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Exergy Analysis of Multistage Axial Flow Compressor

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Abstract. The air compressor is one of the most important devices for many processing industries and the power generation sector. Therefore, the present paper aims to study multi-stage axial flow compressors, especially for thermal power stations. Energy and exergy analysis is used to demonstrate different parameters in the compressor performance and its different stages, where 12 stages are considered; as an example. It is paramount to determine the working parameters such as compressor inlet temperature, inlet relative humidity stage pressure ratio, and the stage's polytopic efficiency at different stages. The results illustrate that the second law efficiency, exergy destruction, and exergy destruction ratio have different behaviors. Whereas, in the last stages compared with the early stages, the exergy destruction ratio is decreased with the increase of stage number, the compressor inlet temperature, the polytropic efficiency, and the stage pressure ratio. This effect is very small; in all compressor stages and could be neglected. Also, the effect of relative humidity changes on air mass flow rate ratio, exergy destruction ratio, and power consumption; throughout each stage, and overall, the compressor; is very small and could be neglected. On the other hand, for each stage and overall compressor, the results indicate that the increase in inlet air temperature leads to decreasing power consumption. In addition, the effect of inlet air temperature changes on exergy destruction ratio may be neglected, as the maximum change of exergy destruction ratio is about 1% when increasing inlet air temperature by about 25ºK.

Keywords. axial compressors, energy, exergy, multi-stage

1. Introduction

Compressed air is important for many manufacturing processes. Therefore, maximizing the compressor's air efficiency is a priority in today's industry to satisfy reliable product quality, increase productivity, and save energy, [1]. Compressor application not for industry only, but also as a component of gas turbines and turbo machinery too. Most gas turbines use axial flow compressors; especially units over 5 MW, [2].

Most compressor companies have long efforted to achieve sufficient energy cost reduction compared with current compressors. Increased efficiency has the possible for significantly lowering energy costs through the improvement of performance and reliability, and through the reduction in the number of parts, [3].

Exergy is the maximum theoretical work obtainable during a process that brings the system into stability with its environment. Therefore, many researchers focus on the exergy during their studies as follows. Therefore, the effect of the following parameters: compressor polytropic efficiency, compressor pressure ratio, inlet temperature, and inlet humidity on the compressor specific work consumption, compressor operating range, energy destruction, energy destruction ratio, and the first and second law efficiencies have been studied. The results show how the compressor acts under different conditions. In addition, the results clarify that first and second law efficiencies provide quantitative and qualitative compressor performance assessments. Moreover, the result charts help in selecting different types of compressors that have higher second law efficiency or have less exergy destruction ratio, [4].

The Equation Solver (EES) software is used to perform detailed analyses of energy and exergy for the axial compressor. The energy-exergy analysis shows that, by increasing the compressor pressure ratio, the energy destruction of high-pressure compressors constantly increases and the exergy destruction of the recuperator, in contrast, decreases continuously, [5].

Also, the effect of water spray in the compressor with variable ambient temperature on the performance of gas turbine (thermal efficiency, power) has been Investigated. The results are compared to the results of the same cycle with a dry compressor too. The results showed that exergy destruction increases with water injection. The compressor's power decreased by 11% when using a wet compressor, [6].

Moreover, the axial flow compressor performance depends upon the blade diameter, mass flow rate, density of the flowing fluids, stage pressure ratio, stage delivery pressure, and temperature, [7]. So, the effect of installing air cooling equipment at the inlet of the compressor has been studied, it is required to have the air mass flow rate and output power as functions of ambient temperature, [8]. Therefore, it is considered the exergy analysis; has become one of the most important tips and solution partners that engineering practitioners have been mindful of in explaining the availability of energy. Also, the exergy analyses of jet engines (gas turbines) used in air vehicles are given comparatively, [9].

The exergy analysis, which is performed according to the thermodynamic laws, is carried out by conducting mass, energy, and exergy balance of each component of the engine, [10]. The exergy destruction rates within the engine components are split into endogenous /exogenous and avoidable/unavoidable parts. The system has low improvement potential because the unavoidable exergy destruction rate is 90 %, [11].

The effects on exergy efficiencies and losses by modifying the isentropic efficiencies of turbomachinery components have been investigated. The studies found that generally the components; with the most exergy destruction in a turbofan engine; are the fan, engine exhaust, and combustion chamber [12]. Also, the changes in the exergy efficiency and exergy destruction rate were investigated, to determine the effect of the changes in the thrust, fuel mass flow rate, and thermal efficiency with changes of the flight altitude and the Flight-Mach number, [13].

According to the above studies, higher efficiency and higher-pressure ratios are required for compressors of aircraft turbofan engines to achieve a fuel burn reduction. In addition, technical issues related to a smaller core size must be overcome to realize a higher overall pressure ratio and a higher bypass ratio of an engine, [14].

On the other hand, the three stages of axial compressor design have been studied to improve and apply mean line analysis to compressor performance prediction. Moreover, the effects of early design parameters on compressor characteristics and gas turbine performance at part load were studied as well. further, that study required optimization of the parameters regarding a specific gas turbine application, [15]. On another way, the impact of geometry changes in axial compressor flow passage on kinematical airflow characteristics is studied, [16]. Moreover, the internal losses which are seen as mechanisms that increase the entropy of the working fluid through the compressor, be investigated and found that, at a fundamental level, all internal losses are a direct result of viscous shearing that occurs wherever there are velocity gradients. [17].

