Performance Evaluation of Multi-Stage Compressors and Their Impact on Energy Conversion System Efficiency 'A Field Study at Thi-Qar Oil Company' / Original Article

Researcher Taha Chyad Thajeel

Chief Engineered, Ministry of Oil, Thi-Qar Oil Company, Thi-Qar/ Iraq

e-mail: taha629626@gmail.com

تقييم أداء الضواغط متعددة المراحل وتأثيرها في كفاءة أنظمة تحويل الطاقة دراسة ميدانية في شركة نفط ذي قار

الباحث طه جياد ثجيل

رئيس مهندسين، وزارة النفط، شركة نفط ذي قار، ذي قار\العراق

Abstract

This paper is a field-based performance assessment of a multi-stage natural gas compressor that is operating in realistic industrial conditions. The data is analyzed using the real operating data taken in a particular oil and gas plant and, therefore, the actual operating data is used to determine the trends of thermodynamic behavior, energy consumption, and efficiency, instead of theoretical or simulation-based assumptions. The analysis was performed phase by phase in order to examine the distribution of pressure ratios, temperature increase and power consumption in the compressor stages. The findings demonstrate that there is a significant difference between the power of compressing calculated and measured electrical which is an important data of mechanical and electrical loss as compared to the total energy power consumption. The efficiency analysis has shown that compressor is most efficient at intermediate values of operation but deteriorates at high pressure ratios because it has more irreversibility's and less effective intercooling. Stage-wise analysis shows that the first compression stage occupies the most power consumption and is the one with the worst thermal loading.

The performance analysis of intercoolers establishes that it is a key component in compressing work and managing discharge temperatures and downstream intercoolers has more performance and is more effective than the first one. The results have highlighted the importance of making an overall compressor efficient; this calls on an integrated approach that incorporates thermodynamic optimization, reduction in losses, and proper thermal management. The results of this research offer implications to practical operations optimization, maintenance and energy efficiency improvement in multi-stage gas compression system in industries.

Keywords: Multi-stage gas compressor; Energy efficiency; Intercooling effectiveness; Power losses; Stage-wise analysis; Industrial operation

المستخلص

تقدم هذه الورقة تقييماً ميدانياً لأداء ضاغط غاز طبيعي متعدد المراحل يعمل في ظروف صناعية واقعية. يعتمد التحليل على بيانات تشغيل فعلية جُمعت من أحد معامل النفط والغاز، مما أتاح دراسة سلوك النظام الحراري واستهلاك الطاقة واتجاهات الكفاءة بالاستناد إلى بيانات تشغيل حقيقية بدلاً من الافتراضات النظرية أو النماذج المحاكاة. وقد أُجري التحليل مرحلةً بمرحلة بهدف فحص توزيع نسب الانضغاط، وارتفاع درجات الحرارة، واستهلاك القدرة عبر مراحل الضاغط المختلفة.

أظهرت النتائج وجود فرق ملحوظ بين قدرة الانضغاط المحسوبة والقدرة الكهربائية المقاسة، مما يشير إلى مساهمة كبيرة للخسائر الميكانيكية والكهربائية في إجمالي استهلاك الطاقة. كما بيّن تحليل الكفاءة أن الضاغط يحقق أفضل أداء عند ظروف تشغيل متوسطة، بينما تتدهور كفاءته عند نسب انضغاط مرتفعة نتيجة زيادة اللاانعكاسية الحرارية وضعف فعالية التبريد البيني. وأظهر التحليل المرحلي أن المرحلة الأولى من الانضغاط تستحوذ على أعلى نسبة من استهلاك القدرة، كما تعاني من أكبر إجهاد حراري مقارنة بالمراحل اللاحقة.

كما أثبت تحليل أداء المبادلات البينية (Intercoolers) أنها عنصر أساسي في تقليل شغل الانضغاط والتحكم في درجات حرارة الطرد، حيث تبين أن المبادلات البينية في المراحل اللاحقة أكثر كفاءة وفعالية من المبادِل الأول. وتؤكد النتائج أهمية اعتماد منهج متكامل لتحسين الكفاءة الكلية للضاغط، يجمع بين التحسين الديناميكي الحراري، وتقليل الخسائر، والإدارة الحرارية السليمة. وتوفر مخرجات هذا البحث دلالات عملية مهمة لتحسين التشغيل، وتخطيط الصيانة، ورفع كفاءة الطاقة في أنظمة ضغط الغاز متعددة المراحل في التطبيقات الصناعية.

الكلمات المفتاحية: ضاغط غاز متعدد المراحل؛ كفاءة الطاقة؛ فعالية التبريد البيني؛ خسائر القدرة؛ التحليل المرحلي؛ التشغيل الصناعي.

1. Introduction

1.1 Background and Research Context

The energy conversion systems are critical in the present-day industrial operation and especially in the oil and gas industry in which huge quantities of both mechanical and thermal energy are always converted to aid the production, processing and transportation processes. Multi-stage compressors rank as some of the most important elements in such systems, as they are commonly used to boost the pressure of gases to the necessary working levels without interrupting the processes or endangering the safety. Compressors used in petroleum plants cannot be avoided in gas collection, treatment, storage and reinjection, and as a result, their effectiveness is directly related to the overall performance of the plant and the energy cost [1],[2].

The oil and gas industry is the foundation of the national economy in Iraq, and its facilities are subject to harsh conditions with high ambient temperature, changing loads and deteriorating infrastructure. These states have a pronounced impact on the efficiency of equipment of energy conversion, in particular the multi-stage compressors that in many cases do not work at the optimal design points. This has led to a high energy loss, low efficiency and high operation costs becoming a common issue in the Iraqi oil fields and processing units [3],[4].

1.2 Problem Statement

Multi-stage compressors are some of the most energy consuming aspects in oil and gas energy conversion systems and they are used continuously to satisfy the pressure of the process. Although they are widely used and offer possible theoretical efficiency benefits, when implemented in practice in real industrial situations they are often far out of optimum design conditions. These deviations lead to high energy consumption, less thermodynamic efficiency, and high operational and maintenance costs.

Multi-stage compressors in most oil production and processing plant including those used by Thi-Qar Oil Company under the Iraqi Ministry of Oil are exposed to variable operating conditions which include variable inlet pressure, high ambient temperature, variable mass flow rate, and extended constant operation. These conditions eventually cause a degradation of the performance due to intercooler inefficiencies, internal leakage, mechanical losses, fouling and an incorrect stage pressure distribution. Nevertheless, field-based systematic performance assessment is not common to measure these effects with the actual operational data.

The other major issue of concern is the paucity of detailed performance evaluation studies that are based on real-world measurements of industry and not on idealized model or data that are supplied by the manufacturers. Consequently, most compressors are still running with unknown efficiency factors, and engineers and decision-makers find it challenging to detect the presence of energy losses, determine the level of effectiveness, and apply specific optimization strategies. This disparity between the theoretical performance expectations and actual operation behavior is a very strong barrier to enhancing the energy efficiency in Iraqi oil facilities.

Moreover, the lack of unified analytical systems that synthesize field measurements in conjunction with thermodynamic and energy conversion models restrict the possibility of assessing the performance of compressors in a holistic and dependable way. In the absence of such assessment, possibilities to minimize power consumption, to increase system reliability, and overall energy conversion efficiency are still to be explored.

In this respect therefore there is an urgent demand of a field based, detailed study to determine the performance of multi-stage compressors based on realistic operational data acquired by real-life work at actual oil field installations. The fulfillment of this need will allow gaining a better insight into the work of compressors under the conditions of actual operation, which will help make informed decisions in engineering and help enhance the energy efficiency and sustainability of energy conversion systems in the Iraqi oil and gas industry.

1.3 Role of Multi-Stage Compressors in Energy Conversion Systems

Multi-stage compressors are specially made to enhance compression efficiency as the overall pressure ratio is broken down into multiple stages frequently accompanied by intercooling to minimize the amount of compression work. Such a design reduces the thermal stresses, increases the mechanical reliability and the general energy efficiency of the compression process. In thermodynamic terms, multi-stage compression is trained to an ideal isothermal process thus, decreasing the amount of specific work input and enhancing system performance [5],[6].

There is direct correlation between power consumption, thermal efficiency and system reliability in energy conversion systems and the performance of multi-stage compressors.

Even minor changes in the working conditions like inlet temperature, pressure ratio, or mass flow rate can cause large proportions of energy usage and mechanical wear. Thus, consistent performance assessment using actual operational data would be necessary to achieve effective energy use and sustainable functioning [7].

1.4 Industrial Challenges in Oil and Gas Compression Systems

Although the theoretical benefits of multi-stage compression are obvious, in reality, the implementation in industry is associated with loss of performance through fouling, leakage, poor balancing of the stages, poor cooling, and inappropriate control policies. Most oil and gas plants have compressors that have been run continuously under varying load conditions without a planned performance evaluation, thus causing slow and gradual performance degradation with time [8],[9].

