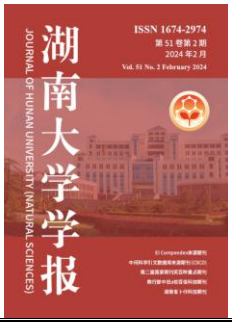

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Development of a Surge and Energy Performance Monitoring Tool for a Centrifugal Compressor

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Abstract: Energy performance and surging dominate the life cycle cost of centrifugal gas compressors. To optimize compressor performance and reliability, the operating point on the compressor performance map is always set far from the surge control line. This results in significantly increased energy consumption owing to the backflow of compressed gas into the inlet pipes. This study presented the development of a novel and robust tool that enables real-time energy performance and surge monitoring of compressors. In the methodology, the off-design performance of the compressor was evaluated on the performance map provided by the OEM and design data. Microsoft Excel was used to digitize compressor performance maps, including surge curves, because it is easier and less expensive than other software, and users have constant access to source code updates. The results showed that the maximum compressing production gas for the 1st stage was 2093.89m3/h, and 1413.53m3/h for the 2nd stage. The polytropic head obtained 130kJ/kg for the low-pressure and 100kJ/kg for the high-pressure stage. While energy consumption was obtained at 5340kWh for the 1st stage and 8000kWh for the 2nd stage, when the compressor was running at full load with 8950 rpm with a 10% surge control line, it showed that the compressor was not surging. According to the findings, the compressor performance deviates from the designed conditions. Therefore, this monitoring tool assists operators and maintenance engineers in tracking the actual health performance of centrifugal compressors, predicting maintenance needs, and reducing maintenance costs and accidental equipment failures.

Keywords: predictive maintenance, surge control, energy performance, compressor.

离心压缩机喘振和能量性能监测工具的开发

摘要：能源性能和激增主导着离心式气体压缩机的生命周期成本。为了优化压缩机性能和可靠性，压缩机性能图上的工作点始终设置为远离喘振控制线。由于压缩气体回流到入口管道中，这导致能耗显着增加。这项研究展示了一种新颖而强大的工具的开发，该工具可以实现压缩机的实时能源性能和喘振监测。在该方法中，压缩机的非设计性能是根据代加工提供的性能图和设计数据进行评估的。微软Excel用于数字化压缩机性能图，包括喘振曲线，因为它比其他软件更容易且更便宜，并且用户可以不断访问源代码更新。结果表明，第一阶段最大压缩产气量为2093.89立方米/小时，第二阶段最大压缩产气量为1413.53立方米/小时。多变头在低压阶段获得130千焦/公斤，在高压阶段获得100千焦/公斤。虽然在第一级为5340

千瓦时、第二级为8000千瓦时时获得能耗，但当压缩机以8950转速、10%喘振控制线满负荷运行时，表明压缩机没有喘振。根据调查结果，压缩机性能偏离设计工况。因此，该监测工具可帮助操作员和维护工程师跟踪离心式压缩机的实际健康性能，预测维护需求，并降低维护成本和设备意外故障。

关键词：预测性维护、浪涌控制、能源性能、压缩机。

1. Introduction

Centrifugal gas compressor performance is a key factor in maintaining gas productivity and attaining maximum techno-economic benefit in the oil and gas industry. Low evolved head and high energy consumption are two of the most typical indicators of performance degradation in centrifugal compressors [1]. Industry also employs compressed air, and the service sector for its handling and processing is both easy and clean. It takes a lot of energy to produce compressed air, and the energy cost of air that has been compressed is high in most industrial ways as opposed to total energy costs. However, there is a scarcity of accurate data on the energy consumption of typical systems of compressed air [2,3]. Centrifugal compressors can be used in various industrial applications and urban operations, and their life-cycle costs are usually dominated by energy costs, making them an appealing option for energy efficiency upgrades [4]. Energy normally overshadows the life cycle cost (LCC) of compressed air equipment. According to a study, the centrifugal gas compressor life cycle costs approximately 78% of the cost of energy, 16% of the investment, and 6% of the maintenance [5,6]. Improvements in compressed-air equipment would result in energy savings of 20–50% [7]. According to many experts, running energy is the single highest expense of compressed-air systems over the course of their lifespan. In certain cases, operating costs are more than five times the original equipment cost [8-10]. Compressed air can only be used if it is necessary to improve safety and efficiency. It should be noted that, as shown in Figure 1, the most expensive form of energy is compressed air [11].

