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Research Article

Experimental testing of scroll machine driven by compressed air for power generation and its integration in small scale organic Rankine cycle

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ABSTRACT

Organic Rankine Cycle (ORC) is a proven technology in the field of waste heat recovery and present days ORC is extensively being used in exploiting biomass, geothermal and solar energy. The overall performance of ORC depends on the expander, making it a core component of the system. Generally, these expanders are classified into velocity type and displacement type. The velocity type expanders find their applications in large scale power generation and are not preferred in small scale power applications as their rotational speeds exponentially increase with a decrease in expander power output. As a result, the displacement type expanders are best suited for small scale power generation in ORC. Yet, till date expanders capable of producing power at small scale are not commercially available in the market for ORC application. As an effect commercially available scroll compressors are modified to work as expanders in ORC systems. The present study aims to examine the feasibility of using one such scroll compressor as an expander in ORC with and without modification. A test rig was developed to test the compressor running in reverse as expander using compressed air, before and after modifications. The scroll machine was tested for operating conditions consisting of pressure varying from 0.5 bar to 4.5 bar and the load varying from 0.2 kg to 2.2 kg for a constant airflow rate. The configurations tested were, scroll compressor with the suction port as inlet, modified scroll compressor with the suction port as inlet and modified scroll compressor with discharge port as an inlet. Based on the experimental test data obtained it is observed that, in all three configurations, for various loading conditions at given inlet air pressure there exists a maximum power generation point and a further increase in the load at given pressure has a negative effect on power output. Also, a significant increase in speed is observed from 300 to 4250 rpm at no load condition with increasing inlet air pressures. Maximum power of 210 W was achieved at a load of 1.1 kg with the inlet pressure of 4.5 bar for modified scroll machine when the discharge port was used as an inlet. Finally, it is recommended to use a modified scroll machine with discharge port as inlet as it gives more power when compared with other configurations for the same operating conditions.

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INTRODUCTION

In present days increased consumption of fossil fuels has caused environmental problems, ozone layer depletion, air pollution, acid rain and global warming [1]. Therefore, interest in renewable energy sources such as solar energy, geothermal energy or industrial waste heat recovery at low temperatures is growing [2]. To exploit these energy sources, ORC has proven to be a great choice due to its simplicity, flexibility and easily available components [3].

ORC is similar to a conventional Rankine cycle but the working fluid is an organic component. In any ORC system expander plays an important role as the power production depends on it. From the literature [1, 4, 5] it is seen that expanders can be classified into two categories i.e., velocity type and displacement type. The velocity type expanders find their applications in large scale power generation and are not preferred in small scale power applications as their rotational speeds exponentially increase with a decrease in expander power output. As a result, the displacement type expanders are best suited for small scale power generation in ORC. In the displacement type, most commonly used and preferred expanders are vane and scroll type expanders as concluded by Qiu et al. [1].

Many researchers throughout the globe have used the expanders which were designed and developed in house or modified from scroll compressors due to underdeveloped technology and suitable expanders of low power capacity are not yet available on the commercial market. Currently, the majority of scroll expanders integrated into ORC systems are mostly modified from scroll compressors as they cut down the cost [5].

Mendoza et al. [2] used a scroll compressor modified to work in reverse as an expander in their research. The expander was characterized in two test setups using air and ammonia as working fluids. In the work, the authors studied the effects of operating parameters on the performance of expander and from the obtained results it was concluded that the scroll expander can be used in absorption power cycles. Another experimental work, conducted by Ayachi et al. [6] revealed that the performance of the expander modified from scroll compressor is promising in high supply conditions of 20 bar and 130^{o} C. furthermore in a resorption cogeneration system, a scroll expander was used [7] and tested with compressed air as working fluid. Based on the results, it is seen that the inlet pressure and inlet volume flow rate are in a linear relationship and the power increased with increase in the inlet pressure. Besides, an experimental study carried out by Quoilin et al. [3] showed positive isentropic effectiveness of expander and validates the feasibility of utilizing a compressor as an expander in a small scale ORC making the ORC system economical by cutting the cost of the expander. Another investigation done by Qiu et al. [8] showed the possibility of using an expander modified from scroll compressor running on compressed air. The expander was operated for various conditions of pressure and flow rates and concluded that optimizing the volume ratio of compressor improves thermal efficiency when operated as an expander.

In extension, Gao et al. [9] studied scroll machines modified from the automotive air-condition scroll compressor to understand the behavior of scroll displacement over the performance of ORC. In the study, two different scroll machines having different fluid handling capacities were chosen and were tested using compressed air as working fluid. The results showed that the increased displacement increases the power output from the machine but increasing inlet pressure reduces isentropic expander efficiency. In another work carried out by Lemort et al. [10] a scroll expander integrated with ORC was tested and a semi-empirical model was generated to predict the mass flow rate, exhaust temperature and shaft power of expander. Based on the experimental results semiempirical relationship was developed and the losses were quantified in the system. To summarize the work carried on scroll machines, Emhardt et al. [5] reviewed various scroll geometries and their performances. It was concluded that the scroll expander with variable wall thickness is to be further designed and developed and it is possible to increase the geometric expansion ratio without increasing the length of the scroll profile. Similarly, Song et al. [11] reviewed scroll expanders used for the field of ORC. Various scroll expanders including hermetic refrigeration compressor, open-drive automotive A/C compressor, semi-hermetic automotive A/C compressor and air compressor were studied and discussed their usefulness according to the ORC system requirements.