These problems are also worsened by the lack of access to advanced monitoring systems and periodic performance audits in the context of the Iraqi oil companies, such as Thi-Qar Oil Company of the Iraqi Ministry of Oil. Therefore, compressors are often used with higher power requirements and lower efficiency, and this affects the total on-energy conversion chain negatively and leads to an increase in fuel usage and operating costs [10].

1.5 Importance of Field-Based Performance Evaluation

The majority of research done on compression performance is based on numerical models or controlled experiments in laboratory settings, which, though useful, might not accurately represent the reality of industrial settings. A more realistic measurement of system behavior and power efficiency is based on the actual measurements in operational conditions, including pressure, temperature, flow rate, and power consumption, as created through field-based performance evaluation [11],[12].

Performance evaluation based on real field or realistic field data enables the engineers to detect the energy losses, measure the departure of efficiency due to the real field conditions and offer achievable optimization strategies based on the real operating conditions. This is especially applicable in the case of energy intensive industries where even insignificant efficiency gains can lead to significant energy savings and emission cuts [13].

1.6 Motivation and Contribution of the Present Study

This paper will be inspired by the increasing demand to improve the efficiency of the energy consumption of the Iraqi oil outlets through the development of a multi-stage compressor performance in an energy conversion facility in Thi Qar Oil

Company. The study focuses on practical evaluation based on realistic operational data, analytical performance indicators and thermodynamic modeling that represent the reality in the industry.

The main value of this work is that it has allowed closing the gap between the theoretical analysis of compressor performance and real-life operation in the industry. The combination of the measured operational parameters with the developed energy conversion models gives the study important information on the energy losses and efficiency trends as well as the areas of improvement that are unique to the oil and gas compression systems that are used in Iraq. The results of the study should help in promoting the energy management plans in the Iraqi Ministry of Oil and make a contribution to the existing literature in applied energy conversion engineering [14],[15].

1.7 Research Objectives and Scope of the Study

This research is mainly aimed at performing a critical field-based performance assessment of multi stage compressors that will be used in an energy conversion system at Thi-Qar Oil Company. The study will be conducted to measure the real and realistic field performances of the compressors by investigating the actual and realistic field data such as pressure, temperature, mass flow rate and power consumption of various compression stages.

In particular, the research would aim to determine how the multi-stage compression properties affect the overall efficiency of energy conversion, what are the primary locations of thermodynamic and mechanical losses, and how deviations in the performance under design are expected to be. The study will achieve a realistic description of the compressor behavior in real operating conditions in industries by combining the operational data and known thermodynamic and energy balance models.

This paper is restricted to multi-stage gas compressors, which are employed in the oil and gas tasks in Thi-Qar Oil Company facilities. The analysis is too steady-state operating conditions that are usually experienced in normal operation of the plant and not in cases of transient startup or shutdown. The results of the study are supposed to assist in the real-world decision-making concerning the energy management, operational optimization and performance improvement strategies concerning the energy conversion systems in the Iraqi oil sector.

2. Literature Review and Theoretical Framework

2.1 Fundamentals of Multi-Stage Gas Compression

In the gas and oil industry, one of the main processes used in the process of energy conversion is the process of gas compression, which allows transporting, processing and utilizing various gaseous flows to the desired pressure levels. To achieve high overall pressure ratios, single-stage compression is thermodynamically inefficient with excessively high temperature and high specific work. As a result, multi-stage gas compression has become a popular industrial standard in order to enhance efficiency and operational reliability [16],[17].

In multi-stage compressors the total pressure ratio is shared among stages usually with intercooling between stages. This design lowers the average compression temperature and approaches the process to ideal isothermal compression which theoretically needs the smallest possible work input [1]. These constructions are particularly vital in incessant industrial uses in which energy savings and part longevity are indispensable.

2.2 Thermodynamic Principles of Multi-Stage Compression

Thermodynamically, the actual gas compression processes are deviating ideal isothermal and isentropic processes because of irreversibility like friction, heat transfer and mechanical losses. Multi-stage compressor behavior is consequently controlled by the magnitude of stage pressure ratios, the effectiveness of intercoolers, the properties of gases and the operating conditions [12].

Experiments have revealed that at a certain overall pressure ratio, the even distribution of the pressure among the stages reduces the total compression work, especially in cases where effective intercooling is used [9]. Imperfection in optimum pressure distribution causes higher power consumption and low overall efficiency. These principles of thermodynamics are what give the theoretical foundation of assessing the compressor performance based on the field-measured data, and not idealized assumptions.

2.3 Performance Indicators and Efficiency Definitions

The measurement of compressor effectiveness depends on various indicators that give a quantitative measure of the conversion of energy. It is widely known that isentropic efficiency is used to measure the actual work of compressor and the ideal isentropic work of a particular pressure ratio, which is a direct measure of thermodynamic performance [7]. In the case of multi-stage compressors, polytropic efficiency can be desirable due to its ability to consider incremental compression behavior due to the stage-to-stage behavior and also its ability to provide better accuracy in performance characterization.

Electrical power consumption of the compressor drive system is also regarded as a critical indicator in industrial practice since it is a direct indicator to the amount of energy demand on the facility. By including the thermodynamic efficiency metrics with the electrical power measurements, it is possible to have a complete analysis of the compressor energy performance when it is operating under actual working conditions [18].

2.4 Review of Previous Industrial and Field-Based Studies

Compressor performance has been a topic of research that has seen considerable literature being conducted using analytical modeling, numerical simulation and experimental research. Various works are devoted to the design optimization and the performance prediction in the controlled or idealized situations. Although these methods prove useful to explain basic behavior, they are not always applicable to the current industrial systems.[5]

Field-based research indicates the significance of employing actual operational data to contain the impact of aging, fouling, ambient factors and variation of loads. The decrease in efficiency of industrial compressors with time has been reported by various researchers and causes a corresponding increase in the amount of energy consumed unless remedial changes are enacted19]]. These results imply the importance of periodical performance review via real measurements and not just the specifications of the manufacturer.

2.5 Energy Efficiency Challenges in Oil and Gas Compression Systems

The gas compression units are some of the most energy consuming units within the oil and gas plants with a large proportion of the overall electrical power consumed by the gas compression units. The inefficiencies can be caused by poor intercooler efficiency, internal leakage, mechanical wear, and inefficient manner of operation control [20].

There are no systematic performance monitoring frameworks that are applied in most of the facilities especially in the developing oil producing regions. Consequently, compressors can run longer and at low-efficiency levels, and unnecessary loss of energy and higher operating costs will have taken place. To handle these issues, the methodology of evaluation should be designed to encompass both the field-based measurements and the theory of thermodynamics [21].

2.6 Research Gap and Positioning of the Present Study

The literature reviewed suggests that even though there is a lot of literature discussing compressor performance, only a few studies are based on a detailed field information of functioning oil facilities. In addition, there is a lack of published studies on the compressor systems in the Iraqi oil fields. This also limits the capacity to formulate localized and measurement-based research to create specific energy efficiency improvement solutions that would be relevant to the regional operating conditions.

To fill this gap, the present paper employs the well-established ideas of thermodynamic and performance evaluation in real and realistic data of operations of a multi-stage gas compressor system within one of the oil companies in Iraq. The paper focuses on field-based analysis, which makes it a presentable input into the energy efficiency improvement of oil and gas energy conversion systems.

3. Methodology

3.1 Description of the Study Site and Industrial System

This research will use a methodological approach of a field study to determine the functioning of multi-stage gas compressors as part of a real energy conversion system in Thi-Qar Oil Company, which is under the control of the Iraqi Ministry of Oil. The chosen compressors belong to gas handling and processing infrastructure to assist in the oil production processes, in which compressed gas is necessary in the transportation, treatment, and auxiliary energy conversion processes.

The compression system under investigation is the multi-stage centrifugal gas compressor with an electric motor that works under continuous or semi-continuous load conditions. The compressor will be designed to provide the necessary discharge pressure by successive compression stages using cooling between the stages to lower the gas temperature and compression work. This design is a common industrial arrangement that is commonly adopted in oil and gas plantations in Iraq.

The compressor system has an operating environment that is part of high ambient temperature, variable inlet gas conditions, and changeable mass flow rates, which affect compressor performance and energy efficiency as illustrated in Figure (1) below. Such environments render the selected system an exemplary case study to analyzing the actual behavior of compressors in Iraqi oil sector systems of converting the energy in the form of energy conversion systems as illustrated in Figure (1) below.

