Trends in advanced sciences and technology

Trends in Advanced Sciences and Technology

Manuscript 1014

Energy and Exergy Analysis of Multi-Stage Axial Flow Compressor: Degree of Reaction, Inlet Temperature, and Pressure Ratio Impacts

Mohamed Abdelaal

Rafea Mohamed Abd El-Maksoud

Nazih Noaman Bayomi

ORIGINAL STUDY

Energy and Exergy Analysis of Multistage Axial Flow Compressor: Impact of the Degree of Reaction, Inlet Temperature, and Pressure Ratio

Mohamed Abdelaal Mohamed*, Rafea Mohamed Abd El-Maksoud, Nazih Noaman Bayomi

Department of Mechanical Power Engineering, Faculty of Engineering, Mattaria, Helwan University, Cairo, Egypt

Abstract

Aim: **This paper presents a comprehensive energy and exergy analysis of a multistage axial compressor, specifically examining a 12-stage model to assess the impact of varying inlet temperatures, degrees of reaction, and pressure ratios.**

Objectives: **This study contributes to the ongoing efforts to optimize compressor technology for better performance and reduced energy consumption, emphasizing the importance of parameter selection in achieving desired operational outcomes.**

Background: **In the current research, the performance of the axial compressor was studied from an energy and exergy point of view while changing the parameters previously mentioned in detail as stages and rotors due to the lack of previous research.**

Methods: **Utilizing the engineering equation solver (EES), detailed simulations were conducted to uncover the thermodynamic behaviors across different compressor stages.**

Results and conclusions: **The findings indicate that increases in the degree of reaction lead to higher exergy destruction yet improve the efficiencies according to the first and second laws. Similarly, elevated pressure ratios were found to enhance stage-specific work consumption and second-law efficiency, providing valuable insights into the operational dynamics of axial compressors. These results offer significant implications for the design and optimization of axial compressors, proposing that careful adjustments of the degree of reaction and pressure ratios can lead to more energy-efficient compressor configurations. A stage pressure ratio from 1.22 to 1.36 for the number of stage 12 leads to an increase in specific work consumption and about a 2% improvement in second-law efficiency. Increasing the degree of reaction from 0.5 to 0.7 results in nearly a 1% rise in the exergy destruction ratio for one rotor of the stage. This adjustment underscores the pivotal role of the degree of reaction in optimizing compressor efficiency.**

Keywords: Axial compressor, Degree of reaction, Exergy destruction, First-law and second-law efficiencies, Pressure ratio, Rotor

1. Introduction

Compressors represent pivotal machinery in industries such as petroleum, refrigeration, and chemicals, necessitating continuous enhancement in their performance. Various research endeavors have been conducted in this domain, given their widespread applications. Therefore, this research presents a study and analysis of the energy on the multistage axial compressor and the effect of some variables on it, such as the pressure ratio and the degree of interaction. From this, designers can choose the best variables affecting the axial compressor according to the design requirements.

Tolba et al. (2022) conducted an exergy analysis of a multistage axial compressor, unveiling distinctive behaviors in the efficiency of the first and second laws. These metrics offer quantitative and

Received 27 March 2024; revised 8 May 2024; accepted 3 June 2024.
Available online 19 July 2024

* Corresponding author.
E-mail address: Engmoh139@gmail.com (M.A. Mohamed).

https://doi.org/10.62537/2974-444X.1014

qualitative insights into compressor performance, with a notable correlation between high air density at lower inlet temperatures and increased power consumption, accompanied by changes in first-law and second-law efficiencies.

A performance improvement technique for axial compressors, involving the introduction of circumferential grooves through extensive casing treatment is introduced by Ahmad et al. (2020). This method enhances stall margin while only marginally decreasing efficiency. The transonic axial compressor rotor's total pressure ratio, adiabatic efficiency, and stall margin are observed to decline as the tip clearance gap is raised when considering various groove forms. Consequently, the total efficiency of the compressor is diminished.

Abdelghany et al. (2020) conducted a comprehensive investigation of compressor performance from both energy and exergy perspectives. Their findings indicated that increased compressor work consumption leads to elevated exergy destruction and reduced exergy destruction ratio. Moreover, higher polytropic efficiency is linked to a reduction in specific work, decreased destructive exergy, and improved efficiency of the first and second laws. The reduction of specific work consumption and enhancements in second-law efficiency is particularly affected by the reduced temperature of the inlet air. Meanwhile, inlet temperature variations minimally impact first-law and second-law efficiencies. In addition, an increase in compressor pressure ratio results in heightened specific work consumption but decreased first-law efficiency.

An investigation into industrial air compressors, employing energy, exergy, sustainability, and emission analyses is conducted by Mascarenhas et al. (2019). They highlighted the utility of exergy and sustainability analyses in identifying inefficient compressors to guide decision-makers in industrial settings. Notably, enthalpy and energy analyses were found to be ineffective in evaluating mechanical work output due to the failure to account for pressure changes. This approach holds practical applicability in diverse industrial sectors, including chemicals, fertilizers, petroleum refining, iron and steel production, sugar manufacturing, and cement industries, thereby promoting sustainable development and facilitating comparisons of alternative scenarios and technologies.

A pragmatic approach for axial compressor design optimization, focusing on blade optimization for enhanced performance characteristics is introduced by Pakatchian and Saeidi (2019). This optimization aims to minimize losses across all operational conditions, particularly in high-temperature gas turbine operations. Altering the geometry of airfoil sections yielded improvements in mass flow and efficiency, with gains of 0.8 and 1% in design operation, and a 0.91% increase in efficiency at 45 °C in off-design operation.

Nomenclature

I_{desr}	exergy destruction ratio (–)
W_{dr}	compressor total work (kJ)
AMF	air mass function (–)
C_p	specific heat at constant pressure [kJ/(kg K)]
D	degree of reaction (–)
h	specific enthalpy [kJ/(kg K)]
I_{des}	exergy destruction (kJ/kg)
K	isentropic exponent (–)
MMW	mixture molecular weight (kg/mol)
P	pressure (kPa)
R	universal gas constant [kJ/(mol K)]
RH	relative humidity (–)
s	specific entropy of humid air [kJ/(kg K)]
T	temperature (K)
VMF	vapor mass function (–)
W	compressor specific work (kJ/kg)

Greek symbols

η_1	first-law efficiency (–)
η_2	second-law efficiency (–)
η_p	polytropic efficiency (–)
π	compressor pressure ratio (–)
ω	specific (–)

Subscript

A	air
av	average
M	mixture of humid air
r	Rotor
rev	reversible
s	isentropic condition
sat	saturation condition
v	vapor
1	inlet condition
2	outlet condition

Ogbonnaya et al. (2019) conducted a detailed analysis of the energy and exergy performance of vapor compression refrigeration systems using nano-lubricants. They clarified important elements influencing the system's energy destruction and performance optimization. The use of nano-refrigerants was found to reduce energy consumption and greenhouse gas emissions within the vapor compression refrigeration system.

Ortmanns (2014) conducted a detailed analysis on the impact of varying the degree of reaction on the flow pattern of the compressor stage. Generally speaking, there is a low association between the degree of stage reaction and the total stage efficiency at constant pressure ratio. However, when the degree of reaction is changed, which is caused by a change in the static pressure increase between the rotor and the stator passageways. The results demonstrate a direct influence on the rotor tip leakage flow and the secondary flow phenomena in the stator end-wall area. The efficiency and stall behavior of a multistage compressor may be influenced by the balance of these two loss sources.

Betelmal and Farhat (2018) delved into a study of a simple gas turbine with varying levels of water injection into the compressor. Their analysis revealed an increase in exergy destruction with water injection, particularly during hotter periods. Water injection between gas turbine compressor stages resulted in elevated power output and electrical efficiency, surpassing that of a conventional gas turbine.

Mohtaram et al. (2017) looked at how an ammonia−water combined cycle's thermodynamic performance was affected by the compressor pressure ratio, highlighting the increased exergy destruction in high-pressure compressors, the intercooler, and the gas turbine with rising pressure ratios. However, the exergy destruction in the recuperator steadily decreased.

Zheng and Ding (2016) investigations are conducted into how temperature and pressure affect the stresses in axial−centrifugal combination compressors operating under various intake circumstances. The impeller's stresses are obtained through the use of three-dimensional structural finite element analysis and conjugate heat transfer analysis. The comparison of the equivalent (von-Mises) stresses between situations that account for temperature and pressure and those that do not yield information about the influence of these variables. The outcome shows that the temperature impact should be carefully taken into account as it is unexpectedly substantial at low inlet temperatures, reaching 57% of the total equivalent stress. The disk thermal boundary conditions and the inlet conditions have a substantial relationship with the effect.

Mousavi et al. (2014) described methods for modeling energy consumption and controlling compressed air systems, including a state-based modeling approach encompassing both fixed and variable speed drive compressors.

Lemire et al. (2009) explored the use of plasma actuation to mitigate boundary layer separation on compressor blades, improving axial compressor performance. From an energy perspective, plasma actuators proved to be highly efficient, yielding substantial power increases while consuming minimal additional power.

An in-depth analysis of industrial air compression systems underscored the benefits of using exergy analysis to enhance energy utilization is conducted by Bader and Kissock (2000). This analysis provided distinct insights compared with traditional energy analysis. Optimal compressor sizing is identified as the most effective means to enhance efficiency and reduce costs. In addition, by accounting for energy quality, exergy analysis allows for prioritizing process improvement measures and more efficient energy resource utilization.

