes and headers. The high momentum (ρV2) could result in high vibration, pipe stress acoustic fatigue, and erosion of the nodal equipment and also, since bend forces (flow induced) are directly proportional to ρV2, the nodal equipment will experience high slug forces (Mukherjee, 2008; Sotoodeh, 2019).

From the three scenarios (normal operation, cooling failure and power failure) considered in this study at high backpressure, it can be deduced that at normal operation and cooling failure scenario, the performance of few relief valves was affected. However, at power failure scenario, the performance of almost all the relief valves were affected which could potentially result in instability and significant reduction in flow capacity across the flare header and turbulence flow or induced vibration in the PRVs, jeopardizing the safety of the equipment which the valve is meant to protect. Hence, high backpressure can result in increase in the pressure required to open the affected relief valve, causing the valves to close too soon and to chatter as well as reduces the relieving capacity any of which may lead to an unacceptable pressure rise in the protected vessel.

Mitigation Measures Against High Back Pressure on the Modelled Flare System
High backpressure operation in flare system portends a threat to the safety and efficiency of flare system and could jeopardize the integrity and safety of the equipment which the flare is meant to protect. As such the need to operate the flare system in a manner that will enhance efficient operation and safety of the oil and gas facility. The effect of high backpressure 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 backpressure has impact to opening of conventional relief valve and as such, the backpressure will result in additional spring force onto the affected relief valves disk when in 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 backpressure.

High backpressure in relief valves reduces the lifting of disc which results in the reduction of flow capacity. For conventional relief valve type, operators should ensure that built up backpressure not to exceed 10% of set pressure at 10% allowable overpressure. For application that allowable overpressure is higher than 10%, say 16% of multiple valve application, then the built-up backpressure up to 16% of set pressure is allowed for conventional type. Also, it was established in the study that excess built up backpressure in the affected relief valves result in unstable condition which could lead to rapid motion of closing and opening in the valve where the disc contacts with the relief valve seat during cycling (chatter) and flutter, where the disc is not in contact with the seat. As such, the operation of the affected relief valves should be operated to avoid chatter which could cause damage to the relief valve.

For future maintenance and/or revamping of the flare system, the use of larger size tail pipe could be considered to reduce back pressure or the use of balance below type relief valve to overcome high backpressure. The flare unit manager and operator should review options for reducing high backpressure particularly for cooling failure and power failure scenario such that the backpressure 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 backpressure. Other possible remedies include making jump-overs to relieve local backpressure, replacing pipes and pressure safety valves (PSVs), running a parallel flare line, and relieving of flare load to different part of the flare system.

Conclusions and Recommendations
This study has demonstrated the modelling and evaluation of the effects of high backpressure (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). From the study carried out, the following conclusion were obtained.

Steady state model of KRPC's flare system was successfully simulated using Aspen Flare System Analyzer software package for normal operation (Surplus Fuel), cooling failure and power failure scenario with the aid of plant data generate from KRPC flare system and the simulated KRPC's flare system shows that the flare system meets operational requirement for normal flare operation and power failure scenario at a system back pressure of 1.01325 bar, except for cooling water failure scenario which show the occurrence of high fluid velocity and momentum (rhoV2), hence the need to avoid the excessive occurrence of cooling water failure scenario in the KRPC's flare system for prolong life span of the flare system.

The effect of back-pressure build-up on the KRPC flare system shows that at normal operation, cooling water failure and power failure scenario, the KRPC's flare system do not generate excessive noise, momentum (ρV2) and Mach number and are all below maximum allowable limit of 91 dB noise, 150000 kg/ms2 momentum and 0.6 Mach number, hence the model showed that the KRPC's flare system is operating within acceptable limit. Therefore, normal backpressure of the KRPC's flare system, for all three-case scenario of normal operation, cooling failure and power failure do not exceed design limits.

The study showed that at normal operation and cooling water failure, the performance of 10PSV05 and 10PSV07 relief valves were affected at high back pressure of 5 bar while at power failure scenario, the performance of 10PSV01, 10PSV02, 10PSV03, 10PSV04, 10PSV06, 10PSV07, 10PSV08 relief valves were affected at high backpressure of 5 bar and could potentially result in instability and significant reduction in flow capacity across the flare header and turbulence flow or induced vibration in the PRVs, jeopardizing 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 backpressure particularly for cooling failure and power failure scenario such that the backpressure 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 backpressure. From the study carried out, it is recommended that further study should be made on predictive model for pollution dispersion of KRPC gas flaring system.

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