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EFFECT OF OPERATING ENVIRONMENT ON VOLUMETRIC EFFICIENCY AND CHARACTERISTIC PARAMETERS OF HEAVY VEHICLE PISTON COMPRESSORS

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Keywords

Piston Compressor, Volumetric Efficiency, Flow Rate, Heavy Vehicle Sector

Abstract

Compressed air is used as an effective power source in industrial applications and heavy vehicles. Piston compressors, which are widely used in pneumatic systems, meet the need for compressed air especially in heavy vehicles. In this study, the volumetric efficiencies of compressors from two different manufacturers were tested at pressures of 8.5, 10 and 12.5 bar and speeds between 500-3000 rpm. The efficiency of Yumak brand compressors was found to be in the range of 48-63%, while the efficiency of OEM products was 44-56%. Although Yumak compressors are more efficient, they consume 10% more energy. While the effect of environmental conditions on performance was limited, speed changes were found to be 400%-650% effective on flow rate and consumption.

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ÇALIŞMA ORTAMININ AĞIR VASITA PİSTONLU KOMPRESÖRLERİN HACİMSEL VERİMLİLİĞİ VE KARAKTERİSTİK PARAMETRELERİ ÜZERİNE ETKİSİ

Anahtar Kelimeler

Pistonlu Kompresör, Hacimsel Verim, Debi, Ağır Vasıta Sektörü

Öz

Basınçlı hava, endüstriyel uygulamalarda ve ağır taşıtlarda etkin bir güç kaynağı olarak kullanılmaktadır. Pnömatik sistemlerde yaygın kullanılan pistonlu kompresörler, özellikle ağır vasıtalarda basınçlı hava ihtiyacını karşılamaktadır. Bu çalışmada, iki farklı üreticiye ait kompresörlerin hacimsel verimleri 8.5, 10 ve 12.5 bar basınçlarda, 500–3000 rpm arası hızlarda test edilmiştir. Yumak marka kompresörlerin verimi %48–63, OEM ürünlerin verimi ise %44–56 aralığında bulunmuştur. Yumak kompresörleri daha verimli olsa da %10 daha fazla enerji tüketmektedir. Çevresel koşulların performansa etkisi sınırlı kalırken, hız değişimlerinin debi ve tüketim üzerinde %400–%650 etkili olduğu görülmüştür.

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Extended Abstract

Introduction

Compressed air is widely used as an effective and reliable energy source in a wide range of applications from industrial plants to heavy vehicles. Especially in heavy vehicles such as trucks, buses and lorries, pneumatic systems are used to operate various mechanisms such as brake systems, suspensions and hatch opening systems. Piston compressors, which are the basis of these systems, are one of the most critical components that meet the in-vehicle air requirement. However, the operating efficiency of these compressors varies depending on many factors such as environmental conditions, mechanical wear and production differences. In this context, it is of great importance to accurately analyse and improve compressor efficiency in terms of vehicle performance, safety and energy consumption.

Research Purpose

The main objective of this study is to comparatively investigate the performance and volumetric efficiency levels of reciprocating compressors with the same technical specifications but from different manufacturers under different ambient conditions. Aftermarket compressors manufactured by Yumak company and original equipment manufacturer (OEM) compressors were evaluated under equal test scenarios and it was aimed to determine the performance differences due to production.

Subject

Volumetric efficiency is a basic parameter that directly affects the performance of reciprocating compressors; it expresses the extent to which the air sucked during the piston's traction movement can be pressurised by the compression movement. There are many studies on this subject in the literature; however, the majority of these studies are focused on compressors used in refrigerators, air conditioning and industrial refrigeration systems. Especially in the heavy vehicle sector, comprehensive experimental comparisons in test environments close to field conditions are limited. Both compressors used in this study have the same cylinder volume (628 cm^3), the same stroke (54 mm) and diameter (Ø86 mm) dimensions and have a double cylinder structure. Thus, all technical conditions were kept constant during the test except for the manufacturer difference. In this respect, the study fills the gap in the literature and makes it possible to directly observe the effect of manufacturing differences on performance. In addition, the highly accurate data obtained from the test rig and sensor-based measurement system used in the study enables reliable analysis of characteristic parameters such as volumetric efficiency, power consumption and flow rate.

Methods

In the study, both compressors were tested at three different tank pressures of 8.5, 10 and 12.5 bar and 6 different engine speeds in the range of 500-3000 rpm. The tests were performed in a total of four different environments: Two of them were carried out under ambient conditions set according to DIN 1343 standard and the other two were carried out under real laboratory conditions. In each environment, first the Yumak compressor and then the OEM compressor were tested and these tests were analysed in terms of both flow rate and energy consumption. The test rig is a life tester driven by a 30 kW motor and measures parameters such as flow rate, temperature, pressure, power with sensitive sensors. Air flow measurements were made with a SICK FTMG sensor with ±1% accuracy. In addition, the accuracy of the flow rate values was checked by measuring the filling time of the 90 litre air tank at certain speeds. The formula used for volumetric efficiency calculations was based on Fujiwara and Osada (1995).

Results

According to the test results, the volumetric efficiency range of the Yumak compressor obtained in DIN 1343 environment varied between 43.06% and 49.92%, and in laboratory conditions between 48.75% and 63.07%. The efficiency range of the OEM compressor was determined as 35.14% to 45.05% in DIN 1343 test and 44.33% to 56.77% in laboratory conditions. While the Yumak compressor offered higher volumetric efficiency in general, it consumed approximately 10% more energy than the OEM compressor in all conditions. In addition, it was observed that the increase in the number of revolutions had an effect on the flow rate up to 440% and on the power consumption up to 630%. For example, while the Yumak compressor pumped 0.183 m^3/min of air at 500 rpm, this value reached 0.810 m^3/min at 3000 rpm. In the OEM compressor, the flow rate of 0.129 m^3/min at 500 rpm increased to 0.740 m^3/min at 3000 rpm. At the same time, it was determined that as the tank pressure increased, the output air quantity decreased due to valve resistances and the volumetric efficiency decreased accordingly. It was concluded that the test ambient conditions did not make a significant difference on flow rate and power consumption, but it is necessary to evaluate in terms of sensor calibration and flow measurement accuracy. The 90 litre tank filling time results also support that the measurements made under laboratory conditions give more accurate results.

Discussion and Conclusions

As a result of this study, the characteristic efficiencies of two compressors with the same nominal specifications but different manufacturing sources were revealed. Although they are aftermarket products, Yumak compressors offer higher volumetric efficiency compared to OEM products. However, it was determined that they need to be optimised in terms of energy efficiency due to their higher power consumption. The study contributes to the literature in terms of being carried out in an experimental environment similar to field conditions and directly analysing manufacturer differences. For future studies, it is recommended to examine the effects of long-term life tests at different load profiles, the effects of parameters such as variable temperature and humidity, and the effects of manufacturing methods (e.g. casting and CNC machining differences) on efficiency. In addition, it may be important to evaluate the test environments in conditions with environmental differences such as high altitude to determine whether different effects on volumetric yield occur.

1. Introduction

Compressed air is needed from time to time in various sectors and applications on a global scale. Pressurized air is used as an output or drive mechanism in brake mechanisms of heavy vehicles, pneumatically driven drills, etc. hand tools, various valve systems and many other areas. The generation of compressed air enters a pneumatic system and is challenging. As a compressed air production system, basically most common production machine is air compressors. There are many compressor usage areas such as industrial type compressors for industrial needs, vehicle compressors for transportation sectors. For characteristics such as the size of air demand and amount of pressure level, operating parameters of compressor and air values that offer change and the nomenclature is differentiated.

