CENTRIFUGAL COMPRESSOR PROLONGED LOW FLOW OPERATION CONSIDERATION FOR OPERATORS

Dayang Nurhan Binti Awang Mahmood
Engineer, Rotating Equipment
Petronas Carigali Sdn Bhd
Miri, Sarawak, Malaysia

Khairul Fata Bin Ahmad Asnawi
Principal, Rotating Equipment
Petronas Carigali Sdn Bhd
Kuala Lumpur, Malaysia

Dayang Nurhan Binti Awang Mahmood has involved in operation and maintenance of Rotating Equipment for more than 8 years mainly in oil and gas industry. At present she is in charge as discipline engineer taking care of a fleet of four gas export centrifugal compressors and ten gas turbines and various rotating equipment, such as pumps and reciprocating compressors.

Khairul Fata Bin Ahmad Asnawi has been working in the company for more than 15 years mainly on Rotating Equipment in the oil and gas industry. As Principal in the specialized division, he provides guidance, technical advices, mentorship and involves actively in various troubleshooting and root cause failure analyses.

ABSTRACT

Centrifugal compressor is the heart of upstream and downstream oil and gas operation as its ability to move large volume of fluid to its end destination. Centrifugal compressors are designed at certain range of operation. One of the biggest concerns is operating the machine at low flow, where the surge is expected to happen. Many research and references addressed the surge phenomenon and how it contributes to enormous damage to centrifugal compressor in seconds. However, to the authors' experiences, there are other situations, where comprehensive attention shall be given by the machine operators. When centrifugal compressor operates near to the predicted surge line for a long time, there are concerns to the centrifugal compressor and its driver, which are further addressed and elaborated in this paper. In summary, prolonged operation at low flow region can contribute to failure to anti-surge valve, increase in suction and discharge temperature, waste of energy, failure of driver and initiation of a diffuser stall. If these potential failures went unnoticed, it may fail the centrifugal compressor promptly without any warning.

INTRODUCTION

Centrifugal compressor is considered as one of the most critical equipment in oil and gas industry that covers offshore, marine, and onshore applications. This machine is part of turbomachinery of which the selection is made based on right process requirement, site location, drive selection, equipment sparing strategy, efficiency & reliability, operability & maintainability and cost effectiveness. With accurate selection of centrifugal compressor, it will deliver its function efficiently and stable. Efficient operation is achieved when the throughput of the compressor is delivering at its best efficiency region.

Operators often face challenges in maximizing production while maintaining the compressor at its optimum running conditions. Often, such ideal conditions can't be met due to insufficient volume available in many depleting reservoirs. Based on authors' experience operating a fleet of centrifugal compressors for upstream operation, nearly 60% of the centrifugal compressor experience operating at prolonged low flow with 40% of the case, the machine is operating at prolonged low flow because of well depletion and 20% is on intermittent low flow due to change in process condition. These compressors are operating at the region, where active movement of anti-surge valve involved and low power demand, which can accelerate wear and tear of the compressors and its components. While the ultimate solution for this case is centrifugal compressor re-rating, the effort is extensive and costly. Based recent compressor re-rating project, the duration to complete the project varies from 18 months to 36 months depend on the complexity of the centrifugal compressor. The cost of re-rating also expected around 60% of the new compressor cost. Hence, centrifugal compressor re-rating options is not easy to be implemented, hence operators need to continue to operate their centrifugal compressors on prolonged low flow operation. Authors' view suggesting machine operators to understand the risk of prolonged low flow operation of centrifugal compressor to mitigate the risk and maximize life of the centrifugal compressor.

PROLONGED LOW FLOW OPERATION

In most common case of centrifugal compressor operation, compressor surge is the main concern when operating at low flow. Surge is a phenomenon that has detrimental effect to centrifugal compressor. When surge happens, centrifugal compressor will have discharge pressure fluctuation with rapid temperature increase, loud noise can be heard from the compressor and possible can cause rotor damage [1]. The level of damage can be varied according to the centrifugal compressor operating pressure, gas density and rotor design. As the surge impact to the compressor is very damaging, anti-surge system is installed.