2. Objectives

The extensive utilization of axial compressors across various industries underscores the imperative for comprehensive research in this field. By reviewing the previous research, there is a need for more studies in the field of compressors due to their great importance in various industries. Therefore, there is a need for more study of multistage compressors using exergy. For example, Abdelghany et al. (2020) comprehensively explore the performance of positive displacement and dynamic compressors, focusing on elucidating the significance of first-law and second-law efficiencies. They did not study the multistage compressor. However, Tolba et al. (2022) presented a study of the exergy of a multistage axial compressor with changing pressure ratio and polytropic efficiency. However, they did not study the effect of the degree of reaction and the stator and rotor in each sage.

Accordingly, the present research is introduced to fill this gap. The novelty of this research is to present an energy and exergy parametric study on multistage compressors, focusing on rotor blades while varying the inlet temperature, pressure ratio, and degree of reaction in various operational conditions. Sample results of the stator are presented to demonstrate that its results can be determined by the results of its rotor and stage, thus avoiding the need for too much data. It delves deeper into a specific multistage axial compressor, assessing its 12 stages for exergy destruction and efficiency, focusing on the rotor stage.

The main point of deficiency in this study, accounting for the distinction with previous research, is the investigation of the impact of reaction degree and effectiveness level on the axial compressor. In addition, the examination of the axial compressor's stages, rotors, and stators is conducted.

3. Methodology

3.1. System description

To elucidate the approach used in this study. Fig. 1 illustrates a T-s (temperature-entropy) diagram for a

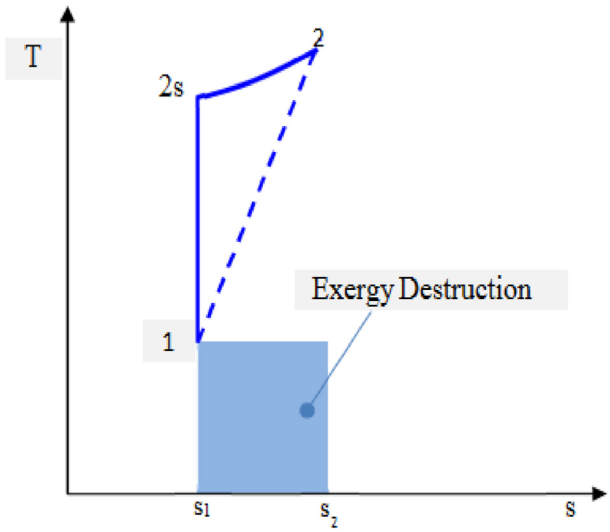


Fig. 1. Typical compressor T-s diagram (Abdelghany et al., 2020).

typical compressor, characterized by specific polytropic efficiency (η_p) and pressure ratio (π). In this diagram, humid air enters the compressor at state 1, indicated by the inlet temperature (T_1), and relative humidity (RH), and exits at state 2, indicated by the outlet temperature (T_2).

In addition, state 2 s signifies the humid air's isentropic outflow condition, serving as a reference point for determining both the isentropic work and the actual work of the compressor. The efficiency of the first-law (η_I) is the ratio between the isentropic and actual works. In parallel, the second-law efficiency of the compressor (η_{II}) is quantified as the work in reverse divided by the actual work. The work in reverse is calculated by subtracting the exergy destruction from the actual work. Fig. 1 offers a comprehensive view that includes both energy and exergy perspectives.

The methodology depicted in Fig. 1 can be extrapolated to the various stages of an axial flow compressor, including both rotor and stator blades. The analysis encompasses each stage, with consideration for the number of stages and the degree of reaction (R) for the rotating blades. Consequently, this approach allows for assessing the first-law and second-law efficiencies and exergy destruction for each internal component of the stage (rotor and stator), thereby enabling a comprehensive examination of exergy destruction within the internal components of the axial compressor.

Engineering equation solver program is a reliable, accurate tool for thermodynamic engineering calculations and analysis of real gases as used in Adibia et al. (2022), Galal et al. (2024), Kareem et al. (2023), Sanusi et al. (2020), Modi and Mody (2019), and Naderi et al. (2023).

3.2. Thermodynamic analysis

The temperature at the exit can be mathematically represented as follows:

$$T2 = T1\pi^{\left(\frac{R_m}{C_{pm}\eta_p}\right)} \tag{1}$$

The symbol C_{pm} represents the specific heat under constant pressure, whereas R_m denotes the moist air's gas constant. The appendix m is used to identify the properties of moist air. To ascertain T_2, it is necessary to specify both C_{pm} and R_m. To carry out this task, the specific humidity at temperature T_1, which is defined as the mass ratio of moist air to water vapor, may be represented as follows (Martínez et al., 2011):

$$\omega_1 = \frac{0.622 \times RH_1 \times P_{sat1}}{P_1 - RH_1 \times P_{sat1}} \tag{2}$$

The relative humidity RH_1 is the ratio of the partial pressure of water vapor at a given temperature T_1 to the saturation vapor pressure P_{sat1} at that temperature, while the compressor's intake pressure is denoted as P_1. The expression for the vapor mass fraction VMF is given as follows:

$$VMF = \frac{\omega_1}{1 + \omega_1} \tag{3}$$

Hence, the air mass fraction air mass function (AMF) can be expressed as:

$$AMF = 1 - VMF \tag{4}$$

The following formula can be used to calculate the mixture's gas constant R_m:

$$Rm = \frac{R}{MMW} \tag{5}$$

The term "mixture molecular weight" (MMW) refers to the molecular weight of a mixture. The subsequent equation can be used to determine the specific heat of moist air:

$$Cpm\ (T) = Cpa\ (T) + W \times Cpv \tag{6}$$

The temperature T can exist at either T_1 or T_2. By taking into account the molecular weights and partial pressures of dry air and water vapor, the value of T_2 may be determined. Humid air's average specific heat during compression procedure 1–2 is given by:

$$C_{pm\ av} = \frac{C_{pm1} + C_{pm2}}{2} \tag{7}$$

The humid air's isentropic exponent is expressed as follows:

$$K = \frac{C_{pm\ av}}{C_{pm\ av} - R} \tag{8}$$

Hence, the isentropic temperature at the exit can be determined using the equation:

$$T_{2s} = T_1 \times \pi^{\left(\frac{K-1}{K}\right)} \tag{9}$$

The isentropic efficiency of a compressor, also known as the first-law efficiency of the compressor, can be defined as:

$$\eta_1 = \frac{C_{pm2s} T_{2s} - C_{pm1} T_1}{C_{pm2} T_2 - C_{pm1} T_1} \tag{10}$$

It is possible to specify the precise compressor work consumption by the following equation:

$$W = (Cpm2\ T2) - (Cpm1\ T1) \tag{11}$$

The exergy destruction can be expressed as:

$$I_{des} = T1\ (s_2 - s_1) \tag{12}$$

where s_1 and s_2 are the specific entropy of the moist atmosphere at input and outflow, respectively. The ratio of energy destruction is expressed as follows:

$$I_{des}\ \text{ratio} = \frac{I_{des}}{W} \tag{13}$$

The concept of exergy destruction serves as a measure of the ineffective utilization of accessible energy, whereas the exergy destruction ratio quantifies this ineffective utilization in relation to the work performed by the compressor. Consequently, the use of exergy destruction and exergy destruction ratio provides distinct perspectives in comprehending the functioning of the compressor. The subsequent equation provides the reversible work:

$$W_{rev} = W - I_{des} \tag{14}$$

where the least amount of labor that might be needed to compress humid air from its intake condition to its exit state is W_{rev}. The efficiency of the second-law may be written as:

$$\eta_{II} = \frac{W_{rev}}{W} \tag{15}$$

The degree of reaction DR is the ratio of static enthalpy change in the rotor to the static enthalpy change in the stage. The degree of reaction points at the average area of the blade between the top and hub areas:

$$DR = \frac{h_r - h_1}{h_2 - h_1} \tag{16}$$

where h_r is the static enthalpy at the moving blade (rotor). h_1 is the static enthalpy at the inlet condition of the stage and h_2 is the static enthalpy at the outlet condition of the stage.

3.3. Simulation assumptions, constants, and investigated parameters

This study is dedicated to a comprehensive examination of the energy and exergy aspects of a 12-stage axial flow compressor. The inclusion of all twelve stages serves as an illustrative example. The research is structured into three distinct sections, each shedding light on different facets of the compressor's performance.

The first section concentrates on the holistic energy and exergy evaluation of the entire compressor, starting from the inlet point and culminating at the outlet point. In the second section, the focus shifts to the energy and exergy attributes of each of the 12 stages in isolation. The third section goes into the extensive study of energy and exergy issues specific to the moving blades associated with every stage of the axial compressor.

Numerous critical parameters are meticulously investigated, encompassing polytropic efficiency, compressor pressure ratio, inlet temperature, inlet humidity, degree of reaction, and the number of stages. The ramifications of varying these parameters are meticulously analyzed in terms of specific work consumption, exergy destruction, exergy destruction ratio, and efficiency of the first and second laws. These assessments are applied to the compressor as a whole, its individual stages, and the rotor components. For reference, Table 1 provides the specific parameter values utilized in the simulations unless otherwise indicated.