The compressor efficiency is ascertained substantially by the softness of the air flowing through it. The multi-stage axial compressor in the Turbojet engine with an application for propulsion is designed based on thermodynamic calculations, [18]. While the effect of the airborne particles has been investigated such as dust and moisture in the ambient air entering through the intake of the gas turbine and adhering to compressor blades. The attached particles on compressor blades increase surface roughness and reduce airflow passage between blades. Those phenomena bring to the reduction of airflow rate, a decrease of pressure ratio, and compressor efficiency, [19].

Due to the significance and vast applications of axial flow compressor to compressors significance, many researchers studied its performance. Accordingly, the present work presents energy and exergy analysis for axial flow compressor and its different stages. The studied parameters are compressor polytropic efficiency, compressor pressure ratio, inlet temperature, and inlet humidity. The effect of these parameters on the compressor performance and its different stages are demonstrated.

2. Mathematical Model

The mathematical model is a part of mathematical model used before for overall gas turbine. Calculating the power for the polytropic process involves the summation of the power for each stage. Each stage is considered a small compressor, [20].

3. Results and Discussion

3.1. Compressor Performance

The axial air compressor is a constant volume compressor. Therefore, the inlet air temperature has no impact on the air density only; but also, on the air mass flow rate. High air density is achieved at lower intake temperatures and leads to an increase in the power consumption of the compressor P_c.

The increase of inlet air temperature T_0 and polytropic efficiency η_p leads to increasing both the 1st law-efficiency η_{Ic} and 2nd low-efficiency η_{IIc}. That means decreasing in exergy destruction, in addition, the exergy destruction depends on the inlet air temperature T_0, while the effect of increasing the pressure ratio $\boldsymbol{\pi}$ leads to rise in both compressor power consumption P_c. Moreover, the increase in P_c leads to an increase in the 2nd low-efficiency η_{IIc}, but a decrease in the 1st low-efficiency η_{Ic}, as shown in Figure 3.

However, the above words mention the exergy destruction, compressor power consumption, the 1st low-efficiency η_{Ic}, and 2nd low-efficiency η_{IIc} are function in inlet air temperature T_o, polytropic efficiency η_p, and the pressure ratio π. Therefore, there is an indication that to improve the compressor performance, consider during design high polytropic efficiency η_p, and the pressure ratio π.

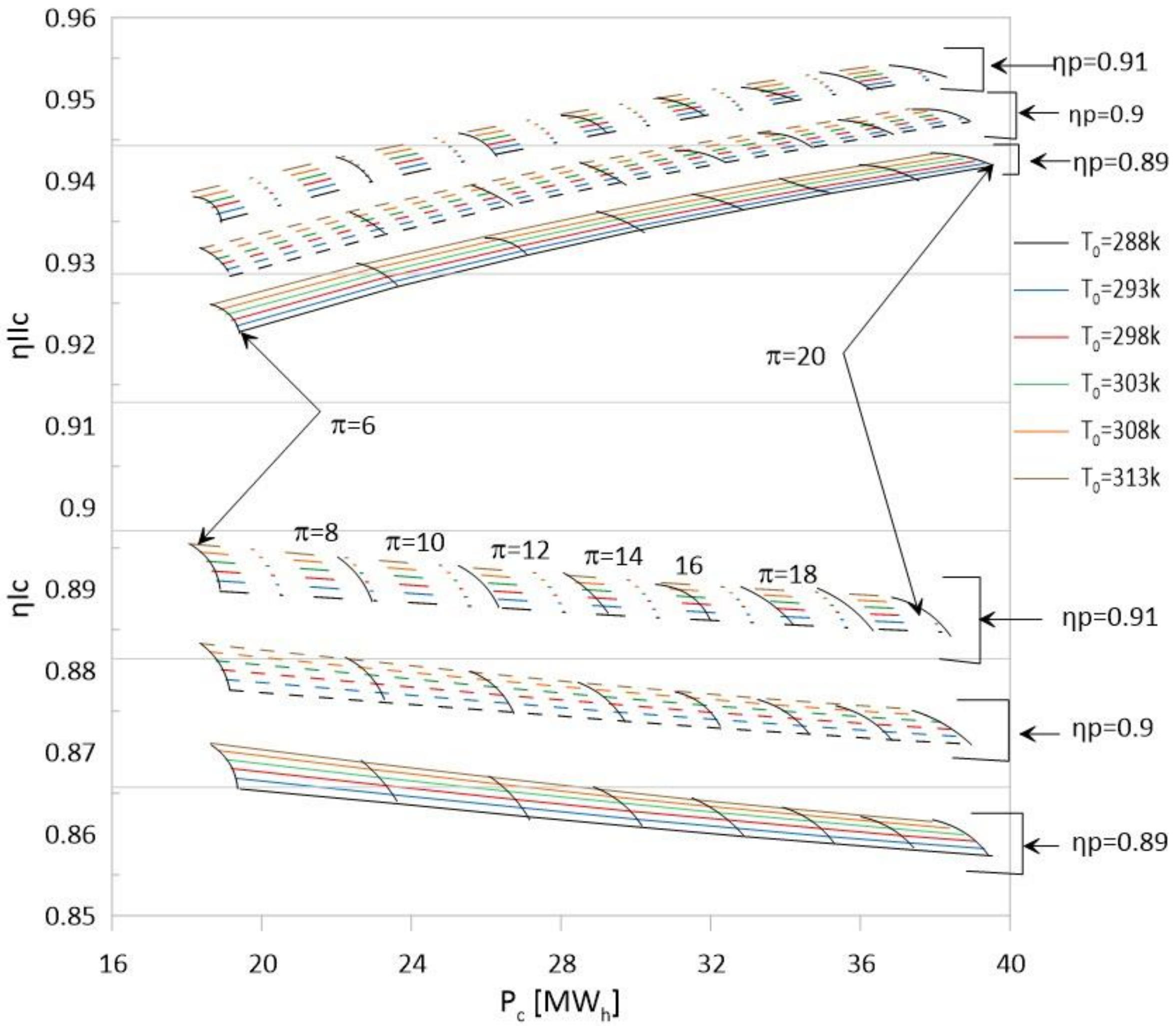


Figure 3: The effect of T_0, π and η_p on P_c with its η_I and η_{II}.

