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The Effect of Pressure ratio on the Compression work done by an Axial flow Compressors

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Abstract:

An axial flow compressor is under investigation and an in-house axial compressor is designed for this study. Therefore, the analysis and the effect of pressure ratio on the compression work done by an axial compressor suitable for understanding the aerodynamics activities in an aero-engine is presented. The axial compressor is designed and adapted in such a way that the air intake unit and the compression unit carried out work simultaneously thereby minimizing delayed time and enhancing pressure analysis. The key principal unit of the compressor namely intake, stator, blade, shaft, and casing are designed for efficient operation, ease of assembly, and disassembly. The pressure ratio of the compressor, the outlet temperature, and the compression work done was detected to be 2 bars, 366.93 K, and 79.32 kJ/kg respectively. The basic results of the effect of pressure ratio increase on the compression work done by the compressor agree with the results in literatures. Proper application of this axial compressor can be ensured by further analyses of increasing the pressure ratio to ascertain the effect on the work done. The axial compressor used in this study is feasible for the aerodynamic study of the essence of an axial flow compressor in an aero-engine.

Keywords: Axial, Compressor, Pressure ratio, Aerodynamics, Aero-engine.

1. INTRODUCTION

The need to understand the fundamental problems associated with the design and operation of axial compressors becomes increasingly important as engineers strive to enhance aero-engine performance. One of the challenges encountered in the design and operation of axial compressors for aircraft gas turbine engines is the analysis of the pressure ratio to help in the study and control of compressor stalls. Axial flow compressor whose working fluid flows parallel to the axis of rotation of the rotor, is compressed by first accelerating the fluid and then diffusion it to increase its pressure. During compression, the gas entering the compressor is at low pressure, it will exit at high pressure. In order to improve the thermodynamic efficiency of aircraft engines and other gas turbine engines, higher pressure ratios are desired. In view of this, an in-house axial compressor designed and constructed to analyse the performance of the axial flow compressor which is critical to the operation of commercial civil aero-engines both for mechanical integrity and performance is employed for this study. Axial compressors find application as they are integral to the design of large gas turbines such as jet engines, high-speed ship engines, and small-scale power stations. They are also used in industrial applications such as large-volume air separation plants, blast furnace air, fluid catalytic cracking air, and propane dehydrogenation. Due to high performance, high reliability, and flexible operation during the flight envelope, they are also used in aerospace rocket engines, as fuel pumps, and in other critical high-volume applications.

Axial compressors are basically high-flow, low-pressure machines, in contrast to lower-flow, high-pressure centrifugal compressors. Axial flow compressors have found wide use in refineries, petrochemical plants, and steel mills. In the environment, where the axial compressor is used, there are always uncertainties arising due to varying atmospheric conditions, unusually assembled rotors, casing properties, and manufacturing tolerance, hence, this study to ascertain the effect of pressure ratio increase in the compression work done by the compressor.

2. LITERATURE REVIEW

This section presents a review of related literature on the design, operation, and performance of axial compressors. The studies include Suriyanarayanan [1] who developed a generalised surrogate model to accurately predict the performance of compressors undergoing random tip gap and stagger angle variation. In the study, the mean absolute percentage error between CFD and surrogate models of stagger angle and tip gap was found to be less than 0.14% and 1.5% respectively. This analysis considers only the aerodynamic effect from geometric variations while neglecting the associated aeroelastic effects. Spakovszky [2] analyses aerodynamically induced whirling forces in axial-flow compressors and a new unsteady low-order model to predict the destabilizing whirling forces. The model consists of two parts: compressor Model I with the effect of tip-clearance-induced distortion, and an aerodynamically induced force model. And in the analysis, a non-dimensional parameter is deduced that determines the direction of rotor whirl tendency in both compressors and turbines due to tangential blade loading forces. Butler [3] carried out an investigation with casing mounted high-frequency response pressure transducers and used it to characterize the flow behavior near the aerodynamic stability limit of a low-speed single-stage axial flow compressor. The experimental data was analysed using multiple techniques in the time and frequency domains and concluded that an increase in the breakdown of flow periodicity as the flow coefficient is reduced. And that, a flow coefficient of 0.40 a two-node rotating disturbance develops with a propagation velocity of approximately 23% rotor speed in the direction of rotation. Pantelidis [4] redesign an axial compressor for a domestic appliance. The study shows that an improved stator design was better matched to the radial distribution of rotor exit flow angle, which led to a decrease in stator loss across all Reynolds numbers. The result shows that with axial compressors designed specifically for low Re, the Re at which the losses start increasing exponentially can be shifted from 10×10^4 to 4×10^4 and that the loss increase is predominantly caused by the rotor hub corner separation.