Most recently, Campana et al. [12] evaluated the performance of a scroll expander with R245fa as working fluids and authors were able to achieve 650 W of mechanical power and highest isentropic efficiency of 45% at an expansion ratio of 1.9. The conclusions drawn from the study were positive on using a scroll expander modified from scroll compressor for small scale ORC applications. Similarly Lin et al. [13] conducted research on 10kW ORC plant using R245fa as working fluid and a modified scroll compressor was used as expander. The modified scroll compressor was a commercial semi-hermetic type refrigeration compressor. The expander was capable of producing 6.2 kW of electricity at a pressure ratio of 5.4 giving up to 9% thermal efficiency. Liu et al. [14] focused their study on finding the dynamic response performance of small scale ORC using a modified scroll compressor and R123 as working fluid. The maximum isentropic efficiency and the power produced from expanders were 45% and 120 W respectively. Further Manolakos et al. [15] tried to characterizing two in-series scroll expanders within a low-temperature ORC at partial load. A 50 kW, 130^{o}C heat source was used for the study and the system was investigated for wide range of pressure ratios. It was highlighted that the use of efficient expanders in the ORC system will give up to 10% thermal efficiency. Similarly, Xi et al. [16] used two scroll expanders having different suction capacities of 66 mL/revolution and 86 mL/revolution in basic ORC and regenerative ORC. The expander having higher suction capacity exhibited higher shaft power output in basic ORC configuration and highest thermal efficiency achieved was 2.96%. The conclusion was, the higher suction volume increases the performance of the system as the mass flow rate of the working fluid increases. Subsequently, Zhao et al. [17] reviewed the turbine and positive displacement type expansion devices for ORC in low-temperature heat recovery. From the study it was concluded that the turbine type expanders are suitable for large scale applications, screw-type expanders for medium-scale applications and piston & scroll type expanders are suitable for small scale applications. Furthermore it was understood that the scroll type expanders are more suitable for laboratory size experimental setups for ORC study and with reference to the refrigeration compressors, the selection method of expansion devices for ORC was also understood.

Finally, the work provided the proper insight into the application and studies on scroll expanders concluding that the commercial-scale expander development is in the early stage. This warrants the study of commercially available scroll compressors modified as scroll expanders to be used in ORC.

SCROLL EXPANDER

Scroll expanders are categorized as positive-displacement machines. The scroll expander consists of a fixed scroll and an orbiting scroll that are at a relative angle of π. Figure 1 shows the parts of a scroll expander.

Scroll expander works in three stages, namely suction, expansion and discharge as shown in figure 2. The high-pressure vapor enters the central chamber of the scrolls through suction port where the vapor expands and orbiting scroll rotates, finally vapor flows out from the discharge port. It can be seen from figure 2 that during expansion stage the volume, linearly increases with respect to orbiting scroll.

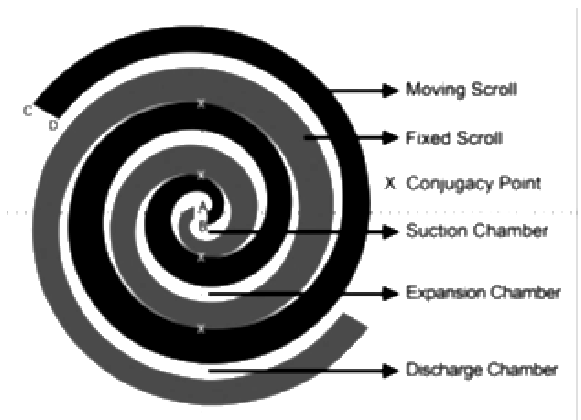

Figure 1. Scroll expander [18].

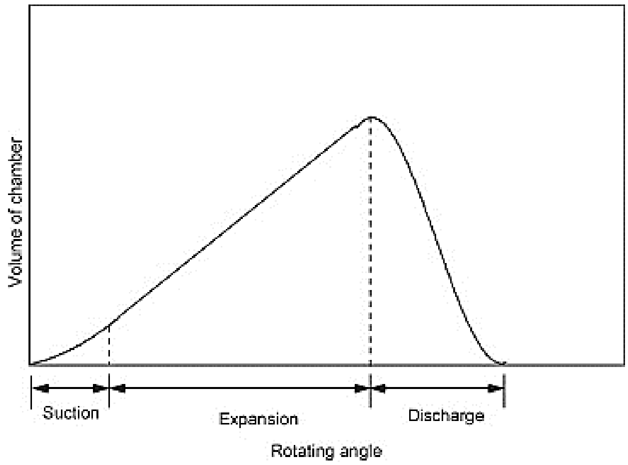

Figure 2. Volume of chamber vs orbiting angle [8].