Compressor types are diversified according to difference in working mechanism, even if the nomenclature of air compressors varies according to the difference in the application that using. There are many types of compressors such as piston, vane, screw, scroll, centrifugal compressors. The main objective of all compressors is to pressurize air, but compressor components change when pressurizing. In screw compressors, the air is pressurized by rotor movement created by two screws with grooves drilled on them, while in vane type compressors, pressurization is provided during the circular rotation of a rotor shaft with plate-shaped blades on it (Wu and Zhang, 2022). The most widely used type of compressor is the reciprocating compressor. Reciprocating compressors, which operate on principle of crank-connecting rod mechanism, basically consist of crank, connecting rod, piston and cylinder components. During one revolution of the crankshaft, a piston, connected to crank by a connecting rod, translates back and forward (Jiang, Mao, Zhang and Zhang, 2017). Current crank-connector mechanism and piston cylinder components are not only found in compressors, but also in internal combustion engines. For compressors, the crank mechanism completes the air suction period by providing air suction while the piston moves backwards. (Shu and Fu, 2022). As the piston moves forward, air sucked in is compressed and pressure of air is increased. Pressurized air is first sent to an air tank and then to the place of use. However, there are problems that can occur in reciprocating compressors.

Sealing is one of the most common problems that occur in reciprocating compressors during operation. Lack of adequate lubrication in the system increases mechanical friction and may cause air leaks due to component wear. Therefore, life of the compressor is prematurely exhausted and its mechanical efficiency decreases (Li, Diao, Guo, Jia, Zhang and Peng, 2023). Another aspect is determined by the volumetric efficiency with which compressor offers successful pressurization. If the compressor pressurizes all of air it sucks in, it shows that it operates with 100% volumetric efficiency, but sealing leaks that occur have a negative effect on the pressurization of all air and the volumetric efficiency of the compressor decreases. In addition to sealing problems, the structural design and operating principle of reciprocating compressor creates a dead volume in the compressor (Nikitin, Asoyan, Nikitin and Turoverov, 2020). Existing dead volume refers to the area where air should be compressed but is not compressed due to working principle. This dead volume means that each full revolution of the crankshaft will have dead volume that is not compressed, and therefore the volumetric efficiency level will drop significantly.

Various studies have been conducted on the volumetric efficiency of reciprocating compressors. There are academic studies in the literature on dead volume effect, sealing and leakage problems or effect of mechanical friction on volumetric efficiency. Air compressors used in many sectors and applications are experiencing current problems and volumetric efficiency is decreasing (Ren, Jia, Jiang, Zhang, Zhao and Peng, 2022). In a study, volumetric efficiency of a refrigerator compressor used for refrigeration was experimentally measured and the reason for low volumetric efficiency was tried to be explained depending on amount of fluid passing through valves, leakage in piston-cylinder cavity and thermophysical properties of refrigerant. A mathematical model was prepared and experimental parameters were compared with theoretical results (Schreiner, Deschamps and Barbosa, 2010). In another study, effect of different refrigerants on volumetric efficiency of compressors in a reciprocating compressor used in refrigeration was investigated. (Roskosch, Venzik and Atakan, 2017). Volumetric efficiency was measured according to refrigerants that can be used and an algorithm that gives volumetric efficiency was developed and it gives accurate results with a deviation of 2.3%. Many studies have been conducted for compressors used in refrigeration applications. In two separate studies, volumetric efficiency was also investigated for reciprocating compressors. In both studies, numerical models were presented to demonstrate effects of thermodynamic effects and leakage problems in the system on volumetric efficiency (Pérez-Segarra, Rigola, Soria and Oliva, 2005; Tuhovcak, Hejcik and Jicha, 2016). In a previous example, an attempt was made to identify main factors causing low volumetric efficiency in reciprocating compressors, and it was found that compressed fluid is parameter that affects volumetric efficiency mostly (McGovern, 1990). There are many examples in literature for refrigerator compressors. In these studies, fluid effect, leakage problems, effect of the dimensional condition of compressor components on volumetric efficiency and fluid motion in motion channels are investigated (Rigola, Pérez-Segarra and Oliva, 2005; Stouffs, Tazerout and Wauters, 2001). In the results obtained in these studies, new mathematical models were derived in which parameters were included by deriving theoretical expressions that give overall volumetric efficiency.

Pressure (P)-volume (v) diagram is drawn to determine the performance graph of reciprocating compressors. Volumetric efficiency is calculated from the P-v diagram. Initial volume of air sucked into a compressor cylinder, volume reduction with piston movement and dead volume can be calculated with P-v diagram. In one study, compressor pressure-volume characteristics were established by determining the movement of valves according to load and idle operation of a compressor. Leakage problems in compressor were also included in study and effect of leakage problems on pressure was measured on P-v diagram (Phillippi, 2016; Pichler, Lughofer, Pichler, Buchegger, Klement and Huschenbett, 2015). Looking at other studies, movement of compressor valves has been measured using pressure sensors. Subtracting times such as when valves open and when they close, P-v diagram is drawn according to cycle (Real and Pereira, 2010; Wang, Gao, Zhao and Cong, 2015). As a result of these studies, it was found that valve movement affects curves in P-v diagrams and indirectly changes volumetric efficiencies. In another study, a strain gage was installed in compression chamber and strain levels during compression were measured, and both pressure change in compressor was determined and P-v diagram was drawn and dynamic load characteristics of components were revealed (Li, Peng, Zhang, Jia and Wang, 2019; Wang, Qi, Xiong and Peng, 2024). There have been many studies on valve movement and valve characteristics in drawing pressure-volume diagrams in compressors. Among these studies, valve motion with linear discriminant analysis and using SVM are available as most different sources in literature. In the studies, various vector support methods were used and parameters such as compression ratio, P-v diagram and volumetric efficiency were achieved (Li, Ren, Zhang, Jia and Peng, 2022; Wang, Song, Zhang and Li, 2010). There have been several studies on P-v diagram of the compressor. Existing studies generally focus on suction and exhaust valves. There are not many studies on compressor velocity and pressure variation.

A number of studies have also been conducted on one of parameters most influential on volumetric yield, dead volume, also known as clearance volume. In one study, a mathematical model was developed to predict volumetric efficiency of an axial compressor by varying amounts of cleaning volume (Storer and Cumpsty, 1993). In another study, it was found that leakage problems can be tolerated in compressors with small dead volumes and depending on type of fluid used in the compressor (Sakulkaew, Tan, Donahoo, Cornelius and Montgomery, 2013; Liu, Kang, Lv, Feng, Wu and Li, 2025). A number of studies have investigated the effects of dead volume in compressors with low compression ratio and low strokes. Linear type reciprocating compressors were used in these studies and it was found that dead volume does not affect volumetric efficiency much when compression is not high (Jiang, Mao, Zhang and Zhang, 2020; Wang, Liu, Zhao and Li, 2015). Dead volume effect has been investigated not only in reciprocating compressors but also in centrifugal compressors. The study determined how the space ratio and dead volume of a centrifugal compressor affect compression and air delivery (Nili-Ahmadabadi, Hajilouy-Benisi, Durali and Ghadak, 2008). Although there is also dead volume in centrifugal compressors, there is a study on this subject by Saaresti et al. in which effect of dead volume on compressor performance was investigated (Turunen-Saaresti and Jaatinen, 2013).

When the parameters affecting compressor volumetric efficiency and performance are examined; compressors used extensively in refrigeration applications and studies in which theoretical determination and prediction of current situation are attempted are found in literature. However, especially in the automotive sector, air compressors are used in heavy vehicles. In the case of on-board compressors, in addition to compressor operating conditions, vehicle operation is also involved, and additional effects on compressor are caused by vehicle movement. In this context, the performances of air compressors produced by Yumak automotive company as aftermarket were compared with the other original manufacturers (OEM) product. Yumak company develops products by applying reverse engineering studies to the product produced by existing manufacturers. This situation is known as aftermarket. In addition to comparing the products of the companies in the study, the tests were tested at 3 different pressure values between 8-13 bar. At each pressure, the compressor operating velocity was started at 500 rpm for 10 minutes and then the velocity value was run for a total of one hour with periodic increases of 500 rpm up to 3000 rpm, repeating the same process. During the study, the suction flow rate was measured using a sensor and volumetric efficiency levels were determined.