In China, 9.4% of compressed air is used, which is a substantial part of the country's energy. Approximately 19% of the overall energy supply is employed in a useful capacity, making compressed air an expensive source of energy in a plant. In the United States, compressed-air devices use approximately 10% of the total energy usage of industry [13] and in Malaysia [14].

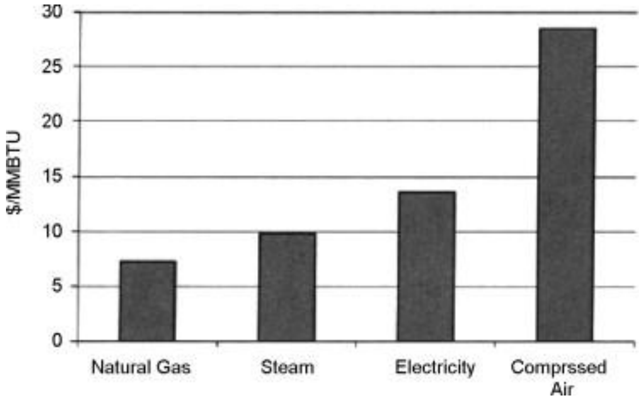

Fig. 1 Energy cost of the distribution modes [12]

In South Africa, compressed air makes up about 9% of the total energy intake [20]. Compressed air is responsible for up to 10% of the commercial energy usage in the European Union. Figure 2 depicts the use of compressed-air energy in 15 European countries [15].

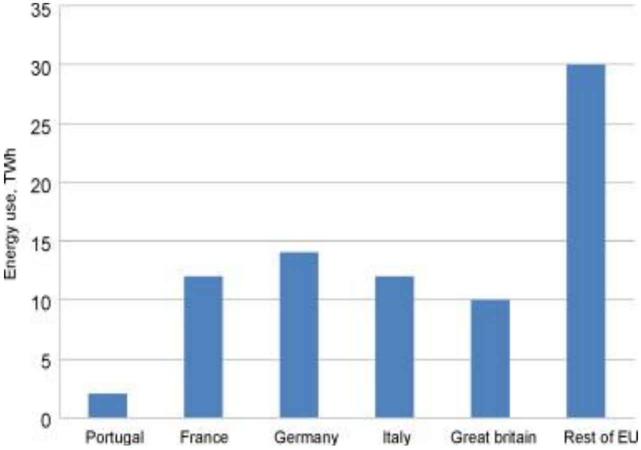

Fig. 2 EU countries using compressed air energy [15]

Small changes have always been seen because of significant gains and quick return times. Reducing leakage, balancing demand with supply, lowering settings where small pressure is appropriate, instead of a big compressor at part load, use a smaller compressor at maximum load, using outside air to reduce average inlet temperature. In the winter, excess heat by the fluid is used to warm up the place, efficient motors are used, at night and during lunch, the compressor is shut down, and an after-cooler is used, both of which contribute to energy conservation [16]-[17]. However, several approaches have been suggested in the literature that are limited to energy performance improvement by the deployment of energy performance technologies and operational improvements from the supply and demand side. Therefore, this research work provided the development of a novel and robust surge and energy performance monitoring tool that supports energy efficiency in the form of compressor maintenance as part of the predictive maintenance approach. This tool assists in future energy cost reductions, reliability optimization, and downtime reduction for compressors. Furthermore, this study is organized as follows: Section 2 presents the review of the techniques for energy performance, surge monitoring, and for energy efficiency maintenance. Section 3 covers the methodology, and Section 4 presents the results and discussion. Finally, Section 5 provides the conclusions.

