

Energy Performance Degradation and Thermodynamic Analysis of A Centrifugal Gas Compressor

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Abstract

Centrifugal gas compressors are the most energy-consuming rotating assets of the gas industry. Continuous operations under various performance conditions lead to energy performance degradation and thermodynamic inefficiency in centrifugal gas compressors (CC). Existing studies have only covered surge prediction, conventional faults, and performance monitoring. However, limited attention has been given to the integration of energy performance degradation and thermodynamic analysis to identify degradation patterns of various performance parameters such as power consumption, shaft speed, volume flow, polytropic head, and polytropic efficiency, which impact the reliability and energy cost of CC. The real-time performance results for LP (1st stage) and HP (2nd stage) CC operating at full load capacity during peak and off-peak demand. The Findings indicate that the compressor is running in off-design conditions, which need maintenance to bring it back to its design conditions. A large portion of the compressed gas is bypassed, which will result in high energy waste, reduced reliability, and increased risk of downtime. Additionally, results showed that the LP (1st stage) consumes 6992.70 kWh of energy, while the HP (2nd stage) consumes 9818.44 kWh of energy, when the compressor runs at full load capacity. Performance maps demonstrated that ASV aggressively opened at 80% in HP and 70% in LP CC to prevent the compressor from surging while operating at full load at 8950 rpm with a 10% surge control line.

Keywords—OEM (Original equipment manufacturer), MMSCFD (Million standard cubic gas per day), Performance Degradation (PD), Energy Efficiency (EE), Condition Monitoring (CM)



1 Introduction

The term energy performance degradation describes the gradual deterioration of compressor operational performance efficiency over time [1]. Compressor performance can be reduced due to various factors such as fouling, wear and tear, surge, leakage, and performance deviations of operating parameters like pressure, temperature, volume flow rate, polytropic head, and power consumption [2]. This degradation has a negative impact on the energy performance of compressors. There are two categories of degradation: recoverable and non-recoverable. Increased gaps between moving and stationary parts are a sign of non-recoverable degradation, while recoverable degradation can be fixed through timely maintenance decisions to improve energy performance and increase the ser-

vice life of the compressor [3,4]. Energy degradation faults depict the three kinds of energy degradation as shown in Figure 1. When a centrifugal compressor operates in an environment with a variety of gas mixtures and pollutants, resulting fouling occurs. Fouling affects the flow of gas, and it increases the discharge temperature and energy consumption. Pressure sensors, shaft speed sensors, temperature sensors, volume flow rate sensors, and energy consumption sensors are very important for monitoring mechanical faults and performance deviations; therefore, they are considered the primary focus of this thesis. All these sensors are correlated with energy performance sensors, which are used to detect any anomalies or faults affecting the energy performance of the compressor [5].

The core reason for centrifugal gas compressor performance deterioration must be examined by maintenance staff. The fundamental difficulty is the inability to accurately predict the ideal maintenance window. Therefore, it is essential to have a strong and robust

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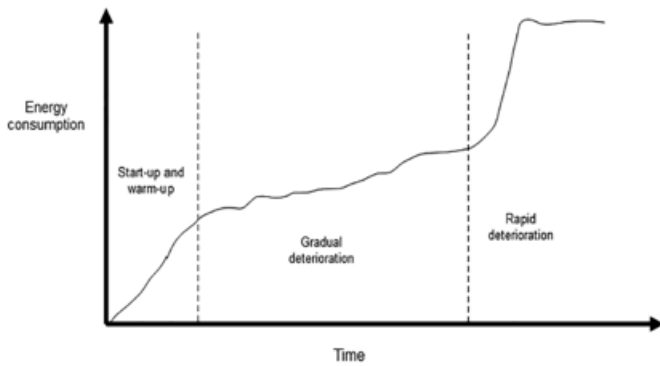