2. Materials and Method

In this study, the volumetric efficiency of air compressors used in heavy duty vehicles was investigated. Two different brands of the same model compressor were tested for the investigation. One of the compressors is a Yumak product and the other is an OEM product characteristic of the compressor are given in Table 1. The parameters that determine the compressor characteristics were kept the same for both companies and the differences were tried to be measured as a result of the tests performed under the same conditions. For this reason, the values in Table 1 cover the compressors of both companies.

Table 1. Compressor Characteristic

Coolant	Water with antifreeze
Bore (mm)	Ø86
Stroke (mm)	54
Swept Volume (cm^3)	628
Max. Working Velocity (rpm)	3000
Max. Pressure (bar)	14
Cylinder Number	Twin cylinder

During the test, air suction flow rates, air outlet pressures and power consumption of the compressors were measured. On the test machine, a 30 kW electric motor is loaded to the compressor velocity. rpm and power consumption data were obtained directly from the electric motor. The intake volume and various power consumption values may vary depending on the operating velocity during the compressor's intake and compression processes. The obtained data enable a more detailed analysis of the compressor performance, providing important insights into system efficiency and energy consumption. In addition to these, many data were taken from the test device. The measurement capabilities of the test device are as shown in Table 2. The specified velocity and various parameters are adjusted on the compressor test device.

Table 2. Test Machine Capabilities

Equipment	Function	Quantity
Pressure sensor for air	Measurement of air discharge pressure	1
Pressure sensor for air	Measurement of air tank pressure	1
Pressure sensor for oil	Measurement of oil inlet pressure	1
Flowmeter for air	Measurement of air inlet flowrate	1
Flowmeter for oil	Measurement of oil inlet flowrate	1
Flowmeter for water	Measurement of coolant inlet flowrate	1
Thermocouple	Measurement of oil inlet temperature	1
	Measurement of air outlet temperature	1
	Measurement of coolant inlet temperature	1

Equal test conditions were provided for both compressors and are given in Table 3.

Table 3. Test Conditions

Oil Inlet Pressure (bar)	5 ± 0,5
Oil Inlet Temperature (°C)	100 ± 5
Coolant Flow Rate (l/min)	10 ± 1
Coolant Inlet Temperature (°C)	90 ± 5

In addition to the comparison of compressor brands, a comparison was also made regarding the flow meter settings used in the air inlet. First of all, the ambient condition settings on the flow meter were set according to DIN1343 standard and both compressors were tested under these conditions. Afterwards, the ambient condition settings on the flow meter were adjusted according to the test laboratory data and both compressors were tested again. DIN1343 and laboratory conditions are given in Table 4.

Table 4. Flow Meter Ambient Condition Settings According to DIN1343 and Laboratory Conditions

Parameter	DIN1343	Laboratory Conditions
Ambient Temperature (°C)	0	25
Atmosphere Pressure (bar)	1.01325	0.9

The DIN1343 standard defines the reference conditions for volume flow measurements of gases. According to this standard, the ambient temperature is 0°C, the atmospheric pressure is 1.01325 bar and the relative humidity is 0%. These conditions are used to ensure that measurements made in different test environments are comparable with each other (DIN,1996). The flowmeter used in this study was first adjusted according to DIN1343 standard and then tested again according to the actual ambient conditions of the laboratory, 25°C temperature and 0.9 bar pressure. Thus, the effect of deviations from the reference environment on the flow rate measurement and thus on the volumetric efficiency calculations was evaluated. This comparison demonstrates the importance of evaluating compressor performance under both standard and real conditions.

While adjusting the sequence of the sensor used for flow measurement, environmental conditions may affect the results. A total of 4 different tests were applied by applying 2 different tests to each of the compressors. The same test scenario was applied for each of these tests. In the test, the air tank was set to 3 different pressures and under these pressures the compressors were operated at 6 different velocities for 10 minutes each. These velocities and pressures are given in Table 5 as a test scenario.

Table 5. Test Scenario for Each Test

Revolution (rpm)	Duration (min)	Tank Pressure (bar)
500	10	8,5
1000	10	
1500	10	
2000	10	
2500	10	
3000	10	
500	10	10
1000	10	
1500	10	
2000	10	
2500	10	
3000	10	
500	10	12,5
1000	10	
1500	10	
2000	10	
2500	10	
3000	10	
	Total = 3 Hour	

In addition to these tests, in order to verify which of the flowmeter results is correct, a test was performed to fill a 90 L air tank at 2000 rpm and 2500 rpm until it reached a pressure of 8.5 bar. With this test, numerical calculation was performed to determine which flow meter setting gave the correct result. Differences in flow meter readings are due to tank volume and operating velocities. Moreover, the ambient conditions and the height above sea level have an impact on the flow meter results. All tests applied to the compressors were carried out with the compressor life test device of Yumak Automotive company. The general view of test device and air tanks on the device, the plumbing section where measurements are made with sensors, the section where compressors are connected and the motor part that drives the test device are given in Figure 1. In addition to measuring the flow rate of the air coming from the suction, the present tester can measure the pressure and temperature of the oil at the inlet and outlet of the compressor, the pressure of the air, the temperature and pressure of the cooling water.

The test machine basically consists of 4 main parts. In the motor section shown in Figure 1.(e), there is an electric motor and the motion from this motor is transmitted to compressor by means of a belt-pulley system and then a coupling. The compressor, which is connected to the fixture and support table on the test machine, is operated by means of motion transmitted from the motor. Figure 1.(c) shows the part where the compressor is connected to the test machine. After the compressor works, the pressurised air is sent to the air tanks by passing through the installation section in Figure 1.(d). The section where the air tanks are located is expressed in Figure 1.(b). As can be seen in Figure 1.(d), there are other pipes apart from the lines through which the air passes. These lines are oil and water lines.

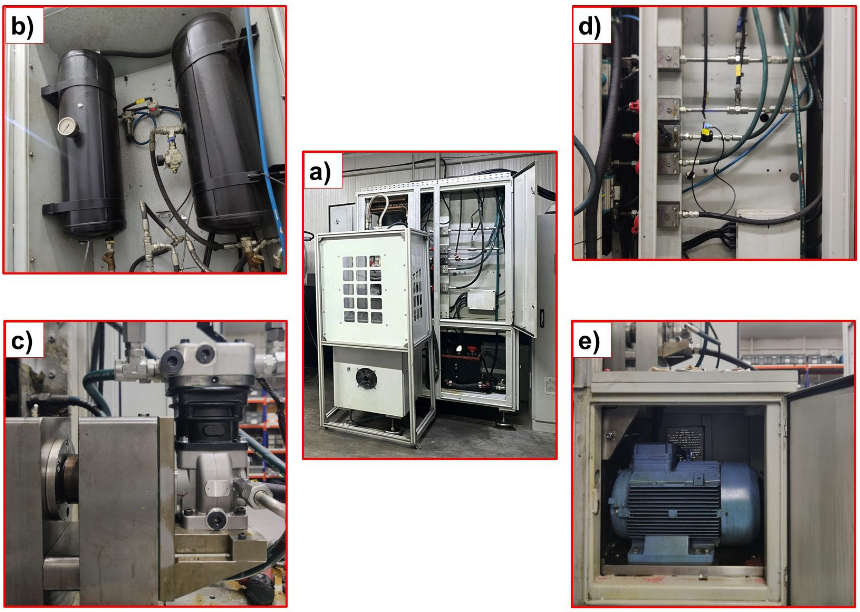

Figure 1. Compressor Life-Test Device; a) External Appearance, b) Air Tank Section, c) Compressor Connection Section, d) Plumbing Section, e) Engine Section

During the operation of the compressor, the compressor is constantly lubricated to minimise friction and reduce wear. For this reason, there are two separate lines for the oil input and output of the compressor. In addition, as the compressor runs, temperatures reach high levels. Water circulates in compressor in order to reduce temperatures. Two separate channels are used for sending and receiving water to and from the compressor. The compressor is cooled by water and factors that may reduce the life of the compressor during operation are prevented. The working principle of the test device and details such as oil, water, air lines are expressed in the schematic test device image in Figure 2.