Hemerly [5] came up with a concept of modular multistage axial compressor design by dividing the compressor into five (5) modules and then maximising the size of the core module, therefore, upgrading for a different application using the same core, hence reducing the cost. Ekong et al [6] studied the effect of increasing the heat transfer coefficient in the H.P. Compressors in Gas Turbine Engine and concluded that an increase in the heat transfer coefficient would increase the reslam characteristics hence reducing the clearances; Ekong [7] indicate in the study that a bypass air can be used to improve clearance in gas turbine HP compressors. Ekong *et al* [8] developed concepts for the control of tip clearance in Gas turbine HP compressors using a creativity technique called TRIZ, which helps in the selection of materials and techniques during the conceptual stage of the research. A review of other related fluid measurement and control equipment to aid in the design and analysis of this study were undertaken to ascertain the effectiveness of the design and operation such as Ekong *et al* (9) that undertook the performance analysis of a single-acting reciprocating compressor using thermodynamic concepts and their results show that, as the mass of air increases, there is a corresponding increase in the efficiency of the compressor, while the performance analysis of a single-acting reciprocating mechanism was studied by Ekong and Ekanem (10) and the results show that an increase in the pump speed increases the pump's discharge, the work done by the pump, and the power required to drive the pump and Ekong *et al* (11) work on single-acting reciprocating pump and concluded that an increase in the pump speed increases will increase the discharge from the pump. The effect of the design parameters on mass flow measurement and control in an orifice plate flow rig was carried out by Ekong (12) indicating that an increase in Reynolds number will increase the flow rate and Ekong (13) performed the parametric effect on the discharge of the Venturimeter flow rig showing that as the head increases, the is a corresponding increase in the discharge through the Venturimeter and Ekong [21], concluded that as the value of the pressure head increase, there was a corresponding increase in discharge, hence confirming the effectiveness of the Bernoulli's principles and continuity equation in the analysis of flow discharge through Venturimeter.

3. MATERIALS AND METHODS

This section presents the materials and methods used in this study. The air used by the equipment is ambient room air without any filtration or treatment. The compressor is run with a 1 horsepower DC electric motor to provide stable rotational speeds to the tune of 2800 r.p.m. There are two pressure gauges to record the inlet pressure and outlet pressure respectively. The blades were arranged with differing dimensions in the compressor to get maximum performance. In this research, the thermodynamic concepts including the law of isentropic compression processes were applied in the determination of the final temperature of the axial compressor, hence the compression work in the compressor. Using the isentropic of P-T for the compression process,

$$\frac{P_{02}}{P_{01}} = [(\frac{T_{02}^1}{T_{01}})^{\frac{\gamma-1}{\gamma}} - 1] \quad (1)$$

Where T_{02}^1, is the isentropic temperature at the outlet,

T_{01} is the inlet temperature,

P_{01} is the inlet pressure,

γ is the heat capacity ratio

P_{02} is the outlet pressure and

η_c is the isentropic efficiency

The isentropic efficiency is given as,

$$\eta_c = \frac{(T_{02} - T_{01})}{T_{02}^1 - T_{01}} \quad (2)$$

The actual outlet temperature given the isentropic efficiency is given as,

$$T_{02} = T_{01} + \frac{(T_{02}^1 - T_{01})}{\eta_c} \quad (3)$$

where η_c is the isentropic efficiency of the compressor.

The work of compression by the compressor is given as,

$$W_c = C_p(T_{02} - T_{01}) \quad (4)$$

where C_{cp} is the heat capacity.

In the selection of the materials, certain factors were taken into consideration such as mechanical strength, size of the components, aesthetics, availability, cost, and ease of assembly. Forty inventive principles, lateral thinking, and brainstorming which are creativity techniques in problem-solving presented in Ekong *et al* [14] the application of Creativity Tools to Gas Turbine Engine Compressor Clearance Control, Ekong [15] the application of Creative techniques in Effective Management of a Power Generation Plant, Ekong [16] the application of Ideal Final Result in the design of a Pneumatic Foot Pump for rural areas, Ekong [17] the application of 40 inventive principles in tip clearance control concepts in Gas Turbine H.P compressor, Ekong [18] the Improvement of Government Parastatals using Creativity tools and Ekong [19] the application of Ideal Final Results in the Establishment and Management of a Cold storage facility for rural areas, were applied in the design and the selection of materials for manufacturing of the in-house axial compressor shown in Figure 1. The part used includes the electric motor, shaft, rotors, stator blade, spindle, steel, acrylic, and PVC rubber shown in Figures 2, 3, and 4. The shaft is to transmit power from one part to another as shown in Figure 2.