The scrolls can be defined by many parameters like the radius of radius of the basic circle of the scroll, the orbiting radius of the rotating scroll, the height of scroll vanes, the initial angle of the outer involute, the initial angle of the inner involute, the rolling angle (or involute ending angle) and the built-in volume ratio [8]. Wang et al. [19] derived the expressions for the chamber volumes as a function of orbiting angle for the compression process in a scroll compressor, as the scroll expander exactly works reverse as compressor the equations for the compression could be used for expansion. So, the chamber volumes of three working stages can be calculated from the following expressions:

For suction:

$$V_s(\theta) = Hr_b r_o \theta(\theta - \alpha_i - \alpha_0 + 3\pi),\ 0 < \theta \leq 2\pi \qquad (1)$$

For expansion:

$$V_e(\theta) = 2\pi H r_b r_o (2\theta - \alpha_i - \alpha_o + \pi),\ 2\pi \leq \theta \leq \varphi_e - 2\pi \qquad (2)$$

For discharge:

$$\begin{aligned} V_d(\theta) = Hr_b r_o (2\varphi_e - 2\theta)\varphi_e - (\varphi_e - \theta)^2 - (\varphi_e - \theta))(\alpha_i + \alpha_o + \pi) \\ +2(1 - \cos(\varphi_e - \theta) - 2(\varphi_e - \pi)\sin(\varphi_e - \theta)) \\ -\frac{\pi}{4}\sin(2\varphi_e - 2\theta),\ \varphi_e - 2\pi \leq \theta \leq \varphi_e \end{aligned} \qquad (3)$$

The built-in volume ratio can be obtained from

$$R_v = \frac{V_e(\theta)|_{\theta=\varphi_e-2\pi}}{V_s(\theta)|_{\theta=2\pi}} \qquad (4)$$

EXPERIMENTATION

An experimental setup was designed and developed to test the scroll expander with compressed air as a working fluid to know the performance of expander and also to predict its performance on ORC. The literature discussed above shows that scroll expanders for domestic ORC systems are not available in the market yet and the modified scroll expander would be a great choice to cut down the investment.

Scroll Compressor Opted for the Study

A market survey was conducted for finding a suitable compressor that can be converted into the expander to use it in ORC. The criteria for market survey mainly include temperature range, pressure range, volume ratio, type of the working fluid and modification capability [8]. With all these factors taken into account, a scroll compressor of an automobile air conditioning system manufactures by the company Mitsubishi shown in figure 3 was selected. The selected scroll compressor is made of aluminium and is semi-hermetic open drive compressor having two scrolls, one among them is fixed and another is orbiting scroll. The specifications of the compressor opted for study are given in table 1. The compressor consists of two openings, namely suction and discharge ports. It was observed that the diameter of the suction port is slightly larger than the discharge port as shown in figure 4

An external non-return valve was mounted on the compressor discharge side to avoid the reverse rotation of the compressor at the time of shut down. The reason for using an external non-return valve is that it will have relatively lower pressure drop than an internal check valve and it can provide good protection against the reversed flow as compared to internal check valve and when the compressor is stopped, then the high-pressure gas trapped in the crescent-shaped spaces between scrolls will flow back to suction side by making the compressor to start unloaded, thus by reducing starting current, torque and mechanical stress.

When the conventional compressor is made to work straight then, the refrigerant enters the compressor through the suction port and leaves through discharge port after compression but, to use it as expander the flow has to be reversed i.e., the high-pressure refrigerant has to be sent through the inlet. This high-pressure refrigerant expands itself by imparting energy to orbiting scroll with which shaft power can be obtained, but after removal of a non-return valve (generally named as modified scroll expander), either suction or discharge port can be used as an inlet. After all this, the interesting fact is to know and assess the performance of the scroll machine before and after removal of the non-return valve. Figure 5 shows the scroll expander before and after the removal of the non-return valve.

Table 1. Specifications of the selected scroll compressor

Type	Semi-hermetic
Refrigerant	R134a
Power	1.8 kW
Motor	3 phase induction
Max pressure	1.67 Mpa
Total pocket volume	80 cc
Pressure ratio	3.53

Description of Experimental Set-up and Tests Conducted

To assess the performance of the scroll expander, a simple testing facility was developed as shown in figure 6. In the system, various measuring devices including, flow meter, pressure gauges were used and the specifications of each component and measuring devices are mentioned in table 2. An air filter was used to remove dust and moisture in the air. Compressed air was used as working fluid and the test was conducted in three different configurations of,

1. Scroll compressor with the suction port as the inlet
2. Modified scroll compressor with the suction port as the inlet
3. Modified scroll compressor with discharge port as an inlet.