Typical anti-surge system consists of a recycle line that equipped with anti-surge valve. The anti-surge valve is activated when the compressor operating point is approaching predicted surge line as per area (1) in *Figure 1*. Hence, this area is considered as a safety margin. If the centrifugal compressor operates at area (1) for a short-term period e.g. few hours, this is not a concern. However, if centrifugal compressor operates at area (1) and anti-surge valve is active for prolonged duration e.g. for months, it can create risk to the compressor. To the authors' experience, the concern is not just only at area (1), but the effect starts to develop at area (2) when centrifugal compressor operating point continuously operate near surge control line.

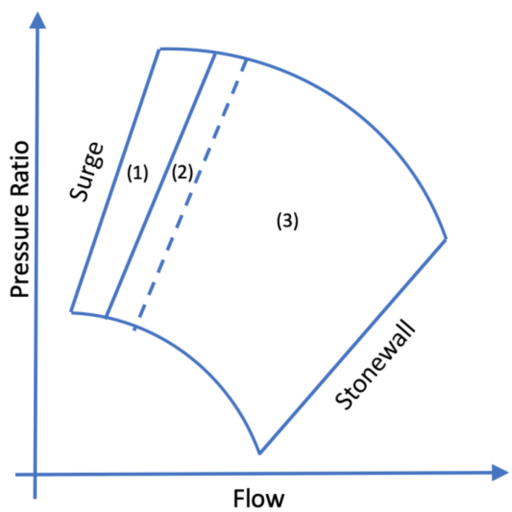

Figure 1 : Typical Compressor Map

RISKS OF OPERATING AT LOW FLOW

Continuous operation close to turndown rate may be enabled by operating compressor control system in manual mode, recycling via anti-surge valve. Such operating condition is normally not favorable as it poses risks to the compressor, anti-surge valve and the driver (mostly gas turbine). Below are some major risks of concern captured at various locations resulting from prolonged low flow.

Hydrate formation at Anti-Surge Valve causing dirt accumulation on valve stem

Multiple events on anti-surge valve failures encountered on flash gas compressor as an effect of Joule-Thompson effect, also known as JT Effect. Hydrate formation can be physically observed with presence of ice at downstream of anti-surge valve. This can be further verified through process simulation software, such as HYSYS to determine the state of matter at operating pressure and temperature.

The JT effect states, that when the pressure of a gas changes, its temperature also changes. This temperature change of direction can be determined by measuring the Joule-Thomson coefficient, μ_{JT}.

$$\mu_{JT} = \left(\frac{\partial T}{\partial P}\right)_h$$

Anti-surge valve is a flow control valve and acts as a throttling device. Natural gas from compressor moves from higher pressure passes through the valve reducing its pressure and temperature. At some instance, decrease of pressure is low enough resulting in μ_{JT} greater than zero causing cooling effect. Some elements of moisture present in the gas freeze and form hydrates attributed by ice that agglomerates at the internal component of the valve or on the valve body.

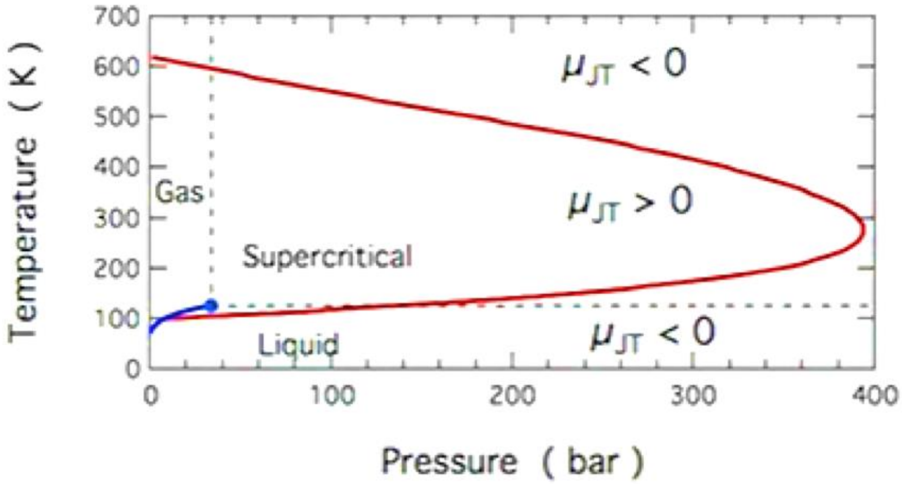

Figure 2 : Joule-Thomson Curve showing the states of matter at different pressure and temperature