2. Literature Review

2.1. Energy Performance and Surge Monitoring Approaches

In this section, different techniques are discussed for energy efficiency optimization. Several petrochemical plants in China were studied in [18], including an oil refinery, where there is significant performance deterioration between compressor real performance and manufacturer warranty. As seen in Figure 3, the surge control line and surge line of the pyrolysis gas are shown as independent lines on the running chart of the compressor for the 800000 t/a ethylene factory in Shandong.

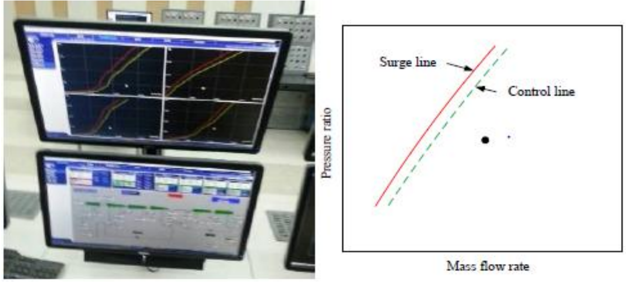

Fig. 3 Operational diagram of the compressor for 800 thousand t/a China’s ethylene plant [18]

The compressor operation reliability is increased because the black point in the figure, which represents the real operating line of the compressor, is usually kept far from the surge control line by activating the anti-surge valve. However, this results in significant power consumption because the compressed gas is returned to the pipe inlet. The real operation performance curves of the centrifugal compressor have a substantial influence on compressor reliability. For instance, if the actual flow rate during the designed conditions is less than the demand, a surge operative condition will occur. It also has a considerable effect on compressor energy consumption.

Emerson [19] developed an anti-surge control, which is the first and most effective approach to reduce compressor energy consumption, from measurement to control algorithm to anti-surge valve, as shown in Figure 4. The necessary safety margin is determined by your position in relation to the surge and your response time. The surge line can be operated safely closer by having a quick response. By opening the anti-surge valve as little as possible, this method prevents the compressor from surging. Performance control, often referred to as load control, is the second strategy for reducing the amount of energy used by compressors. This strategy entails optimal stabilization of the primary process parameters, such as discharge/suction pressure or flow.

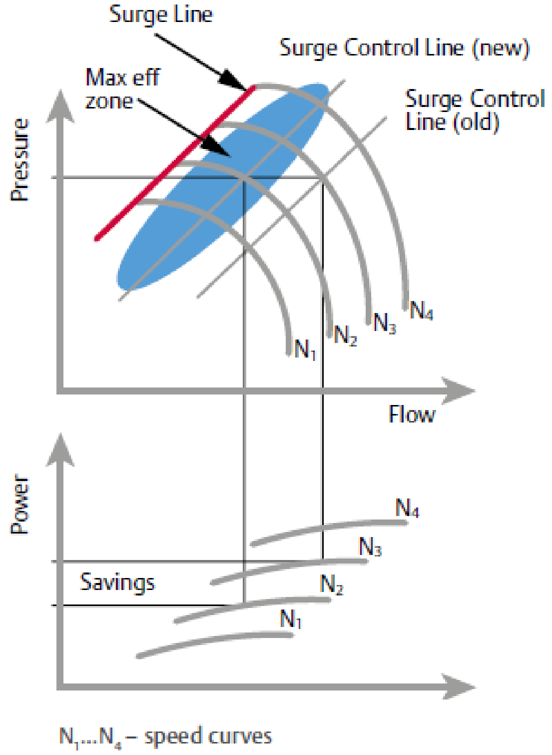

Fig. 4 Energy saving by performance control [19]

As discussed in [20], compressor control has two goals: satisfying external process demands and maintaining the operational boundaries of the compressor. Adjusting shaft speed is the most efficient method to control a compressor compared to other controls such as recycling, suction throttle, and inlet guide vanes, as shown in Figure 5.