Moreover, Figure 4 shows the relation between m_{airR} and P_{cR}; referring to ISO condition (T_0 = 288 and rh = 60%); with T_0 at different rh. The curves at low T_0 are so closer than at higher T_0. That means the effect of rh is very clear, especially at high rh as increasing rh leads to decreasing m_{airR} and P_{cR}, in addition to the same effect of raising the inlet air temperature.

However, the rh change range is about equal or greater than 40% leads to the maximum change value in each m_{airR}, and P_{CR} is about 4% only at the T_0 equal 313 K. Meanwhile, the minimum effect of rh on m_{airR} and P_{cR} is about 1.5% and 1.1% respectively at the minimum T_0 equal 288 K. Therefore, the effect of rh may be neglected.

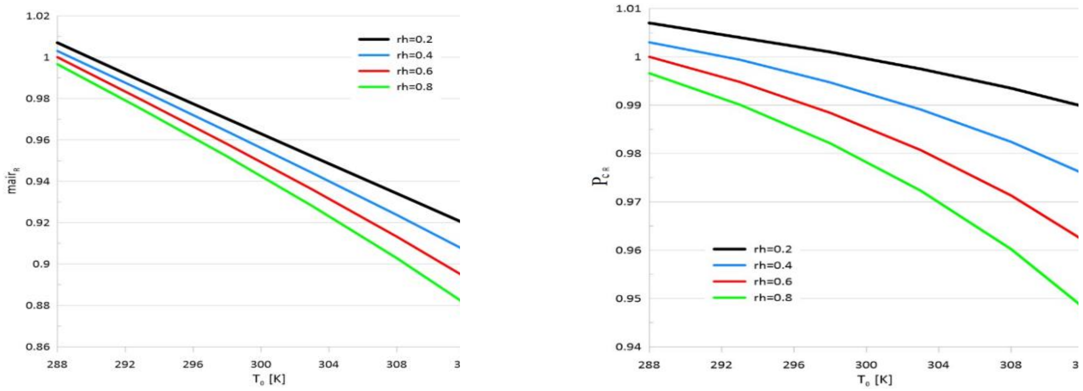
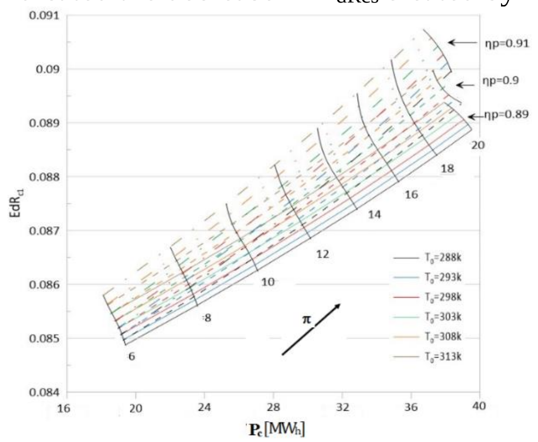


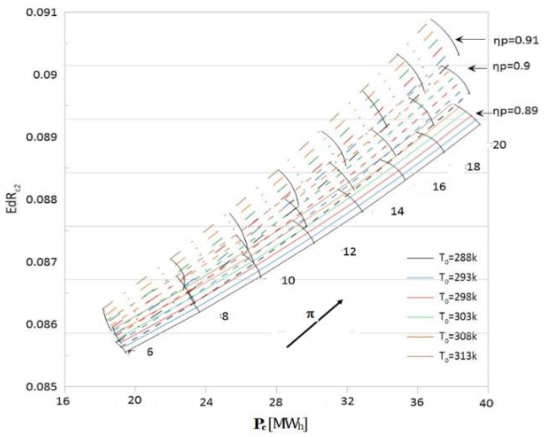
Figure 4: The effect of T_0 and rh on the m_{airR} and P_{cR} at constant π=12 and η_p=0.9

3.2. The performance for Each Stage of the compressor

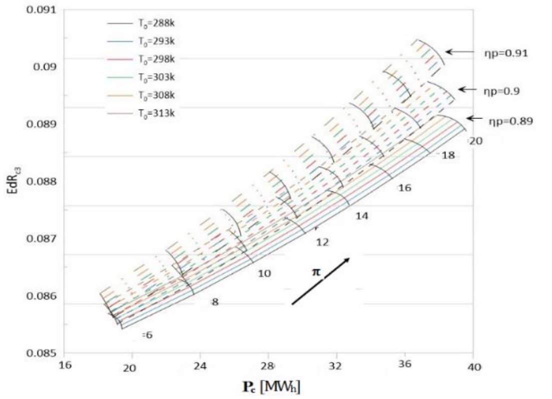
The effect of T_0, π, and η_p on the relation between P_c and E_{dRc} of each stage of the compressor as simulation performance results are shown in Figure 5. These Figures show the effect of T_0, π, and η_p on the exergy destruction ratio of each compressor stage (E_{dRcs}) (referring to total exergy destruction of compressor E_{dc}) behavior of each stage. Moreover, in the first stages, the curves start with high overlaps and then become groups for each η_p. These groups are very clear by increasing the stage order up to stage number 8, as in stage number 8 the overlaps are so high. Moreover, the overlaps come down again. That indicated that the effect of η_p is so clear at higher Pc. In addition, the results dictate that the increase in π, T_0, and, or η_p leads to an increase in E_{dRcs} up to the 8^{th} stage, as the increase in T_0 leads to a decrease in E_{dRcs}. The 8^{th} stage may be called a critical stage as the effect of η_p causes overlaps, but the curves have the same behavior. while, at the 9^{th} stage and after stages, the E_{dRcs} curves collapsed. In addition, that noted that the effect of η_p is so clear on E_{dRcs} of compressor for the first 7 stages, especially at high π. In addition, by increasing stage order the curves shifted down. That indicated the decrease in E_{dRcs} created by increasing the stage order.



