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Analysis and Evaluation of The Performance of 7 Stage Centrifugal Compressor Apparatus with Variations in Blade Speed and Flow Rate

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Abstract

Centrifugal compressors have an important role in industry because they function to increase gas pressure through the impeller. However, efficiency and power consumption issues frequently arise, particularly under variations in blade speed and flow rate. Previous studies have mostly employed CFD simulations without direct experimental analysis of blade speed and valve opening on actual compressor performance. This study aims to analyze the performance of a seven-stage centrifugal compressor with variations in blade speed and flow rate through experimental methods to obtain efficient operating conditions. The research method involved collecting data three times with variations in blade speed and valve openings of 50%, 75%, and 100%, and analyzing isentropic efficiency based on motor power. The results showed the highest efficiency of 67% occurred at 550 RPM with a 50% valve opening, while efficiency decreased at 100% valve opening across all RPM levels. Motor power consumption increased from 35 Watts at 450 RPM to 280 Watts at 1350 RPM, but the increase in power was not accompanied by an increase in efficiency, especially at high speeds, which led to turbulence and decreased performance. In conclusion, the optimal compressor performance was achieved at medium blade speeds with partial valve openings, resulting in optimal efficiency and power consumption. These findings can serve as a reference for the design and operation of centrifugal compressors to achieve more energy- and cost-efficient performance.

Keywords: *Centrifugal; Compressor; Efficiency; Motor Power; Performance*

Abstrak

Kompressor sentrifugal dalam industri penting keberadaannya karena untuk meningkatkan tekanan gas melalui *impeller*, tetapi efisiensi serta konsumsi daya kompresor sentrifugal sering terdapat masalah, terutama dalam variasi kecepatan sudu dan debit. Penelitian yang dilakukan sebelumnya banyak menggunakan simulasi CFD tanpa adanya analisis eksperimental langsung tentang kecepatan sudu dan bukaan katup terhadap performa nyata komppresor. Tujuan penelitian untuk menganalisis performa kompresor sentrifugal 7 stage dengan variasi kecepatan sudu dan debit yang dilakukan secara eksperimental untuk memperoleh hasil yang efisien. Metode penelitian yakni dengan pengambilan data sebanyak tiga kali dengan variasi kecepatan sudu dan bukaan katup 50%,75%, dan 100%, dan menganalisis efisiensi isentropik pada daya motor. Hasil penelitian menunjukkan efisiensi tertinggi 67% terjadi pada 550 RPM dengan bukaan katup 50% sedangkan efisiensi turun pada bukaan katup 100% disemua RPM. Konsumsi daya motor meningkat dari 35 Watt pada 450 RPM menjadi 280 Watt pada 1350 RPM, peningkatan daya tidak diikuti peningkatan efisiensi terutama pada kecepatan tinggi yang akan menimbulkan turbulensi dan penurunan performa. Kesimpulan dari penelitian ini adalah performa kompresor optimal pada kecepatan sudu menengah dengan bukaan katup sebagian untuk efisiensi dan konsumsi daya yang optimal. Serta dapat dijadikan acuan sebagai desain dan pengoperasian kompresor sentrifugal yang hemat biaya dan energi.

Kata kunci: Daya Motor; Efisiensi; Kompresor; Sentrifugal; Performa

1. Introduction

The importance of centrifugal compressors in the industrial sector is such as power generation, transportation, to the oil and gas industry. This device is a core component in the industrial sector because it functions to increase gas pressure efficiently, thus supporting the continuity and reliability of production operations. Operational efficiency in industrial systems is highly dependent on compressor performance. An optimized compressor can help reduce energy consumption and overall production costs. This happens because of the way the compressor works by increasing fluid pressure using centrifugal force generated by the rotation of the impeller which then converts kinetic energy into potential energy so that it can produce higher pressure when the gas exits the compressor [1]. Centrifugal compressors can be used to increase gas pressure by utilizing the centrifugal force generated by a rotating impeller [2]. Compression can be achieved by the inertial force present in the fluid and how to rotate the impeller [3]. Centrifugal compressors can produce high pressure through the rotation of the impeller with a high rotation speed, while mass gain can occur due to the incoming air and cause centrifugal force so that it can thicken the air out [4].