Repetitive operation with hydrate formation mixed with dirt or hardened grease may result to sticky valve stem and at worst lead to anti-surge valve failure.

Figure 3 : Anti-surge valve stem dirty due to accumulation of dirt and hardened grease.

High Suction Temperature

When centrifugal compressor operating at lower load region, chances of the gas recycle back to suction is high as the centrifugal compressor is expected to surge. The gas from discharge is route back to the suction. Depends on the configuration, the discharge gas can be tapped before or after discharge cooler and route back to the suction system of the compressor. Any of this configuration will elevate suction temperature, where tapped directly from discharge (hot gas recycle) has greater impact to the centrifugal compressor suction system. If this scenario not properly assessed during prolonged low load operation, it may be resulted in higher suction temperature for the centrifugal compressor. Higher suction temperature will be affected the compressor performance and gas turbine is required to produce more power. Discharge temperature also directly affected by the suction temperature and will cause problem to the centrifugal compressor that already has small margin between discharge temperature and high limit discharge temperature.

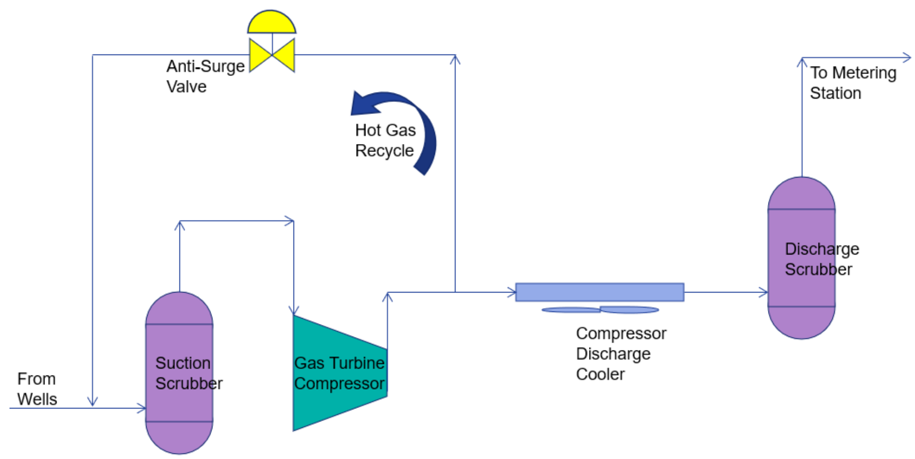

Figure 4 : Typical anti-surge valve recycle line configuration.

Recycle is a waste of energy

Considering the above situation, any recycle gas back to suction is consider as waste of energy. As the gas turbine produces power for centrifugal compressor to moves the gas from one point to another, recycle return the compressed gas back to the suction and the centrifugal compressor re-compressed the gas. The action re-compressing the gas cause the energy added is not considered as useful work to the centrifugal compressor and consumed more fuel for the driver.

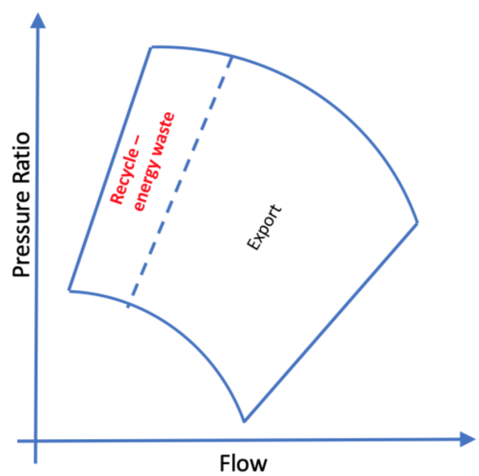

Figure 5: Area represents recycle gas waste of energy on compressor map.