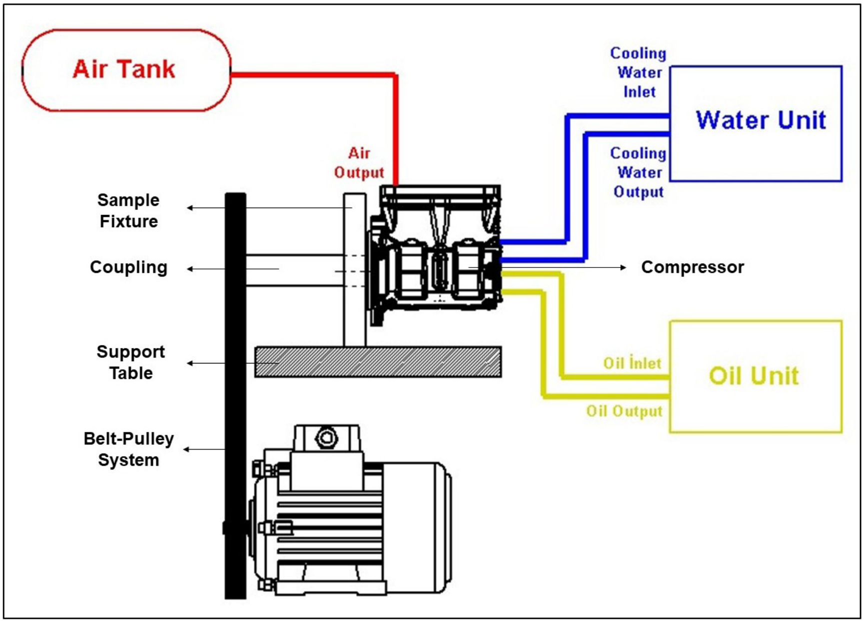

Figure 2. Compressor Life Test Device Schematic View

Performance tests of compressors belonging to two different sectors and having identical characteristics were carried out by using the test device whose working principle is explained in detail. The main technical specifications of the compressors subjected to the test are presented in Table 3. The measurement capabilities of the tester are based entirely on a sensor-based system. There is a total of five separate lines in the device; oil inlet-outlet, water inlet-outlet and pressurised air is transmitted to the air tank. While the air pressure is measured via the air line, the outlet temperature of the compressed air is also determined with the help of a temperature sensor located on the same line. TRAFAG/ECT brand pressure sensor was used for pressure measurement in the air line and PT100 brand temperature sensor was used for temperature measurement. These sensors have both high accuracy and sensitivity at ± 0.5% FS level. The temperature sensor is capable of measuring values up to 400°C. As the compressor operates, the internal temperature increases and this directly affects the life of the mechanical components. For this reason, the heavy vehicle compressors tested were designed as 'water-cooled air compressors' to meet the cooling requirement. During the test, cooling water is supplied into the compressor via a water line. This water circulates through the compressor to stabilise temperatures and then exits the system via a return line. Water lines are equipped with the same brand and model sensors as those used in the air line; thus, pressure and temperature measurements can also be taken from these lines. In addition, water flow rate is also measured with a flowmeter on the water line. For this purpose, SICK/FTMG brand flow sensor was preferred.

However, the air flow rate, which is the most critical parameter of the test, is the basic data that reveals the characteristic performance of the compressor. A SICK/FTMG brand sensor is used to measure the air flow rate and the measurement accuracy of this sensor is ±1% FS. Most of these sensors can be seen in the installation section shown in Figure 1.(d). Some other important measurement equipment not shown in the figures are SIEMENS SINAMICS 37 kW drive and SICK AFC tachometer sensors used to measure power consumption and compressor rotation velocity. Thanks to this equipment, both electrical power consumption and rotational velocity of the compressors were determined with high precision. These measurements were carried out during the transmission of the movement of the motor from the connection point in the test device to the compressor.

The results obtained as a result of the measurements were used for volumetric efficiency comparison. Volumetric efficiency is a characteristic of the compressor and directly represents its performance. Literature review reveals the most commonly used formulation on volumetric efficiency. The following formula was used in the calculation in Equation (1). The equation is taken from a study (Fujiwara & Osada, 1995)

$$\text{Volumetric Effiency (\%)} = \frac{\text{Air flow rate}}{\text{Swept volume of compressor} * \text{rpm}} * 100$$

The technical capabilities and working principle of device used in the compressor test are explained in detail. With this device, the test process of two different compressors with the technical specifications specified in Table 1 was carried out. One of the compressors subjected to the test belongs to Yumak company operating in the aftermarket sector, while the other belongs to an original equipment manufacturer (OEM) company. Although both compressors are identical in terms of physical dimensions and technical specifications, they exhibited different performance superiorities as a result of the measurements made. In the experimental process, both compressors were tested in two different ambient conditions. The numerical parameters of these ambient conditions are given in Table 4. Firstly, the compressors were operated under the ambient conditions determined according to DIN 1343 standard using the appropriate sensor software. In these tests, the power consumption, air flow rate and outlet pressure of the compressors were measured with sensors and the volumetric efficiency was calculated by using theoretical formulae with the flow rate values obtained. The same compressors were then subjected to the same test procedure, this time under real laboratory conditions. In this way, the effect of ambient conditions on compressor performance was comparatively evaluated. Under both ambient conditions, the compressors were first tested at a pressure level of 8.5 bar for a total of 1 hour. During this time, the compressors were operated at 500 rpm increments every 10 minutes. The test was started at 500 rpm, the compressor was operated at 8.5 bar pressure for 10 minutes, then the speed was increased to 1000 rpm and the same procedure was followed. With this method, a total of 1 hour of testing was completed with increasing speeds between 500 and 3000 rpm under constant pressure. The same procedure was repeated at two more pressure levels, 10 bar and 12.5 bar. During the test, the power consumption and air flow rate of the compressors at different speed and pressure levels were recorded by sensors. Volumetric efficiency was calculated based on these data and the effect of ambient conditions and manufacturer variation on compressor characteristics were analysed. Thus, the study reveals the performance behaviour of the compressors under different conditions and the effect of ambient variability on this performance. The test scenario and details are presented in Table 5.

3. Results and Discussion

Firstly, the test of the Yumak compressor was carried out with a flow meter set to DIN1343 standard. Afterwards, the Yumak compressor test was carried out with a laboratory condition regulated flow meter. Following this, the OEM compressor was first tested with a flow meter set to DIN1343 standard and then with a flow meter set to laboratory conditions. Four different tests were completed, each lasting 3 hours. No problems were encountered during the test that would affect the result.

First, the flowmeter was adjusted according to DIN 1343 standards and the Yumak compressor was tested. Test results were investigated in detail. Power consumption and air flow rate data of the compressor at different velocities and pressures are available in Table 6. In sequence, flow rate and power consumption were measured at different operating pressures and velocities to determine the relationship between power consumption and flow rate.