Multi-stage centrifugal compressors have more than one impeller that is used to compress the fluid [5]. The speed and diameter of the impeller can affect the increase of the maximum pressure in centrifugal compressors, so multistage centrifugal compressors produce higher pressures than 1-stage centrifugal compressors, so they are usually used as applications at higher pressures [6]. The working principle of a centrifugal compressor is to generate pressure by increasing the speed of the gas passing through the impeller, to be able to obtain the desired flow and pressure can be done with control equipment to be able to adjust the speed [7]. The construction and workings of a centrifugal compressor are similar to a centrifugal pump, namely with fluid flowing air and gas with a density (kg $/m3$) that is small enough, so that it can be affected by gas pressure and temperature [8]. Converting the gas or air velocity energy generated by the action or movement of the rotating impeller from the mechanical energy of the drive unit to the potential energy of the pressure in the diffuser is the working principle of the centrifugal compressor [9]. Analysis of the performance of centrifugal compressors at varying heights shows that it will have a different effect on air flow and varying speeds [10]. The performance characteristics of a centrifugal compressor have variations based on the rotational speed (rpm), significantly affecting its efficiency and optional range [11].

The efficiency of a centrifugal compressor is the ratio or comparison between the energy used to compress gas and the energy produced by the compressor [12], while the isentropic efficiency of a compressor is the state when entering the compressor and the pressure remains with negligible heat transfer, kinetic energy, and potential energy [13]. High efficiency can indicate that the compressor operates optimally so as to minimize losses of energy during the compression process [14].

Blade or impeller speed greatly affects compressor performance. Variations in blade or impeller speed can cause changes in the fluid flow characteristics at each stage, which can increase or decrease the overall performance of the system. Higher blade speeds tend to result in higher pressure ratios and can approach surge conditions. Higher discharge conditions can also cause a decrease in isentropic efficiency and approach choke conditions. The power required by the compressor also increases along with the increase in blade speed and discharge. In this study the authors tried to analyze and evaluate a 7 stage centrifugal compressor with variations in blade speed and discharge. This variation is done to identify the advantages and disadvantages of each speed and discharge variation applied. To determine whether a certain blade speed and discharge are able to provide maximum performance and efficiency. It is important to keep the blade speed and discharge within safe limits to maintain compressor performance and stability.

Research on centrifugal compressor performance analysis has been conducted previously by Blanco-Patiño, et al (2023) where the research focuses on discussing the evaluation of centrifugal compressor performance by using Computational Fluid Dynamics (CFD) techniques [15]. The purpose of the study was to analyze more deeply the effect of operating conditions such as surge and choke on compressor performance and to compile compressor maps for various operating conditions. The result of the study is to present a complete graphical understanding of compressor performance under various operating conditions and speeds of rotation. Research by Blanco-Patiño et al. (2023) focused on numerical analysis using CFD to evaluate the performance of centrifugal compressors under various operating conditions, including surge and choke conditions. However, they have not explored experimentally how blade speed variation and flow discharge variation directly affect performance parameters such as isentropic efficiency and compressor motor power. Therefore, this study fills the gap by conducting direct experimental tests to obtain actual data on the effect of blade speed variation and valve opening on centrifugal compressor performance.

This study aims to analyze and evaluate the performance of a 7-stage centrifugal compressor with variations in blade speed and discharge. The variation is carried out to be able to identify the advantages and disadvantages in each speed variation applied and determine whether a certain blade speed is able to provide maximum performance and efficiency. The results of this study are expected to contribute to the development of more efficient centrifugal compressor technology because in this study using blade speed and discharge can be used as a more efficient and effective compressor design that can reduce energy consumption and operational costs. The evaluation conducted by the author in this study also aims to be able to assist in determining the optimal operating conditions and improve the operational reliability of the compressor, reduce the risk of failure, and extend the service life.