Fig. 1: Energy Degradation vs time [5]

system that can forecast equipment downtime. When it comes to compressor maintenance, engineers usually follow original equipment manufacturer (OEM) instructions [6]. It is important to remember that the OEM performance plot is based on theoretical conditions and does not account for fouling and other contaminants. The compressor performance degrades over time, causing it to deviate from the OEM-expected performance curve. As a result, the OEM plot may either underestimate or overestimate performance [7]. Moreover, the shortage of spare parts and equipment sometimes makes it difficult to make timely maintenance decisions. On the other hand, unnecessary maintenance activities are performed, and wasteful costs result if the OEM overestimates performance [8]. The complexity of maintenance decisions highlights the need for more accurate predictive maintenance approaches to improve cost-effectiveness and operational efficiency. Energy efficiency measures have been described as an important method for lowering energy, production, and operational costs of centrifugal gas compressors based on studies and results. It also assists in identifying where energy waste occurs, allowing for the appropriate steps [9]. This research work developed a framework that integrates energy performance degradation and thermodynamic analysis to identify degradation, efficiency losses, and their impact on energy utilization, reliability, and downtime of the compressor. Furthermore, performance degradation of the CC was validated with the designed performance curves provided by the manufacturer. This study can be helpful in assisting plant operators in monitoring the energy performance of centrifugal compressors to identify the best energy-saving opportunities and implement appropriate energy-saving steps to improve industrial energy efficiency.

2 Literature Review

A compressor is an important piece of mechanical equipment used in various industrial applications that reduces the volume of gas to increase its pressure. Centrifugal gas compressors are mechanical devices that increase the pressure of gas or fluid by transferring kinetic energy to the gas and then converting it into potential energy via a diffuser or airfoil. These devices are widely used in a wide range of industrial applications that need gas compression [10]. Industrial compressors are vulnerable to faults that may lead to failure or gradual decline in energy efficiency, demanding regular maintenance [11]. While early-stage performance failures have been widely studied and used in the industry, there is still significant unused potential for developing and employing various approaches to detect faults affecting energy performance. This stresses the need to explore and implement energy performance-based fault detection and prediction monitoring methods, which provide significant information in early fault detection to improve reliability, reduce operational cost, and optimize energy consumption. Leveraging such data allows for optimum scheduling of maintenance activities and production planning depending on compressor performance, resulting in significant cost savings [12]. Monitoring centrifugal compressors is critical to ensure their reliable and efficient performance. Various monitoring approaches are used to detect potential anomalies, reduce unplanned breakdowns, and improve performance. Here are some existing conventional performance monitoring methods for compressors available in the literature, such as condition monitoring, vibration monitoring, temperature, pressure, oil analysis, and thermography. Effective monitoring of centrifugal compressors requires a combination of these methods to offer a complete picture of the health of compressors [13]. Routine maintenance and fast response to monitoring system alarms can assist in avoiding unexpected downtime and extend the life of the compressor. The existing conventional performance monitoring indicators for compressor failure depend on the applications and operating conditions; compressor performance must be closely monitored in order to ensure smooth operation and detect failures. Ensuring energy performance requires constant monitoring of centrifugal gas compressor performance [14]. These days, energy performance and environmental factors are given a lot of attention while designing new industrial facilities. However, an important portion of the already installed assets in place are older, with less effective facilities. Regularly, frameworks serve as financial incentives in

