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Experimental Study of Novel Linear Compressor in Refrigeration System

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ABSTRACT

This study investigates the performance of linear compressor used in vapour compressor refrigeration systems (VCRS). Conventionally, crank-drive reciprocating compressors or rotary compressors are used in VCRS, but the study deals with the innovative Linear compressor, which has been found to pose many merits in comparison to conventional ones. The objective of this research is to provide a comprehensive understanding of the system's performance characteristics from various perspectives, ultimately contributing to the enhancement of future VCRS designs. The experimental test rig has been meticulously designed and developed, utilizing a simple VCRS that incorporates both a crank drive reciprocating compressor and a spring-based linear compressor. A solenoid valve facilitates the operation of one compressor at a time. The performance of this experimental setup was assessed by varying the air flow speed of the fan mounted on the evaporator, ranging from 1 m/s to 2.5 m/s in increments of 0.5 m/s. Also, the observations were made at different ambient conditions. Performance evaluation was conducted based on key parameters, including power consumption, cooling capacity and the Coefficient of Performance (COP). The refrigerant considered for analysis in this study is R600a, which is used in both crank drive and linear compressors. The experimental results indicate the relative advantages and disadvantages of the spring-based linear compressor over the crank-drive compressor. With a redesigned configuration, it is expected that the linear compressor's overall performance could be further improved.

Keywords:
Vapour compression system; crank-drive compressor; linear compressor

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1. Introduction

Vapor Compression Refrigeration System (VCRS) is a widely utilized and fundamental technology that holds significant importance in our daily lives, ensuring our comfort and preserving perishable goods. This system serves as the foundation for common household appliances like refrigerators, air conditioners and heat pumps, operating inconspicuously to regulate temperature and create a pleasant living environment. At its core, the VCRS functions based on a straightforward yet highly efficient principle: the circulation and phase change of a refrigerant to facilitate heat transfer and generate cooling. This system consists of several crucial components that work in unison to accomplish the cooling process. The primary constituents of a VCRS encompass the compressor, condenser, expansion valve and evaporator.

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But our concern here, is the compressor. The compressor serves as the central component of the VCR system, responsible for circulating and compressing the refrigerant, typically a specialized gas or fluid, which absorbs and releases heat during its state change. The compressor assumes a pivotal role in elevating the pressure and temperature of the refrigerant gas. Upon entering the compressor, the refrigerant exists in a low-pressure and low-temperature gaseous state. The compressor's function is to draw in this gas and compress it, thereby increasing both its pressure and temperature. This compression is of utmost importance as it raises the temperature of the refrigerant above that of the surrounding environment, setting the stage for subsequent heat exchange processes in the condenser and evaporator. Generally crank drive reciprocating compressors are used in VCR systems. Numerous research efforts have significantly advanced the field of refrigeration and cooling technology. The study conducted by Zubair [1] offers significant contributions to the comprehension of the effectiveness and suitability of reciprocating refrigeration systems through design and performance evaluation. Their research paper provides valuable insights that enhance our knowledge in this field. Elhaj *et al.,* [2] found that pressure waveform and angular speed changes are key in detecting compressor issues like valve spring degradation and leakage. Suamir *et al.,* [3] show that condensing temperature and evaporating temperature together with degree of superheat at suction gas line can significantly affect temperature performance of a scroll compressor.

The experimental setup that is used for the study is installed with linear compressor. A linear compressor is an innovative and efficient technology utilized in various applications, particularly in refrigeration and air conditioning systems. Liang *et al.,* [4] compared a reciprocating compressor (induction motor-driven with a crank) to an oil-free linear compressor, often used in refrigeration. Results showed that as clearance volume decreases, the reciprocating compressor is 20% more efficient than the linear one, with a 13 mm stroke being the maximum length in the study. What distinguishes the linear compressor from traditional types is its unique design and operational approach. Unlike rotary or reciprocating compressors, a linear compressor compresses the refrigerant by employing a back-and-forth, linear motion. This motion is often facilitated by an electromagnetic mechanism, such as a solenoid. Saengsikhiao *et al.,* [5] found that the most viable solution was to use a digital semi-hermetic compressor that can operate in unload and full load status, that was being controlled by the evaporator temperature (TEV) which was set at -10 degree, the condenser temperature (TCD) set at 38 degrees and the superheat temperature (TSH) at 10 degrees. Nnanna *et al.,* [6] studied vapor compression refrigeration system's response to fast changes in evaporator load for cooling high heat electronics. Analytical and numerical models showed 1D temperature distribution assumption was impractical. Chen *et al.,* [7] analysed a moving magnet linear motor using a linear compressor model, finding that stroke was proportional to input voltage through a blend of finite element and magnetic circuit analysis. Linear compressors offer several distinct advantages, including quieter operation, increased energy efficiency and extended operational lifespans. Furthermore, the linear compressor's design with fewer moving parts contributes to its longer lifespan, thereby reducing maintenance and replacement costs. Ekong *et al.,* [8] found that higher compression pressure boosts compressor efficiency. Consequently, linear compressors represent a promising technology in the pursuit of quieter, more efficient and longer-lasting refrigeration and air conditioning solutions. In a similar vein, Chun *et al.,* [9] have introduced an innovative method to enhance linear compressor systems, utilizing PWM inverters to improve energy efficiency in industrial settings.