Figure 1: The in-house axial compressor

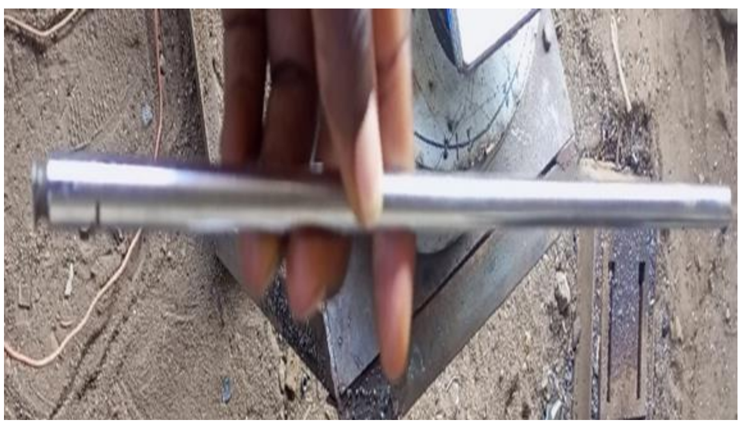

Figure 2: Shaft is to transmit power

Several variables were considered in the design and manufacturing of the rotor and stator blades to have the correct aerodynamic shape, materials to be lightweight, tough, and not prone to excessive noise and excessive vibrations, and for substantial pressure differentials per stage as shown in Figure 3 while the Polyvinyl chloride (PVC) which is a thermoplastic polymer was used at the inlet of the compressor as shown in Figure 4.

Figure 3: Rotor and Stator blades assembly

Figure 4: Polyvinyl chloride used as inlet with accessories

4. RESULTS AND DISCUSSION

In this study, an axial air flow compressor was produced that was used for the analysis to demonstrate the compression of air in an axial air flow compressor

4.1. Design Analysis

The axial flow compressor designed and used for this study has a diameter of 114 mm with rotor blades attached to a single shaft. The total length of the compressor is 300 mm. The air inlet stagnation temperature is 288K, at stagnation pressure of 1 bar. The pressure ratio is 2 and the rotor rotates at 2800 rpm. The outlet temperature and the compression work were analysed, assuming the compressor efficiency of 80%, Cp of 1.005 kJ/Kg K, and γ of 1.4.

Using the isentropic P-T relation for compression proceses of Equation 1,

$$\frac{P_{02}}{P_{01}} = [(\frac{T_{02}^{1}}{T_{01}})^{\frac{\gamma-1}{\gamma}} - 1]$$

Then, the isentropic temperature at the outlet becomes,

$$T_{02}^{1} = T0_1 \times \left(\frac{P0_2}{P0_1}\right)^{\frac{\gamma-1}{\gamma}} = 288 \ (2)^{0.286} = 351.15 \text{ K}$$

The actual temperature at the outlet was analyse using the Equation 3,

$$T_{02} = T_{01} + \frac{(T_{02}^{1} - T_{01})}{\eta_c} = 288 + \left(\frac{351.15-288}{0.80}\right) = 366.93 \text{ K}$$

The work of compression by the compressor is analyse using Equation 4,

$$W_c = C_p(T_{02} - T_{01}) = 1.005 \ (366.93 - 288) = 79.33 \text{ kJ/kg}$$

4.1.2 Computation analysis of the effect of pressure ratio on the work done by Compressor

The computation analysis of the effect of pressure ratio on the compression work done by the axial compressor was carried out by increasing the pressure ratio for four analyses to ascertain the effectiveness of the design. The results are presented in Table 1 for the actual temperature outlet and Table 2 for the work of compression respectively. The resultant effect for the actual temperature and compression work by the compressor is demonstrated graphically in Figures 5 and 6 respectively.

Table 1: The relationship between pressure ratio and the actual temperature outlet

S/N	Pressure ratio	Actual Outlet Temperature, T_{02} (K)
1	2	366.93
2	3	420.90
3	4	463.17
4	5	498.44
5	6	528.97