Justifying the use of a 12-stage axial compressor involves several technical and operational considerations. First, multistage compressors like this allow for greater efficiency optimization through intercooling between stages, which reduces the

Table 1. Different studied parameters.

Parameters	Parameter range or value
Compressor inlet temperature (K)	288, 298, 308, and 318
Axial compressor stage pressure ratio	1.22, 1.26, 1.3, 1.32, and 1.36
Polytropic efficiency	90%
Inlet relative humidity	0.6
Degree of reaction (average of blade)	0.5, 0.6, and 0.7
Number of stages	12

work of compression and enhances thermodynamic efficiency, crucial for applications requiring high-pressure ratios (Smith & Stosic, 2012). These compressors also manage heat more effectively by spreading out heat generation across multiple stages, thereby increasing system reliability and extending lifespan (Kovacevic et al., 2013).

Furthermore, 12-stage compressors can achieve higher pressure ratios essential for industries such as petrochemicals, natural gas, and aerospace, where they ensure stable and efficient operation (Johnson, 2016). They also produce less noise and vibration due to the distribution of workload across more stages, reducing the strain on individual components (Aungier, 2006). Although the initial investment might be higher, the operational costs are generally lower over the compressor's lifetime due to lower energy consumption and maintenance needs (White, 2018). In addition, the flexibility in adjusting the load across different stages allows these compressors to adapt to varying operational conditions, offering a versatile solution for dynamic industrial environments (Balje, 1981). These factors collectively justify the selection of a 12-stage compressor for detailed studies and industrial applications.

The fixed polytropic efficiency throughout the 12 stages was chosen to isolate and examine the effects of varying inlet temperatures, degrees of reaction, and pressure ratios on compressor performance. This simplification aligns with common practice in parametric studies, where controlling one variable allows for a focused exploration of other influential factors. This approach may not fully capture the variations in aerodynamic behavior across different pressure zones. It facilitates a clear analysis of the targeted variables. Future work will incorporate variable polytropic efficiencies across the stages to provide a more comprehensive understanding of the multistage compressor behavior under different conditions.

4. Results and discussion

4.1. Model verification

Upon an exhaustive review of existing literature pertaining to the subject matter of this current study, the necessity of research validation became apparent. The validation process was conducted through a comparative analysis with the work of Abdelghany et al. (2020), which delves into the examination of exergy and energy within an axial compressor as a unified entity. The parameters under scrutiny in the aforementioned study encompass polytropic efficiency = 90%, compressor pressure ratio (4, 8, 12, 16, and 20), inlet temperature = 318 K, and inlet humidity = 0.6.

The present paper extends this validation endeavor to encompass the comprehensive assessment of energy and exergy within an axial compressor, scrutinizing the unit as a whole, its constituent stages, and the individual rotors associated with each stage. The parameters investigated within the scope of this study encompass the compressor pressure ratio, inlet temperature, and the degree of reaction.

To facilitate this validation, a comparative analysis was undertaken, aligning the results of the compressor as a unified entity in both studies, culminating in Fig. 2, whereas in this research, the highest I_{desr} = 7.194% and the lowest I_{desr} = 4.668% is compared with the work of Abdelghany et al. (2020), where it reached the highest I_{desr} = 6.834% and the lowest I_{desr} = 4.435%. Likewise, the current research reached the highest I_{des} = 25.92 kJ/kg and the lowest I_{des} = 3.58 kJ/kg compared with Abdelghany et al. (2020), which reached the highest I_{des} = 25.37 kJ/kg and the lowest I_{des} = 13.3 kJ/kg. As a result of this convergence between values and ratios, it enhances the strength of the current research.

Subsequently, the current research delves into a granular examination of the compressor's components. It includes in-depth investigations into the individual stages and rotor blades for each stage. Furthermore, the study explores the ramifications of altering the degree of reaction on energy, exergy, and efficiency of the first and second laws. It contributes to a more comprehensive understanding of axial compressor performance.

5. Results and discussion for axial compressor as a block

5.1. Exergy destruction

The intricate interplay between W (expressed as specific work), W_{dr} (work per unit mass), and the associated I_{des} is illustrated in Fig. 3. This analysis is conducted under conditions of a relative humidity (RH) of 0.6 and a polytropic efficiency (η_p) of 90%. The dataset spans various pressure ratios for stage (π_{st} = 1.22, 1.26, 1.3, 1.32, and 1.36) and diverse range temperatures at the inlet (T_1 = 288 K, 298 K, 308 K, and 318 K), corresponding to a 12-stage axial flow compressor.

It is discernible that an escalation in W correlates with increased I_{des}. Furthermore, both exergy destruction and the magnitude of irreversibility experience growth when the pressure ratio and inlet temperature are elevated. The influence of

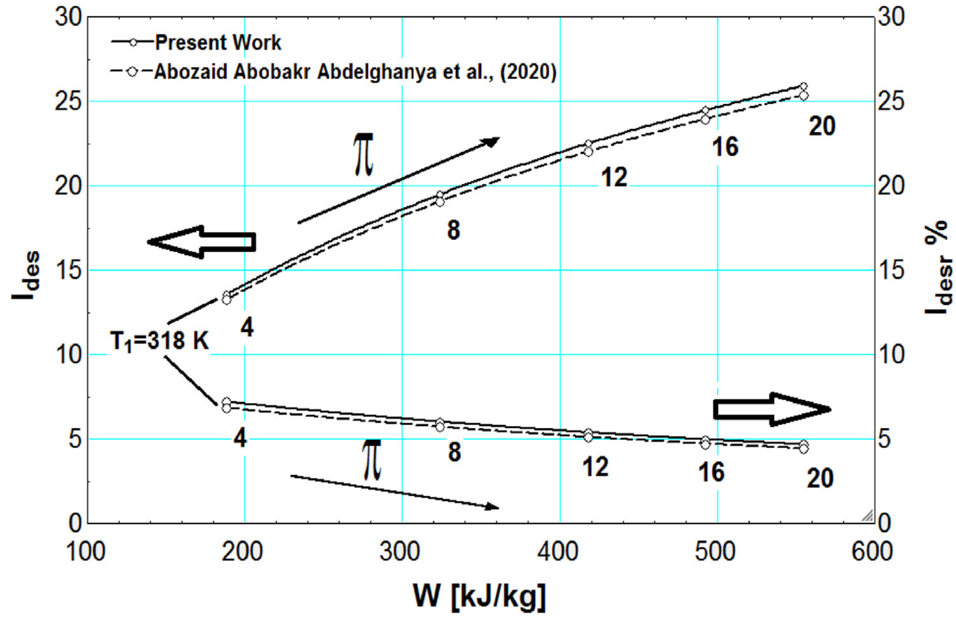


Fig. 2. Exergy destruction ratio versus specific work at T_1 *= 318 K and* η_p *= 90%.*

temperature at the inlet on I_{des} exhibits a noticeable sensitivity. As the inlet temperature increases and π_{st} increases, Ides and W increase. The exergy destruction increased from approximately 19.45 kJ/kg at T_1 of 288 K and π_{st} of 1.22 to about 30.1 kJ/kg at an T_1 of 318 K and π_{st} of 1.36.

However, it is essential to note that an uptick in inlet temperature results in a reduction in total work (W_{dr}) as shown in Fig. 3 whereas the highest exergy destruction value (I_{des}) = 25.97 kJ/kg at T_1 = 288 K and $\pi_{st=}$1.36. Also the lowest exergy destruction value (I_{des}) = 17.99 kJ/kg at T_1 = 318 K and $\pi_{st=}$1.22.

From this comparison, it can be concluded that W increases with an increase in the inlet temperature and pressure ratio. W_{dr} decreases with an increase in the inlet temperature and with a decrease in the pressure ratio.

This paradox arises from the decrease in air density, which is a direct consequence of the increased inlet temperature. For instance, as T_1

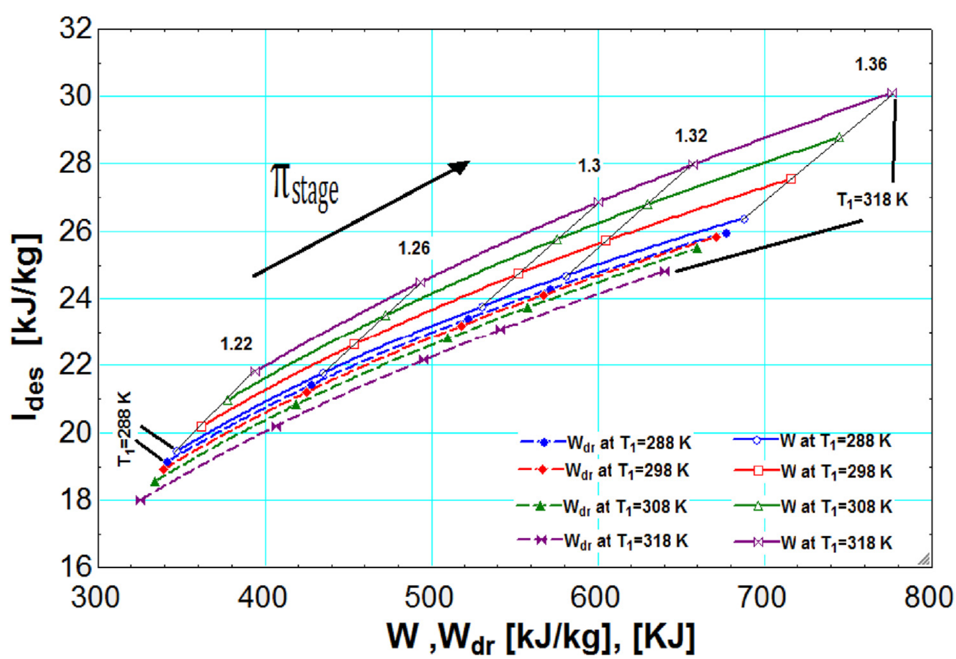


Fig. 3. Exergy destruction versus specific work and total work at variously examined π_{st} *and* T_1 *for axial compressor as a block.*

rises, it engenders a subsequent elevation in T_2, thereby leading to an augmentation in specific compressor work consumption. This phenomenon stands in contrast to actual power consumption, as heightened inlet temperatures ultimately yield a reduction in power consumption. This divergence can be attributed to the diminishing air density and airflow rate entering the compressor. Fig. 3 effectively encapsulates the interrelationships between the values of compressor work, as influenced by variations in the inlet temperature and pressure ratio.