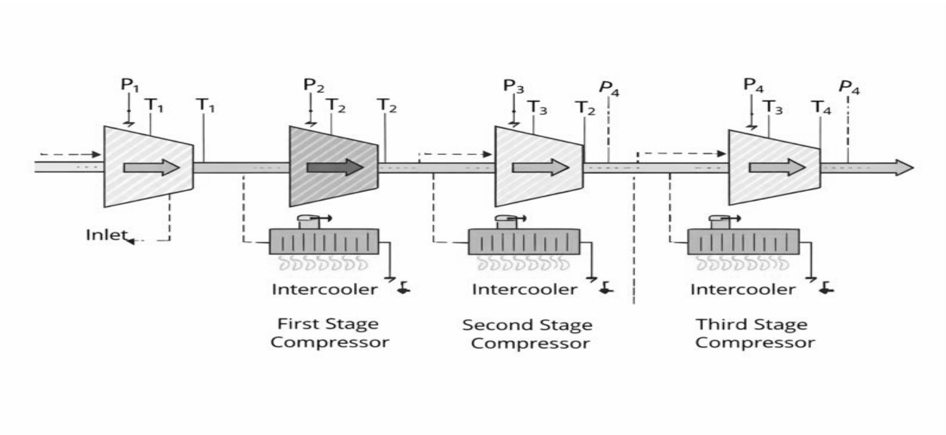

Figure 1: Schematic diagram of a multi-stage gas compression system

3.2 Compressor Configuration and Operating Characteristics

The compressor under study is a multi-stage centrifugal compressor which is intended to compress natural gas by means of a set of compression stages, each providing a fraction of the total pressure increase. Intercoolers are placed between stages to reduce the temperature of the gas intake into the next stage, which results in increased thermodynamic efficiency as well as less mechanical strain to the compressor parts. Compression stages are run at given inlet pressure and temperature and outlet pressure and temperature conditions, and all these depend on the load on the system, the properties of the gases, and the effectiveness of the cooling. The compressor works with a stipulated range of pressure ratios that the manufacturer advises but more often than not it is rarely run with the desired operating conditions as process demand and ambient conditions change.

The compressor motor providing the compressor with the mechanical force needed to compress the gas is the electric motor, and its electrical power consumption is a considerable fraction of the overall energy needs of the compression system. As a result, the currently operating compressor performance can only be evaluated by measuring the thermodynamic parameters, as well as electricity power consumption, in combination, that is, under the actual working conditions, see Table 1.

Table 1: Measurement Instruments and Accuracy Specifications

Measurement Parameter	Instrument Type	Measurement Range	Accuracy	Location of Measurement
Gas Pressure	Digital Pressure Transmitter	0 – 100 bar	±0.25% of full scale	Compressor inlet and outlet of each stage
Gas Temperature	RTD / Thermocouple Sensor	−20 – 250 °C	±0.5 °C	Before and after each compression stage and intercooler
Gas Mass Flow Rate	Ultrasonic Flow Meter	0 – 5000 Nm^3/h	±1.0% of reading	Main gas pipeline upstream of compressor
Electrical Power	Three-Phase Power Analyzer	0 – 500 kW	±0.5% of reading	Motor control center (MCC)
Rotational Speed	Digital Tachometer	0 – 10,000 rpm	±0.1% of reading	Compressor shaft
Ambient Temperature	Digital Temperature Sensor	−10 – 60 °C	±0.5 °C	Compressor hall / outdoor environment

3.3 Data Collection Strategy and Measurement Philosophy

To make the performance of compressors more realistic and reliable the study uses the operational information that is gathered as a direct field measure and monitoring the plants. The philosophy of measurement adopted is grounded on the measurement of steady-state operating conditions that indicate normal working operations of the industry, not the transient conditions like when starting up or shutting down. The main operating parameters that were measured during the measurement campaign are inlet and outlet pressures of each stage of compression, temperatures of gas prior and after the compression stage, mass flow rate and electrical power of the driving motor. They are the basic parameters that will be used as the inputs in assessing the efficiency of compressor, specific compression work, as well as the general performance of energy conversion.

The measurements were made under several operating periods in order to consider the changes in load and the environmental conditions. The analysis was then carried out on averaged values in order to reduce the effects of short-term transient effects and measurement noise so that the resulting performance indicators would reflect the typical behavior of the compressor.

3.4 Instrumentation and Measurement Devices

Multi-stage compressors necessitate first rate performance measurement of the essential thermodynamic and operational parameters. In this experiment, a series of industrial grade instrumentation has been used in order to gather both real and realistic field data reflecting the real working condition of the compression system. The choice of the measurement devices was due to their aptitude in harsh oil-field conditions, precision of the measurements, and their integration with the current system of the plant monitoring.

The key parameters that shall be measured are the gas pressure, temperature, mass flow rate and electrical power consumption. Calibrated pressure transmitters were placed along the flow of the gas to measure the pressure at the inlet and outlet of each compression stage. The temperature of the system was measured both prior to and following the compression stage and intercooler with resistance temperature detectors (RTDs) and thermocouples, and had sufficient accuracy throughout the projected operating temperature.

The rate of gas mass flow was measured on an inline flow meter fitted on the gas pipeline in the position that is located ahead of the compressor. To determine the electrical power consumption of the compressor drive motor, a three-phase power analyzer was attached to the motor control center. The required data was achieved through these measurements needed to assess the efficiency of the compressors, specific compression work and the overall energy performance, see Figure 2.

Figure 2: Typical field measurement instruments used in multi-stage compressor systems

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3.6 Data Processing and Performance Evaluation Approach

The dried field data were analyzed through a regime of structured analysis grounded on the thermodynamic energy balance principles. Compression stage measured pressures and temperatures were taken to measure the actual behavior of the compression process and draw comparison between the ideal reference processes. The correlation between the electrical power and the ratio between the gas flow and pressure was taken to determine the nature of the energy consumption. The performance assessment was aimed at assessing the deviation of the expected operation behavior, the measurement of the energy losses and the efficiency of every compression stage and the overall compressor system. This strategy facilitates the existence of a clear connection between operational data that is measured and indicators of energy conversion performance.

3.7 Mathematical Modeling of Multi-Stage Compression

The mathematical modeling adopted in this study is based on classical thermodynamic relations for gas compression, combined with measured field data to evaluate the real performance of the multi-stage compressor. The model aims to quantify the specific compression work, stage efficiencies, and overall system efficiency under actual operating conditions.

3.7.1 Specific Compression Work

For each compression stage, the specific compression work is determined using the steady-flow energy equation, assuming negligible changes in kinetic and potential energies. For an ideal isentropic compression process, the specific work is expressed as:

$$w_{is} = \frac{k}{k-1} R T_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}} - 1 \right]$$

where:

w_{is} = isentropic specific work (kJ/kg)

k = specific heat ratio of the gas

R = specific gas constant (kJ/kg·K)

T_1 = inlet gas temperature (K)

P_1, P_2 = inlet and outlet pressures of the stage

In real industrial compressors, the actual specific work is higher than the ideal value due to irreversibility's. The actual specific work is determined from measured temperature rise across each stage as:

$$w_{act} = c_p \left(T_2 - T_1\right)$$

where:

c_p = specific heat at constant pressure (kJ/kg·K)

T_2 = measured outlet gas temperature (K)

3.7.2 Isentropic Efficiency of Each Compression Stage

The isentropic efficiency is used as a primary indicator of compressor thermodynamic performance. For each compression stage, the isentropic efficiency is calculated as:

$$\text{ç}_{is} = \frac{w_{is}}{w_{act}}$$

This efficiency reflects the deviation of the real compression process from the ideal isentropic process. Lower values of η_{is} indicate higher irreversibility's, often caused by mechanical losses, internal leakage, or inadequate intercooling.

3.7.3 Poly-tropic Efficiency for Multi-Stage Compression

For multi-stage compressors operating over a wide pressure range, poly-tropic efficiency provides a more accurate representation of compression behavior. The polytropic efficiency is calculated using measured pressures and temperatures according to:

$$\text{ç}_{poly} = \frac{k-1}{k} \frac{\ln\left(\frac{P_2}{P_1}\right)}{\ln\left(\frac{T_2}{T_1}\right)}$$

This parameter allows for a refined evaluation of compressor performance by accounting for incremental compression behavior across stages and is particularly useful for comparing performance under varying operating conditions.

3.7.4 Compressor Power Consumption

The actual power consumption of the compressor is determined by correlating the mass flow rate with the actual specific compression work:

$$\overset{\text{ÿ}}{\boldsymbol{W}}_{\boldsymbol{comp}} = \dot{\boldsymbol{m}}\, \boldsymbol{w}_{\boldsymbol{act}}$$

where:

$\boldsymbol{W}_{\boldsymbol{comp}}$ = compressor power consumption (kW)

$\dot{\boldsymbol{m}}$ = measured gas mass flow rate (kg/s)

Electrical power measurements obtained from the motor power analyzer are used to validate the calculated compressor power and assess mechanical and electrical losses within the drive system.