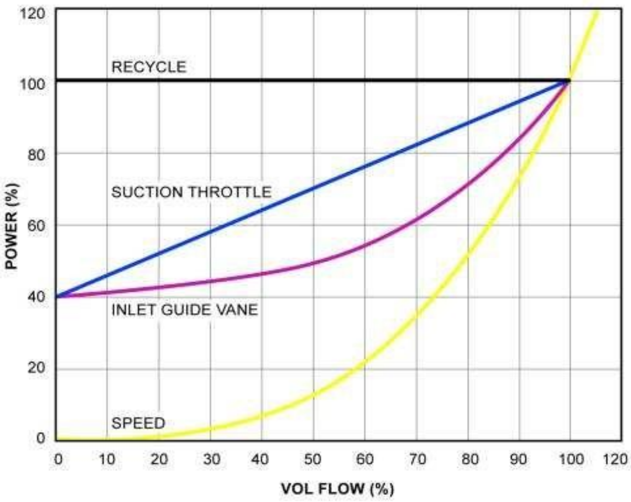

Fig. 5 Power use of various control methods [20]

An online performance monitoring system developed in [21] allows users to compare real-time performance data with factory-set parameters to assess the health of a compressor. The input power can be calculated using the original compressor parameters, such as pressure, temperature, speed, and flow rate, with the performance calculation software that they developed. The harmful effects of seasonal variations in ambient temperature and humidity on the operation of a four-stage CO2 compressor were examined in [22]. Additionally, this study replicates various suction conditions for a multistage compressor using Aspen HYSYS and saves a sizable amount of energy (663 kW), net savings (Gross Savings -OPEX: 72 289 $/y), and the total process carbon footprint (954 ton/y). The energy-saving potential of variable speed TACCS was studied using an inverter compared to constant speed TACCS using an IGV control [23]. Two controls were suggested to eliminate electrical and mechanical losses to decrease power consumption while employing the VSD in a TACCS. Initiatives made to at least match the SAC 2B air compressor performance in terms of performance of other compressors were explored in [24]. It can save up to 284,165 kWh of energy a year by improving the specific power consumption of other compressors.

New technologies were suggested in [25], such as bottoming processes for recovering waste heat from gas turbines and recovering heat from compressor trains for gas export, to make offshore oil and gas platforms more energy efficient. According to the findings, a 33% boost in energy efficiency leads to a 25% decrease in fuel consumption and CO2 emissions 517 g CO2/kW-h. Methods were proposed in [26] to increase centrifugal gas compressor energy efficiency, such as antifouling coating, which results in better performance over a longer period and the use of non-metallic labyrinth seals that can achieve lower clearance and slight deformity. A model for the analysis of energy efficiency was developed in [27], involving online energy efficiency analysis and interactive electric gas scheduling optimization of offshore platform energy equipment technology. A moving window approach with adaptive regression analysis was developed in [28] for energy savings, presenting a data-driven algorithm for improved turbomachinery estimation and prediction of a depreciation predictor to estimate the predicted value of deterioration and calculate the volatility of the forecast.

Genetic programming was used to create a diagnostic model to predict output degradation and sustain centrifugal gas compressors (GP) [29]. The reported thesis used a GP model to construct certain machine codes for OEM isentropic and actual isentropic heads of a gas compressor. The GP model projected a 7.95 % RMSE for efficiency degradation. Methods for energy consumption and controlling the CA system were reviewed in [30]. A simulation model that incorporates both variable- and fixed-speed drive compressors was created using the state-based modeling technique. Different scenarios for controlling the system were analyzed using this. The energy consumption dynamic of the system and the reliability of the suggested model are shown using an industrial case study with two variable speed and one fixed speed drive compressor. The compressor simulation model using Aspen HYSYS software offers a dynamic baseline to estimate the predicted performance of the compressor under various thermodynamic conditions of the incoming gas and can be very valuable as a monitoring tool [31]. This model replaces the current approach to measuring energy performance, which relies on a statistical ratio without considering operating variables.