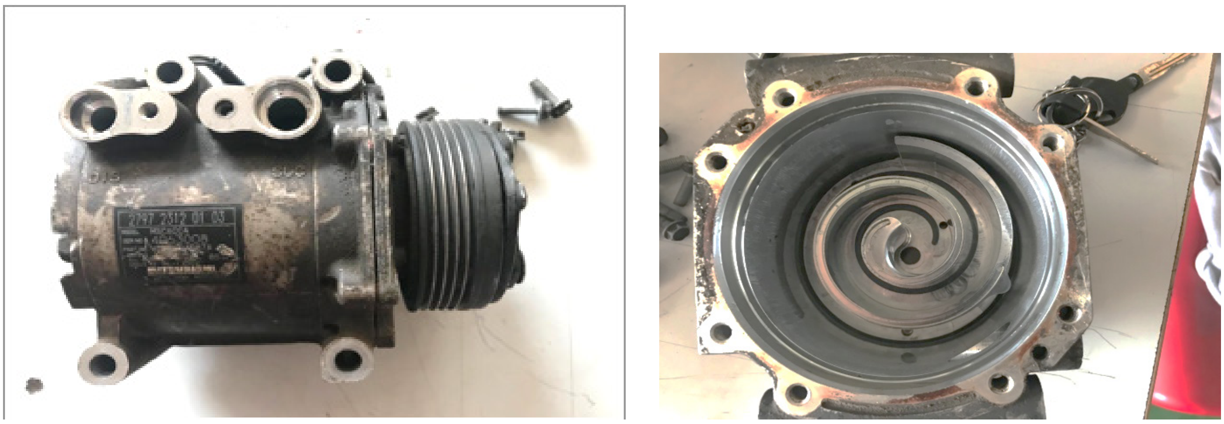

Figure 3. Selected scroll compressor (Left side) and inside view of scroll compressor (Right side).

Figure 4. Discharge and suction port diameters of selected scroll compressor.

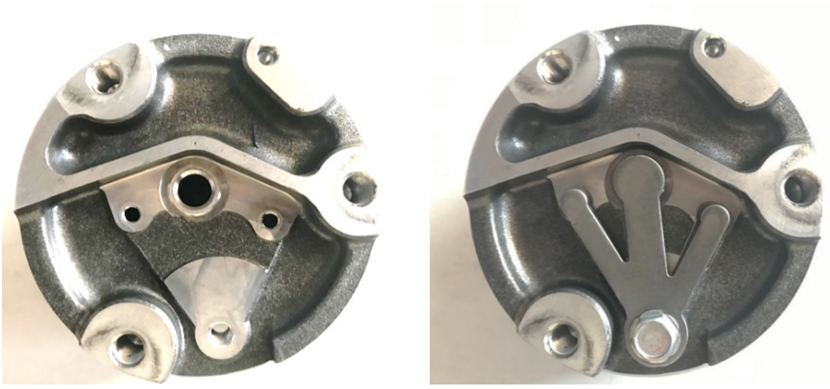

Figure 5. Before modification (Left side) and after modification (Right side).

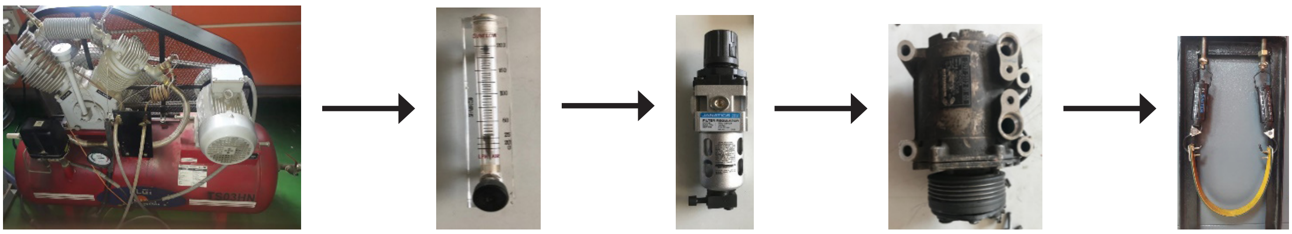

Figure 6. Test setup developed to test scroll compressor.

Table 2. Specification of components and measuring devices used in the test setup

Air compressor	15 bar max
Flowmeter	0 to 200 LPM of air
Air pressure regulator	0.5 to 10 bar
Air filter	Polycarbonate type
	10 bar max
Mechanical load	Upto 5 kg

The scroll machine was tested for operating conditions consisting of pressure varying from 0.5 bar to 4.5 bar and the load varying from 0.2 kg to 2.2 kg for a constant airflow rate.

According to the selected parameters the power produced by expander was calculated using the formula,

$$Power = \frac{2\pi NT}{60}$$

RESULTS AND DISCUSSIONS

A series of tests were done using compressed air as the working fluid to estimate and analyze the performance of the expander under various operating conditions of pressure and loads as mentioned earlier. This provided the elementary data required to develop an ORC system.

The results obtained from the tests conducted show that the pressure has a positive effect on speed for all three configurations as shown in figure 7 but, the configuration of modified compressor with discharge port as inlet has the highest speed in the range of 4200 rpm at 4.5 bar pressure whereas, the other two configurations had the speed in the range of 4000 rpm.

In the later stage, the tests were conducted for various load conditions for the three configurations by varying load and inlet pressure. Based on the results obtained, graphs were plotted as shown in figures 8–10. On comparison of figures 8-10, it is observed that the increasing pressure increases the power produced by the scroll expander in all three configurations and also it was noted that, in all three configurations, for the various loading conditions there exists a maximum power generation point but the power developed is not sufficient at lower pressures and the power increases with increase in pressure.