It can also be concluded that the specific work consumption has a greater effect than the total work consumption with a difference in the inlet temperature and the pressure ratio, as shown in differences between the results shown in Fig. 3.

5.1.1. Exergy destruction ratio

Fig. 4 presents a graphic representation of I_{desr} as a function of W and W_{dr}, under the conditions of RH = 0.6 and a polytropic efficiency of 90%. The exergy destruction ratio provides an alternative perspective on the unattainable work relative to W. In contrast to the trend observed for I_{des}, I_{desr} exhibits an inverse relationship with W.

An increase in the compressor pressure ratio and the inlet temperature of the surrounding environment leads to a reduction in the exergy destruction ratio. Notably, Figs. 3 and 4 demonstrate that different aspects of compressor operation can be assessed using two distinct criteria. Fig. 3 focuses on exergy destruction, revealing the extent of accessible losses. Conversely, Fig. 4, with its exergy destruction ratio, offers a more profound insight by measuring available losses in relation to compressor work.

The exergy destruction ratio (I_{desr}) decreased from around 5.6% at an inlet temperature of 288 K and a stage pressure ratio of 1.22 to ~3.8% at an inlet temperature of 318 K and a stage pressure ratio of 1.36.

It is worth highlighting that exergy destruction and exergy destruction ratio follow dissimilar trends, primarily because the latter is inversely related to the amount of work used by the compressor. Consequently, when evaluating or selecting from various compressors, a reliance solely on lower exergy destruction or exergy losses might be misleading. In this context, the exergy destruction ratio emerges as a superior criterion for the evaluation and selection of different compressors.

5.1.2. First-law and second-law efficiencies

A comprehensive comparative analysis of the efficiency of the first and second laws in relation to W and W_{dr}, with a constant polytropic efficiency of 90% is shown in Figs. 5 and 6. This assessment is conducted under conditions of RH = 0.6. As π_{st} ascends, the first-law efficiency diminishes, while specific work and efficiency of the second-law experience an increase. In contrast, variations in the inlet temperature exert a limited influence on the efficiency of the first and second laws, albeit they

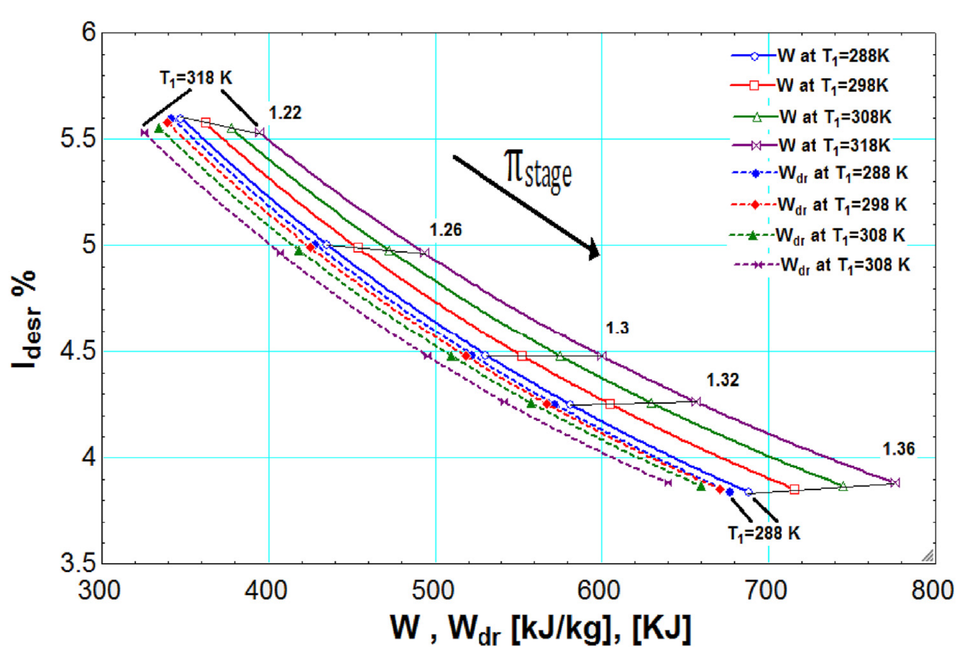


Fig. 4. Exergy destruction ratio versus specific work and total work at variously examined π_{st} and T_1 for axial compressor as a block.

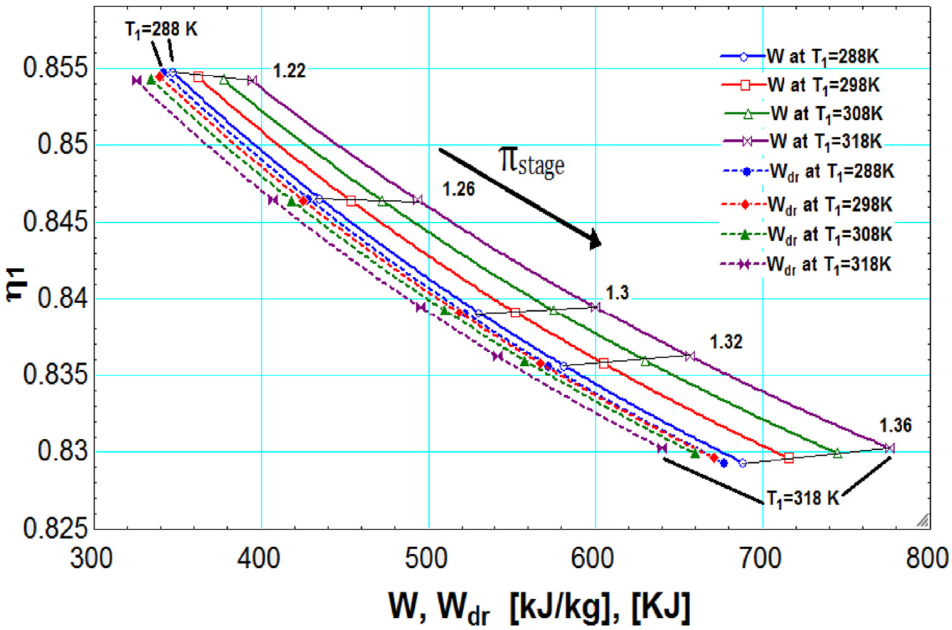


Fig. 5. First-law efficiency versus specific work and total work variously examined π_{st} and T_1 for axial compressor as a block.

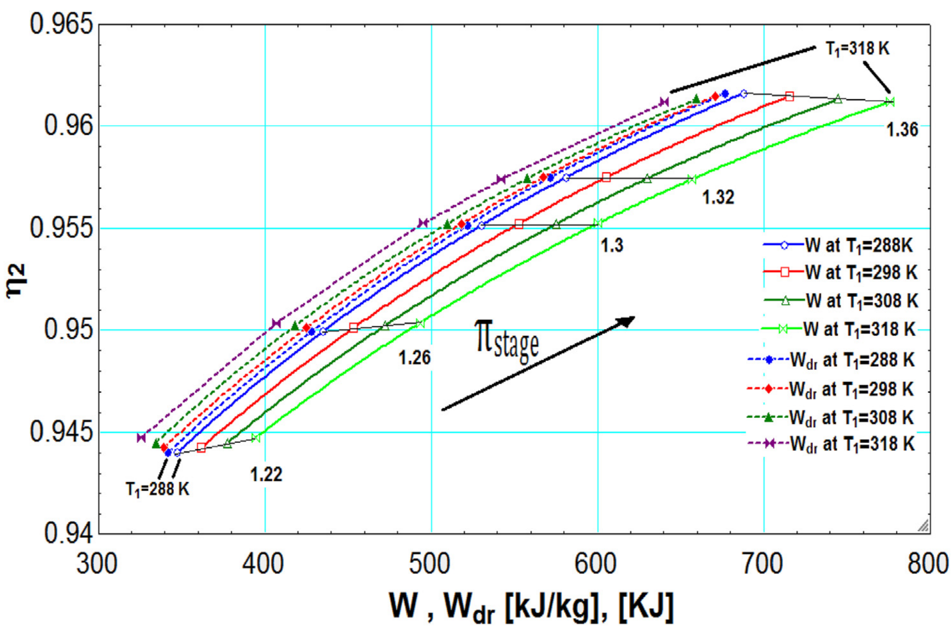


Fig. 6. Second-law efficiency versus specific work and total work variously examined π_{st} and T_1 for axial compressor as a block.

have a positive impact on specific work. It is noteworthy that the effects of the inlet temperature and pressure ratio parameters are less pronounced as the polytropic efficiency escalates.