2.2. Maintenance of Energy Efficiency

The concept of a maintenance strategy is a collection of standards that specify the process that triggers different maintenance tasks. What determines whether maintenance is necessary is a matter of timing [32]. Preventive maintenance, predictive maintenance (PdM), condition-based maintenance (CBM), housekeeping, fault identification and diagnosis, and other services are available for energy quality maintenance techniques [33]. In today’s literature, the term "maintenance policy" refers to a paradigm that optimizes maintenance. Corrective, reactive, predictive, and design-out maintenance are the different types of maintenance policies [34]. Unfortunately, there are only a few maintenance policies in the literature that take energy conservation into account [35]. Compressor fouling, blade tip ribs, shaft movements as indicators of rotor issues, tip seal and labyrinth wear and damage, deterioration, and corrosion are only a few of the factors that lead to performance degradation of a centrifugal compressor. There are two types of compressor degradation: recoverable and non-recoverable. The moving and stationary sections of the compressor need replacement of damage among widening clearances. It is linked to light maintenance such as washing and cleaning in terms of recoverable performance degradation. Fouling, the most common cause of compressor failure, is an example of recoverable performance degradation [36]. Energy monitoring usage, likewise, allows maintenance technicians to identify the cause of breakdown (which system and where it occurred) and diagnose the type of failure [37]. Energy monitoring in the field was tested for the maintenance of two presses, a molding unit and four compressors in a separate production facility. Compressed air flow and energy waveforms were described by Endo as activity energy and data as target data. Under the stop state, energy was lost. Using activity and energy data visualization patterns, and the operating state of equipment, numerous enhancement steps were taken to reduce energy usage. The fixed pressure of the compressor system must first be reduced. Second, pipes near the dicing machine need to be improved. Energy savings of 7% in terms of kWh use and 20% in terms of real consumption of energy (kWh/m^3) were achieved because of the improvements. Power tools and compressors saw a boost in efficiency and a reduction in energy demand [38]. Xu suggested a productivity- and energy-efficiency-based periodic maintenance model. This model could, in a special case, result in the highest overall output and efficiency. However, in most situations, a trade-off between average production and quality is almost inevitably required [39]. In addition, Yildrim suggested a joint prototype for maintenance and manufacturing problems, considering the minimum usage of energy and maintenance to reduce overall costs [40]. Yan has suggested a strategy for assessing how maintenance impacts energy use. The findings showed that as reliability declines, energy usage rises sharply [41]. This definition differs from conventional opportunistic servicing, which focuses solely on maintenance costs and downtime [42]. However, many techniques were suggested in the literature that are limited to energy performance improvement by the use of energy performance technologies and operational improvements from the supply and demand side. Therefore, this paper provides the development of a novel and robust surge and energy performance monitoring tool that supports energy efficiency in the form of compressor maintenance as part of the predictive maintenance approach. This tool assists in future energy cost reductions, reliability optimization, and downtime reduction for compressors.

3. Methodology

Monitoring surge and energy performance is a useful method for identifying potential centrifugal compressor energy performance degradation caused by surging. It forecasts compressor performance based on historical or real-time data. The first step in creating the monitoring tool is to gather information on the reasons behind the deterioration in compressor performance and the methods used to track it. Consequently, compressor performance under steady-state circumstances is described using the thermodynamics approach. Historical data on centrifugal compressor operating conditions must analyze compressor performance. Thus, PETRONAS Carigali, Kertih, a partner company, provides the design specifications and historical data provided by the manufacturer. A research methodology flow chart is presented in Figure 6. The designed conditions of the compressor are shown in Table 1. In addition, the input and output parameters for the predicting monitoring tool are shown in Table 2.