2. Material and Method

2.1 Research Methods

This research uses experimental methods in data collection. Data collection in this study was carried out 3 (three) times, this was done to be able to ensure that the data taken was accurate data. Data processing in this study will be carried out using Microsoft Excel, the data obtained will be analyzed to be able to determine the optimal performance of the compressor based on the isentropic efficiency value and the motor power generated from the centrifugal compressor, after which the resulting data will be presented in the form of graphical data.

2.2 Compressor Isentropic Efficiency Calculation

Compressor isentropic efficiency is the ratio between ideal work and actual work [12].

$$\boldsymbol{\eta_s} = \frac{\mathbf{h_{2s}-h_1}}{\mathbf{h_2-h_1}}100\% \tag{1}$$

η_s : Compressor isentropic efficiency (%), h_1 : Inlet enthalpy (Kj/Kg), h_2 : Outlet enthalpy (Kj/Kg), h_{2s} : Isentropic exit enthalpy (Kj/Kg)

2.3 Compressor Motor Power Calculation

Compressor motor power is the electrical power input to the compressor. The input power is determined by the voltage (V) and current (I) consumed by the compressor. Input power is measured in watts (W).

$$W_{motor} = V \text{ x } I \tag{2}$$

W_{motor} = Motor input power (Watt), V = Voltage , I = Current

2.4 Research Variabels

The variables in this study consist of independent variables, control variables, and dependent variables. The independent variable is a variable that is regulated to determine its effect on the dependent variable, namely blade speed,. discharge or compressor open valve. The blade speed set in this study has 10 variations with multiples per 100 RPM. Starting from 450 RPM to 1350 RPM. In the debit setting using a ball valve stop valve "2" with opening levels ranging from 50%, 75%, and 100%. The dependent variable is a factor that is influenced by changes in the independent variable and is used to measure the results of the centrifugal compressor performance, namely compressor efficiency, and motor power generated by the centrifugal compressor. The control variable is a fixed and constant factor in this study, namely the type of centrifugal compressor used with type YS 0042 demonstration unit 7 stage.

2.5 Tools and Materials

Figure 1. YS 0042 Centrifugal Compressor *Demonstration unit* 7 *stage*

Figure 2. Stop Ball Valve “2”

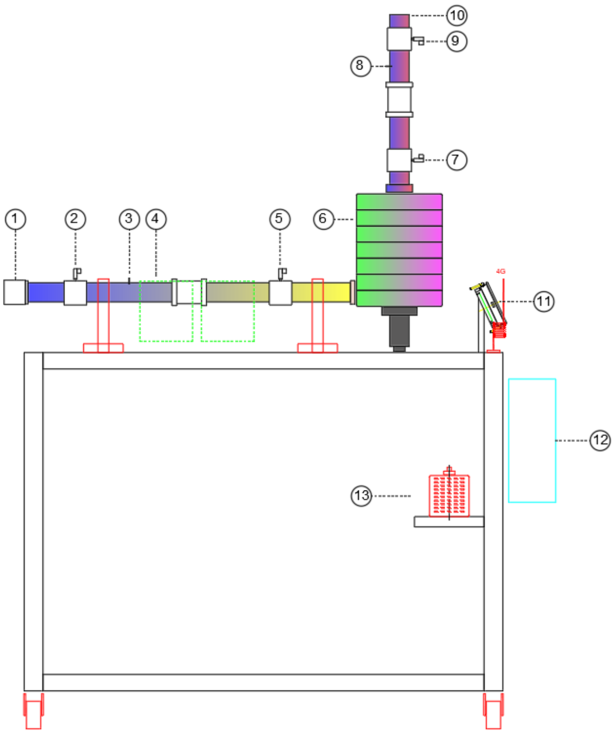

Figure 3. Component schematic of YS 0042 Centrifugal Compressor Demonstration unit 7 Stage