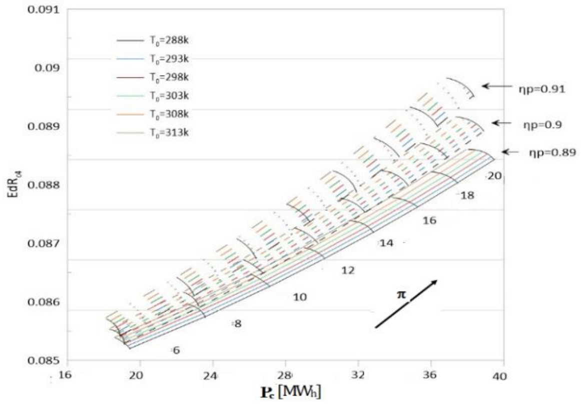
1^{st} stage



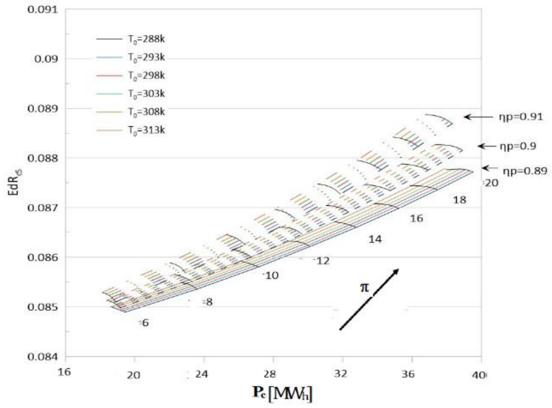
2^{nd} stage



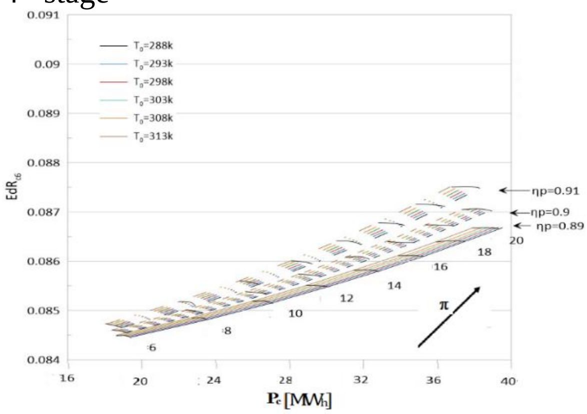
3rd stage



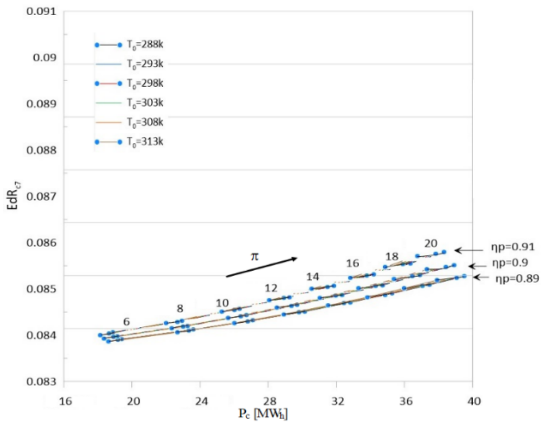
4th stage



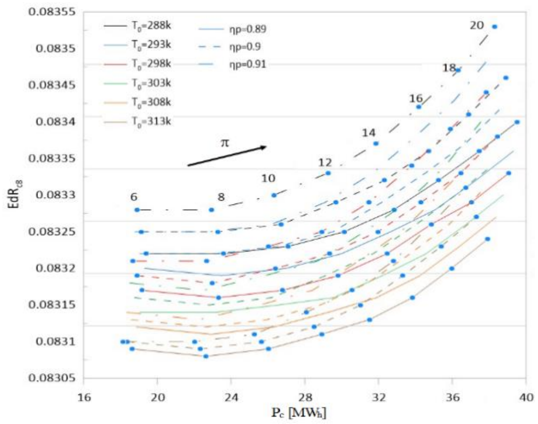
5th stage



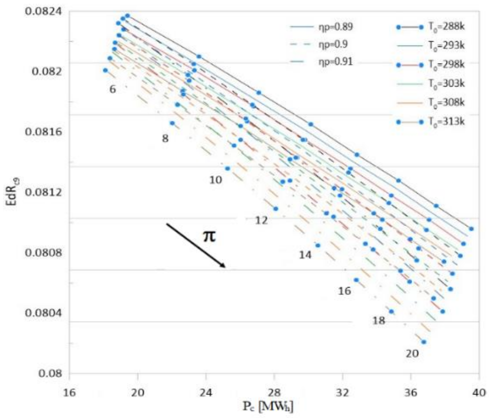
6th stage



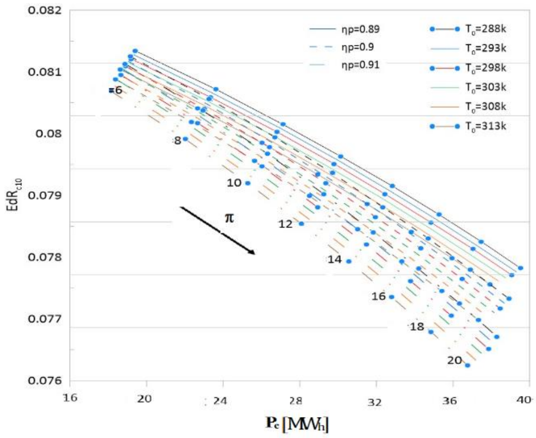
7th stage



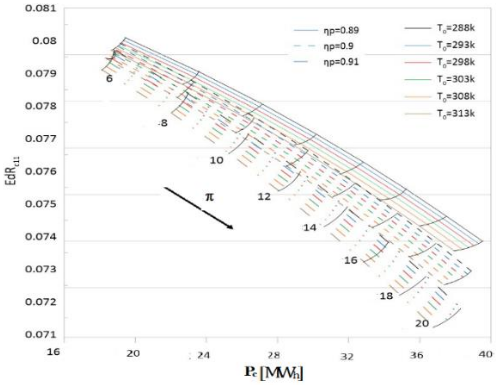
8th stage



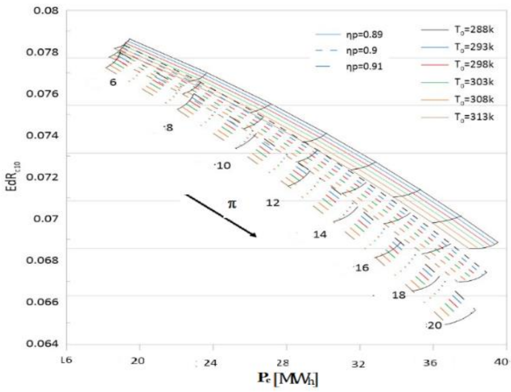
9th stage



10th stage



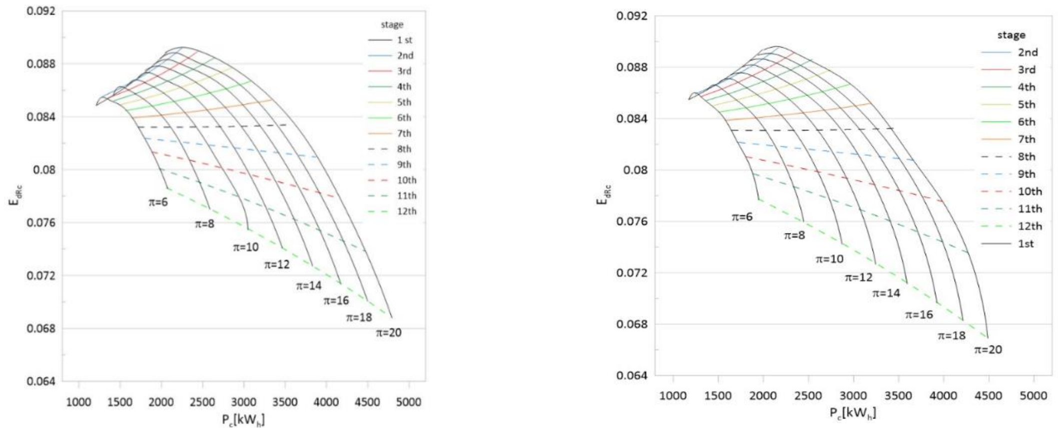
11th stage



12th stage

Figure 5: The effect of T_0, π and η_p on the relation between P_c with E_{dRc}

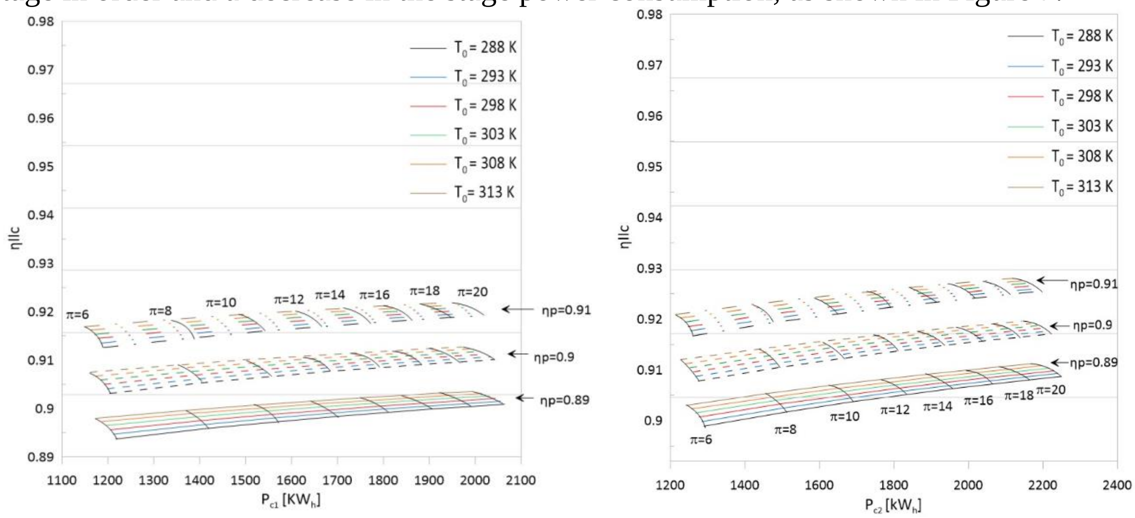
Figure 6 shows the relation between E_{dRcs} and P_{sc} for each stage. The curve at high E_{dRcs} is narrow while wider at the lower E_{dRcs}. That means the P_{sc} increases by increasing the stage order. For the 1st and the 2nd stages, the increase of P_{sc} leads to the increase of E_{dRcs} too. While the upper order stages (the 3rd stage up to the last stage) E_{dRcs} collapses with increasing P_{sc}. In addition, the curves at high E_{dRc} are so closer than at lower E_{dRc}, that indicates that, the effect of π clearer at high π. Whereas the increasing of π leads to the increase of P_{sc}. In addition, the increasing of π leads to the increase of E_{dRc} until stage number 8th, While the upper order stages (the 9th stage up to the last satge) E_{dRc} collapses. In addition, the curve level at $T_0 = 313$ K is a lower than at T_0= 288 K. that it indicates, the increasing T_0 leads to the decreasing both of P_{sc} and E_{dRc} for each stage. In order, regarding the maximum change of E_{dRc} is about 1%, that maybe neglect the effect of change of T_0.