Initially, when the load is increased on the expander, the power production increases gradually and reaches a maximum point and after which increasing load has a negative effect on power generation at the given operating pressure. This happens due to the overload on the expander. But it is evident that expander can be operated at an optimum loading condition irrespective of pressure and flow rates to get maximum power. As a concluding remark, it is observed that the modified expander with discharge port as inlet has the capacity of producing more power at a given load and pressure when compared to the other two configurations.

Figures 11-13 shows the variation in power with respect to pressure. From the figures 11–13, it is observed that the pressure and power are in a positive relationship and maximum power achieved is in the range of 210W at a load of 1.1 kg for the modified scroll expander, with discharge port as inlet at 4.5 bar pressure and this configuration is suited well, to be used in ORC.

According to the data obtained by the tests conducted, modified scroll expander with discharge port as inlet was integrated with ORC for power generation as shown in figure 14.

FUTURE WORK

The performance of the modified scroll expander will be analyzed in ORC with R134a as a working fluid and validation of results will be carried out by developing a mathematical model for the expander.

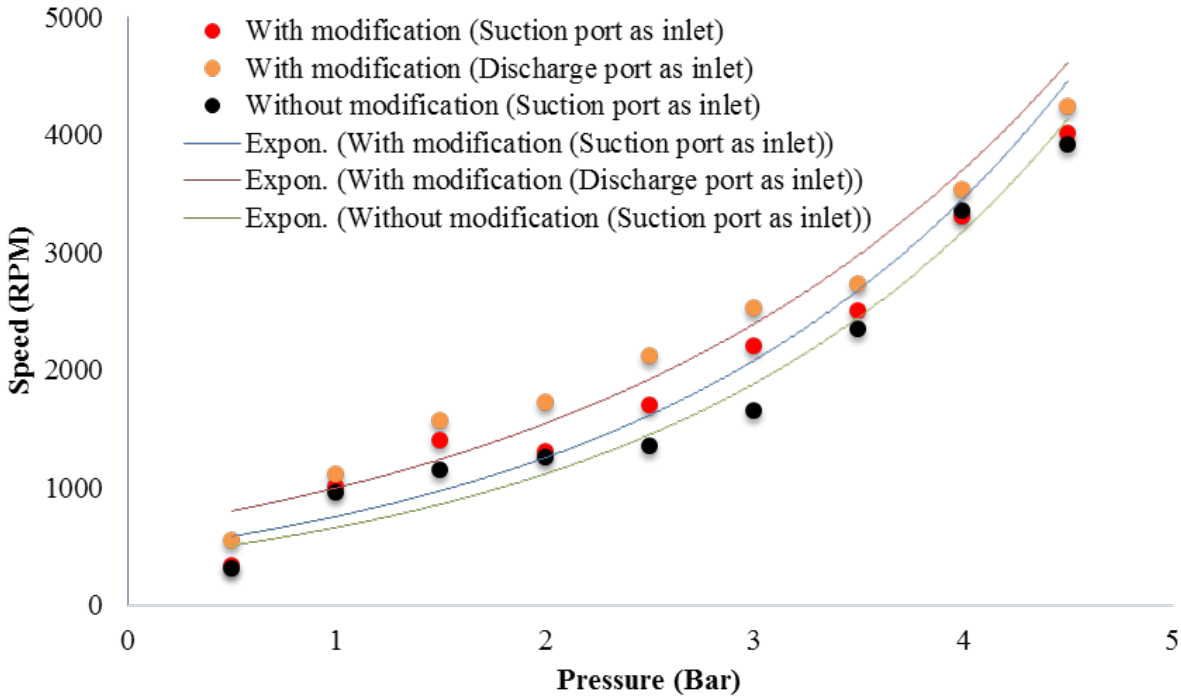

Figure 7. Performance of Scroll compressor before and after modification at no load condition.

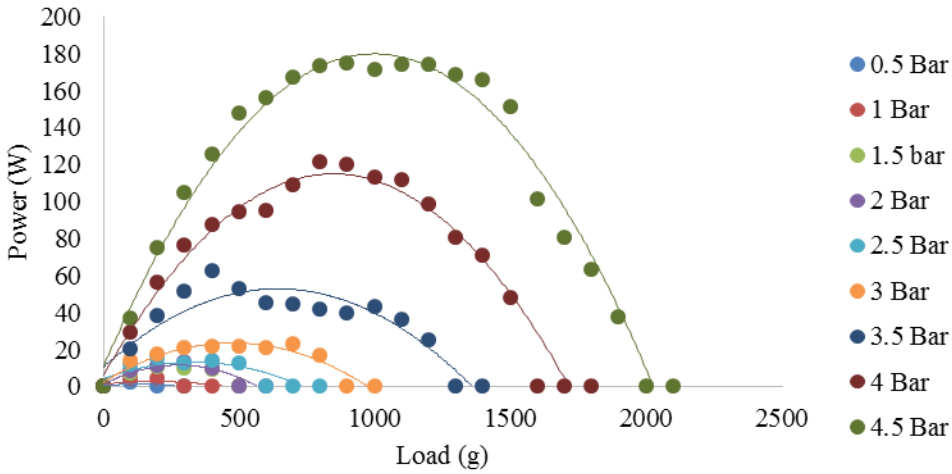

Figure 8. Load vs Power without modification (Suction port as inlet).