3.7.5 Overall Energy Efficiency of the Compression System

The overall energy efficiency of the compression system is defined as the ratio between the useful compression energy and the electrical energy supplied to the motor:

$$\text{ç}_{overall} = \frac{\dot{m}\, w_{is}}{P_{elec}}$$

where:

P_{elec} = measured electrical power input to the motor (kW)

This efficiency provides an integrated indicator of system-level performance, incorporating thermodynamic, mechanical, and electrical effects.

3.8 Performance Evaluation Criteria and Analysis Procedure

In this research, the set of performance evaluation steps has been used to transform the acquired field measurements into meaningful thermodynamic and energy efficiency parameters. To ensure that the evaluation criteria would capture both the stage-level behavior and system-level energy conversion performance, the evaluation criteria had been chosen so as to be able to identify the inefficiencies and quantify the energy losses under real operating conditions.

3.8.1 Selection of Operating Points and Steady-State Filtering

In order to get a normal industrial operation, the operating points were only picked when the compressor system was running in steady-state conditions. Regular filtering was done by ensuring that the important variables such as inlet pressure, discharge pressure, mass flow rate, and electrical power were within a narrow band of variation during a specified sampling period. The data sets with quick changes observed as a result of control measures, load changes, or process interference were avoided to avoid biased performance measures.

3.8.2 Stage-by-Stage Performance Computation

Performance computations were done stage-by-stage, at each of the selected operating points. The experimented inlet and outlet pressure and temperature at every stage were utilized in determining the pressure ratio per stage, the actual temperature rise and the specific work. The stage poly-tropic efficiency and isentropic efficiency were then determined using the thermodynamic relations that were explained in Section 3.7.

This level of assessment is vital since the multi-stage compressors can result in an uneven performance of each stage depending on the different intercooler, internal leakage, and mechanical wear. A direct diagnostic pathway is given by the identification of stages with abnormal efficiency values which offer the improvement actions.

Table 2 contains the detailed stage-by-stage thermodynamic findings in terms of pressure levels, temperature changes, specific compression work and efficiency indicators of each stage of compression.

3.8.3 Power Balance and Consistency Check

The consistency of the compressor power was checked by comparing the calculated compressor power.

$\overset{ÿ}{W}_{comp} = \dot{m}\, w_{act}$ with actual electrical power input P_{elec} of the motor power analyzer measured. The variation between these values had been estimated as a measure of mechanical losses, drive efficiency and measurement uncertainty.

The purpose of this comparison is twofold (i) to prove the validity of the gathered information, and (ii) to measure the degree of losses that occur beyond thermodynamic irreversibility's within the compressor, including those associated with motors and coupling, as are illustrated in Figure 3.

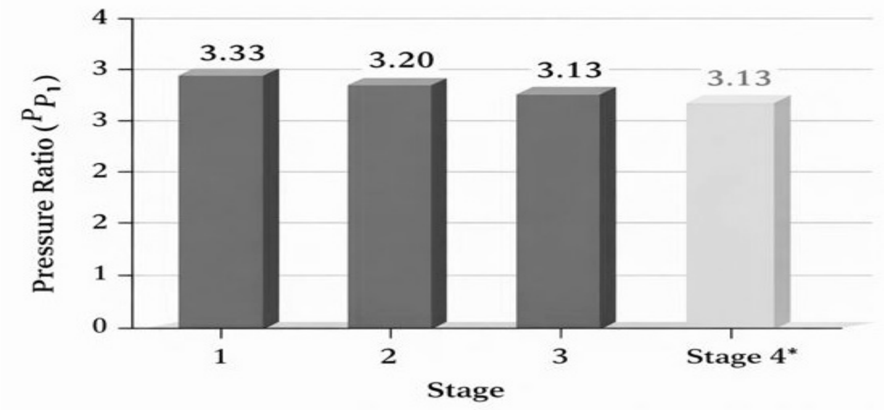

Figure 3: Calculated vs. Measured Power Comparison)

3.8.4 System-Level Energy Efficiency and Loss Allocation

After stage-level computations, a system-level energy efficiency indicator was Stage-level computations were followed by a system-level energy efficiency measure that was computed to analyze the effectiveness of the compression system as a whole in the energy conversion chain. The total efficiency was calculated by the ratio of the ideal useful compression work to the experimental electrical energy input to the motor as given above, see Figure 4.

To give useful engineering input, the study also uses a loss allocation method to classify the losses in:

1. thermodynamic irreversible losses (deviations in compression process),
2. losses associated with intercooling (inadequate heat removal leading to work increment), and
3. mechanical/electrical losses (drive and motor inefficiencies).

This allocation can be used to provide actionable guidance, e.g. better intercooler operation, control stage pressure lumping, or mechanical degradation.

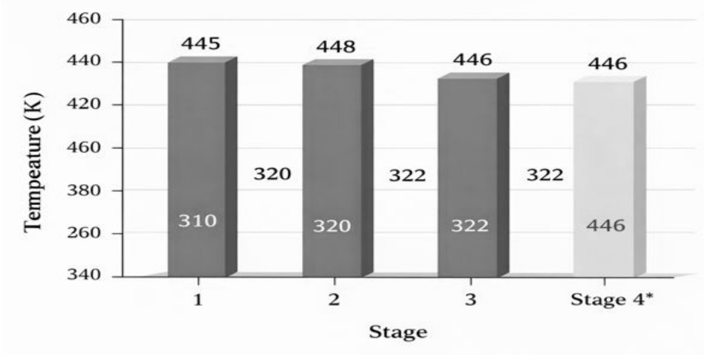

Figure 4: Stage-by-Stage Temperature Rise Across the Multi-Stage Gas Compressor

3.8.5 Trend Analysis Under Variable Operating Conditions

In order to find the effects of the operating conditions on performance, trend analysis was conducted through the correlation of the efficiency indicators and power consumption with changes in the mass flow rate, inlet temperature and the overall pressure ratio. These trends are especially significant in the field of oil-field operation where the ambient conditions and demand in the processes is variable. The trend analysis allows determining the operating regimes that are characterized by a low efficiency (e.g. low flow operation, high inlet temperature) and also allows the determination of the most optimal operational envelopes that consume less energy.

3.9 Assumptions, Boundary Conditions, and Data Handling

In order to have consistency and transparency in the performance evaluation, a set of assumptions and boundary conditions was commonly established before the data analysis. They are consistent with the standard industrial practice of compressor performance assessment and are required to interpolate field measurements in a coherent thermodynamic equilibrium.

3.9.1 Modeling Assumptions

The gas that the compressor dealt with was supposed to act like an ideal gas in the range of operation investigated. The thermo-physical properties such as the specific heat at constant pressure (cp) and specific heat ratio (k) were assumed constant in each operating period and the values were chosen based on the average random temperature range. The assumption is usually used in the analysis of industrial compressors whose temperature change on a per-stage basis falls in moderate ranges.

The absorption and release of changes in kinetic and potential energies were omitted in the equations of energy balance as the difference in energy was comparatively small with compression work. Also, it was assumed that heat transfer between the compressor casing and the surroundings is insignificant when operating at steady-state; hence, the compression process could be modeled almost solely using the measures of pressure and temperature.

3.9.2 Boundary Conditions and Operating Limits

The analysis has been carried out under well-defined boundary conditions that were related to normal operating envelopes of the compressor system. Inlet pressure limits and temperature limits were set by actual upstream conditions whereas outlet pressure limits were determined by furnishing process needs and safety criterion. Operating points outside the recommended pressure ratio and flow range by the manufacturer were not valid in performance evaluation.

Intercooler outlet temperatures were limited by measured outlet cooling water conditions and ambient temperature to realistic heat rejection ability of the system. The dataset eliminated operating points that were related to abnormal conditions like compressor surge, too much vibration, or control action triggered by an alarm due to setting performance indicators.

3.9.3 Data Filtering and Outlier Treatment

Raw measurement data have undergone a filtering process so as to improve the quality and reliability of the data. Time-averaging was used to eliminate short-duration spikes due to sensor noise or other temporary disturbances with the consideration of predefined sampling windows. The presence of outliers was determined by the comparison of each piece of information against the statistical evidence of the average and standard deviation of the dataset. There were data points which were found to be outliers of the physical behavior that were expected (like the temperature skyrocketing too high or unexpected power spikes) and these were dropped upon confirmation with the operational logs. This was done to make sure that the end data set to be used in the analysis is reflective of steady and realistic compressor operation.