The influence of temperature at the inlet on η_1 and η_2 exhibits a noticeable sensitivity. As the inlet temperature increases and the pressure ratio increases, η_1 decreases and W increases. The highest first-law efficiency value $(\eta_1) = 85.47\%$ at $T_1 = 288$ K and $\pi_{st} = 1.22$. Also the lowest first-law efficiency value $(\eta_1) = 83.03\%$ at $T_1 = 318$ K and $\pi_{st} = 1.36$. However, it is essential to note that an uptick in inlet temperature results in a reduction in total work (W_{dr}) as shown in Fig. 5. This can be explained by the fact that it is due to the effect of density. If mass is taken into account, increasing the temperature at the entrance leads to a decrease in density, and thus the value of W_{dr} decreases.

As the inlet temperature increases and the pressure ratio increases, η_2 and W increase. The highest second-law efficiency value (η_2) = 96.12% at T_1 = 318 K and π_{st} = 1.36. Also the lowest second-law efficiency value (η_2) = 94.4% at T_1 = 288 K and π_{st} = 1.22. However, it is essential to note that an uptick in inlet temperature results in a reduction in total work (W_{dr}), as shown in Fig. 6. This can be explained by the fact that it is due to the effect of density. If mass is taken into account, increasing the temperature at the entrance leads to a decrease in density, and thus the value of W_{dr} decreases.

The distinctive trends observed in the efficiency of the first and second laws are attributable to the latter's dependence on exergy destruction, thus providing two distinct vantage points for a profound comprehension of compressor performance. Notably, reliance on first-law efficiency alone as a yardstick for evaluating the compressor may be misleading, as it predominantly addresses the quantity of energy. Conversely, second-law efficiency offers a quantitative and more nuanced assessment of compressor performance. The outcomes presented in the figures prove invaluable in the evaluation and selection of diverse compressor types, favoring those with higher efficiency of second-law or a lower exergy destruction ratio.

When comparing the first and second efficiency, it was found that the first efficiency decreases with the increase in the inlet temperature, in contrast to the second efficiency, which increases with the increase in the inlet temperature, and this is shown in Figs. 5 and 6.

6. Results and discussion for each stage of axial flow compressor

6.1. Exergy destruction

Fig. 7 illuminates the intricate relationship between W, encompassing 12 distinct stages, and I_{des} for each stage of a 12-stage axial flow compressor under specific conditions of RH = 0.6 and a constant polytropic efficiency of 90%. The dataset provides insights across various stage pressure ratios (π_{st} = 1.22, 1.26, 1.3, 1.32, and 1.36), as well as diverse temperatures at the inlet (T_1 = 288 K, 298 K, 308 K, and 318 K).

Fig. 7 also shows that the difference in inlet temperature does not affect the exergy destruction of the axial compressor stages. Therefore, all the lines fit together. It also shows that as the pressure ratios of the stage increase, the exergy destruction of the stages increases.

Fig. 7 highlights exergy destruction increased from 1.78 kJ/kg at T_1 = 288 K and π_{st} = 1.22 at stage number 1−8.52 kJ/kg at T_1 = 318 K and π_{st} = 1.36 at stage number 12, reflecting a 20.8% increase.

Elevating the pressure ratio results in a concomitant increase in exergy destruction and specific work consumption. Furthermore, both exergy destruction and specific work are augmented as the pressure ratio and inlet temperature are raised. Thus, an intriguing pattern emerges from the plotted data, with the lines intersecting at a difference of four inlet temperature values, underscoring the relationship between exergy destruction and its

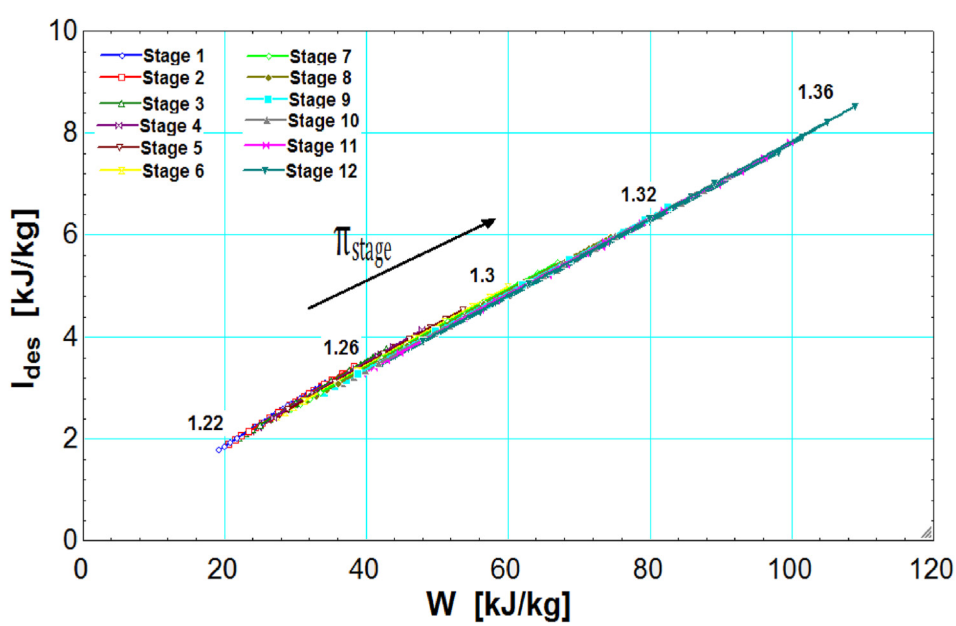


Fig. 7. Exergy destruction versus specific work at variously examined π_{st} and T_1 for the different stages of the axial flow compressor.

dependency on both pressure ratio and inlet temperature.

6.2. Exergy destruction ratio

In Fig. 8, an insightful visualization of I_{desr} as it relates to W is presented for each stage of a 12-stage axial flow compressor. Under the defined conditions of RH = 0.6 and a fixed polytropic efficiency of 90% I_{desr} provides a distinct perspective on W.

Fig. 8 displays I_{desr} decreased from 0.0927 at T_1 = 288 K and π_{st} = 1.22 at stage number 1 to 0.0783 at T_1 = 318 K and π_{st} = 1.36 at stage number 12, representing an 84.64% reduction.

Notably, this ratio exhibits an inverse relationship with specific work consumption, in stark contrast to the trend observed for exergy destruction. It is observed that elevating the compressor pressure ratio and increasing the temperature at the inlet yield a notable reduction in the exergy destruction ratio. This distinctive pattern highlights the sensitivity of the exergy destruction ratio to variations in pressure ratio and inlet temperature, shedding light on the intricate relationship between these parameters and the accessibility of work within the compressor system.

6.3. First-law and second-law efficiencies

Figs. 9 and 10 depict the intricate interplay between η_1 and η_2 in relation to W for each stage of a 12-stage axial flow compressor. The data gleaned from these visual representations distinctly reveal that an increase in compressor pressure ratio corresponds to a decrease in first-law efficiency, concomitant with a surge in specific work and second-law efficiency.

The first-law efficiency decreased from 89.73% at T_1 = 288 K and π_{st} = 1.22 at stage number 1 and from 12 to 89.51% at T_1 = 318 K and π_{st} = 1.36 at stage number 5 and 6. The first efficiency increases after it decreases in the middle stages. The second-law efficiency increased from 90.73% at T_1 = 288 K and π_{st} = 1.22 at stage numbers 1−92.17% at T_1 = 318 K and π_{st} = 1.36 at stage numbers 11 and 12, reflecting a relative increase of 2%.

Moreover, it is discernible that the inlet temperature exerts a pronounced impact on first-law efficiency, while its influence on second-law efficiency, particularly in the context of individual stages, remains relatively insubstantial. In contrast, the inlet temperature exerts a notably positive effect on specific work. These observations offer invaluable insights into the multifaceted dynamics of compressor performance under the influence of varying pressure ratios and inlet temperatures.