addition to being social responsibility measures for optimizing the efficiency of these organizations. As a result, there is an increasing interest in exploring and implementing ways of monitoring and improving the operation of critical equipment [15]. System pressure can be reduced in many situations, resulting in energy savings. One or more key applications in most systems define the system's minimum permissible pressure. Even in noisy industrial environments, detection of hissing air leaks is challenging. At end-use stages, pressure drops of up to 40% of the discharged pressure of the compressor are not rare [16]. However, rather than inspecting the system and determining the source of the problem, installing a larger compressor is a standard solution to such a problem. After the larger compressor has failed to fix the issue, the latter course of action is usually taken. Energy loss in air-compressed systems owing to inadequate maintenance and installation will be responsible for up to 50% of the energy used by the compressor, with energy-saving strategies expected to save around half of this volume [17]. Gas Compressed assets should be operated at the lowest possible functional load while still meeting production needs. When the pressure supply is higher than what is needed, more air is ejected for each end-use, resulting in wasted energy [18]. Various energies saving measures such as energy savings through leak prevention, energy saving utilising outdoor air intake, energy saving owing to drop of pressure, energy saving due to heat recovery, cleanliness of compressor, energy saving due to performance improvements, shut off compressor not in use, compressor adjustment to load demand, minimise over compression, optimised operation of compressor, optimised control of compressor, and proper maintenance are all possible fields wherever energy saving choices can be implemented for a large volume of energy retrieval which helps in lower energy, production, and operating costs of centrifugal compressor. The deviations in performance parameters cause energy performance degradation [19]. There are various types of anti-surge valve (ASV) control strategies such as surge control based on performance maps, flow-to-head control, feed-forward control, adaptive anti-surge control, PID-based control, and operation control. These ASV control strategies are very useful to prevent CC from surging [20]. Various energies saving measures such as energy savings through leak prevention, energy saving utilizing outdoor air intake, energy saving owing to drop of pressure, energy saving due to heat recovery, cleanliness of compressor, energy saving due to performance improvements, shut off compressor not in use, compressor adjustment to load demand, minimize over compression, optimized

operation of compressor, optimized control of compressor, and proper maintenance are all possible fields wherever energy saving choices can be implemented for a large volume of energy retrieval which helps in lower energy, production, and operating costs of centrifugal compressor [21]. This paper gathers the most recent literature in the form of journal papers, conference proceedings, online resources, surveys, books, and handbooks to demonstrate the value of energy performance degradation and thermodynamic analysis of centrifugal gas compressors.

3 Contribution and critical synthesis

Centrifugal gas compressors are the most energy-consuming rotating assets of the gas industry. Continuous operations under various performance conditions lead to energy performance degradation and thermodynamic inefficiency in centrifugal gas compressors (CC). Existing studies have only covered surge prediction, conventional faults, and performance monitoring. However, limited attention has been given to integrating energy performance degradation and thermodynamic analysis to identify degradation patterns across various performance parameters. The findings of this study showed that the proposed energy performance degradation and thermodynamic analysis are effective for early detection of faulty conditions, as evidenced by performance curves provided by original equipment manufacturers (OEMs). It empowers operators and maintenance professionals to monitor energy performance degradation, conduct thermodynamic analysis, and predict surges that affect the reliability and downtime of the centrifugal gas compressor. This framework is also very useful for proactive maintenance checks to reduce energy consumption and environmental impacts, prevent unscheduled downtime, and improve the reliability of centrifugal gas compressors. Furthermore, by analysing trends in the graphs, maintenance managers and engineers can make informed decisions on resource allocation, maintenance prioritisation, and optimising CC to increase its reliability and productivity. The outcome of this research opens up a new possibility for various industries, specifically the oil and gas industry, to reduce downtime across assets, increase sustainable performance and reliability, cut maintenance and energy costs, and increase revenue.

3.1 Methodology

This study was conducted on a two-stage centrifugal gas compressor, and a detailed literature review was conducted to find research gaps, investigate energy

performance degradation and thermodynamic analysis models, and develop a framework to validate its real-time working performance. After developing the model, the real performance maps provided by the OEM were digitized in Excel for both stages of the compressor and used to test the thermodynamic model using actual operational data, as shown in the methodology flow chart Figure 2. The performance maps provided by the OEM were limited to polytropic head vs volume flow for both stages of the compressor. In this study, both the verified thermodynamic model and real-time performance data were used to investigate the relationship between energy performance degradation and other operational parameters. It is important to analyze the gas composition shown in Table.1 that the specific centrifugal compressor will compress in advance since the compressor working state is dependent on that composition. This model can be used as the framework for evaluating energy performance degradation and thermodynamic analysis of centrifugal gas compressors. Furthermore, the methodology evaluates the overload and part-load performance due to varying supply and demand of the examined two-stage CC using energy performance degradation and thermodynamic analysis, as described in the methodology flowchart. The centrifugal compressor ought to run for a longer duration under conditions other than its design point; this is known as performance degradation. A performance degradation situation occurs due to a shift in the load and ambient conditions. For instance, changes in performance parameters such as volume flow rate, polytropic head, shaft speed, and energy consumption. Furthermore, the effects of changing climate conditions from winter to summer will have a considerable impact on CC performance.