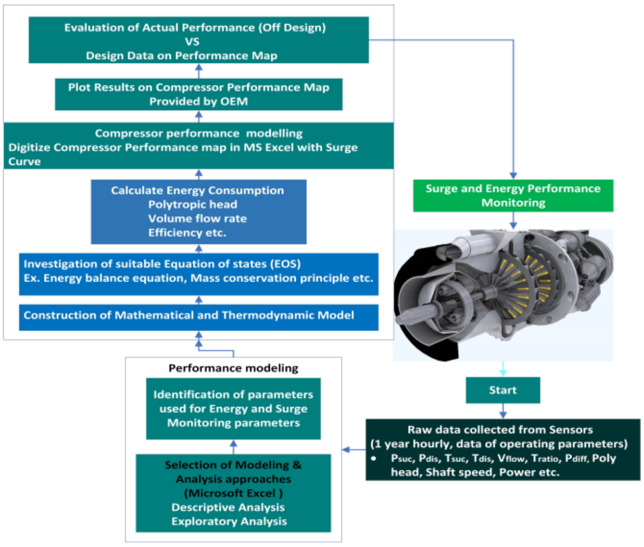

Fig. 6 The methodology flow chart

Table 1 The designed conditions of the compressor (Developed by the authors)

Description	**Units**	**Min**	**Max**
Vol flow rate	MMSCFD	100	225
Inlet pressure	kPa	1724	5378
Inlet temperature	C^0	40	41
Outlet pressure	kPa	5516	13989
Outlet temperature	C^0	132.2	119.7
Compressor shaft speed	rpm	8950	9400
Molecular weight	Kg/kmole	24.785	23.169
Polytropic head	kJ/kg	130.42	102.72
Polytropic efficiency	%	77.61	77.19
Power	kW	5812	9650

Table 2 Required input and output for the predicting monitoring tool (Developed by the authors)

Input	**Output**
Suction pressure	Volume flow rate
Discharge pressure	Polytropic head
Suction temperature	Energy consumption (kWh)
Discharge temperature	Energy performance deviation
Outlet temperature	Polytropic head deviation
Compressor shaft speed	Volume flow deviation
Gas Composition	Polytropic efficiency deviation
Polytropic head	
Polytropic efficiency	
Power	

4. Results and Discussion

A thermodynamic-based performance evaluation model was developed to predict compressor power consumption, compressor shaft speed, and energy performance of stages 1 and 2 to determine and assess the energy performance of centrifugal gas compressors that have lost efficiency due to internal wear or fouling. The OEM performance curve is required for comparative evidence to assess performance degradation. The design performance curve is then plotted with the operational conditions of the compressor performance. The OEM performance map, including the surge curve, was digitized in Microsoft Excel. PETRONAS The compressors from Angsi are separated into two stages: low pressure and high pressure. However, the designed performance curve provided by OEM is presented in Figures 7 and 8, which were digitized in MS Excel.

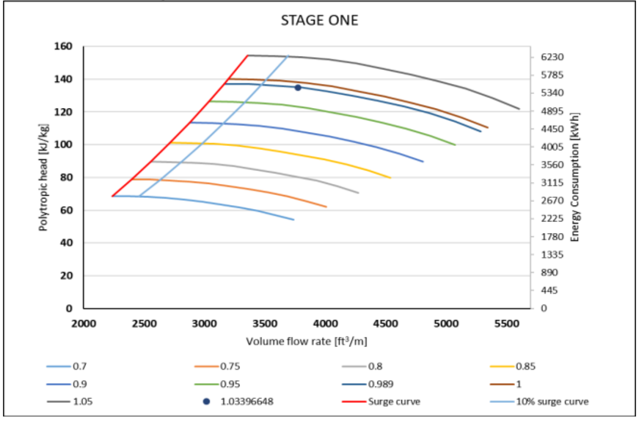

Fig. 7 Designed performance curve, Stage 1 (Developed by the authors)

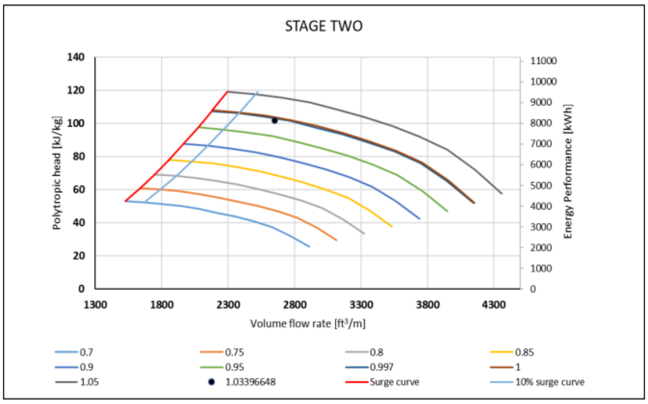

Fig. 8 Designed performance curve, Stage 2 (Developed by the authors)

4.1. Energy Performance Monitoring

The results of the performance monitoring tool are displayed in Figures 9 and 10, which are tabulated into the performance curves of both stages 1 and 2 and are based on the performance deviation of the polytropic head, volume flow rate, and energy consumption.