Reduced power demand causing driver issues

Operating at prolonged low flow reduces power consumption by the centrifugal compressor and impact the driver load particularly gas turbine. At low power demand the gas turbine operate close to its stall region and lower combustion and exhaust temperature. Gas turbines equipped with hardware such as bleed-off valve (BOV) and variable inlet guide vane (VIGV) to prevent its axial compressor from stall. Normally, the hardware is active during start-up and shut-down period where the axial compressor is more prone to stall and not designed to operate at prolonged duration. Hence, operating at prolonged low load can associate gas turbine with several risk and cause failure that can disturb centrifugal compressor operation. Most common problems when gas turbine operates at prolonged low flow are high failure of bleed-off valve (BOV) ducting, variable inlet guide vane (VIGV) worn out rate and high cycle fatigue at stationary combustor component.

a) *Failure of BOV ducting* – Certain aero-derivative gas turbines use BOV to protect axial compressor from stall. The BOV activated when the certain low load is detected by gas turbine through non-dimensional parameters tracked by the gas turbine control system. When BOV activated, it releases hot compressed air from mid-section of axial compressor to exhaust stack through a ducting. The ducting is not designed for continuous operation hence, during normal operation there should be no any release of hot compressed air from axial compressor. In case of low load operation, BOV may open at prolonged duration which cause the ducting stressed. To some extent, the ducting may fail at its weakest point and release hot air inside the gas turbine enclosure. When this happen, the immediate impact is increase in enclosure temperature. Worst thing can happen is melting of cable insulation which subsequently cause minor damage inside gas turbine enclosure.

b) *High VIGV wear rate* – For gas turbine doesn't equipped with running BOV, stall prevention is achieved by manipulating the VIGV. When gas turbine run at low load, the speed of turbine will be varying accordingly and require more active VIGV movement. Hence, it increases the wear rate of the actuator, linkages and VIGV blades itself. There are several symptoms causes by VIGV failure such as vibration, low gas turbine performance and flame-off.

c) *Failure of stationary combustor hardware* – While most of the failures of gas turbine causes by rotational and moving components, stationary components also prone to failure when operate at prolonged low load. Stationary components at combustors are subjected to thermal expansion. These components are best fit together at normal operating temperature range where thermal expansion is designed to be at optimum level. At lower temperature, as in low load operation scenario, lower combustion temperature cause inadequate expansion where it creates gap between stationary components. The gap may be huge enough to cause rattling when exposed to high velocity flue gas resulted from combustion. High cycle fatigue is likely to happen to the combustor's hardware due to this rattling. In many cases, gas turbine also experiences increase level of vibration due to this phenomenon.

Figure 6: Example of crack happened at stationary combustor hardware resulted from high cycle fatigue

Aerodynamic instability causing rotor failure

Diffuser stall is one of the aerodynamic instabilities that can damaged centrifugal compressor rotor. When the centrifugal compressor operates nearing predicted surge line the flow become more unstable and initiates non-uniform pressure profile across impeller tip and diffuser inlet. This phenomenon is not a problem for a short period of time i.e. few hours but proven to be detrimental if the condition is prolonged for a few months or more. As an example, as per *Figure 7*, the centrifugal compressor rotor failed after operating more than six months reducing throughput (towards predicted surge line) due to production well depleted. Diffuser stall is expected to be happened and excited impeller shroud natural frequency which subsequently lead to the failure of the weakest point of the impeller i.e. impeller shroud as seen in *Figure 6.* The failure of this shroud can be accelerated if presence of moisture in hydrocarbon gas increases.

It is quite difficult to detect diffuser stall. One of the potential detections of this phenomenon is through vibration monitoring and diagnostic. Diffuser stall may be indicated by presence of sub-synchronous vibration at frequency range 0.1x and 0.3x [2] and vane pass frequency (*Figure 8*). Hence, attention need to be given to any centrifugal compressor that shows related vibration signature and operating at lower throughput to avoid diffuser stall to happen.