Table 6. Test Results of Yumak Sample with DIN1343 Flowmeter Setting

System Pressure (bar)	Revolution (rpm)	Air Flow Rate (m^3/min)	Power Consumption (kW)
8,5	500	0,183	1,70
	1000	0,486	3,60
	1500	0,547	5,50
	2000	0,626	7,10
	2500	0,726	8,90
	3000	0,810	10,80
10	500	0,176	1,80
	1000	0,480	3,80
	1500	0,535	5,50
	2000	0,601	7,20
	2500	0,696	9,20
	3000	0,773	10,90
12,5	500	0,154	1,80
	1000	0,478	3,90
	1500	0,516	5,70
	2000	0,563	7,30
	2500	0,654	9,30
	3000	0,726	10,90

90 L tank filling tests were performed at 2000 rpm and 2500 rpm. According to the

test result, the compressor filled the tank in 63 seconds at 2000 rpm and 52 seconds at 2500 rpm. The average flow rate at 2000 rpm was 691 l/min while the average flow rate at 2500 rpm was 777 l/min. Pressure, flow rate and power consumption data taken during tank filling are available in Figures 3,4 and 5. The effect of different velocities on pressure is an important parameter that directly affects the compressor's performance. As the compressor velocities increases, the airflow rate and intake capacity change, which can affect the outlet pressure. At higher velocities, the pressure increase may be more pronounced, while at lower velocities, pressure drops may be observed. Therefore, the relationship between velocities and pressure should be carefully monitored in terms of system efficiency and energy consumption. This relationship is crucial for determining the optimal operating conditions of the compressor and ensuring the system operates efficiently. In addition, by increasing the compressor rotation velocity from 500 rpm to 3000 rpm, the flow levels increase by approximately 440% depending on the pressure. Power consumption has also increased by 630%. This level is not an excessive value, but it is a possible value according to the compressor operating principle. However, the effect of ambient conditions on these increases should also be analysed.

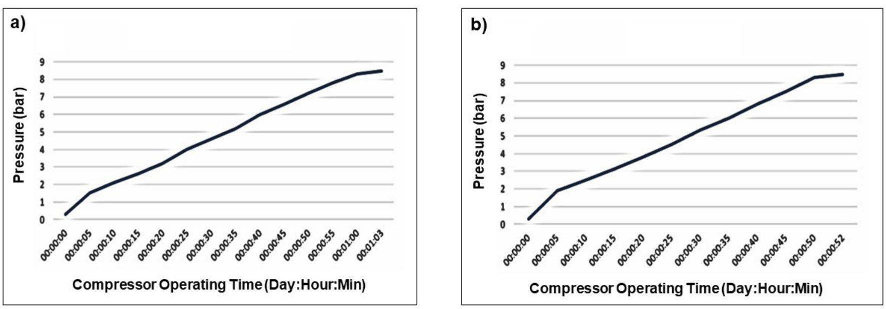

Figure 3. Yumak Specimen Pressure-Time Relationship on DIN 1343, a) 2000 rpm, b) 2500 rpm

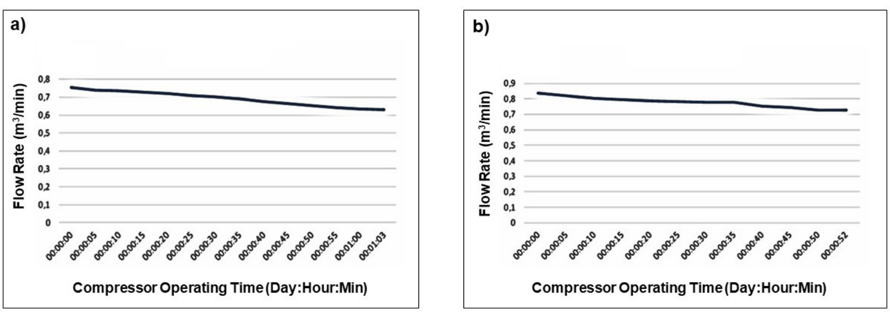

Figure 4. Yumak Specimen Pressure-Time Relationship on DIN 1343, a) 2000 rpm, b) 2500 rpm

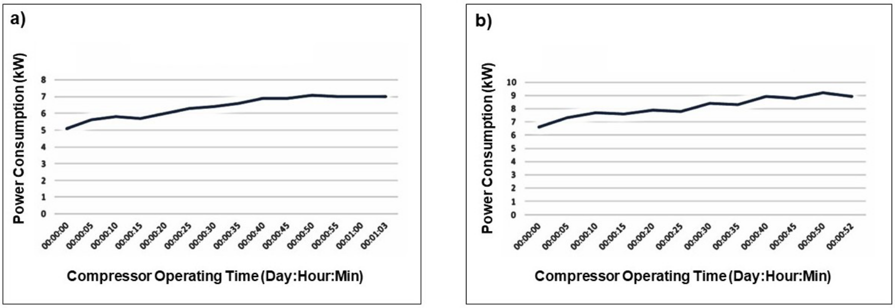

Figure 5. Yumak Specimen Power Consumption-Time Relationship on DIN 1343, a) 2000 rpm, b) 2500 rpm

With the results obtained, the volumetric efficiency of the compressor was calculated. The calculation was performed for 2000 rpm, 2500 rpm and 3000 rpm under 8.5 bar, 10 bar and 12.5 bar loads. These velocities were chosen because they are the nominal operating velocities of the compressors.

The volumetric efficiency results obtained according to the calculation are available in Table 7.

Table 7. Volumetric Efficiency Results According to DIN1343 Settings

System Pressure (bar)	Revolution (rpm)	Volumetric Efficiency (%)
8,5	2000	49,92%
	2500	46,31%
	3000	43,06%
10	2000	47,92%
	2500	44,40%
	3000	41,09%
12,5	2000	44,89%
	2500	41,72%
	3000	38,60%

From the data in the table, it can be seen that with the increase in pressure, the volumetric efficiency of the compressors decreases according to DIN 1343 standards. In addition, when the figures are analysed, power consumption data were also monitored when pressure was constant and velocity variable. According to the test results at 500, 1000, 1500, 2000, 2500 and 3000 rpm, it is observed that power consumed by the compressor increases as the velocity increases under constant pressure. The power consumption parameter was monitored at each of the pressures of 8.5, 10 and 12.5 bar and both compressors, and the increase in power consumption due to the increase in velocity was detected in all of YUMAK compressor. The test results also include compressor data at variable pressures at the same velocities. In this direction, according to the data taken at different velocities, it was observed that the air flow rate decreased with the increase in pressure at 8.5, 10 and 12.5 bars at the same velocity.

After the tests of Yumak compressors were carried out according to DIN1343 standard, Yumak compressors were started to be tested with laboratory condition. Laboratory conditions are defined in Table 4, and differences in the table compared to the DIN standard are due to the height of the laboratory area above sea level. DIN standards refer to data measured at sea level, but laboratory conditions vary due to altitude above sea level. Atmospheric pressure at sea level results from weight of air column above and air density. As altitude rises, amount of air above decreases, reducing air density due to weaker gravitational pull at higher elevations. This causes a drop in atmospheric pressure. Lower layers of atmosphere are denser, while higher altitudes have fewer air molecules, leading to lower pressure. Thus, atmospheric pressure decreases with increasing distance from Earth's surface. As altitude increases and atmospheric pressure decreases, temperature generally drops. This occurs because thinner air retains less heat. Additionally, as air moves farther from Earth's surface, it cools due to reduced solar heating at higher elevations, contributing to an overall decrease in temperature.