7. Results and discussion for the moving blade (Rotor) of different stages with varying degrees of reaction

7.1. Exergy destruction

Fig. 11 elucidates the intricate connection between W and I_{des} for the rotors of each stage of a 12-stage axial flow compressor. Under specified conditions of RH = 0.6, a constant polytropic efficiency of 90%, and three different degrees of reaction points at the

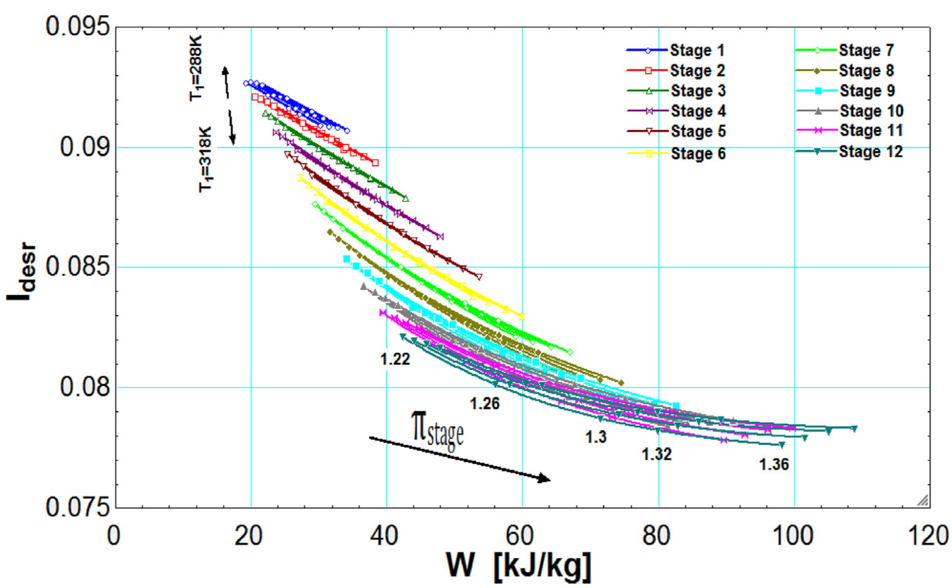


Fig. 8. Exergy destruction ratio versus specific work at variously examined π_{st} and T_1 for the different stages of the axial flow compressor.

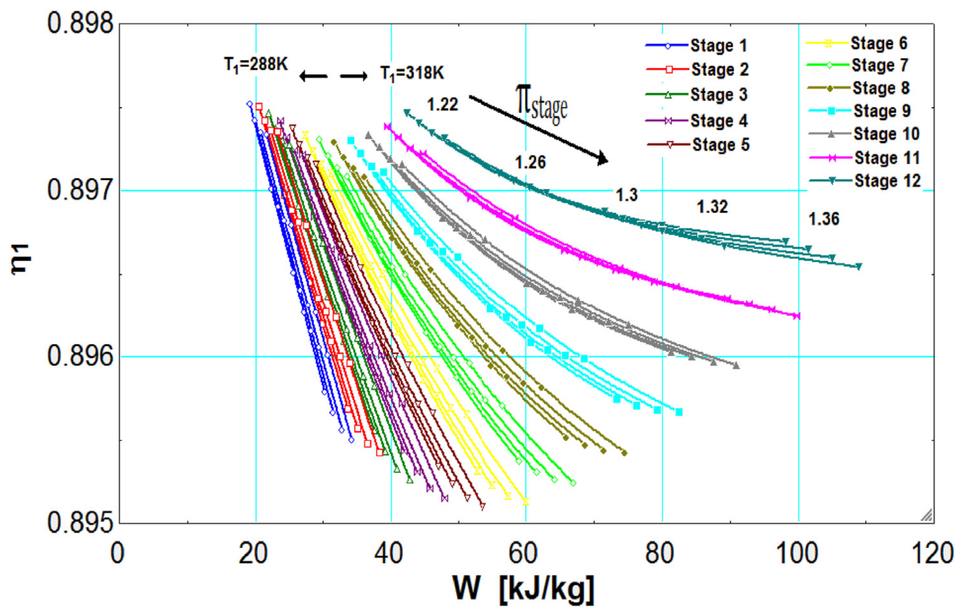


Fig. 9. First-law efficiency versus specific work at variously examined π_{st} and T_1 *for the different stages of the axial flow compressor.*

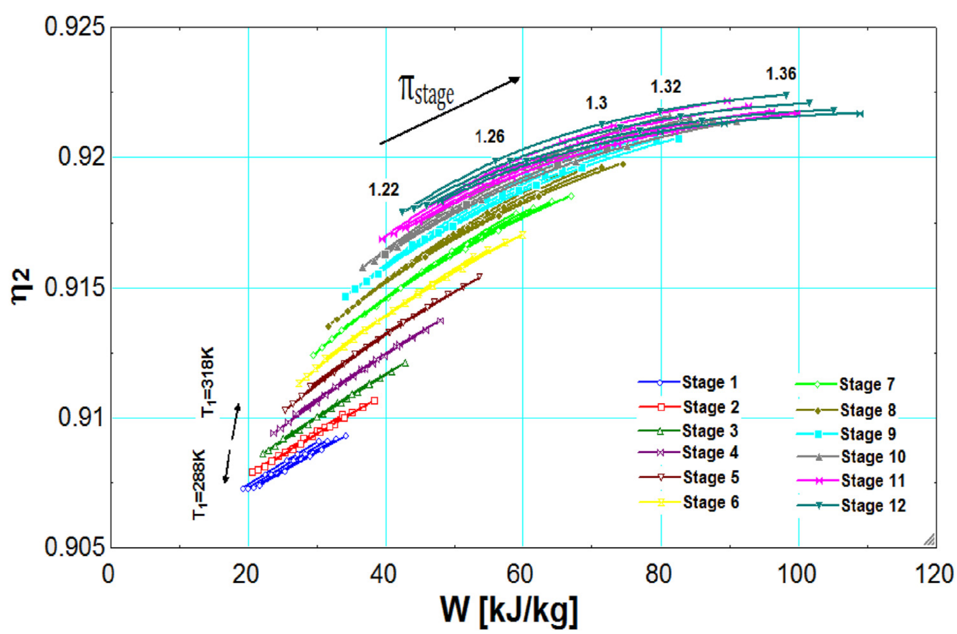
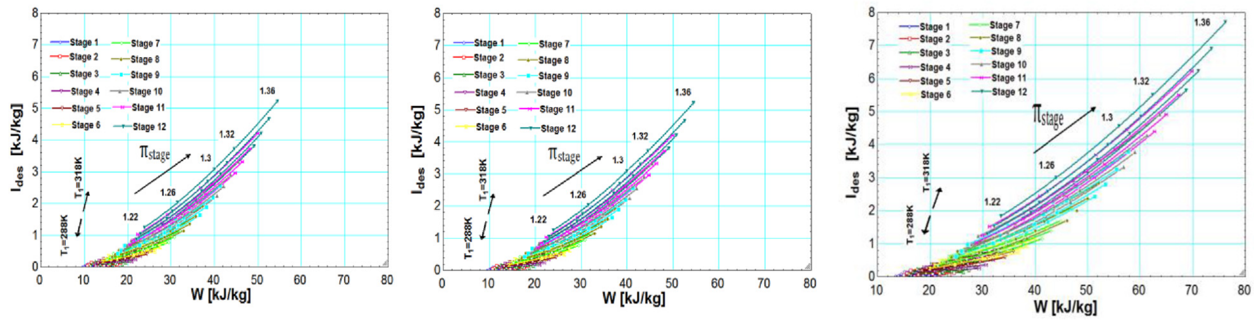


Fig. 10. Second-law efficiency versus specific work at variously examined π_{st} and T_1 *for the different stages of the axial flow compressor.*

average blade area (0.5, 0.6, and 0.7). The dataset encompasses various pressure ratios for stages (π_{st} = 1.22, 1.26, 1.3, 1.32, and 1.36) and diverse temperatures at the inlet (T_1 = 288 K, 298 K, 308 K, and 318 K).

A discernible trend emerges, highlighting the direct correlation between the degree of reaction and an increase in specific work consumption, thereby resulting in heightened exergy destruction. This relationship is consistent across different inlet temperatures and pressure ratios at all degrees of reaction points.

It is noteworthy that the inlet temperature exerts negligible effects on I_{des} of rotors for each stage. The plotted data further reveal that certain lines converge, especially within a range of four inlet temperatures, indicating their proximity in the early stages, before gradually diverging in the later stages. For instance, the lowest W, amounting to 9.603 kJ/kg, is achieved at the rotor of stage number



(a) (b) (c)

At DR=0.5 At DR=0.6 At DR=0.7

Fig. 11. Exergy destruction versus specific work at variously examined degrees of reaction, π_{st} and T_1 for rotors of the different stages of the axial flow compressor.

1, with a DR of 0.5, π_{st} of 1.22, and $T_1 = 288$ K. Conversely, the highest W, reaching 76.23 kJ/kg, is attained at the rotor of stage number 12, with a DR of 0.7, π_{st} of 1.36, and $T_1 = 318$ K.

The exergy destruction increased from 0.005698 kJ/kg at DR = 0.5, $\pi_{st} = 1.22$, and $T_1 = 288$ k at the rotor of stage number 1–7.712 kJ/kg at DR = 0.7, $\pi_{st} = 1.36$, and $T_1 = 318$ K at the rotor of stage number 12.

The analysis of the stators can be determined by the results of its rotor and stage. Fig. 12 is a sample of the results of the exergy analysis on the stator at inlet temperature = 288 K, pressure ratios for stages π_{st} = 1.22, 1.26, 1.3, 1.32, and 1.36, and degree of reaction = 0.5.

These findings underscore the significance of the degree of reaction as a pivotal factor for compressor design, offering valuable guidance for the selection of axial compressor rotors tailored to specific operational requirements.