Figure 7: Example of rotor failure at impeller shroud due to diffuser stall.

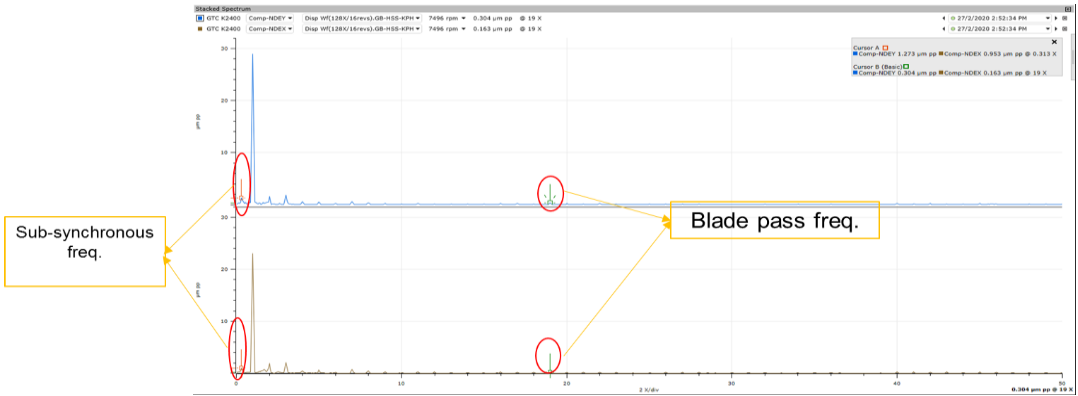

Figure 8 : Indication of diffuser stall from vibration diagnostic.

RISK MITIGATION AND WAY FORWARD

As discussed in earlier section, when the compressor is expected to run at prolonged low flow mode, re-rating is the best solution, however it is costly and consumes longer time to realize. On operational perspective, debottlenecking or adjustment of the system to allow more flow coming to compressor can be considered, of which detail study of the overall system also requires more time to complete.

Known risks to the compressor shall be targeted as a short-term mitigation whenever operator intends to operate at low flow condition to avoid unwanted issues on the compressor and its driver during plant uptime. Thorough risk assessment should be conducted and associated risks must be properly addressed, and mitigations are in place. Based on prior lesson learnt mentioned in the earlier section, below are some mitigations that can be considered:

Short-Term Mitigations

- Thorough risk assessment.
- Conduct process simulations to determine any increment of moisture content in the process medium to avoid potential Joule-Thompson effect.
- Predictive approach through data analysis to identify running parameters or process parameters potentially causing equipment to trip, e.g., compressor discharge temperature, suction temperature, and vibration.
- Detailed vibro-acoustic analysis approach to determine safe compressor speed range to operate.
- Manipulation on surge control line margin to allow lower flow with anti-surge valve still in close position.
- Periodic inspection on driver's hardware, such as gas turbine BOV and its flexible ducting, VIGV and stationary combustor and ensure availability of spares.
- Periodic inspection on anti-surge valve and ensure availability of spares.

Long-Term Mitigations

- Centrifugal Compressor Re-rating to cater for depleting reservoirs.
- Feasibility study to identify process and equipment causing bottlenecking to allow low flow operation.

CONCLUSIONS

Based on past failure records, operating at low flow condition may result to extensive damage on the equipment and high cost for repair. Mitigations and guidelines regarding multiple lesson learnt, can be established to allow temporary operating centrifugal compressor at low flow condition. If the condition is expected to be permanent, long-term mitigation as per recommendations shall be put in place to ensure equipment and production integrity are intact.

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ACKNOWLEDGEMENTS

Authors would like to acknowledge the Leadership Team of Petronas Carigali Sdn Bhd – Sarawak Asset, Operations and Specialized Maintenance Team, and regional technical support team from Integrated Value Assurance (IVA) for this opportunity and sharing valuable insights and motivations, ensuring this paper a success and creates value to all, essentially to centrifugal compressor operators.