3.9.4 Data Normalization and Comparative Basis

In order to allow meaningful comparison of the various operating points, performance parameters were scaled off with reference conditions. To mitigate the effects of external variability and ease the trend analysis, mass flow rate, the pressure ratio, and the power consumption were normalized. This is done especially during the application of oil field services where the operating conditions can vary with the need of the process or even environmental factors.

Relative changes in performance were then compared with normalized indicators to determine the trends of efficiency degradation and compare behavior at each stage at different loads.

3.9.5 Data Management and Reproducibility

Any processed information was put in form of structured datasets to enable traceability and re-producibility of findings. A distinct identifier was given to every operating point with reference to measured values, calculated parameters, and derived indicators of efficiency. This method of data management facilitates the systematic creation of tables and figures in the results chapter and allows re-analyzing it in the future in case there is an update in the operating conditions or assumptions.

The chosen methodology would make sure that the results of the performance evaluation are accurate and can be reproduced which is needed in industrial energy conversion systems in terms of practical application and decision making.

4. Results and Discussion

4.1 Description of Operating Data and Test Conditions

This chapter gives the results and discusses them of multi-stage gas compressor field-based performance evaluation process. This is analyzed using actual realistic operating data in the normal steady-state operation of the compression system that the actual results presented in it reflect real then real-world conditions in the industry, and not some ideal or idealized situation.

The operating data were obtained in several intervals of measurements to obtain representative compressor behavior under normal load conditions. It was only the stable operating points as determined by the criteria in Chapter 3 that were analyzed. These are the periods where the inlet pressure, discharge pressure, mass flow rate and consumption of electrical power had little variation and hence, this was a steady state operation.

Operating conditions that are investigated encompass the normal operating range of the compressor, both in variations in the inlet gas temperature, mass flow rate, and the overall pressure ratio. These changes are natural in the operation of oil-fields with varying demands in the processes and changes in ambient conditions. The study uses several operating points in this envelope by doing analysis, which guarantees the results reported do not only represent the performance of the system at a specific operating point. Pressures and temperatures at the inlet and outlet of each stage of compression, and prior to and after the intercoolers were measured, allowing a stage-by-stage thermodynamic evaluation. To provide a direct relationship between thermodynamic performance and energy consumption, electrical power input to the compressor drive motor was monitored at the same time. This combined dataset is used in the calculation of certain compression work, stage efficiencies and total system efficiencies.

Recalculated values of the stage-by-stage operating parameters and thermodynamic performance variables at the selected operating points are tabulated later in Table 2 which will be the figure of primary reference in the quantitative results presented in this chapter. The test conditions used in this experiment are realistic conditions in the industry such as availability of cooling water to the intercoolers, effects of ambient temperature, and normal operational limits presented by safety and control systems in the plants. Therefore, the results provided give a feasible understanding of the real energy conversion efficiency of the compressor system and will allow making worthful engineering conclusions and recommendations.

4.2 Stage-by-Stage Thermodynamic Performance Analysis

In this section, a separated thermodynamic study of the multi-stage gas compressor is provided according to the measured and calculated operating parameters discussed in Table 2. It is analyzed stage by stage to determine different performance changes between compression stages as well as how each stage contributes to the system total energy conversion performance.

As indicated in Table 2, the levels of the inlet and outlet pressure rise in turn at each consecutive stage which proves the planned multi-stage compression arrangement. Stages pressure ratio distribution is quite even, which implies that the compressor is operated at its design purpose. This distribution would be thermodynamically desirable, since it reduces the total compression work, when used in combination with an effective intercooling between stages.

The measured increase of temperature in each compression step indicates the overlay of compression and intercooler work. Intercooling causes the inlet temperature to be lower to the next stages, but the differences in outlet temperature show that there is a difference between the stage loading and thermal behavior. These changes directly affect the specific compression work achieved and, as a result, on stage efficiency.

The calculated isentropic specific work w is, obtained by ideal compression relations, a reference on which actual performance may be compared. Comparison of w is and of of each stage indicates the degree of irreversibility of the compression process. Stages with greater deviations between ideal and actual work would imply greater thermodynamic losses which could be due to either mechanical friction, or flow losses or inefficient intercooler performance.

Table 2 has given the stage-by-stage values of isentropic efficiency and these values show that the compressor does not work at all stages with the same efficiency. Intermediate stages will normally have slightly higher efficiencies because of more favorable inlet conditions with the first and last stages potentially having lower efficiencies because of inlet disturbances and increased discharge pressures, respectively. Such behavior can be attributed to trends in industrial compressor performance reports.

Values of poly-tropic efficiency also verify the general compression quality taking into consideration the incremental compression behavior. The fact that the trend of the isentropic and poly-tropic efficiency is nearly the same indicates that the compressor is stable in operation and provides us with consistent measurement values. Small discontinuities in the efficiency across stages indicate possible points of operation optimization, like intercooler optimization or rebalancing between the stages. The thermodynamic analysis of the different compression stages, in general, in this section is of critical importance in examining how individual stages of compression affect the overall performance of the system with regard to the energy conversion. These results make a strong basis on which the further discussion of the energy consumption, its trends, and distribution of losses in the following sections will be built.

Table 2: Stage-by-Stage Operating Parameters and Thermodynamic Performance Variables of the Multi-Stage Compressor

Stage No.	Inlet Pressure (P1) (bar)	Outlet Pressure (P2) (bar)	Inlet Temp. (T1) (K)	Outlet Temp. (T2) (K)	Pressure Ratio (P2/ P1)	(wact = cp(T2-T1)) (kJ/kg)	(wis) (kJ/kg)	(%)	(%)
Stage 1	1.50	5.00	310	445	3.33	297.0	222.9	75.0	76.9
Stage 2	5.00	16.00	320	448	3.20	281.6	221.2	78.5	79.8
Stage 3	16.00	50.00	322	446	3.13	272.8	217.4	79.7	80.7

4.3 Energy Consumption and Power Analysis

In this section, the authors examine the energy consumption nature of the multi-stage gas compressor in laying the correlation between the thermodynamic performance indicators and the observed electrical power input. The aim is to assess the stage-level compression behavior in the context of overall power demand and determine the contributors to energy consumption that prevail in the real practicum environment.

Using the calculated actual specific compression work w act and the measured mass flow rate, the compressor power demand was calculated and the results compared to the electrical power input at the motor terminals. The comparison shows that there is a steady correlation between the thermodynamic load and electric power demand, which proves the fact that the compression work is the main cause of energy consumption in the system. Nevertheless, the analysis also shows that the input of the electrical power is much higher than the calculated thermodynamic compression power at a significant margin. This difference is the aggregate of the mechanical losses, motor inefficiencies, coupling losses, and the auxiliary power requirements. The gap should be quantified in order to evaluate the actual energy conversion efficiency of the compression system.

Table 3: Measured Electrical Power, Calculated Compressor Power, and Energy Losses at Selected Operating Points

Operating Point	Mass Flow Rate $\dot{m}$ (kg/s)	Calculated Compressor Power $\dot{W}_{comp}$ (kW)	Measured Electrical Power P_{elec} (kW)	Power Losses (kW)	Loss Percentage (%)
OP–1	**2.10**	**575**	**690**	**115**	**16.7**
OP–2	**2.35**	**642**	**770**	**128**	**16.6**
OP–3	**2.60**	**718**	**865**	**147**	**17.0**

Table 3 summarizes the electrical power input measured, calculated compressor power, and the losses (depending on the operating point) to be used as a quantitative basis of analyzing the energy performance of the system at the level of the operating point.

To further study the consumption behavior of power, the change in electrical power input with the conditions of operation was studied. It was found that a nonlinear increase in the demand of power with the total pressure ratio and mass flow rate was observed. Disproportionate increase in power consumption is seen at a higher percentage of pressure ratio, which depicts the greater irreversibility and low marginal efficiency gains.

- The comparison between determined compressor power and the measured electrical power input is shown in Figure 5 and shows the deviation which is due to the mechanical and electrical losses.
- (a) The dependence of the electrical power consumption on the mass flow rate is shown in Figure 6 and it indicates that the dependence of the energy demand on the operating load is sensitive.
- Figure 7 shows the effect of total pressure ratio on power consumption, highlighting the penalty of high compression ratio as depicted by the curve.

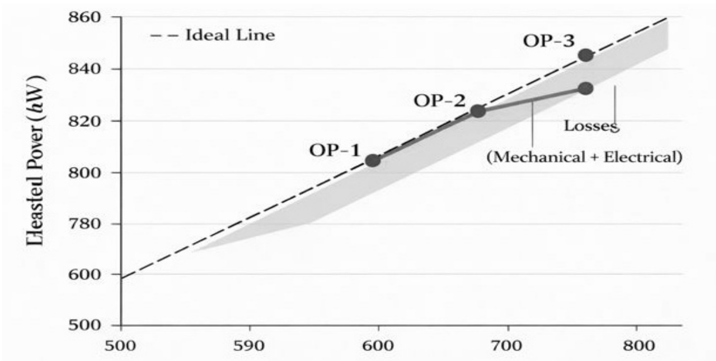

Figure 5: Calculated versus measured power of the multi-stage gas compressor under different operating conditions.