7.2. Exergy destruction ratio

Fig. 13 presents a comprehensive analysis of I_{desr} in relation to W for the rotors of each stage of a 12-stage axial flow compressor under the conditions of

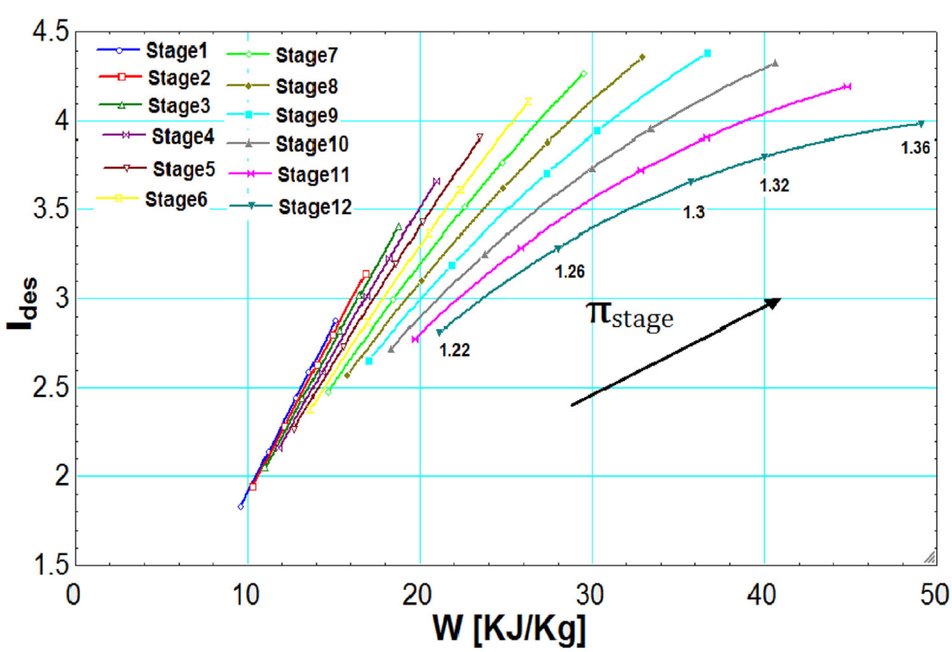
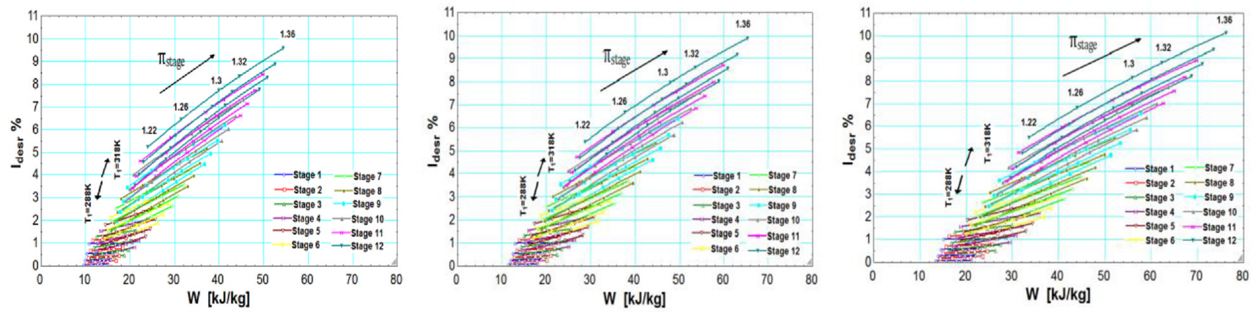


Fig. 12. Exergy destruction versus specific work at DR = 0.5 and variously examined π_{st} for stators of the different stages of axial flow compressor at $T_1 = 288$ K.



(a) (b) (c)

At DR=0.5 At DR=0.6 At DR=0.7

Fig. 13. Exergy destruction ratio vs. specific work at variously examined degrees of reaction, π_{st} and T_1 for rotors of the different stages of the axial flow compressor.

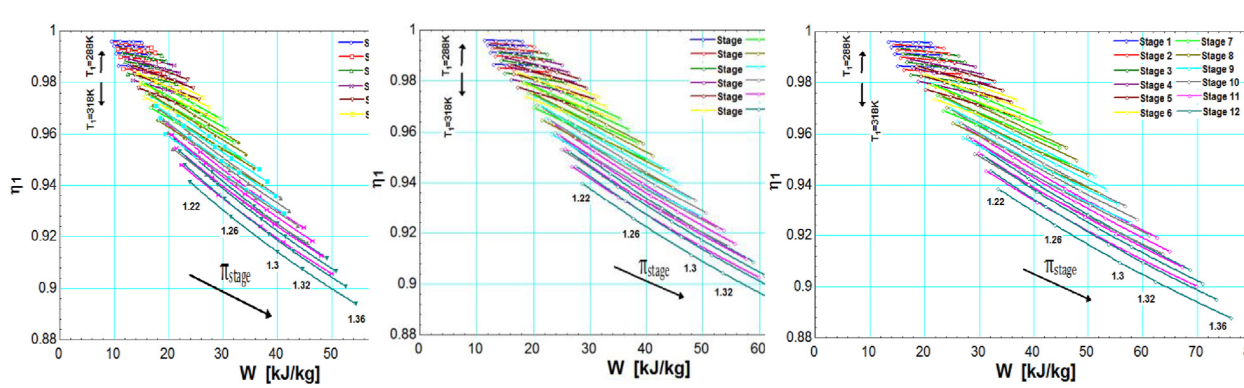
DR at the average blade area (0.5, 0.6, and 0.7), RH = 0.6, and consistent polytropic efficiency of 90%. The data reveal a compelling relationship between key parameters. Elevations in both π_{st} and ambient T_1 consistently correspond to an escalation in I_{desr} across all degrees of reaction points. A notable trend emerges, demonstrating that as DR increases, W, and the I_{desr} also rise.

The plotted data illuminate the progressive divergence in I_{desr} of rotors for each stage with varying inlet temperatures. This divergence is particularly pronounced in the later stages, reflecting increased disparities. The exergy destruction ratio increased from 0.05934% at DR = 0.5, π_{st} = 1.22, and T_1 = 288 K at the rotor of stage number 1–10.12% at DR = 0.7, π_{st} = 1.36, and T_1 = 318 K at rotor stage number 12.

Remarkably, the temperature at the inlet has negligible effects on I_{desr} of rotors at each stage. The convergence of certain lines within the dataset, especially across a range of four different inlet temperatures, underscores their proximity in the initial stages before diverging more prominently in the later stages. These observations underscore the critical role of pressure ratios, inlet temperatures, and degree of reaction in shaping the exergy destruction ratio, offering insights into optimizing compressor performance under varying operational conditions.

7.3. First-law and second-law efficiencies

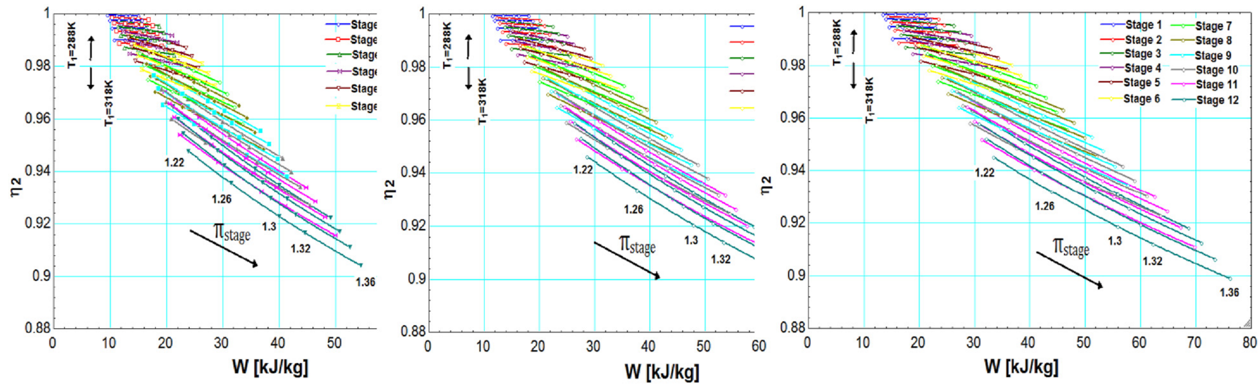
The intricate relationship between η_1 and η_2 in conjunction with W for rotor components at each stage of a 12-stage axial flow compressor is examined under the parameters of DR at the average blade area (0.5, 0.6, and 0.7), constant polytropic efficiency of 90%, and RH of 0.6. Figs. 14 and 15 collectively provide a nuanced perspective on the influence of varying π_{st}. It is evident from the



(a) (b) (c)

At DR=0.5 At DR=0.6 At DR=0.7

Fig. 14. First-law efficiency versus specific work at variously examined DR, π_{st}, and T_1 for rotors of the different stages of the axial flow compressor.



(a) (b) (c)

At DR=0.5 At DR=0.6 At DR=0.7

Fig. 15. Second-law efficiency versus specific work at variously examined DR, π_{st}, and T_1 for rotors of the different stages of the axial flow compressor.

graphical representations that an increase in π_{st} is associated with a concurrent reduction in both η_1 and η_2. Simultaneously, this rise in π_{st} results in an increase in W.

The first-law efficiency decreased from 96.6% at DR = 0.5, $\pi_{st} = 1.22$, and $T_1 = 288$ K at the rotor of stage number 1–88.77% at DR = 0.7, $\pi_{st} = 1.36$, and $T_1 = 318$ k at the rotor of stage number 12, showing about an 8% decrease.