Table 8. Test Results of Yumak Sample with Lab. Condition Flowmeter Setting

System Pressure (bar)	Revolution (rpm)	Air Flow Rate (m^3/min)	Power Consumption (kW)
8,5	500	0,23	1,70
	1000	0,611	3,70
	1500	0,688	5,50
	2000	0,791	7,10
	2500	0,914	8,90
	3000	1,018	10,80
10	500	0,219	1,80
	1000	0,602	3,80
	1500	0,671	5,50
	2000	0,753	7,20
	2500	0,880	9,20
	3000	0,978	10,90
12,5	500	0,195	1,80
	1000	0,601	3,90
	1500	0,655	5,70
	2000	0,710	7,30
	2500	0,829	9,30
	3000	0,917	10,90

Regarding the results, it is understood that suction amount and power consumption of compressor increases as velocity level increases. However, regardless of the velocity, the increase in the pressure level did not increase the power consumption of the compressor and had little effect on the suction quantity. Power consumption at the same velocity level at different pressures and flow rate and power consumption values were close to each other. 90 L tank filling tests were performed at 2000 rpm and 2500 rpm.

According to the test result, the compressor filled the tank in 62 seconds at 2000 rpm and 52 seconds at 2500 rpm. The average flow rate at 2000 rpm was 877 l/min while the average flow rate at 2500 rpm was 985 l/min. When it is questioned whether the laboratory conditions have an effect on the flow rate and power consumption of the compressor, the flow rate increased by 440% and power consumption increased by 630% due to 6 times speed increase. In this context, the same results were found as the tests in DIN 1343 conditions. From this point of view, changing the ambient conditions has no effect on the flow rate and power consumption for the Flail compressors. Pressure, flow rate and power consumption data taken during tank filling are available in Fig. 6,7 and 8.

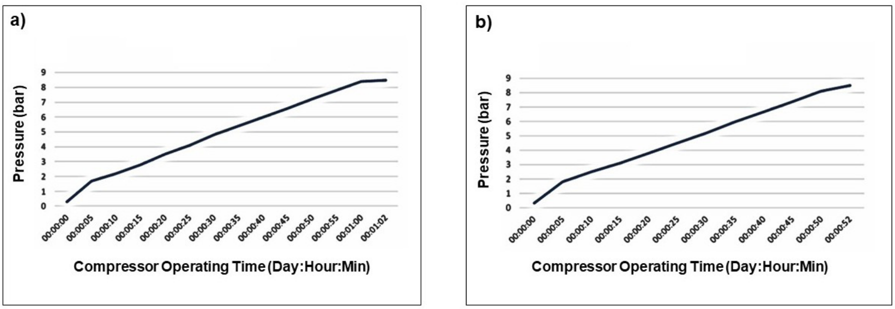

Figure 6. Yumak Specimen Pressure-Time Relationship According to Lab. Conditions, a) 2000 rpm, b) 2500 rpm

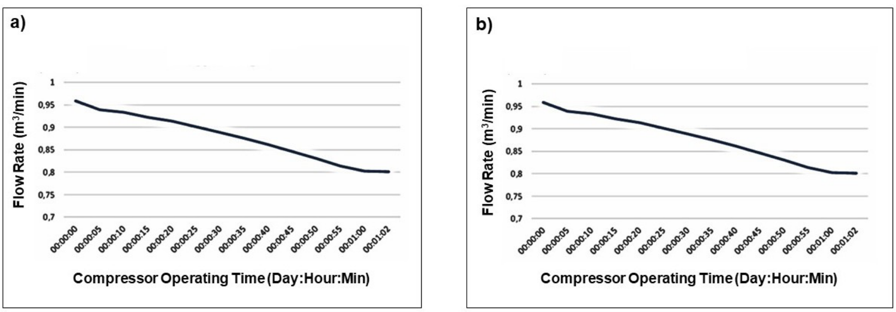

Figure 7. Yumak Specimen Flow Rate-Time Relationship According to Lab. Conditions, A) 2000 rpm, B) 2500 rpm

When the power consumption amounts of the compressors under laboratory conditions are evaluated depending on time, Increasing the velocity level from 2000 rpm to 2500 rpm increased power consumption by approximately 40%. In addition, approximately 1 hour of operation with the compressor running, power consumption increased from 5 and 7 Kw to 7-9 Kw.

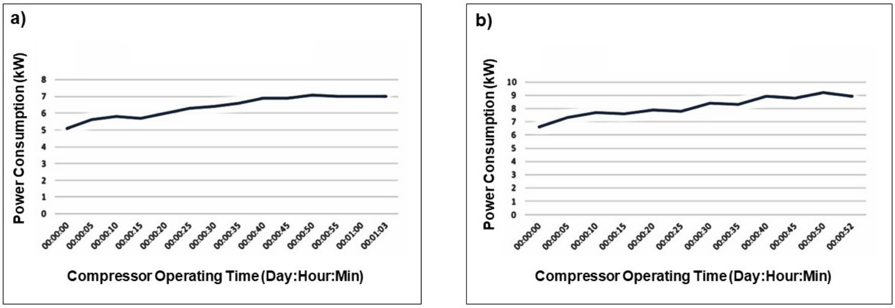

Figure 8. Yumak Specimen Power Consumption-Time Relationship According to Lab. Conditions, A) 2000 rpm, B) 2500 rpm

With the results obtained, the volumetric efficiency of the compressor was calculated. The calculation was performed for 2000 rpm, 2500 rpm and 3000 rpm under 8.5 bar, 10 bar and 12.5 bar loads. These velocities were chosen because they are the nominal operating velocities of the compressors. The test data of Yumak compressors under laboratory conditions were calculated using Equation 1 and volumetric efficiency results are given in Table 9.

Table 9. Volumetric Efficiency Results of Yumak Specimen According to Lab. Condition Settings

System Pressure (bar)	Revolution (rpm)	Volumetric Efficiency (%)
8,5	2000	63,07
	2500	58,11
	3000	54,12
10	2000	60,04
	2500	56,14
	3000	51,99
12,5	2000	56,61
	2500	52,88
	3000	48,75

The process of testing the mound compressors under two different conditions was completed and the same test procedure was applied to the products of the original product manufacturer (OEM) company. Firstly, OEM compressors were tested according to DIN 1343 standard. For this purpose, the flow meter is adjusted according to the standard. Power consumption and air flow rate data of the compressor at different velocities and pressures are available in Table 10.

Table 10. Test Results of OEM Sample with DIN 1343 Flowmeter Setting

System Pressure (bar)	Revolution (rpm)	Air Flow Rate (m^3/min)	Power Consumption (kW)
8,5	500	0,129	1,70
	1000	0,424	3,60
	1500	0,486	5,10
	2000	0,565	6,60
	2500	0,686	8,60
	3000	0,740	10,00
10	500	0,105	1,70
	1000	0,418	3,70
	1500	0,468	5,20
	2000	0,551	6,80
	2500	0,651	8,60
	3000	0,702	10,00
12,5	500	0,101	1,80
	1000	0,387	3,80
	1500	0,433	5,30
	2000	0,508	7,10
	2500	0,587	8,70
	3000	0,661	9,90

The results of the OEM compressor samples analysed according to the flow meter set according to DIN 1343 standard showed similar values and trend to the Yumak compressors. Increasing operating velocities increased the air suction flow rate and power consumption. On the other hand, the increase in pressure decreased the flow rate. OEM Compressor tests have been made to be exactly the same as the conditions applied to Yumak compressors. Operating velocities and tank volume were kept at the same level and tests were started in this way. 90 L tank filling tests were performed at 2000 rpm and 2500 rpm. According to the test result, the compressor filled the tank in 64 seconds at 2000 rpm and 53 seconds at 2500 rpm. The average flow rate at 2000 rpm was 649 l/min while the average flow rate at 2500 rpm was 750 l/min. Under DIN 1343 ambient conditions, with a 6-fold increase in speed level, the flow rate of the OEM compressor increases by approximately 570-650%, while the power consumption increases by 590%. The increase is due to the nature of the compressor, but there are differences with the Yumak compressor. While the flow rate increases by 440% in Yumak compressors, this value is much higher in OEM compressors. In power consumption, the OEM compressor seems to be more advantageous than the Yumak compressor by remaining at lower levels. Pressure, flow rate and power consumption data taken during tank filling are available in Fig 9,10 and 11.