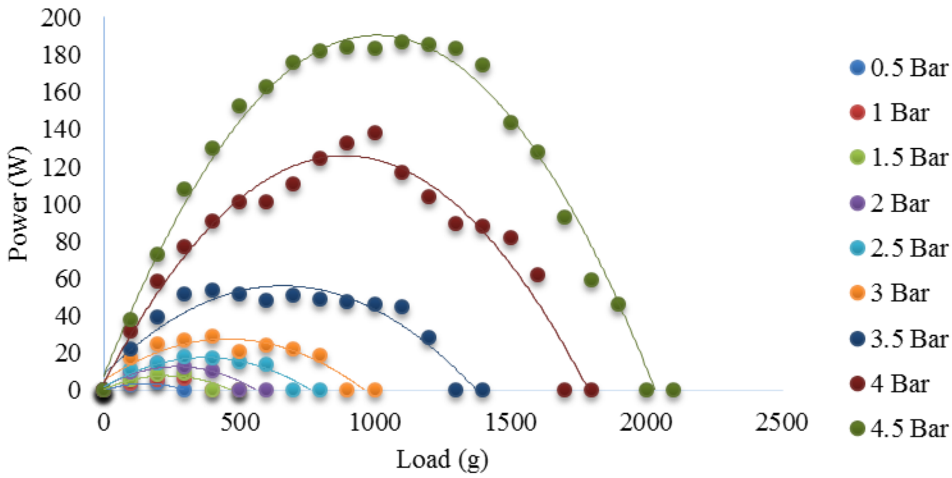

Figure 9. Load vs Power with modification (Suction port as inlet).

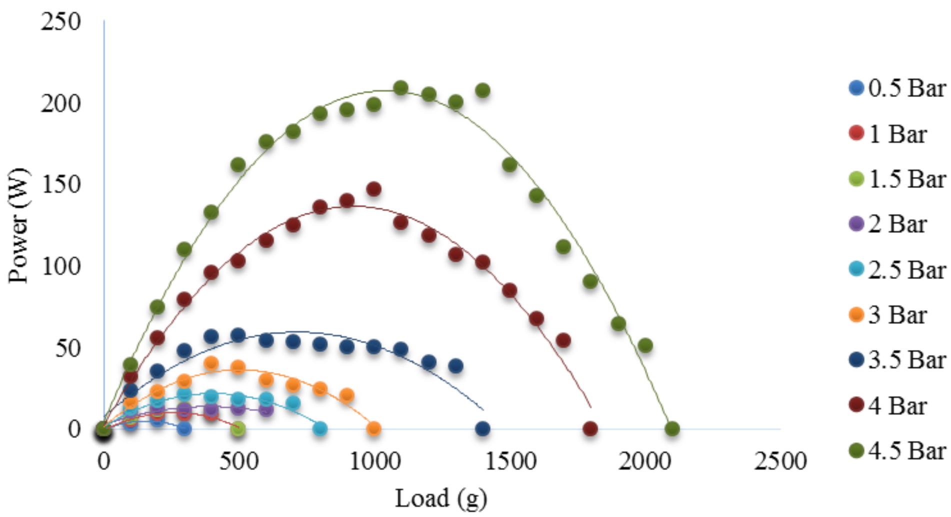

Figure 10. Load vs Power with modification (Discharge port as inlet).