3.2 Thermodynamic Model

This section addresses the thermodynamic model used to assess the thermodynamic analysis of CC using governing equations for real-gas compression. The equation of state is discussed in equation 1; polytropic head or work in equation 2; compressor power in equation 3; and polytropic and Isentropic efficiencies in equations 4 & 5 are discussed as follows:

$$PV = ZnRT \quad (1)$$

$$H_p = \frac{ZRT_1}{M_w} \left[\frac{n_v}{n_v - 1} \right] \left[\left(\frac{P_2}{P_1} \right)^{\frac{n_v - 1}{n_v}} - 1 \right] \quad (2)$$

$$\eta_{poly} = \frac{n - 1}{n} \frac{\ln\left(\frac{P_2}{P_1}\right)}{\ln\left(\frac{T_2}{T_1}\right)} \quad (3)$$

$$\eta_{Isen} = \frac{H_S}{H_{act}} \quad (4)$$

4 Results and discussion

The performance maps are only available for the volume flow vs polytropic head for the simulation of energy performance degradation and thermodynamic analysis for both stages of CC. In this section, the authors discuss the detailed analysis of the results in Section 4.1, which displays the results of energy performance degradation and thermodynamic analysis for the first-stage compressor. Similarly, section 4.2 presents the results for the second stage of the compressor.

4.1 Energy Performance Degradation and Thermodynamic Analysis of 1st Stage CC

The results of real-time performance are displayed in Figure 3, which are plotted on the performance curves provided by the OEM for the 1st stage or Low Pressure (LP) CC. Based on the results, CC is operating in off-design conditions; the performance degradation of polytropic head and volume flow rate is clearly illustrated on the performance map. Furthermore, the performance curve clearly showed that the ASV aggressively opened at 80% to prevent the compressor from surging, while CC operates at full load at 8950 rpm with a 10% surge control line. Figure 3 describes the results for fixed load, which shows that the maximum compressed production gas for the 1st stage was observed 4767.68ft³/mint, and the minimum was 3164.15ft³/mint. The maximum polytropic head was 124.50kJ/kg, and the minimum was 100.72kJ/kg. Additionally, it was observed that when the flow rate of gas increases, the polytropic head decreases, and vice versa. Finally, the findings indicate that the CC may have inefficient operations during the time of low demand if it runs at full load and real demand varies. Because the compressor operates at a higher capacity than is necessary, this is causing energy waste.

Similarly, Figure 4 demonstrates the results in the case of variable load; the compressor adjusts the load or speed based on the actual demand for compressed gas to optimize the energy performance and decrease energy waste during off-peak demand. Moreover, ASV was utilized to reduce energy waste; the main purpose of anti-surge control was to maintain the flow and pressure below the surge limit. This is evident from the real performance plotted on the performance map that ASV opens up to 35% when the compressor operates at a minimum 70% load with 6200 rpm, indicating that