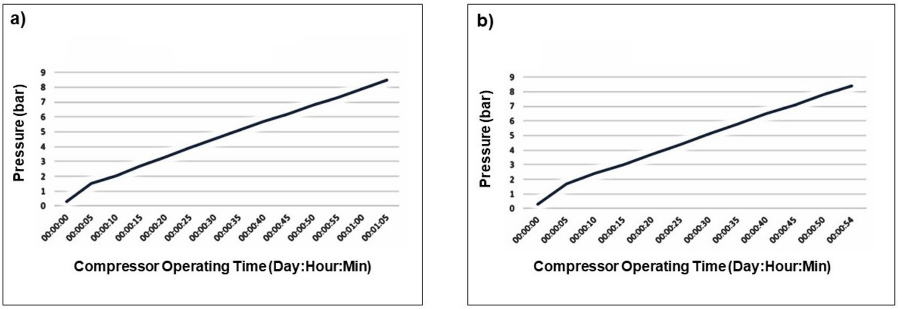

Figure 9. OEM Specimen Pressure-Time Relationship According to DIN 1343, a) 2000 rpm, b) 2500 rpm

OEM products refer to items produced by the original manufacturer of the product, while aftermarket products are those produced by reverse engineering the original manufacturer's product. In this context, YUMAK's products represent aftermarket items. Upon reviewing the graphs, very similar trends are observed, as the final products exhibit only minor point-to-point differences. This study investigates how variations in production processes impact the resulting outcomes.

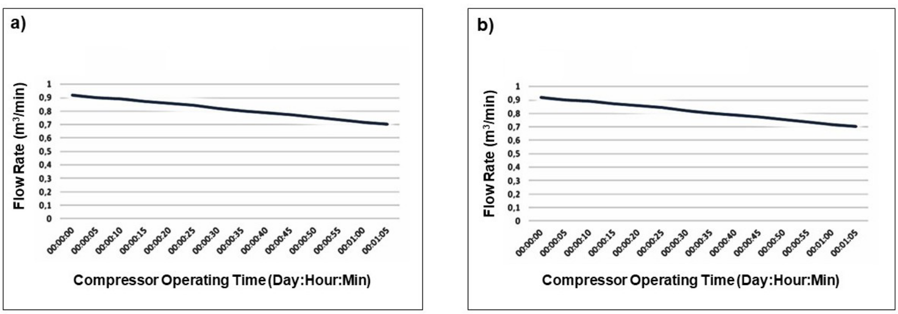

Figure 10. OEM Specimen Flow Rate-Time Relationship According to DIN 1343, a) 2000 rpm, b) 2500 rpm

In the experiments performed by adjusting the flow meter according to DIN 1343 standards for OEM samples, depending on the operating time of the compressor, the cycle completed increased and with this increase, the compressor reached the desired pressure level and followed a linear trend. However, as the operating time of the compressor increased, the suction amount decreased and therefore the flow rates decreased. At the end of 1 hour of operation, a decrease of approximately 10% was observed in the amount of air sucked and in the flow rate level.

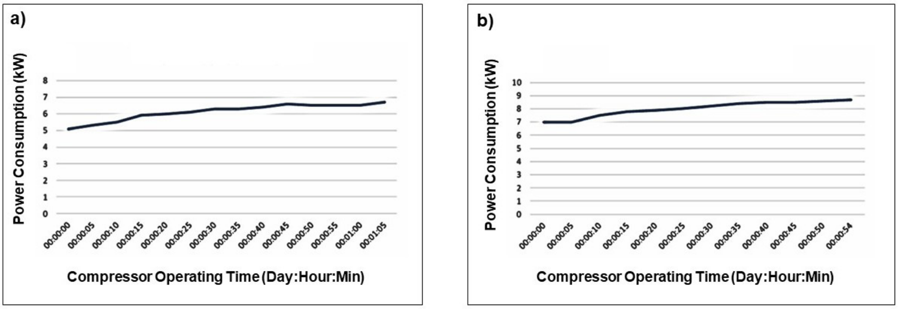

Figure 11. OEM Specimen Power Consumption-Time Relationship According to DIN 1343, a) 2000 rpm, b) 2500 rpm

When the power consumption of OEM compressors at different velocities is analysed, power consumption variation at 2000 rpm is high. The vibration created when compressor is running creates these interferences. With the results obtained, the volumetric efficiency of the compressor was calculated. The calculation was performed for 2000 rpm, 2500 rpm and 3000 rpm under 8.5 bar, 10 bar and 12.5 bar loads. These velocities were chosen because they are the nominal operating velocities of the compressors. The test data of OEM compressor according to DIN 1343, were calculated using Equation 1 and volumetric efficiency results are given in Table 11. At each of 8.5, 10 and 12.5 bar tank pressures, the compressor was operated at 500, 1000, 1500, 2000, 2500 and 3000 rpm. It was found that the air flow rates increased with the rpm pulses under constant pressure conditions. In all the tests performed and in both brands of compressors, the increase in air flow rate with the increase in rpm was also confirmed. Similar graphs were observed in other experiments.

Table 11. Volumetric Efficiency Results According to DIN 1343 Settings

System Pressure (bar)	Revolution (rpm)	Volumetric Efficiency (%)
8,5	2000	45,05
	2500	43,76
	3000	39,34
10	2000	43,93
	2500	41,53
	3000	37,32
12,5	2000	40,51
	2500	37,44
	3000	35,14

Experiments and test results were taken according to the standard. Finally, the OEM compressors were tested under laboratory conditions. Power consumption and air flow rate data of the compressor at different velocities and pressures are available in Table 12.

Table 12. Test Results of OEM Sample with Lab. Condition Flowmeter Setting

System Pressure (bar)	Revolution (rpm)	Air Flow Rate (m^3/min)	Power Consumption (kW)
8,5	500	0,162	1,70
	1000	0,521	3,60
	1500	0,613	5,20
	2000	0,712	6,50
	2500	0,865	8,60
	3000	0,934	10,00
10	500	0,135	1,70
	1000	0,503	3,70
	1500	0,594	5,20
	2000	0,694	6,80
	2500	0,824	8,60
	3000	0,892	10,00
12,5	500	0,127	1,80
	1000	0,487	3,80
	1500	0,550	5,40
	2000	0,643	7,10
	2500	0,742	8,70
	3000	0,834	9,90

When the results of OEM compressor samples were analysed according to laboratory conditions, similar outputs to Yumak compressors occurred. Increasing operating velocities increased air intake flow rate and power consumption. However, the pressure increase decreased the flow rate. 90 L tank filling tests were performed at 2000 rpm and 2500 rpm. According to the test result, the compressor filled the tank in 65 seconds at 2000 rpm and 54 seconds at 2500 rpm. The average flow rate at 2000 rpm was 812 l/min while the average flow rate at 2500 rpm was 946 l/min. When the operating conditions were changed to laboratory conditions, the percentage increase in flow rate and power consumption of the OEM compressors was found to be approximately similar. Therefore, the percentage of increase in the flow rate and power consumption of the compressor does not change by changing the working environment conditions. Pressure, flow rate and power consumption data taken during tank filling are available in Fig. 12,13 and 14.