The second-law efficiency decreased from 99.94% at DR = 0.5, $\pi_{st} = 1.22$, and $T_1 = 288$ K at the rotor of stage number 1–91.79% at DR = 0.7, $\pi_{st} = 1.36$, and $T_1 = 318$ k at the rotor of stage number 12, with a degree of reaction of 0.7 and a stage pressure ratio of 1.36, reflecting about an 8% increase.

Furthermore, as the degree of reaction increases, there is a discernible escalation in specific work. This observation holds consistently across the range of T_1 examined in the study. The convergence of certain lines within the dataset, especially in the early stages, followed by more pronounced divergence in the later stages, reflects the nuanced interplay of these parameters in shaping rotor performance and offers valuable insights for the design and evaluation of axial compressors under varying operational conditions.

8. Conclusions

The present work utilizes energy and exergy analysis to demonstrate axial compressor performance, different stages, and moving blades (rotors) for each stage using the engineering equation solver program. This analytical study can be considered an input for designers to choose the compressor and its blades with the best possible results for the compressor design. This study is not an absolute postulate, but rather a relative study of these cases in the present study, according to the studied parameter inlet temperature (288 K, 298 K, 308 K, and 318 K), degree of reaction (0.5, 0.6, and 0.7), and stage pressure ratio (1.22, 1.26, 1.3, 1.32, and 1.36). The present study yields several significant conclusions:

(1) Quantitative data revealed that an elevation in inlet temperature not only affects specific work but also increases the overall energy consumption of the compressor, requiring careful thermal management for optimized operations.
(2) A stage pressure ratio from 1.22 to 1.36 for the number of stage 12 leads to an increase in specific work consumption and about a 2% improvement in second-law efficiency. These findings emphasize the critical impact of pressure ratios on the energy performance of axial compressors.
(3) The study found minimal variation in first-law efficiency, nearly less than 2% when inlet temperatures were adjusted between 288 and 318 K. However, the increase in specific work demonstrates the sensitivity of compressor performance to thermal conditions.
(4) The second-law efficiency increased nearly by 2% from stage number 1 to stage number 12, when inlet temperatures were adjusted between 288 and 318 K and pressure ratios were adjusted between 1.22 and 1.36. These findings emphasize the impact of inlet temperatures, pressure ratios, and the number of stages on the energy performance of axial compressors.
(5) Increasing the degree of reaction from 0.5 to 0.7 results in nearly a 1% rise in the exergy

destruction ratio for one rotor of the stage. This adjustment underscores the pivotal role of the degree of reaction in optimizing compressor efficiency.

(6) The interplay between the increased degree of reaction and pressure ratios illustrates a potential for considerable gains in both exergy destruction and efficiency, proposing a balance between these factors for optimal design configurations.

(7) Despite the negligible direct impact on first-law efficiency, the variations in inlet temperature provide crucial insights into the thermodynamic behavior of compressors under different operational conditions, aiding in the precise calibration of systems for enhanced performance.

(8) The study reinforces the importance of integrating both first-law and second-law analyses in evaluating compressor performance, advocating for a holistic approach to understanding and improving energy systems.

(9) The comprehensive analysis across 12 stages offers in-depth insights into the cumulative effects of stage-wise adjustments, establishing a benchmark for future design improvements in similar compressor setups.

(10) The research contributes significantly to the understanding of multistage axial compressors, suggesting that detailed parameter optimization can lead to significant improvements in both energy efficiency and operational costs.

(11) Future research should focus on exploring the dynamic interactions between these parameters in varying compressor designs and operational environments, aiming to generalize the findings across a broader range of applications.

Ethics information

Ethics approval and consent to participate not applicable.

Funding

The authors confirm that all the work is done by the authors and no external funds were provided by any organizations.

Authors contribution

Prof. Dr. Nazih N. Bayomi: Supervision, Conceptualization, Methodology, Validation, Reviewing and Editing Prof. Dr. Rafea M.A. El-Maksoud: Supervision, Methodology, Validation, Reviewing and Editing Eng. Mohamed A. Mohamed: Conceptualization, Methodology, Formal analysis, Writing, Review and Editing.

Conflict of interest

The authors declare that they have no competing interests.

References

Abdelghany, T. A. A., Abd El-Maksoud, R. M., & Nawar, M. A. A. (2020). Compressor energy and exergy analysis. *Eng Res J, 168*, 211–226.

Adibia, T., Adibia, O., & Saha, S. (2022). Evaluation of the optimum pressures of gas turbines based on energy and exergy analyses. *Energy Equipment and Systems, 10*, 169–181.

Ahmad, N., Zheng, Q., Fawzy, H., Jiang, B., & Ahmed, S. A. (2020). Performance improvement of axial compressor by introduction of circumferential. *Grooves. Energy Sourcest A Recov Utilizat Environ Effects, 00*, 1–21.

Aungier, R. H. (2006). Noise and vibration reduction in multistage compressor design. Atlanta, USA. In *Proceedings of the mechanical engineering conference on design and manufacturing* (pp. 421–430).

Bader, W. T., & Kissock, J. K. (2000). Exergy analysis of industrial air compression. *Ind Energy Technol Conf, 3*, 89–98.

Balje, O. E. (1981). *Turbo machines: A guide to design, selection, and theory*. New York, NY: John Wiley & Sons.

Betelmal, E. H., & Farhat, S. A. (2018). Energy and exergy analysis of a simple gas turbine cycle with wet compression. *Mechanical Engineering Research, 8*, 30.

Galal, M., El-Maksoud, R. A., & Bayomi, N. N. (2024). Exergy analysis of a steam power station in a sulfuric acid plant. *Case Studies in Thermal Engineering, 53*(December 2023), Article 103937.

Johnson, M. (2016). Application of multi-stage compressors in the petrochemical industry. *Chem Eng Trans, 22*, 89–97.

Kareem, A. F., Akroot, A., Abdul Wahhab, H. A., Talal, W., Ghazal, R. M., & Alfaris, A. (2023). Exergo–economic and parametric analysis of waste heat recovery from taji gas turbines power plant using rankine cycle and organic rankine cycle. *Sustainability, 15*, 12.

Kovacevic, A., Mujic, E., & Stosic, N. (2013). Heat management in multi-stage compressors. *Applied Thermal Engineering, 31*, 1050–1063.

Lemire, S., Vo, H. D., & Benner, M. W. (2009). Performance improvement of axial compressors and fans with plasma actuation. *International Journal of Rotating Machinery*, , Article 2009, 1–13.

Martínez, F. R., Martínez, A. A. R., Velázquez, M. T., Diez, P. Q., Eslava, G. T., & Francis, J. A. (2011). Evaluation of the gas turbine inlet temperature with relation to the excess air. *Energy and Power Engineering, 3*, 517–524.

Mascarenhas, J. D. S., Chowdhury, H., Thirugnanasambandam, M., Chowdhury, T., & Saidur, R. (2019). Energy, exergy, sustainability, and emission analysis of industrial air compressors. *Journal of Cleaner Production, 231*, 183–195.

Modi, N., & Mody, P. (2019). Parametric evaluation of gas turbine system with exergy method. In *Twelve International Conference on Thermal Engineering: Theory and Applications* (pp. 2–3). Gandhinagar, India.

Mohtaram, S., Chen, W., Zargar, T., & Lin, J. (2017). Energy-exergy analysis of compressor pressure ratio effects on thermodynamic performance of ammonia water combined cycle. *Energy Conversion and Management, 134*, 77–87.

Mousavi, S., Kara, S., & Kornfeld, B. (2014). Energy efficiency of compressed air systems. *Proc CIRP, 15*, 313–318.

Naderi, P. A., Lahonian, M., Mirzaei, H., Aminian, S., & Ranjbari, L. (2023). Exergy and economic analyses of CCP system using full capacity of steam production and waste heat recovery in

Kurdistan petrochemical complex. *SN Applied Sciences, 5*, 517−524.

Ogbonnaya, O., Ajayi, O. O., Waheed, M. A., & Oyedepo, S. O. (2019). Review on the energy and exergy analysis of vapour compression refrigeration system using nanolubricant. *J Phys Conf Series, 1378*.

Ortmanns, J. (2014). Numerical investigation of axial compressor stages with differing degrees of reaction. In *Proceedings of ASME Turbo Expo 2014: Turbine Technical Conference and Exposition GT2014 June 16-20, 2014*. Düsseldorf, Germany.

Pakatchian, M. R., & Saeidi, H. (2019). A practical axial compressor design optimization approach based on gas turbine operation. *Int Conf Fluid Flow Heat Mass Transfer, 131*, 1−11.

Sanusi, Y. S., Ukanu, J., & Dandajeh, H. A. (2020). Performance characteristics of GE Frame 8 gas turbine power plant at different climatic zones in Nigeria. *FUOYE J Eng Technol, 5*, 127−132.

Smith, L., & Stosic, N. (2012). Efficiency optimization in multistage compressors. *Journal of Thermal Engineering, 29*, 112−123.

Tolba, H., Abd El-Maksoud, R., & Emara, K. (2022). Exergy analysis of multistage axial flow compressor. *Eximia J 2009*, 1−13.

White, G. (2018). Economic benefits of multi-stage compressors over single-stage designs. *J Ind Manage, 40*, 158−172.

Zheng, X., & Ding, C. (2016). Effect of temperature and pressure on stress of impeller in axial-centrifugal combined compressor. *Advances in Mechanical Engineering, 8*, 1−11.