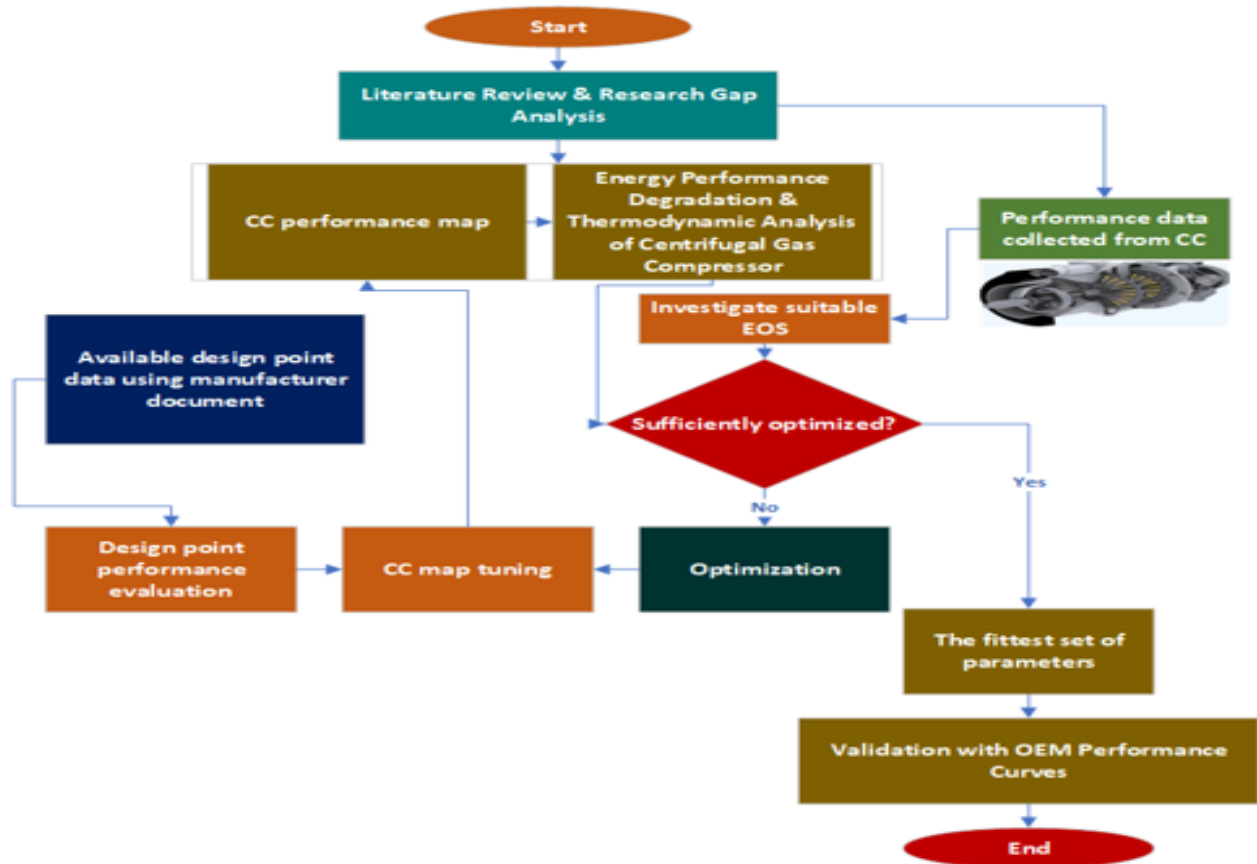


Fig. 2: Methodology Flow Chart

TABLE 1: Hypothesis Testing Results

Gas Type	Symbol	Molar Mass (kg/kmol) M_i	Mole fraction (Y_i)	Molecular weight (kg/kmol) $M_w = M_i \cdot Y_i$
Methane	CH ₄	16.043	0.6927	11.1129861
Ethane	C ₂ H ₆	30.02	0.094	2.82188
Propane	C ₃ H ₈	44.097	0.062	2.734014
i-Butane	C ₄ H ₁₀	58.124	0.0212	1.2322288
n-Butane	C ₄ H ₁₀	58.124	0.0169	0.9822956
n-Pentane	C ₅ H ₁₂	72.151	0.016	1.154416
Hexane	C ₆ H ₁₄	86.178	0.0075	0.646335
n-Heptane	C ₇ H ₁₆	100.16	0.0042	0.420672
Nitrogen	N ₂	28.013	0.0024	0.0672312
Water vapor	H ₂ O	18.02	0.0046	0.082892
Carbon dioxide	CO ₂	44.01	0.0778	3.423978
Total			1	24.6789287