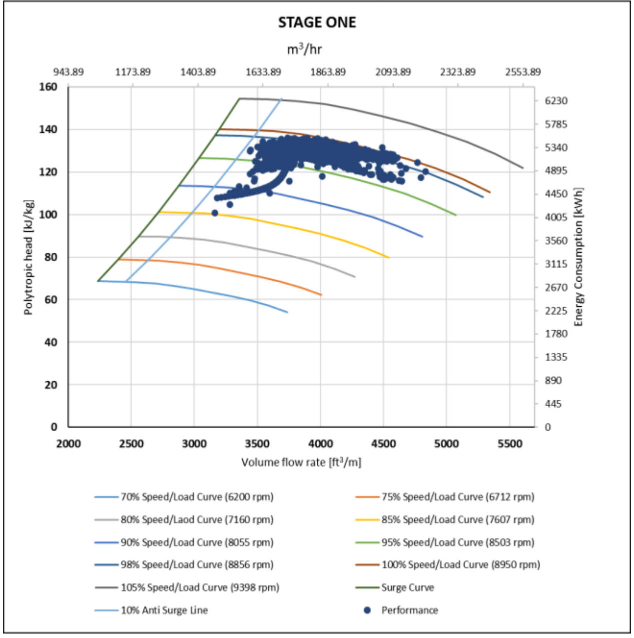

Fig. 9 Real-time performance for Stage 1 (Developed by the authors)

Additionally, the performance curve makes it quite evident that the compressor is not surging. The results showed that the maximum compressing production gas for the 1st stage was 2093.89m^3/h, and 1413.53m^3/h for the 2nd stage. The polytropic head obtained 130kJ/kg for the 1st stage, and 100kJ/kg for the 2nd stage. Energy consumption was obtained 5340kWh for the first stage, and 8000kWh for the second stage, when the compressor was running at full load at 8950 rpm with 10% surge control line showing that the compressor is not surging. The polytropic head vs. volume flow rate of both compressor stages was the sole performance map provided.

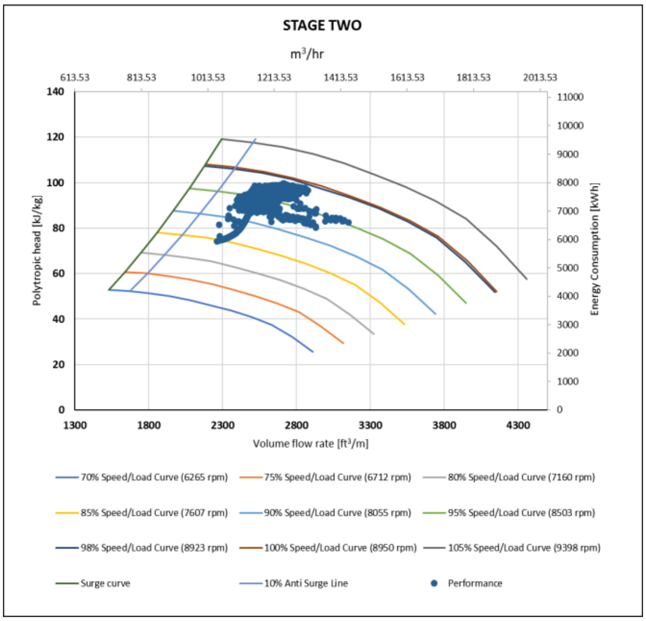

Fig. 10 Real-time performance for Stage 2 (Developed by the authors)