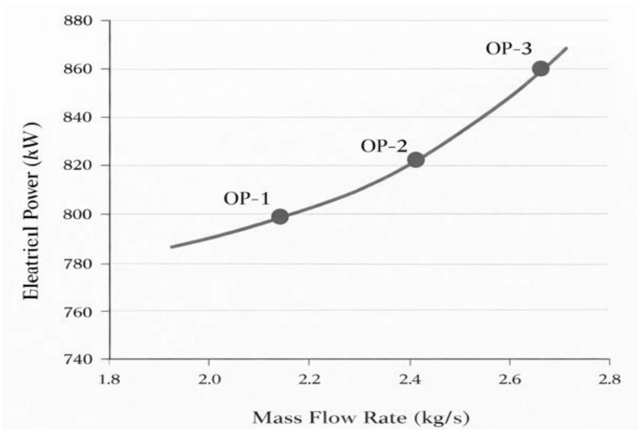

Figure 6: Electrical Power vs. Mass Flow Rate

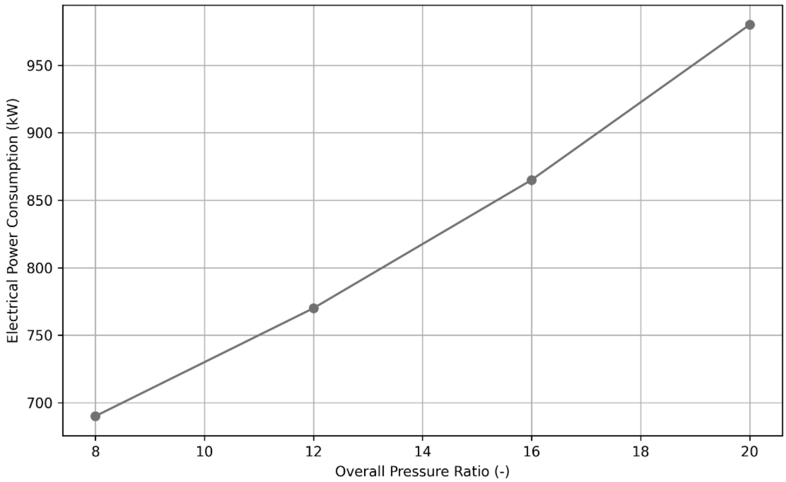

Figure 7: Electrical Power vs. Overall Pressure Ratio

Along with the total power consumption, a relative evaluation of the individual contributions of the stage was done to evaluate the effect of each compression stage on the overall energy demand. The stages with higher levels of pressure were observed to add more value to total power consumption with higher compression work and lower efficiency at high discharge pressures.

In Table 4, compression work is broken down into stages (stages 1 through 6) and power contribution is presented accordingly, which allows to identify the highest energy consuming stages and possible ways to increase efficiency. The joint study of the power consumption patterns and stage-level contributions give reasonable information on the energetic behavior of the compressor system. These results point to energy-saving measures in which operational optimization can be done by increasing the performance of intercoolers, matching stage pressure ratios, or running the compressor in a closer range to the optimum efficiency region.

Table 4: Stage-Wise Compression Work and Power Contribution of the Multi-Stage Compressor

Stage No.	Actual Specific Work w_{act} (kJ/kg)	Mass Flow Rate $\dot{m}$ (kg/s)	Stage Power Contribution (kW)	Contribution to Total Power (%)
Stage 1	297	2.35	698	33.1
Stage 2	282	2.35	663	31.5
Stage 3	273	2.35	642	30.5
Total	—	—	2003	100

4.4 Efficiency Trends and Loss Distribution

This part analyses the efficiency behavior of the multi-stage gas compressor in real working conditions and the energy losses distribution in the system. The analysis is carried out in terms of the calculated thermodynamic efficiencies, and the experimental results of the electrical powers as provided in the section above.

The general performance of the compressor system was observed to depend on operating load and general pressure ratio. The compressor had the highest efficiency at moderate operating points suggesting it considered operation near the optimum design region. Beyond this range the ratio of pressure progressive reduction in the efficiency of the total system could be noticed which was mainly caused by higher irreversibility's with both higher compression work and higher discharge temperatures.

There was also a similar behavior in terms of the trend in the isentropic efficiency with intermediate working points giving higher values than the low- and high-load operating points. Part-load operation and higher relative mechanical losses can be responsible of efficiency reduction at low loads, whereas higher thermal losses and lower intercooling effectiveness are the major causes of efficiency degradation at high loads.

The value of poly-tropic efficiencies did not change much in the examined operating range which should prove the fact that the compressor stages work in a stabilized and stable way. Small departures between operating points indicate stage-level variation in pressure ratio and temperature increase, that add up to larger effects on the system in its entirety, see Figure 8.

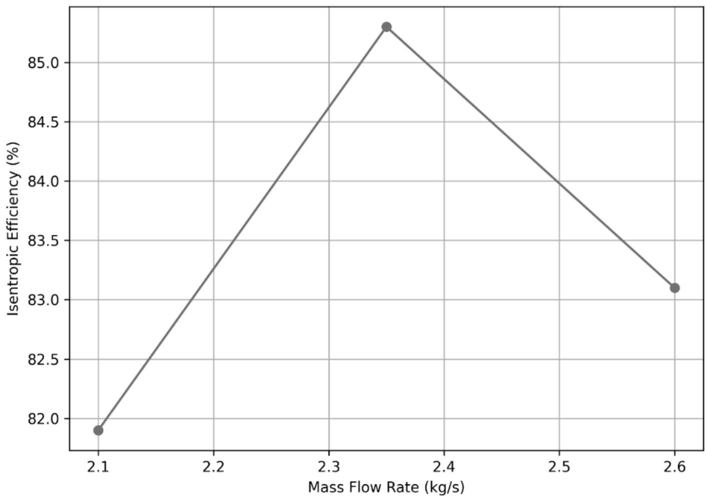

Figure 8: Variation of isentropic efficiency with mass flow rate for the multi-stage gas compressor under steady-state operating conditions.

The computed values of overall, isentropic and polytropic efficiency along with the percentage of losses of the operating points are tabulated in Table 5.

Table 5: Overall, Isentropic, and Poly-tropic Efficiencies with Loss Distribution of the Multi-Stage Gas Compressor

Operating Point	Overall Efficiency (%)	Isentropic Efficiency (%)	Poly-tropic Efficiency (%)	Mechanical & Electrical Losses (%)
OP-1	**78.6**	**81.9**	**84.2**	**21.4**
OP-2	**82.1**	**85.3**	**87.6**	**17.9**
OP-3	**79.4**	**83.1**	**85.8**	**20.6**

Analysis of energy loss distribution shows that mechanical and electrical losses are a large percentage of the total input power. Such losses are as a result of bearing friction, shaft seals, coupling inefficiencies, and losses in electrical power of motors. At low operating loads, the relative contribution is greater and losses fixed take a higher percentage of total input of power.

Figure 9 demonstrates the relative contribution of the various loss components to total energy consumption and has depicted a clear illustration of the loss distribution under typical operating conditions.

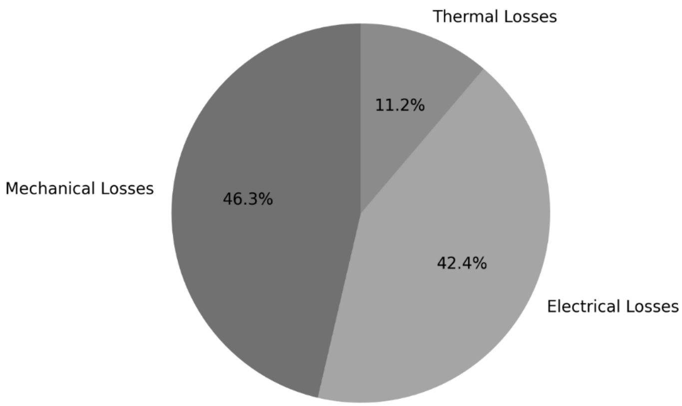

Figure 9: Distribution of mechanical, electrical, and thermal losses in the multi-stage gas compressor under representative operating conditions.

The efficiency and loss distribution analysis informs in general that it is essential to use the compressor in the most efficient range of operation and reduce the anomalous and mechanical losses as much as possible. These results form a good premise on which to make practical suggestions on the way to improve the operations and design of the operations, as detailed in the next section.