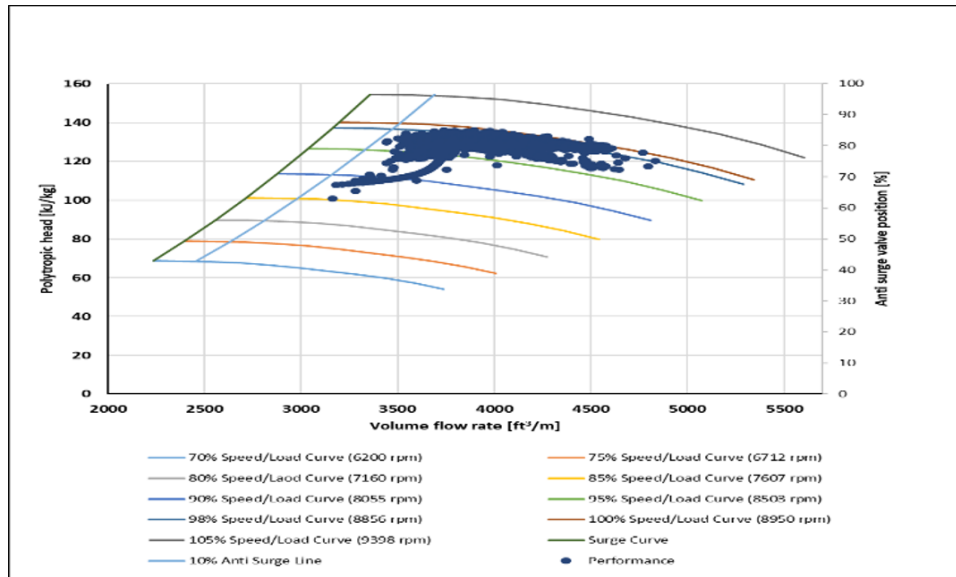


Fig. 3: Fixed Load Energy Performance Degradation and thermodynamic analysis for LP CC

a small portion of the compressed gas was bypassed, wasting less energy and meeting demand efficiently. When the compressor operates at maximum load with 8950 rpm, the ASV opens up to 80%, indicating that a large portion of the compressed gas is bypassed, which will result in high energy waste.

4.2 Energy Performance Degradation and Thermodynamic Analysis of 2nd Stage CC

The results of the real-time performance are displayed in Figure 5, which are plotted on the performance curves provided by the OEM for HP CC (2nd stage). Based on the results, CC is operating at off-design conditions; the performance deviation of polytropic head, volume flow rate, and energy consumption is clearly illustrated on the performance map. Furthermore, the performance curve clearly shows that, in order to prevent the compressor from surging, the ASV aggressively opened at 70% while CC operated at full load at 8950 rpm with a 10% surge control line. Additionally, Figure 5 describes the results for fixed load, which shows that the maximum compressing production gas for the 2nd stage was observed $3152.48 \text{ ft}^3/\text{mint}$, and the minimum was $2262.69 \text{ ft}^3/\text{mint}$. The maximum polytropic head was seen 99.65 kJ/kg , and the minimum was 74.19 kJ/kg . Additionally, it was observed that when the flow rate of gas increases, the polytropic head will decrease, and vice versa. Finally, the findings indicate that the CC may have inefficient operations during the time of low demand if it runs at full load and real demand varies. Because the compressor operates at a higher capacity than is necessary, this will waste energy.