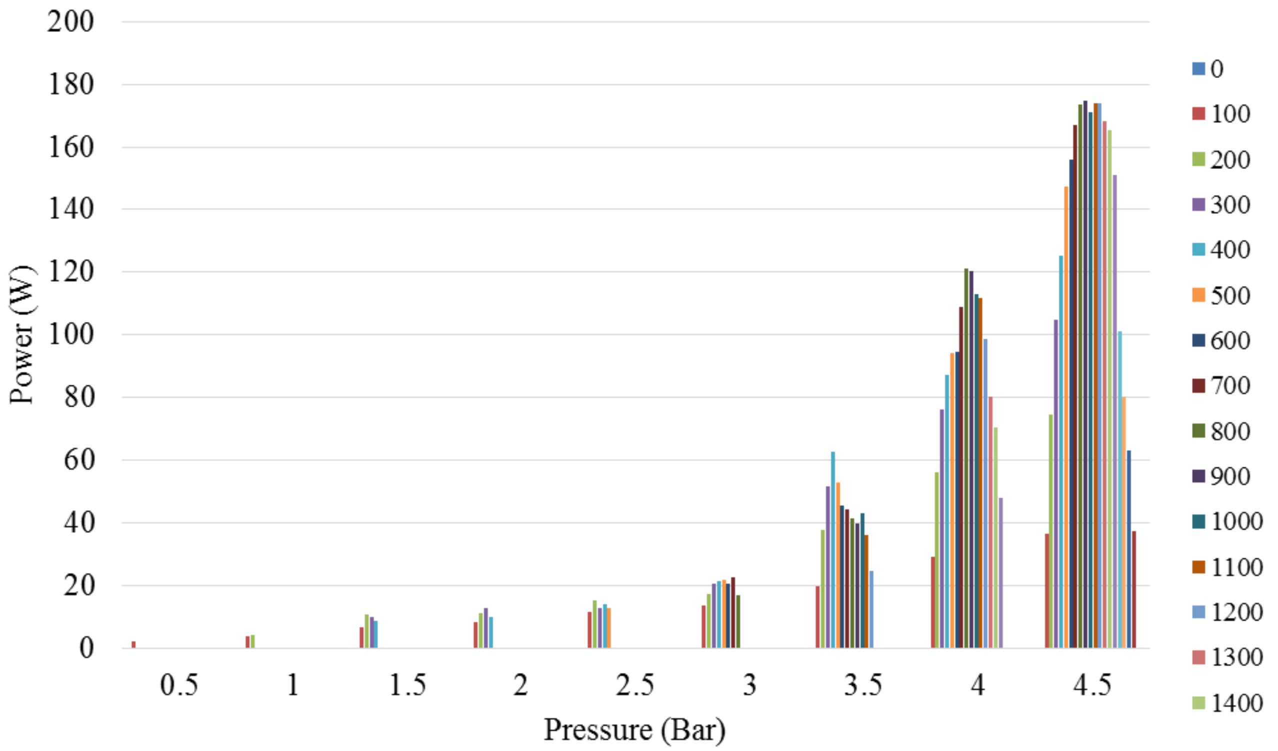

Figure 11. Comparison of variation in power with varying pressure and load for scroll compressor without modification (Suction port as inlet).

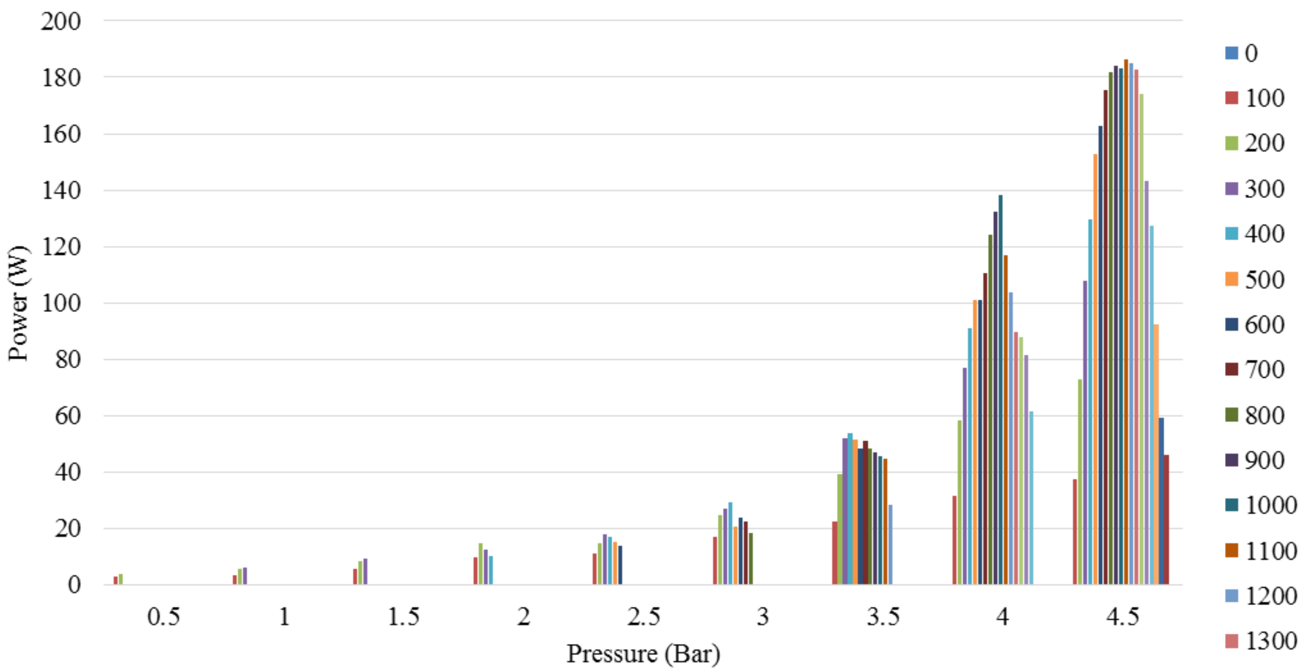

Figure 12. Comparison of variation in power with varying pressure and load for modified scroll compressor (Suction port as inlet).