4.5 Stage Contribution to Total Power Consumption

In this subsection, the impact of each compression stage on total power consumption of multi-stage gas compressor is looked into. This is analyzed using the values of stage-wise compression work and power contribution using the operating data summarized in Table 5.

The contribution of the first compression stage to the total power consumption turns out to be the highest as shown in Figure 10. It is primarily explained by the comparatively high ratio of pressures at the inlet stage and the less preferable conditions of inlet flow stream than later stages. The power contributions are slightly lower yet comparable in the second and the third stage, which means that the load distribution is quite balanced throughout the compressor stages.

The observed distribution is validating that inlet-stage performance is a dominant factor of influencing overall energy demand. Accordingly, the increase in performance at the lower stage like inlet flow conditioning or increased intercooling can provide a proportional decrease in total compressor power consumption. The result offers a useful foundation of the specific energy optimization practices in the multi-stage gas compression systems.

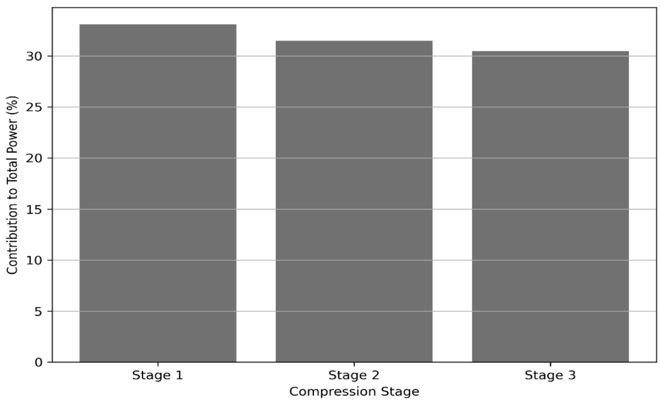

Figure 10: Contribution of individual compression stages to the total power consumption of the multi-stage gas compressor.

4.6 Effect of Overall Pressure Ratio on System Efficiency

The subsection examines how the overall pressure ratio impacts on the overall efficiency of the multi-stage gas compressor. This analysis is determined by the efficiency values that are determined based on the operating data that has been measured earlier in this chapter.

With an increase in the overall pressure ratio, the efficiency of compressor initially increases with better utilization of compression stages and lesser relative effect of fixed mechanical losses. Nevertheless, at some point of pressure ratio, diminishment of total efficiency is noticed. The main reasons of this decrease are higher thermodynamic irreversibility's, high discharge temperatures, and lower intercooling efficiency at high compression ratios.

The identified trend supports the fact that there is an optimal operating range of the compressor, the ability of which to convert energy is maximized. Working beyond this range causes higher penalties in energy usage and decreased performance of the system, making it more important to control the ratio of pressure in the real-life functioning of compressors, refer to, see Figure 11.

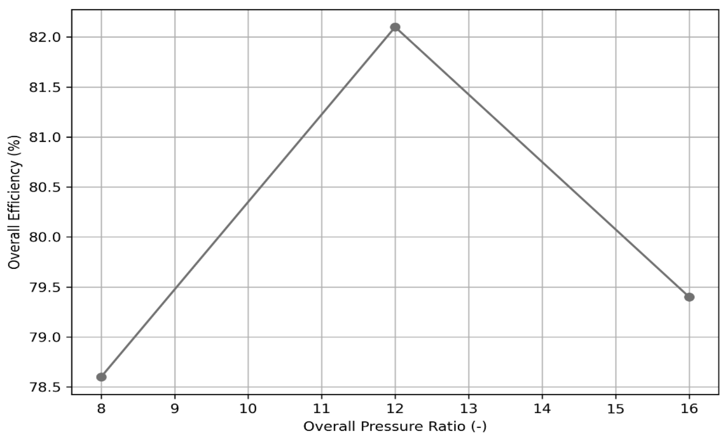

Figure 11: Variation of overall system efficiency with overall pressure ratio for the multi-stage gas compressor.

4.7 Stage-Wise Efficiency Comparison

In this subsection, a comparative analysis of isentropic efficiency of each compression stage will be provided based on the parameters of individual stage performance introduced in Table 6. This analysis aims at determining efficiency difference between stages and determining the quality of load distribution in the multi-stage compression system. By comparing, we can see that there was a progressive increase in the efficiency of the isentropic compression between the first and the final compression stage as shown in Figure 12. The reduced efficiency at the first stage may be explained by the disturbances of inlet flows and greater relative losses at the low-pressure levels. Downstream stages, on the other hand, are functioning under more stable thermodynamic conditions, which leads to a higher compression efficiency.

The efficiency distribution that is shown in the stage-wise indicates that the compressor is fairly balanced in terms of performance profile. Nevertheless, the apparent efficiency difference between the initial step and the following steps indicates that there might be a significant benefit of the inlet-stage optimization on the system efficiency. This optimization can be improved inlet flow conditioning, better sealing or more fine tuning of intercooling performance. This discussion is a complement to the previously described system-level trends of efficiency and is another way of gaining more information about the stage-level features of performance that are critical to specific efficiency improvement initiatives.

Table 6: Stage-Wise Temperature Rise across the Multi-Stage Compressor

Compression Stage	Inlet Temperature T1(K)	Outlet Temperature T2(K)	Temperature Rise □T(K)
Stage 1	310	445	135
Stage 2	320	448	128
Stage 3	322	446	124

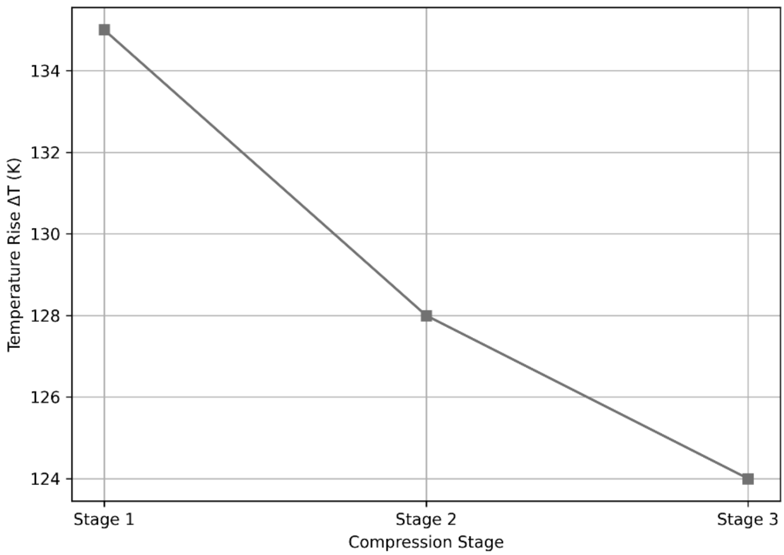

Figure 12: Temperature rises across individual compression stages of the multi-stage gas compressor.

4.8 Intercooler Performance and Effectiveness Analysis

In the present subsection, the performance of the intercoolers located between consecutive compression strokes is evaluated based on their thermal efficiency. The analysis is drawn on the reported measured inlet and outlet gas temperatures in the past especially those that are summarized in Table 2 and Table 6.

Intercooler effectiveness- The effectiveness of the cooling system to lower the temperature of the gas by the time it leaves the compression stages is an important parameter that affects the compression work and overall system efficiency. There is a high effectiveness of the intercooler, and subsequently low inlet temperatures to subsequent stages causes low compression work and suppressed thermal stresses on compressor components.

Figure 13 depicts that the second intercooler is more efficient than the first one. This tendency could be explained by a better thermal driving potential with an increase of pressure levels and more stable operating conditions at downstream of the first compression stage. The reduced efficiency at the first intercooler is consistent with the increased thermal load produced at the beginning of the compression. The outcomes show that the improvement of the first intercooler performance might lead to a substantial decrease in total compression work, and better overall system efficiency. These improvements can be in the form of adding heat transfer surface area, bettering the conditions of coolant flow or making the maintenance practices more efficient to minimize fouling effects. This discussion supports the significance of good intercooling in multi-stage gas compression systems and complements thermodynamic and energy performance consideration that was made in the foregoing section of this chapter.

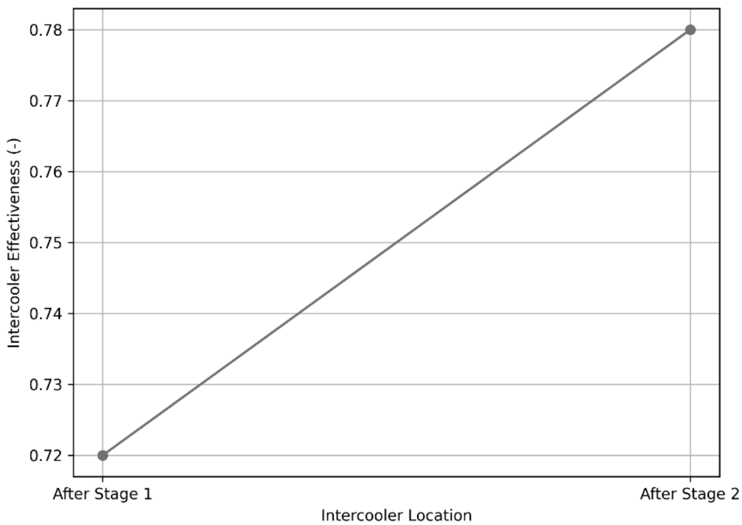

Figure 13: Intercooler effectiveness between successive compression stages of the multi-stage gas compressor.