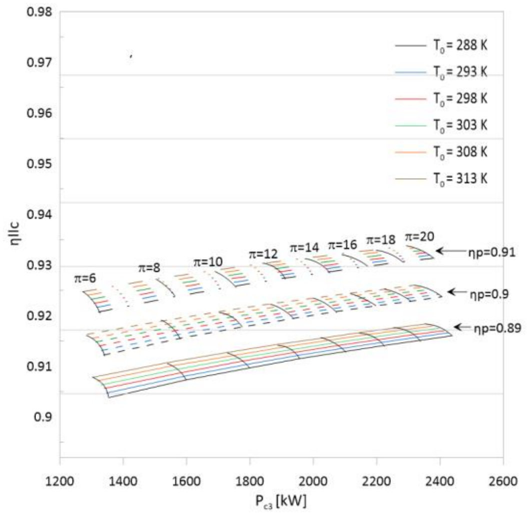
a. T0 = 288 K   b. T0 = 313 K

Figure 6: The effect of stages order number, **π** and T0 on the relation between P_{sc} with E_{dRc} of each stage.

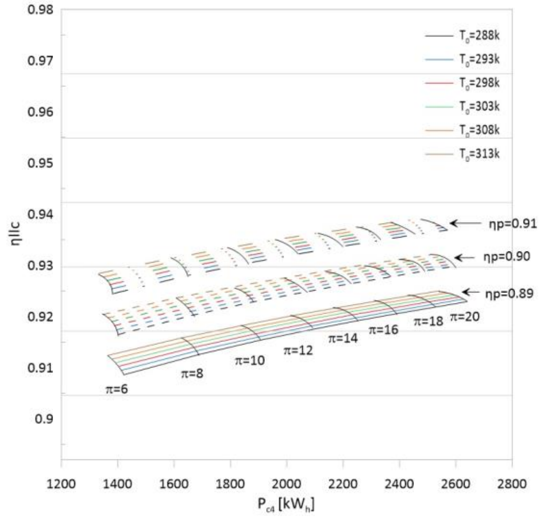
The exergy increases when rising ambient air temperature means increasing the 2nd low-efficiency η_{IIcs}. In addition, the increase of π and/or the number of stage orders causes an increase in stage power consumption; therefore, increasing the output pressure; and 2nd low-efficiency of the stage. Moreover, increasing η_p leads to an increase 2nd low-efficiency of the stage in order and a decrease in the stage power consumption, as shown in Figure 7.