Description :

1. *Air Outlet*
2. *Pressure Sensor* 1
3. *Temperature Sensor* 1
4. *Junction Box (Sensor Box)*
5. *Pressure Sensor*
6. *Compressor Stack*
7. *Pressure Sensor* 3
8. *Temperature Sensor* 2
9. *Pressure Sensor* 4
10. *Air Inlet*
11. HMI (Monitor Screen)
12. *Panel Control*
13. *Adjustable Trafo*

The tools and materials used in this research are using a centrifugal compressor with the number YS 0042 demonstration unit 7 stage and stop valve ball faucet "2". In Figure 1, and 2, it can be seen that Figure 1 shows a 7 stage centrifugal compressor apparatus that uses acrylic pipe material measuring "2". This compressor is also equipped with several sensors to measure compressor performance parameters such as pressure, temperature, and flow rate. The complete specifications of the sensors on the 7 stage centrifugal compressor can be seen in Table 2. In Figure 2, it can be seen that the ball valve stop valve measuring "2" is used to regulate the compressor discharge. The valve is installed at the air inlet of the compressor with the aim of regulating the air flow discharge into the centrifugal compressor. The component scheme of the research tool can be seen in Figure 3.

To provide an understanding of the working characteristics and design of the test system, it is necessary to know the specifications of the centrifugal compressor used. These specifications include voltage, frequency, power, sensors, and inlet and outlet dimensions of the compressor. The following is presented in Table 1 which describes the complete specifications of the centrifugal compressor.

Table 1. YS 0042 Centrifugal Compressor Demonstration Unit 7 Stage

YS 0042 Centrifugal Compressor Demonstration Unit 7 Stage	
Voltage	*1 PHASE/220VAC-240VAC*
Frequency	50 HZ
Power	1200 W
Curent	6 A (MAX)
RPM	2986
Blade Dim	θ 5”
Inlet Dim	θ 1,5”
Outlet Dim	θ 1,5”
Inlet Pipe	θ 2”
Outlet Pipe	θ 2”
Pressure Sensor	0-10 Kpa
Mass Air Flow Sensor	175 gm/sec
Temperature Sensor	0-100℃

Table 2. Specifications of 7-Stage Centrifugal Compressor Measuring Instrument

Measuring Instrument	Range	Accuracy
Pressure Sensor	0-10 kPa	±0.01kPa
Mass Air Flow Sensor	175 g/sec	±0.1g/s
Temperature Sensor	0-100 ºC	±1ºC

3. Results and Discussion

The results of this study indicate that compressor efficiency tends to decrease as the valve opening increases, both at low and high speeds. This phenomenon occurs due to the principle of flow losses caused by increased turbulence at high flow rates. In centrifugal compressors, as the flow rate through the impeller increases, the relative velocity distribution of the fluid becomes uneven. This aligns with the research conducted by Zhao et al. (2018), which states that an increase in flow rate at high speeds can accelerate the occurrence of choking, resulting in a drastic decrease in efficiency. This efficiency decline occurs due to a phenomenon known as choking. As the valve opening increases, the air mass also increases. This causes the flow velocity within the diffuser and impeller to become turbulent and uneven, ultimately reducing overall isentropic efficiency.

In Figure 4, it can be seen that the isentropic efficiency of the compressor has decreased, where at a blade speed of 550 RPM, the highest efficiency was recorded at about 67% at 50% valve opening. However, the efficiency decreased drastically to about 50% at 75% valve opening and continued to decrease to about 42% at 100% valve opening. This significant drop in efficiency indicates that there is an optimum operating point with respect to the valve opening for each blade speed, and going beyond that point will reduce the performance of the compressor. When the valves were opened wider at 75% and 100%, there was a significant drop in efficiency at all RPM levels. At 550 RPM, the efficiency dropped from 68% at 50% open valve to about 51% at 75%, and further decreased to about 42% at 100%.

