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Experimental analysis of the performance of a bidirectional single-unit air compressor with a semi-gear and rack mechanism in power transmission

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Abstract

In this paper, a bidirectional single unit air compressor equipped with two reciprocating pistons and operating with a new semi-gear and rack type mechanism in power transmission has been made, developed and analyzed. In this structure, there are two reciprocating pistons positioned opposite each other to produce compressed air, therefore, there are two compressed air stroke in each rotation of the output shaft. In the power transmission mechanism, a rack gear and a semi-gear have been used, so that the rotation of the compressor shaft causes the semi-gear to rotate, resulting in the reciprocating movement of the rack and the pistons. The results show that in the experimental situation, the amount of energy consumed to reach the tank pressure of 4 bar is equal to 142.6 kJ, while the minimum theoretical work of the compressor in the isotherm state to reach the same pressure is equal to 72.5 kJ and this represents 51% efficiency of this structure in the form of working in compressor mode. Furthermore, the results indicate that utilizing waste heat sources to increase the tank pressure from 4 to 5 bar can result in an efficiency increase of approximately 60 percent.

Keywords: Bidirectional air compressor, Rack transfer mechanism, Semi-gear mechanism.

1. Introduction

The limitation of energy resources, the need to reduce environmental pollutants and air pollution, and consequently climate changes have led to the growing interest of humanity in renewable energies and the use of clean energy sources. Compressed air energy production and storage systems are among the sources that have received more attention in recent years [1-3]. Currently, about 10% of the energy consumed in the world is produced and consume as compressed air [4]. Availability, easy transportation and maintenance, simple structure, high efficiency and compatibility with the environment are among the characteristics of compressed air [5]. One of the earliest applications of compressed air storage is to use its energy to generate electricity [6]. The conducted studies show that the direct use of compressed air in compressed air engines, the possibility of cheap storage, low leakage losses, long life, the ability to create renewable power plants, as well as laying the foundation for the presence of efficient, clean and inexpensive air conditioning systems will be easily possible [7].

In 2017, Massimo et al. [8] conducted an experimental analysis and thermal, fluid and dynamic simulation of a reciprocating compressor with an unconventional crank mechanism. In this research, two mutual cylinders equipped with a double connecting rod and a solar gear were used to move the pistons. This compressor was used at 1450 rpm and up to 8 bar pressure by a 3.5 kW motor, and the experimental and numerical results obtained indicated a reasonable agreement with an error of less than 7%. In 2018, He et al. [9] conducted an experimental study of a rotary screw compressor for fuel cell systems installed on a truck. The results of this research were achieving a rotor speed of 9000 rpm, at a pressure of 0.2 MPa, with a production power of 50 kW, with a volumetric efficiency of 70%, an isentropic efficiency of 55%, and a mechanical efficiency of 80%.

In 2020, Epokua et al [10] analyzed the energy recovery of the condensed air of the compressed air compressor for heating water. The results of this research show that by using the heat recovery unit, hot water with a temperature of 42 to 70 degrees Celsius was obtained and the efficiency of the heat recovery unit was determined to be 54.5%.

Azizifar et al. [11] modeled and optimized the power consumption of a two-stage industrial compressed air system. The power consumption of the compressors as the objective function, the isentropic efficiency of the first and second stage compressors, the thermal efficiency of the intermediate cooler and the entropy production in the compressors are considered as the problem constraints. Their results showed that the optimization effectively reduced the power consumption of system's compressors.

As seen in most of the above researches, compressed air production and consumption mechanisms generally utilize cylinder and piston structures equipped with cranks or rotating rotor structures. Given the significance of enhancing efficiency and minimizing losses today, it is necessary to conduct extensive research on the investigating, presenting and analyzing new mechanisms to find the most suitable structure based on the intended application. Therefore, this article proposes a new compressor with a different structure. The proposed compressor is a single unit with two sets of cylinders and pistons that are mutual and symmetrical, which works through a double rack gear and a semi-gear in the power transmission path. This compressor is activated by using wasteful sources of energy and receives air from the environment and directs it into a steel tank after compression. Then by using the wasted heat from a heat source, it reaches a higher pressure to be used in the required condition.

2. New Compressor Structure

According to Figure 1, if the mechanism operates in the structure of a compressor, in this situation, the three-way flow control valves connect the paths (9 to 7), (10 to 12), (1 to 3) and (6 to 4) allowing the working fluid to pass through them.

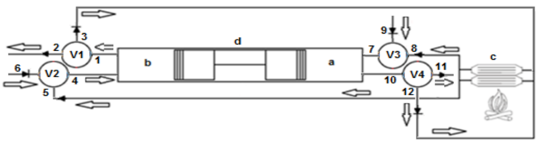

Figure 1. Schematic of the proposed new compressor

For example, if the piston is on the far right side, as the energy enters the compressor shaft, the piston will move from the top dead center to the bottom dead center. In this case, due to the decrease in pressure in the cylinder chamber on the right side, air flows into the cylinder chamber from the environment and through the one-way valve installed in path number 9. Simultaneously, in the opposite point, i.e., in the cylinder chamber b on the left side, the existing air is condensed and discharged into the compressed air tank c equipped with a heat source through the one-way valve in path number 3. This situation continues until the piston reaches the extreme left. Now, by changing the direction of the piston movement, there will be a decrease in pressure in the cylinder chamber b on the left and an increase in the pressure in cylinder chamber a on the right. By reducing the pressure in the left chamber, air flows from the environment into the cylinder by passing through the one-way valve installed in path number 6, and the compressed air passes through the one-way valve installed in path number 12 into the compressed air tank equipped with the heat source and is discharged.