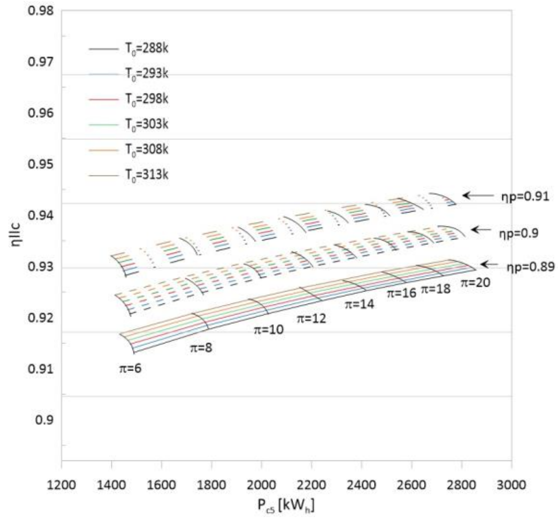
1st stage   2nd stage



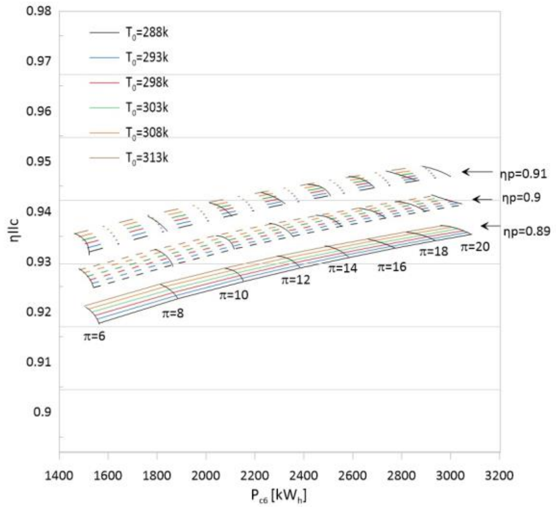
3rd stage



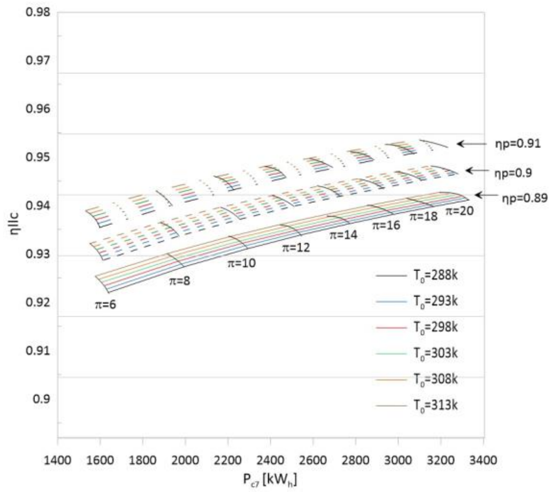
4th stage



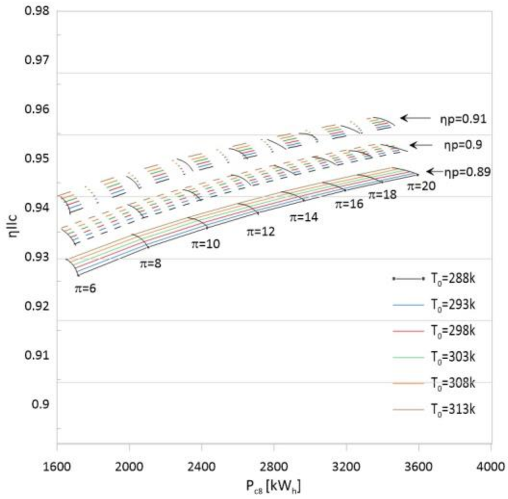
5th stage



6th stage



7th stage



8th stage

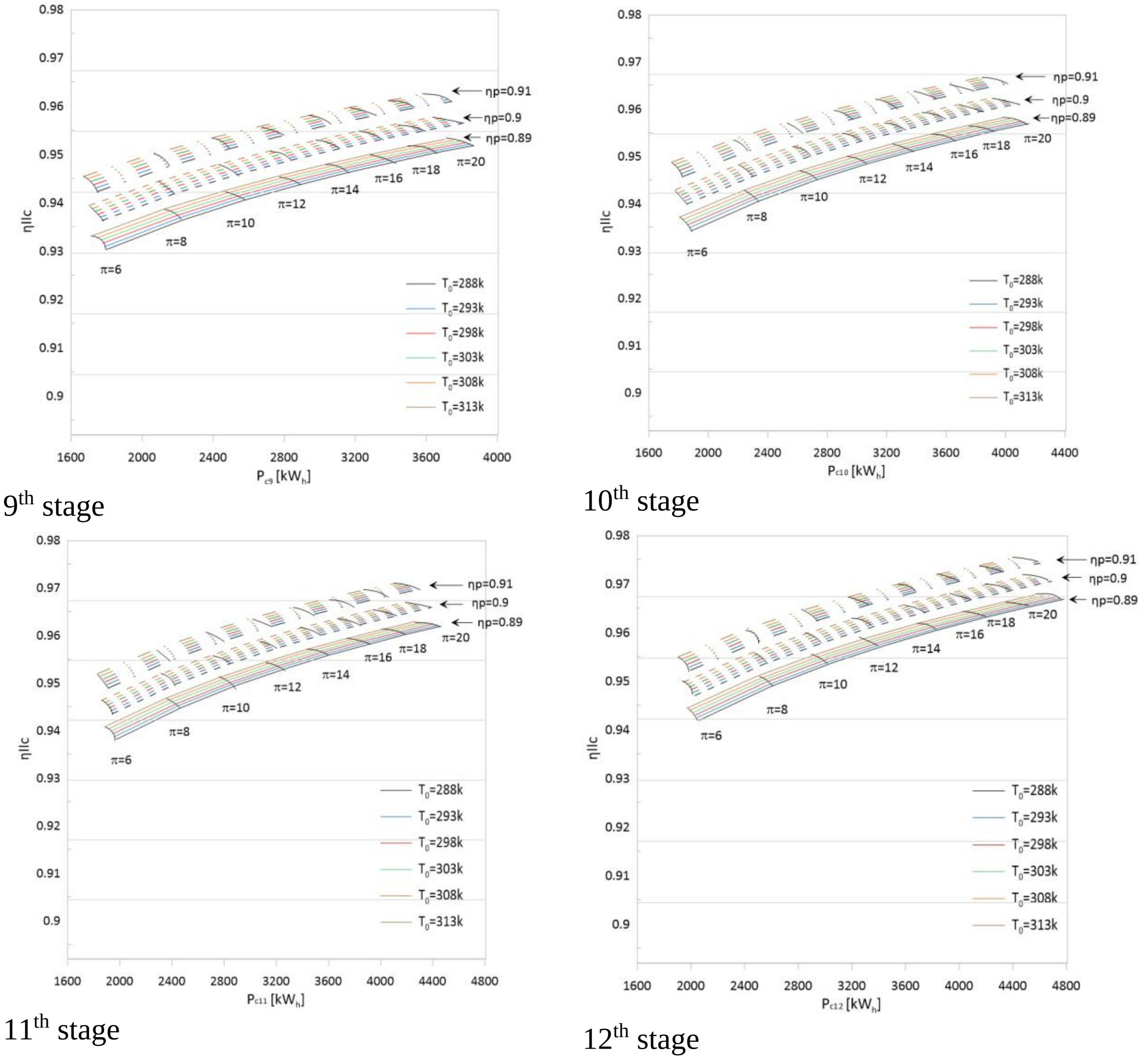
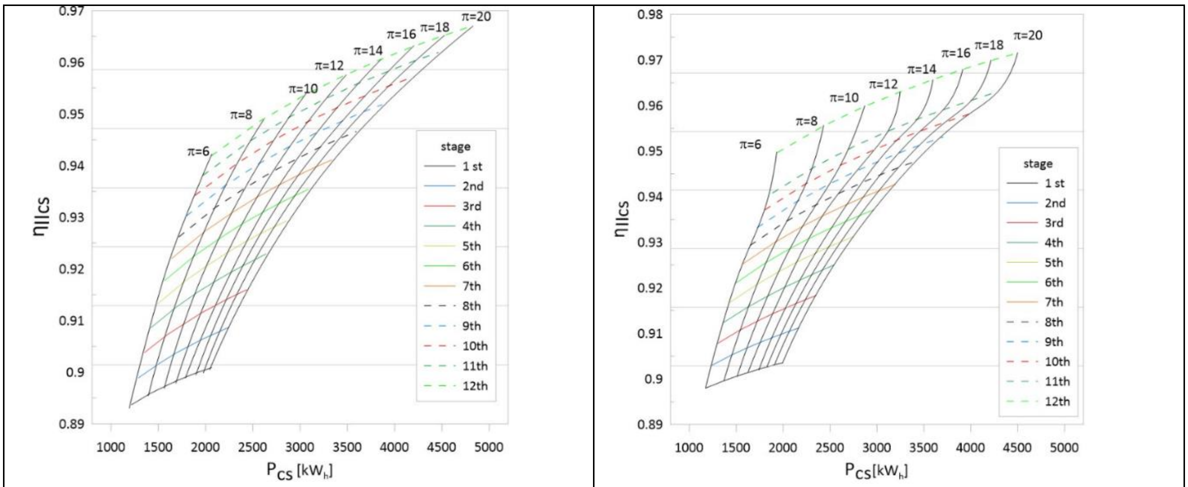