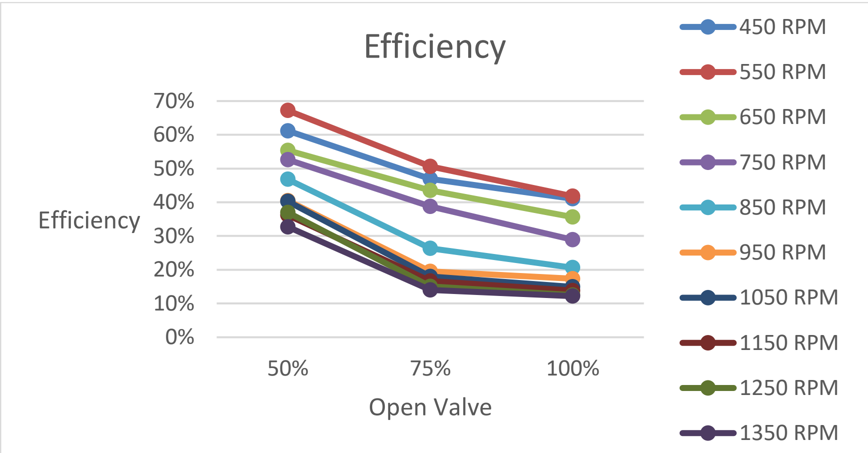

Figure 4. Graph of Centrifugal Compressor Efficiency against RPM Variations and Valve Openings

In Figure 4, it can be seen that the highest efficiency occurs at medium RPM (550-650 RPM) with the valve partially open (50%). In this speed range, the flow profile inside the impeller and diffuser tends to be more stable. In contrast, at high RPMs such as 1250 and 1350 RPM, the efficiency tends to be very low and stagnates at around 10-15% even when the valve is only 50% open. This indicates that over-speed occurs, where the flow becomes turbulent and unstable resulting in inefficient compressor performance. When the valve is 100% open, the entire curve tends to converge in the low efficiency range of about 10-40%.

This phenomenon occurs when excessive flow causes uneven pressure distribution. This results in increased compressor work but disproportionate output, thereby reducing compressor efficiency. When compared to the CFD-based research by Blanco-Patiño et al. (2023), a trend of decreasing efficiency also occurs when the flow rate increases, even under simulated conditions. However, in this study, experimental results show that optimal conditions are achieved at medium speeds (550–650 RPM) with a valve opening of 50%. This indicates that experimental results align with CFD predictions but provide real-world data that can be used for validation.

Figure 5 shows the relationship between motor power and valve opening variation at various rotational speeds (RPM) of the centrifugal compressor. The three opening levels analyzed are 50%, 75%, and 100%, with a motor speed range from 450 RPM to 1350 RPM. Motor power increases as rotational speed increases. From the perspective of motor power consumption, the increase in power with increasing rotational speed aligns with the input power theory for compressors. An increase in blade speed raises the specific enthalpy of the output, thereby increasing the required power. At low speeds such as 450 RPM, power consumption is only around 35–40 Watts, while at the highest speed of 1350 RPM, the motor power reaches 280 Watts. Research by Dwiaji & Firdaus (2022) shows that an increase in the operating load of a centrifugal compressor is directly proportional to the energy consumption of the electric motor, although this is not always accompanied by an increase in efficiency. This aligns with the findings of this study, where power consumption reaches 280 W at 1350 RPM, but efficiency is only 12–14%.