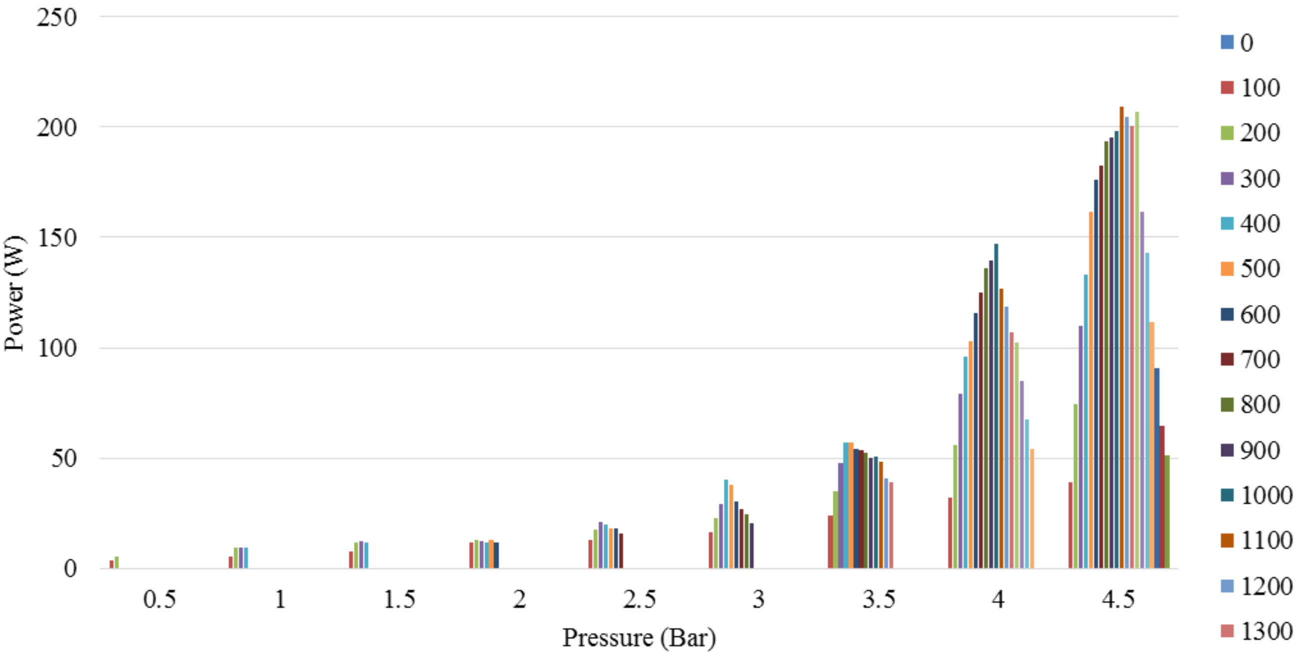

Figure 13. Comparison of variation in power with varying pressure and load for modified scroll compressor (Discharge port as inlet).

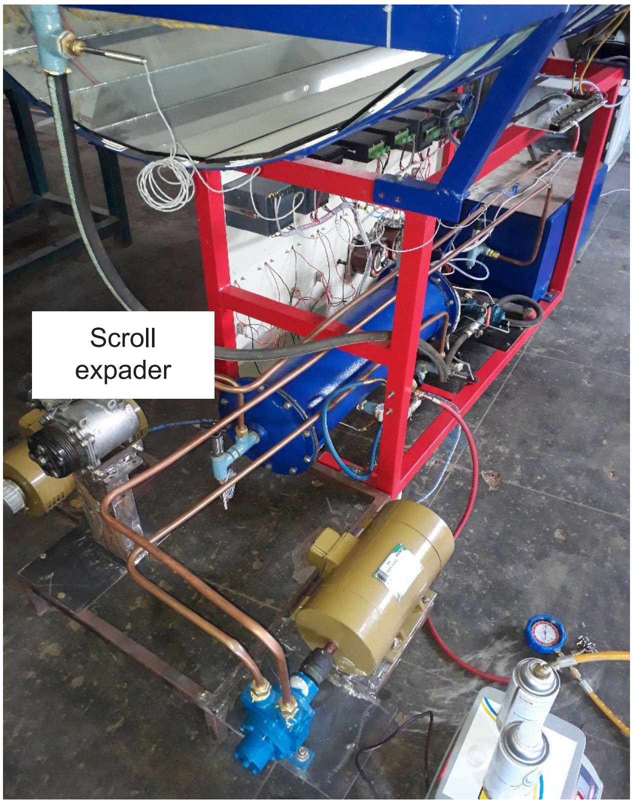

Figure 14. Modified scroll compressor integrated with ORC.

CONCLUSION

Present work demonstrates the success of a modified automotive AC compressor into an expander and its application for power generation using small scale ORC.

1. Minor modification such as removal of nonreturn valve of scroll compressor converts it into an expander.
2. The studies highlight that, at no-load condition, the rotational speed of scroll expander increases with increased inlet pressure.
3. For a set operating pressure of 4.5 bar, modified scroll expander attains the highest speed of 4230 rpm when discharge port is used as inlet
4. The power generated with a modified scroll compressor as expander (that uses discharge port as inlet) was 210 W at 1.1 kg and is significantly higher than that of 180 W at same load condition for the expander without modification (suction port as inlet).
5. It was observed that for all the pressure and loading conditions there exists an optimum operating condition for the modified expander to get the highest power.
6. The modified scroll expander demonstrates its success when integrated into the ORC test setup.

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Engineering, RRIT, Bengaluru and MSRUAS-Bengaluru for their support for this present research work.

NOMENCLATURE

θ	Orbiting angle,
H	Height of scroll vanes
r_b	Radius of the basic circle of the scroll
r_o	Orbiting radius of the rotating scroll
α_i	Initial angle of the inner involute
α_o	Initial angle of the outer involute and
φ_e	Rolling angle
π	Constant, 22/7
N	Rotational speed, RPM
T	Torque, N-m.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

No new data were created in this study. The published publication includes all graphics collected or developed during the study.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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