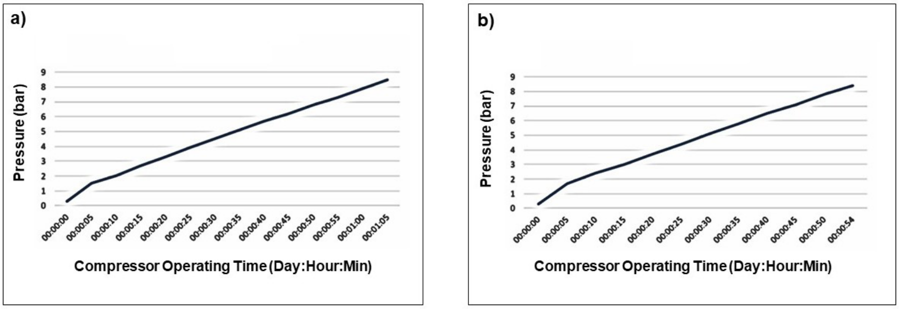

Figure 12. OEM Specimen Pressure-Time Relationship According to Lab. Conditions, a) 2000 rpm, b) 2500 rpm

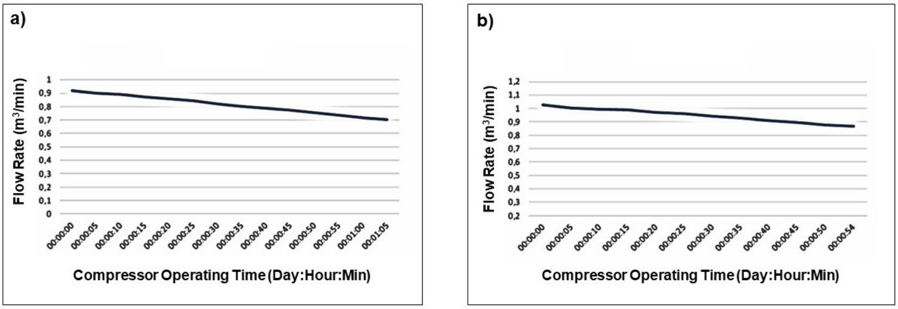

Figure 13. OEM Specimen Flow Rate-Time Relationship According to Lab. Conditions, a) 2000 rpm, b) 2500 rpm

Differences in work settings lead to both a shift in curves and the emergence of small disturbances. However, trends in OEM and YUMAK products show similarity with minor differences. This suggests that reverse engineering efforts have been successfully executed. In the tests, the air flow rate was measured with the flow meter on the air inlet side of the compressor. The effect of the ambient data on the volumetric flow rate was analysed by changing the ambient data through the flow meter. Atmospheric pressure of 0.9 bar and ambient temperature of 25°C were defined in the flow meter and compared with the data in DIN1343 standard. According to DIN1343, the ambient temperature is 0°C and the atmospheric pressure is 1.043 bar. Measurement in both conditions showed that the flow meter gives the correct result when set according to the real ambient data. This was verified by comparing tank filling times and measured flow rates.

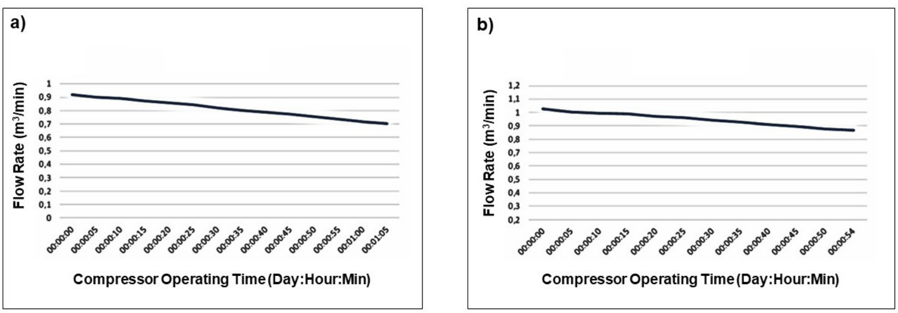

Figure 14. OEM Specimen Power Consumption-Time Relationship According to Lab. Conditions, a) 2000 rpm, b) 2500 rpm

With the results obtained, the volumetric efficiency of the compressor was calculated. The calculation was performed for 2000 rpm, 2500 rpm and 3000 rpm under 8.5 bar, 10 bar and 12.5 bar loads. These velocities were chosen because they are the nominal operating velocities of the compressors. The test data of OEM compressor according to DIN 1343, were calculated using Equation 1 and volumetric efficiency results are given in Table 13. Another result of the study is the performance of compressor brands. According to the results, the volumetric efficiency and flow rate of Yumak compressor is higher than OEM. In terms of power consumption, it is seen that the OEM compressor consumes less power.

Table 13. Volumetric Efficiency Results According to Lab. Condition Settings

System Pressure (bar)	Revolution (rpm)	Volumetric Efficiency (%)
8,5	2000	56,77
	2500	55,18
	3000	49,65
10	2000	55,34
	2500	52,56
	3000	47,42
12,5	2000	51,27
	2500	47,33
	3000	44,33

Under constant tank pressure, volumetric efficiency values were also evaluated along with revolution increases. According to all test results, it was observed that volumetric efficiency decreased with increase in velocity. The reason for decrease in volumetric efficiency while flow rate increases is that while the amount of air sucked per minute increases with increase in velocity per minute, the volume of air filled into the pressure chamber in 1 cycle of the compressor decreases. In another direction, according to calculated values, it was observed that volumetric efficiency decreased with increasing tank pressure. The reason for this is that at higher tank pressures, the air outlet valves are more difficult to open and transmit less air to tank. Because the air in pressure chamber cannot be fully discharged to the tank, the amount of air drawn from the atmosphere also decreases.

4. Conclusions

In this study, air compressors from 2 different industries were tested. Both of them have the same dimensional characteristics and only the manufacturers are different. The compressors were tested under tank pressures of 8.5, 10 and 12.5 bar. They were operated at 500, 1000, 1500, 1500, 2000, 2500 and 3000 rpm under each pressure. Power consumption and air flow data were monitored during the test. The air flow meter was set to 2 different settings, both DIN1343 and laboratory conditions. In other words, a total of 4 different tests were applied. According to the data obtained, the volumetric efficiency of the compressors was calculated. Air tank filling times were compared with the flow meter results and it was determined that the measurements made under laboratory conditions were accurate.

According to the results obtained from the flow meter set to laboratory conditions, the compressors were compared and the effect of operating conditions on compressor function was examined. The volumetric efficiency of Yumak compressor was calculated between 48.75% and 63.07% with the data at the lowest and highest tank pressures and speeds. The volumetric efficiency results of the OEM compressor under the same conditions were calculated as 44.33% to 56.77%.

Under the same conditions, under the lowest speed and tank pressure, i.e. 8.5 bar and 500 rpm, the OEM compressor consumed 1.70 kW of power while the Yumak compressor consumed 1.70 kW of power. At the highest tank pressure and speed, i.e. 12.5 bar and 3000 rpm, the OEM compressor consumed 9.90 kW while the Yumak compressor consumed 10.90 kW. In other words, it was determined that the power consumption of the Yumak compressor was higher than the OEM compressor as the speed and tank pressure increased.

In addition to comparing 2 compressors, it was also evaluated how the operating conditions of a compressor affect the compressor performance.

i. Increasing operating velocities increases the intake air flow rate.

ii. Under constant tank pressure, increasing operating velocities reduces volumetric efficiency.

iii. Power consumption is directly proportional to operating velocities. Increasing the velocities indicates that the compressor consumes more power to compress the air.

iv. Flow rate decreases as the compressor pressurizes the air.

v. As the tank pressure increases, the compressor cannot send all the air it sucks into the tank due to the creation of counter pressure on the compressor exhaust valves and the volumetric efficiency level decreases.

vi. It was observed that changing the settings of the sensor used in flow measurement according to the ambient conditions changed the results.

vii. Compressors believed to be the same compressor but manufactured with different manufacturing techniques may vary in their characteristic values.

5. Acknowledge

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This study was compiled with research and publication ethics.

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