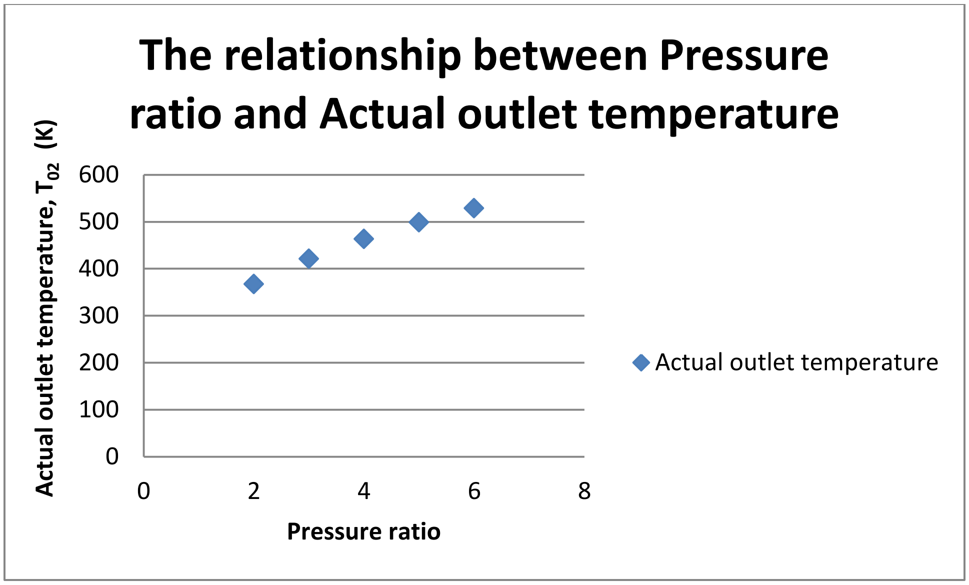

Figure 5: The relationship between pressure ratio and the actual outlet temperature

Table 2: The relationship between pressure ratio and the compression work

S/N	Pressure ratio	Compression work, kJ/kg
1	2	79.33
2	3	133.56
3	4	176.05
4	5	211.50
5	6	242.18

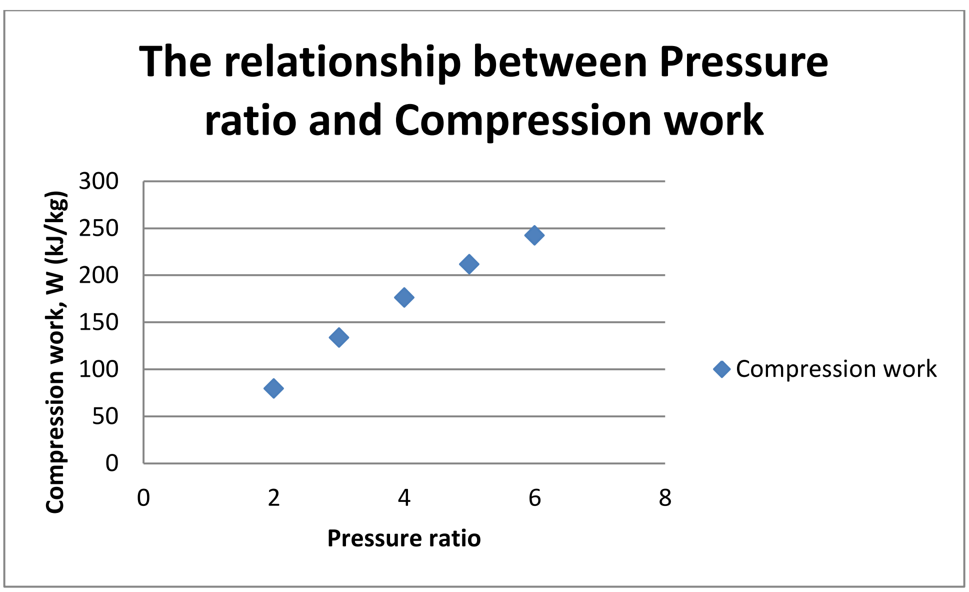

Figure 6: The relationship between pressure ratio and the compression work by the compressor

In the computation analysis, the results indicate that an increase in the pressure ratio gave a corresponding increase in the actual temperature at the inlet as shown in Figure 5, while an increase in the pressure ratio gave also a corresponding increase in the compression work done by the compressor as presented in Figure 6. This analysis is confirmed by literature, that the higher the pressure ratio the more compression work, hence, the more effective an axial compressor.

5. CONCLUSIONS

The increasing use of axial flow compressors in aero-engine technology to increase lift and smooth operation of aero-engine is of great importance to airline operators. It generates energy, a higher pressure ratio, and compression capabilities useful for the efficient operation of airlines. This research focused on the design analysis of the effect of pressure ratio on the compression work done by the compressor suitable for understanding the aerodynamic activities in an aero-engine. The results indicate a pressure ratio of 2 with an outlet temperature, and compression work done of 366.93 K and 79.32 kJ/kg respectively. Further investigation indicated that as the pressure ratio increases, there is a corresponding increase in the outlet temperature, hence, an increase in the compression work done by the in-house axial compressor, hence, a better efficiency. Therefore, this research has demonstrated the fact that the developed axial compressor setup is reliable, affordable, and environmentally friendly. This will greatly serve as a source of compressor analysis in fluid mechanics and aerodynamics studies in institutions.

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