A semi-gear mechanism and rack gear are also used for power transmission, which is shown in Figure 2. In this structure, the input axis of the compressor is connected to the semi-gear axis, and the pistons are connected to the rack gear from the sides. In this mechanism, in the compression stroke of one of the pistons, the semi-rotary gear engages with the upper rack gear and the rotational movement of the compressor axis leads to the linear movement of the piston and rack gear. When the piston reaches the end of the stroke, the semi-gear disengages from the upper rack gear and simultaneously engages with the lower rack gear. In this situation, the other piston is at the beginning of the compression stroke, and the continuation of the rotation of the compressor axis leads to the linear movement of the piston and rack gear, consequently, producing dense air and sending it to the compressed air storage tank.

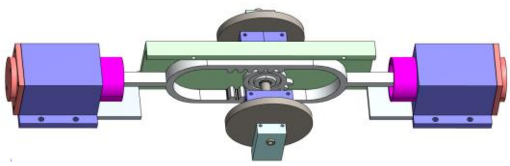

Figure 2. Power transmission mechanism

This type of compressor consists of two double-sided piston cylinder chambers with a piston diameter of 71mm and a stroke of 134mm in each of the cylinders, two cylinder heads, valves and one-way fluid flow control valves, semi-gear power transmission mechanism and rack, driving steel shaft, compressed air storage tank, heat source and fluid transmission pipes are formed as shown in Figure 3.

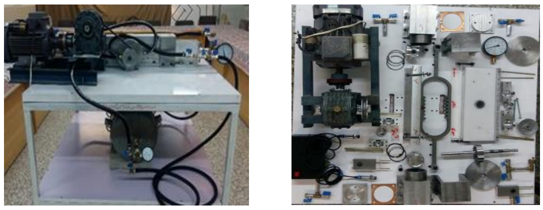

Figure 3. Compressor engine in two states of assembly and disassembly

3. Stress analysis

All the parts in the mechanism have been loaded into the stress analysis software and analyzed for stress. The results of the analysis indicate that the maximum stress applied among the main parts, such as the compressor shaft, semi-gear, rack, cylinder and piston, are located in the area of semi-gear and rack. The strengthening of this area is necessary for the power transmission mechanism. As shown in Figure 4, the highest stress was in the rib area, so by applying a torque of 60 Nm, the amount of stress applied according to the materials and the dimensions of the parts in the design was equal to 275 MPa, which of course is lower than the yield stress of steel, which is equal to 380 Mpa.

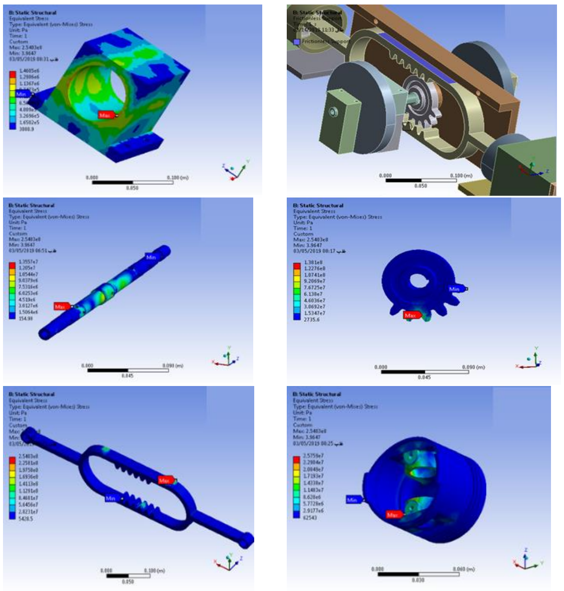

Figure 4. Stress analysis of main parts

4. Experimental result

In the proposed compressor engine, the mechanism is initially placed in the compressor state to charge the two tanks used, with two capacities of 25 and 50 liters. In this situation, a single-phase 220V,1.5hp synchronous generator motor equipped with a speed reduction gearbox is used. The speed of the electric motor is equal to 1420rpm and it is transferred to the cranville pinion reduction gearbox through a coupling. The output of the gearbox is transferred to the compressor shaft through two identical pulleys with an equal ratio, and the mechanism moves at 95 rpm. Air is sucked from the environment with a temperature of 29 degrees Celsius through the valves and one-way valves installed in the gas flow path and then it is discharged into the storage tanks. First, the air enters the small tank and then it is directed to the big tank. The experimental results are shown in Table 1.

Table 1. Parameters measured

Pgage (bar)	Operating time (s)	Ampere (A)	Wattage (W)
1	53	2.2	448.8
2	121.5	2.4	489.6
3	200	2.6	530.4
4	317.5	2.7	550.8
5	439	2.8	571.2
6	557	2.9	591.6

5. Conclusion

- In the experimental situation, the amount of energy consumed to reach the relative pressure of 4 bar, which is the predetermined pressure in the tank, is equal to 142.6 kJ. While the amount of exergy in the tank in this condition will be equal to 28 kJ, therefore, the performance efficiency obtained from the ratio of these two equals to 19%.
- Also, the minimum theoretical work of compressors in a constant temperature state to reach a relative pressure of 4 bar is equal to 72.5kJ, and this represents 51% efficiency of this structure in the form of operation in the compressor state. In the state of charging the tanks with a normal cylinder and piston compressor, the tanks reached a relative pressure of 6 times by spending 252kJ of energy, while the new engine in the form of a compressor was able to bring the tank to this pressure by spending 281.5kJ of energy, which indicates that the efficiency of the new compressor is equal to 83% of the cylinder and piston compressor with a crank. According to the obtained results, this type of mechanism has acceptable results in terms of efficiency and energy, and by optimizing the accessories, it can serve as a viable alternative to the conventional cylinder and piston structure.

6. References

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