Finally, Figure 6 demonstrates the results in the case of variable load; the compressor adjusts the load or speed based on the actual demand for compressed gas to optimize the energy performance and decrease energy waste during off-peak demand. Moreover, ASV is utilized to reduce energy waste; the main purpose of anti-surge control is to maintain the flow and pressure below the surge limit. This is evident from the real performance plotted on the performance map, where ASV opens up to 28% when the compressor operates at a minimum 70% load with 6200 rpm, indicating that a small portion of the compressed gas is bypassed, wasting less energy and meeting demand efficiently. When the compressor operates at maximum load with 8950 rpm, ASV opens up to 70%, indicating that a large portion of the compressed gas is bypassed, which will result in high energy waste.

5 Conclusion

The Findings indicate that the compressor is running in off-design conditions, which need maintenance to bring back to its design conditions. Furthermore, a large portion of the compressed gas is bypassed, which will result in high energy waste, reduced reliability, and increased risk of downtime. Similarly, the results showed that the real-time performance results for LP (1st stage) and HP (2nd stage) CC operate at full load capacity during peak and off-peak demand. Off-design or performance degradation occurred due to load shifting and ambient conditions. For instance, degradation in volume flow rate, polytropic head, and shaft speed directly influences energy consumption.

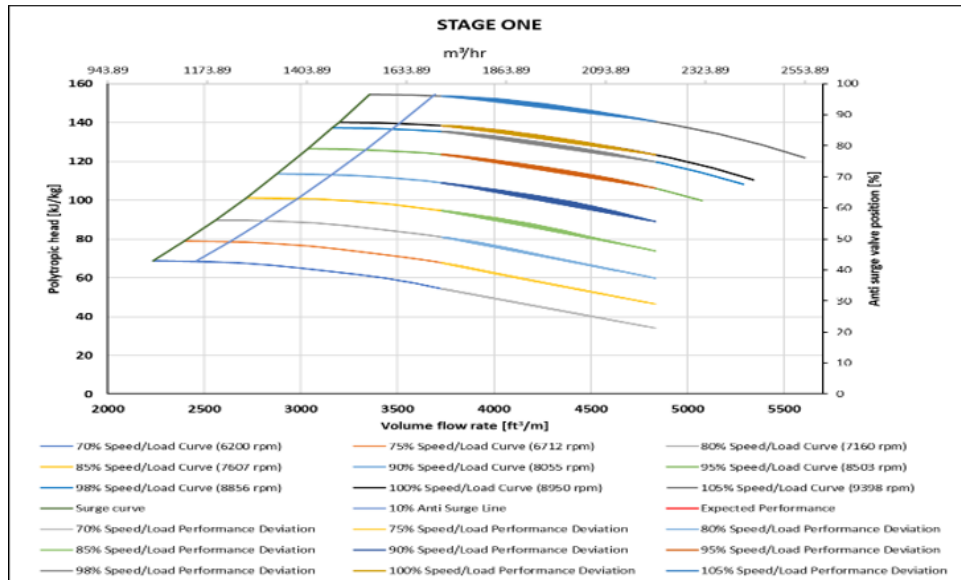


Fig. 4: Variable Load Energy Performance Degradation and thermodynamic analysis for LP CC