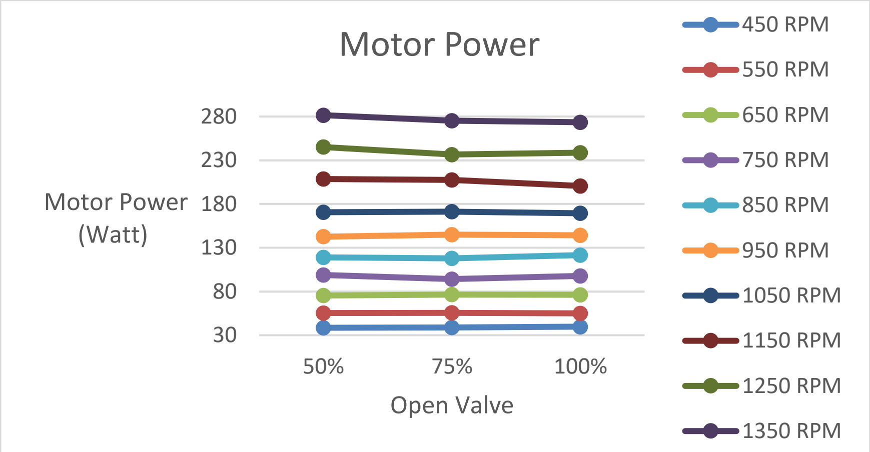

Figure 5. Graph of Motor Power against RPM Variations and Valve Openings

This pattern is consistent across all valve opening variations. At the highest blade speed of 1350 RPM, the motor power at a 50% valve opening produces 280 Watts, and at a 100% valve opening, it decreases slightly to 275 Watts. A similar pattern, i.e., a slight decrease in power or stability, is also observed at blade speeds of 1250 RPM and 1150 RPM. Meanwhile, at lower RPMs such as 450 RPM to 1050 RPM, the motor power remains relatively constant across all valve opening variations. Some RPM values show stable power consumption across all three valve opening levels. At 850 RPM and 950 RPM, the curve is nearly flat from 50% to 100% valve opening, with motor power ranging from 130–170 Watts. At 1050 RPM and 1150 RPM, the motor power slightly decreases at 100% valve opening. Meanwhile, at 1350 RPM, although it is the highest value in the graph, it still shows a relatively constant power consumption trend from 50% to 100% valve opening, around 275–285 Watts. At constant speed, the power curve tends to be relatively flat within the normal operating range.

Although the flow rate increases, power requirements do not increase significantly or even decrease slightly if the compressor operates far from its peak efficiency point. Thus, the total power required by the motor does not increase significantly. This condition can occur due to a decrease in isentropic efficiency and the occurrence of turbulence in the air flow. Although the motor consumes more power, the energy supplied cannot be fully utilized to generate additional pressure. At high rotational speeds, although motor power increases, efficiency decreases due to aerodynamic losses. Conversely, at medium speeds, a balance between flow stability and power consumption can be achieved, resulting in optimal efficiency.

4. Conclusion

Based on the analysis that has been carried out, it can be concluded that the highest efficiency values are obtained in the middle rotational speed range, between 550 to 650 RPM, with a valve opening condition of 50%. The compressor efficiency is higher at lower blade speeds, with a peak efficiency of about 67% recorded at 550 RPM and 50% valve opening. Conversely, significantly increasing blade speed demands significantly more motor power consumption. As the valve opening increases to 100%, the efficiency tends to decrease significantly across the speed variations. Motor power consumption shows a consistent increase as the rotational speed increases. However, this increase in power is not always followed by an increase in efficiency. At high speeds such as 1250 to 1350 RPM, although the required motor power is very large, the efficiency is at its lowest.

The resulting motor power varies from about 35 Watts at 450 RPM to a peak of about 280 Watts at 1350 RPM. The motor power showed relatively stable or slightly decreasing characteristics as the valve opening increased at a given blade speed and the efficiency changed at higher discharge. Overall, this study confirms that to achieve optimal compressor performance, both in terms of efficiency and power consumption, to select the right combination of blade speed and valve opening. Although lower blade speeds tend to be more efficient and require less motor power.

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