Figure 7: The effect of T_0, π and η_p on the relation between each stage of Compressor P_c with its η_{IIc}.

Figure 8 shows the relation between η_{IIcs} and P_{cs} for each stage, the curves at low η_{IIcs} are so much closer than at higher η_{IIcs}, this means the P_{cs} increase by increasing the stage order due to an increase in pressure. This also, indicates that the effect of π is clearer at high π. The increase in P_{cs} leads to an increase in η_{IIcs}. Whereas, the increase of π leads to the increase in P_{cs} and η_{IIcs}. Also, the curve width; at T_0 = 313 K is less than at T_0 = 288 K. In addition, the curve level at T_0 = 313 K is higher than at T_0 = 288 K. That indicates; the increase of T_0 leads to the increase of η_{IIcs} but decreases P_{cs}. Moreover, the effect of T_0 clears as its raising as leads to an increase η_{IIcs} for each stage. Meanwhile, raising T_0 leads to a decrease in each stage order power consumption.



a. T_0=288K b. T_0=313K

Figure 8: The performance of each stage of compressor.

4. Conclusions

The present work utilizes energy analysis and exergy analysis to demonstrate compressor performance with different aspects and insights. The following conclusions can be drawn according to the examined values of parameters:

1. The first and the second law efficiency show different behaviors and they give a quantitative and qualitative picture of compressor maps, respectively.
2. The high air density is at lower intake temperatures T_0 and leads to increase of the power consumption of the compressor P_c, the 1st low-efficiency η_{Ic} and the 2nd low-efficiency η_{IIc}.
3. The increase of P_c leads to increase the 2nd low-efficiency η_{IIc} but decrease of the 1st low-efficiency η_{Ic}.
4. the increasing of π and/or the number of stage order causes increasing of stage power consumption P_{sc} and 2nd low-efficiency of the stage. Moreover, increasing of η_p leads to increase 2nd low-efficiency of the stage in order and decrease the stage power consumption
5. increasing η_p leads to reduce power consumption P_c, reducing exergy destruction, and increasing 1st and 2nd law efficiencies.
6. Inlet relative humidity has a sensible effect on work consumption and an insignificant influence on 1st and 2nd law efficiency.
7. The effect of inlet relative humidity on the exergy and energy destruction could be neglected.
8. The raising of T0 leads to a decrease in each stage power consumption.
9. The decreasing of EdRcs created by increasing the stage order.
10. the increasing of π and, or the number of stage order causes increasing of stage power consumption Psc and 2nd low-efficiency of the stage. Moreover, increasing of η_p leads to increase 2nd low-efficiency of the stage in order and decrease the stage power consumption.

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Nomenclature

E_{desc}	exergy destruction	(KW_h)
h_i	inlet air enthalpy	(KJ)
h_{os}	outlet air isentropic enthalpy	(KJ)
h_o	real outlet air enthalpy	(KJ)
m_a	Air mass flow rate at ISO condition	(kg/hr)
m_{ISO}	Air mass flow rate	(kg/hr)
T_0	Inlet air Temperature	(K)
T_a	Ambient Temperature	(K)
S	entropy	(KJ/Kg. k)
P_c	Compressor Consumption Power	(KW_h)
P_{revc}	reversible power	(KW_h)
P_{cISO}	Compressor Consumption Power at ISO condition	(KW_h)
P_{cR}	Compressor Consumption Power ratio	
ρ	Density	(kg/m^3)
V	Compressor volume	(m^3)
$mair_R$	Air mass ratio	

Acronyms

EES	Engineering Equation Solver
GT	Gas Turbine
ISO	International Organization for Standardization

Abbreviations

π	Pressure ratio
π_S	Stage pressure ratio
η	Efficiency %
η_{Is}	isentropic efficiency
η_p	and polytropic efficiency

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