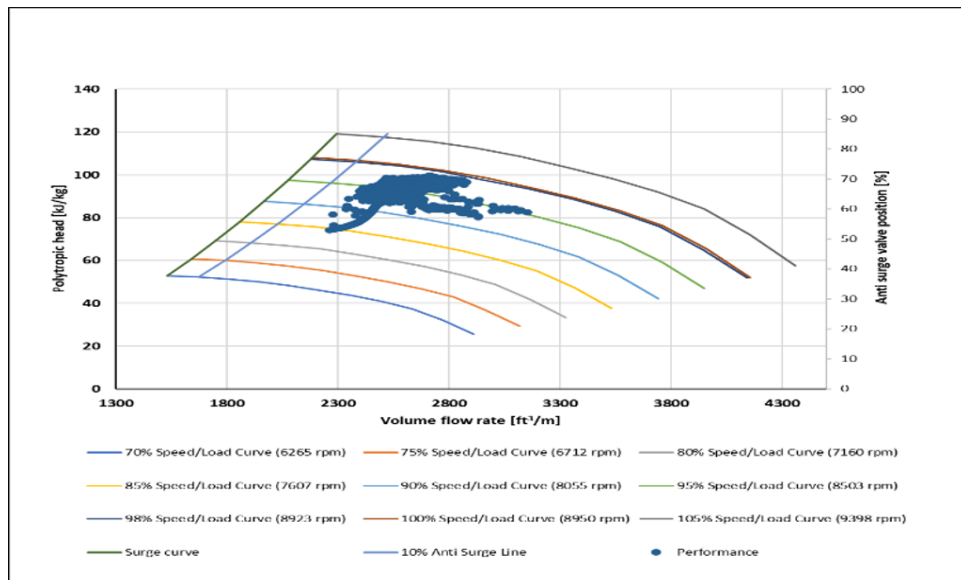


Fig. 5: Fixed Load Energy Performance Degradation and thermodynamic analysis for HP CC

Furthermore, performance maps demonstrated that ASV aggressively opened at 80% in HP and 70% in LP CC to prevent the compressor from surging while operating at full load at 8950 rpm with a 10% surge control line. For the fixed load, the maximum volume of the compressed gas was transported $4767.68 \text{ ft}^3/\text{mint}$, while the minimum was $3164.15 \text{ ft}^3/\text{mint}$ for the LP. The maximum volume of compressed gas transported by HP was $3152.48 \text{ ft}^3/\text{mint}$, while the minimum was $2262.69 \text{ ft}^3/\text{mint}$. The results indicate that the HP volume flow rate is decreasing compared to LP due to the rise in pressure. The maximum polytropic head was 124.50 kJ/kg , and the minimum was 100.72 kJ/kg

for the LP. The maximum polytropic head for HP was 99.65 kJ/kg , and the minimum was 74.19 kJ/kg . The loss in polytropic head for HP caused by friction and fouling resulted in energy inefficiency. Finally, the findings showed that the CC may have inefficient operations during times of low demand if it runs at full load and actual demand declines; this is also the primary cause of energy waste.

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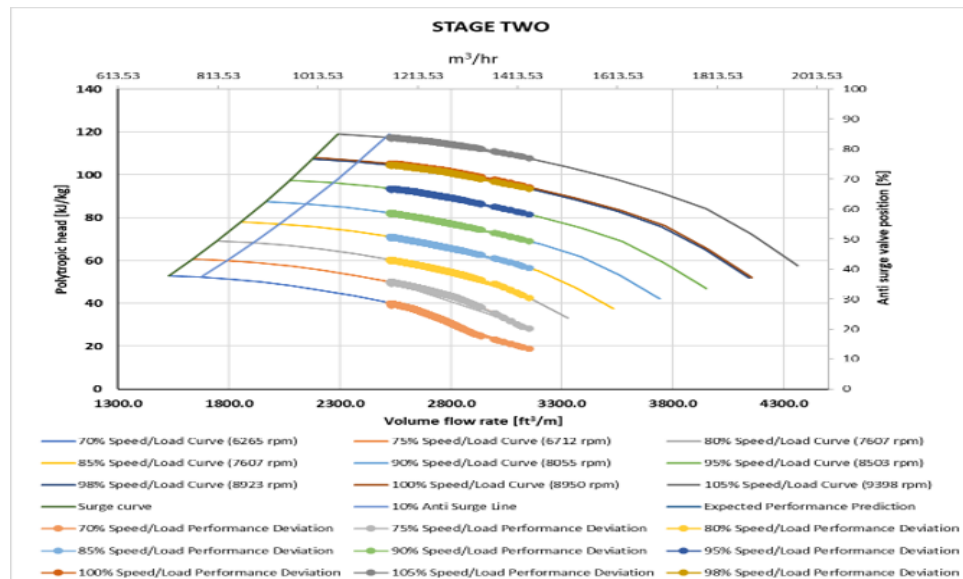


Fig. 6: Variable Load Energy Performance Degradation and thermodynamic analysis for HP CC

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