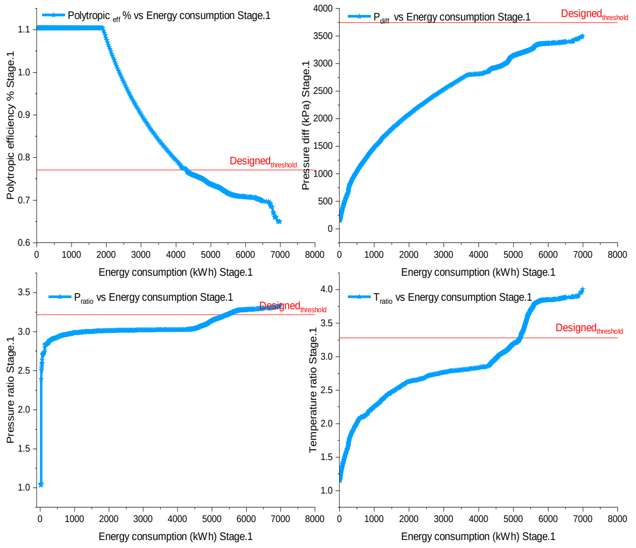

Fig. 11 Real-time performance for Stage 1 (Developed by the authors)

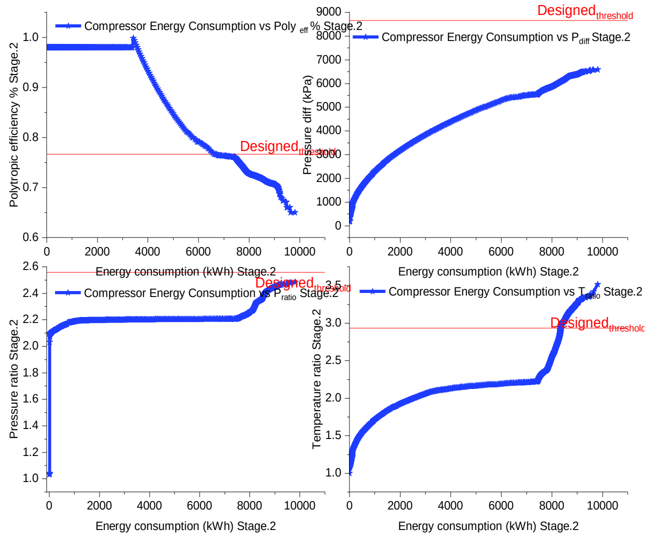

Fig. 12 Real-time performance for Stage 2 (Developed by the authors)

In Figures 11 and 12, a distinct performance was assessed. It showed how an increase in pressure ratio, temperature ratio, pressure differential, and loss in polytropic efficiency resulted in a rise in energy usage. The findings demonstrate that the compressor performance deviates from the designed conditions.

5. Conclusion and Future Research

Surge and energy performance monitoring are effective methods for detecting potential deterioration or decrease in centrifugal compressor performance in the form of energy consumption and surge prediction. The proposed tool offers a less expensive substitute for the expensive performance monitoring and diagnostic tools that are extensively available in the industry. In this research, a monitoring tool was developed in MS Excel, and the health monitoring of a centrifugal compressor was evaluated using the thermodynamics principle. The results showed that the maximum compressing production gas for the 1st stage was 2093.89m^3/h and 1413.53m^3/h for the 2nd stage. The polytropic head obtained 130kJ/kg for the 1st stage and 100kJ/kg for the 2nd stage. While energy consumption was obtained 5340kWh for the first stage, and 8000kWh for the second stage, when the compressor was running at full load with 8950 rpm with 10% surge control line, which showed that the compressor is not surging. The findings demonstrated that the compressor performance deviated from the designed conditions. Therefore, this monitoring tool assists operators and maintenance engineers in tracking the real health conditions of a centrifugal compressor, predicting maintenance needs, and reducing maintenance costs and accidental equipment failures. For future research, the integration of AI, modern sensors, energy optimization strategies, user-friendly interfaces, and cost-benefit analysis can increase the accuracy of surge detection and energy performance monitoring tools.

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