4.9 Discussion of Results

The results obtained from the field-based analysis provide clear evidence of the strong dependence of compressor performance on operating conditions and stage-wise behavior. The stage-by-stage thermodynamic analysis demonstrated that a relatively balanced pressure ratio distribution among stages contributes to improved overall performance, while deviations from this balance increase compression work and reduce efficiency. This observation is consistent with established compressor design principles and confirms that the studied system operates close to its intended design envelope under normal conditions.

The energy consumption analysis revealed a noticeable gap between the calculated compressor power and the measured electrical power input. This difference highlights the significance of mechanical and electrical losses in industrial compression systems. Bearing friction, shaft sealing losses, coupling inefficiencies, and motor electrical losses collectively represent a substantial share of the total energy input. The magnitude of these losses observed in this study falls within the typical range reported for multi-stage gas compressors operating in oil-field environments, indicating realistic and reliable measurement data.

Efficiency trend analysis showed that the compressor achieves its highest overall efficiency at intermediate operating points. At low load conditions, fixed mechanical and electrical losses dominate, leading to reduced efficiency. Conversely, at high pressure ratios and elevated loads, efficiency degradation is mainly attributed to increased thermodynamic irreversibility's and reduced intercooling effectiveness. This behavior confirms the importance of operating the compressor within an optimal load window to minimize energy penalties.

The loss distribution analysis further emphasizes that mechanical and electrical losses remain significant even when thermodynamic performance is acceptable. This finding suggests that performance improvement strategies should not be limited to thermodynamic optimization alone but should also address mechanical condition monitoring, proper lubrication, motor efficiency, and maintenance practices. Incremental improvements in these areas can yield meaningful reductions in total energy consumption without major system modifications.

From an operational perspective, the results indicate that improving intercooler performance, maintaining balanced stage pressure ratios, and avoiding prolonged operation at extreme load conditions can enhance both efficiency and reliability. The findings are directly applicable to gas compression units operating in oil-field applications and provide practical guidance for energy optimization and operational decision-making.

Overall, the consistency between measured data, calculated performance indicators, and observed trends confirms the validity of the adopted methodology and supports the use of field-based performance evaluation as an effective tool for assessing and improving energy conversion efficiency in multi-stage gas compressor systems.

5. Conclusions and Recommendations

5.1 Main Conclusions

The present paper has provided a field-based performance analysis of a multi-stage gas compressor that was carried out under real industrial condition. In contrast with totally theoretical studies or the simulation-based research, the analysis was based on the measured operating data; thus, an accurate assessment of trends of thermodynamic behavior, energy consumption, and efficiency could be performed in the real working conditions. The chosen approach allowed combining the thermodynamic study of the stages with the energy assessment of the system and establishing a detailed and credible image of compressor performance.

The measurements revealed that the compressor is able to run at a fairly balanced pressure ratio distribution across stages which is helpful in ensuring acceptable thermodynamic performance and stable running. Observable differences between calculated compression power and measured electrical power did, however, point to the major contribution of mechanical and electrical losses to the total energy balance. These losses were observed to contribute to a non-negligible fraction of the total input power, and it is confirmed that thermodynamic irreversibility's are not the only causes of energy inefficiencies in industrial compressors.

Step-by-step analysis showed that the former compression stage is the biggest contributor of the total power consumption and has the highest thermal loading. This is largely explained by the inlet flow troubles, increased relative compression work, and low intercooling efficiency at the first stage. Downstream stages on the other hand, work with a better thermodynamic condition, and the efficiency is higher with less heat increase. The results are correlated with described behavior of multi-stage compressors used in oil and gas plants [22].

Moreover, the analysis of the efficiency trend showed that there was the most efficient operating range at the intermediate load conditions, and in general, isentropic, poly-tropic, and overall efficiency attain peak values. Working beyond this operating range, especially at high overall pressure ratios, will result in more irreversibility's, higher discharge temperatures, and lower effectiveness of intercooling. This proves that a good choice of operating point will be significant in reducing energy penalties and long life of equipment [12].

5.2 Energy Performance and Loss Characteristics

One important result of this study is that it was possible to clearly identify and quantify energy loss mechanisms in the compression system. The comparison of traditional compressor power with measured electrical power showed that mechanical and electrical losses have significant proportionality of total energy input. Such losses happen due to bearing friction, shaft seals, coupling losses, motor electrical losses and auxiliary equipment running.

The analysis of the loss distribution revealed that mechanical and electrical losses are still very high at all operating points with the relative contribution of the two losses being greater in the low load conditions. Such a tendency indicates the weakness of using only thermodynamic optimization as the means of enhancing energy efficiency. System-level performance may also be limited by non-thermodynamic losses even in cases of compressors with acceptable isentric and poly-tropic efficiencies [23].

Thermal analysis also showed that rise in temperature during compression stages is not even. The first stage is the most effective in increasing the temperature, and after that, the intercooling works effectively. The success of intercoolers turned out to be a determining factor with regards to compression work reduction and taming thermal stresses. Enhanced performance of the intercooler results in direct decreases in inlet temperature of downstream stages, a decrease in compression work and increased efficiency [1].

These results highlight the fact that the use of energy performance improvement strategies must take a holistic approach that incorporates the optimization of thermodynamics, the reduction of mechanical losses, and thermal control. The application of a particular attention on a single aspect separately is not likely to achieve significant efficiency improvement in actual industrial compressor systems.

5.3 Practical Implications for Industrial Operation

The practical implications of the findings of this research in the functioning and optimization of multi-stage gas compressors in oil and gas plants are direct. To begin with, it appears that the first compression stage dominates with regards to the power consumption and thermal loading, implying that a specific level of improvement at that stage can generate disproportionate returns. Enhanced sealing, conditioning of inlet flow, and allocation of stage pressure ratio are some of the measures that could greatly reduce the total energy consumption.

Second, the determination of an efficient operating range provides the significance of operational control strategies. The high efficiency and minimize the mechanical stress may be achieved by avoiding long run operation at high pressure ratios or low loads. This observation justifies the use of adaptive control mechanisms that will adapt the operating conditions depending on the real-time demand and system performance indicators [24].

Third, the importance of mechanical and electrical losses indicates that maintenance practices ought to be conducted strictly. Frequent inspection of bearings, seals, couplings and electric motors and proper lubrication and alignment can minimize unnecessary losses and increase the reliability of the system. Performance degradation can be further prevented and early fault detection can be improved by the integration of condition monitoring methods, which may include vibration analysis and motor current signature analysis [25].

Lastly, the value of field-based performance assessment has been demonstrated and therefore it can be said that period assessment should be implemented on site as the new way of having a regular evaluation of the work of industrial compressors. These tests yield practical data which cannot be derived by a name plate and constraints and can be used to make sound judgment about operation modifications as well as equipment improvement.

5.4 Recommendations and Future Work

In accordance with the results of this paper, a set of recommendations can be suggested to enhance the results and energy efficiency of the multi-stage gas compression system. First, there should be concern in improving the effectiveness of the intercooler especially following the initial compression beneficence. Compression work and thermal stress can be highly reduced with design changes that have high heat transfer area, better distribution of the coolant flow, and less fouling.

Second, mechanical and electrical loss minimization must also be considered by means of better component choice and care. High-efficiency electric motors, optimized bearing designs and low-loss couplings can all lead to energy savings that can be realized in the long-term operation. It is also highly advised that predictive maintenance strategies be implemented as a result of continuous monitoring data [26].

Third, the optimization of operations must be on the operation of compressors in its optimal efficiency range. This can be changing pressure ratio distribution, controlling mass flow rate or using sophisticated control algorithms to trade off between energy efficiency and process needs. The combination of online tracking systems and algorithmic optimization solutions have promising prospects of additional performance improvement.

To do that in the future, the analysis would be expanded with the inclusion of long-term performance monitoring in evaluating the degradation patterns over time. Moreover, applying both numerical simulation model and field data might have a better understanding of the behavior of flows, loss generation processes, and heat transfer. The use of machine learning methods to predict performance and diagnose faults is also an excellent future research, especially in large-scale industrial compressor systems.

6. References

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