Bradshaw *et al.,* [10] developed a detailed model for a linear compressor used in cooling electronics like computers. They tested the model's accuracy using data from a prototype compressor with a 0.6 cm mean stroke and about 3 cm3 total displacement. Bradshaw *et al.,* [11] employed the same model as [10] to assess energy recovery in linear and reciprocating compressors, highlighting the impact of clearance volume. Unlike the reciprocating compressor, the linear compressor-maintained efficiency with increasing dead volume due to gas energy recovery during expansion. Ajaicimhan *et al.,* [12] design a centrifugal compressor test rig with an integrated combustor, optimizing performance without speed-reducing gears and ensuring efficient testing.

Refrigerants play a crucial role in Vapor Compression Refrigeration Systems (VCRS) by facilitating the transfer of heat to achieve the desired cooling effect. These specialized fluids circulate throughout the VCRS, undergoing transitions between gas and liquid states as they absorb and release heat.

Notable refrigerants commonly utilized in this context include R-134a, R-410A and R-22. R-134a, classified as an eco-friendly hydrofluorocarbon (HFC), is widely prevalent in modern cooling systems. Liang *et al.,* [13] created an oil-free linear compressor using R134a for electronic cooling. They adjusted stroke length, achieving a COP of ~3 at 2.5 pressure ratio and 20°C evaporator temp. Linear compressor excels at low power but crank-drive is 20% better in volumetric efficiency. Iterative design improves linear compressor performance. On the other hand, R-410A, a blend of HFCs, is favoured for its superior efficiency, while R-22, although less environmentally friendly, is still present in older systems. The selection of a specific refrigerant is contingent upon various factors such as its environmental impact, efficiency and safety. As technology progresses, there is an increasing emphasis on adopting environmentally responsible alternatives to address concerns related to global warming. Kim *et al.,* [14] studied a linear compressor using R600 refrigerant, presenting numerical and experimental results. They found that the natural frequency fluctuated, impacting compressor performance, especially with varying evaporator and condenser pressures.

Linear compressors have emerged as a promising technology for cooling. Liang *et al.,* [15] have developed an energy-efficient linear electromagnetic-drive oil-free refrigeration compressor, which is particularly relevant when considering the use of R134a refrigerant. Chang *et al.,* [16] have demonstrated the feasibility of miniature vapor compressor refrigeration for electronic cooling, offering effective thermal management. Furthermore, Shaoshuai *et al.,* [17] have advanced cryogenic cooling technology through their analysis of two-stage valved linear compressors.

Liang [18] have explored high-pressure oil-free linear compressors for domestic refrigeration, promoting energy efficiency and environmental benefits. Liang [19] conducted a thorough examination of linear compressors for refrigeration in their review, presenting a comprehensive analysis of this technology. Their study offers significant contributions by shedding light on the various applications and the potential of linear compressors in achieving energy-efficient cooling solutions.

Choe *et al.,* [20] have delved into the nonlinear dynamics within linear compressors, enhancing our understanding and optimization of these systems. Nnanna [21] has emphasized the vital role of refrigeration in electronic cooling, enhancing performance and dependability. Alzoubi *et al.,* [22] have highlighted the potential of linear compressors in sustainable refrigeration.

Bijanzad *et al.,* [23] have analysed solenoid-based linear compressors in household refrigerators, elucidating their efficiency and potential as sustainable cooling technology. These research endeavours collectively reshape refrigeration and cooling technology, enhancing energy efficiency, sustainability and thermal management across various applications, from household to industrial settings. Li *et al.,* [24] experimental analysis enhances understanding of oil-free linear compressor discharge valve dynamics, contributing valuable insights to advance sustainability in refrigeration systems. Huang *et al.,* [25] comprehensively explored and compared the efficiency of a single-piston valved linear compressor and a symmetrical dual-piston valved linear compressor, providing valuable insights for advancing compressor technology.

The main objective of this study is to evaluate and compare the performance of spring-based linear compressors and crank-drive reciprocating compressors. This study will encompass aspects such as volumetric efficiency and the compressor work required, considering different mass flow rates. The research also aims to design and construct an experimental test rig to conduct a practical comparative analysis between these two compressor types. The goal is to gain insights into the advantages of spring-based linear compressors, such as their oil-free operation, reduced frictional losses, suitability for compact heat exchangers and application in electronics cooling, particularly in miniature VCR systems and small-scale refrigeration systems for electronics cooling, where lower pressure ratios are essential.

2. Methodology

2.1 Experimental Setup and Its Working

The basic components of the setup operating on the vapor compression cycle are the compressor, condenser, expansion valve and evaporator. In this research we have used two different types of compressors for the study- Crank drive compressor and Linear compressor. These compressors are used one at a time and can be switched using a solenoid valve. In this study, we employed the refrigerant R-600a to power the entire VCR system within our configuration, including both the crank-drive and linear compressors. R-600a has garnered favour as a substitute for chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) in the realm of refrigeration. Figure 1 shows the different component of the setup.

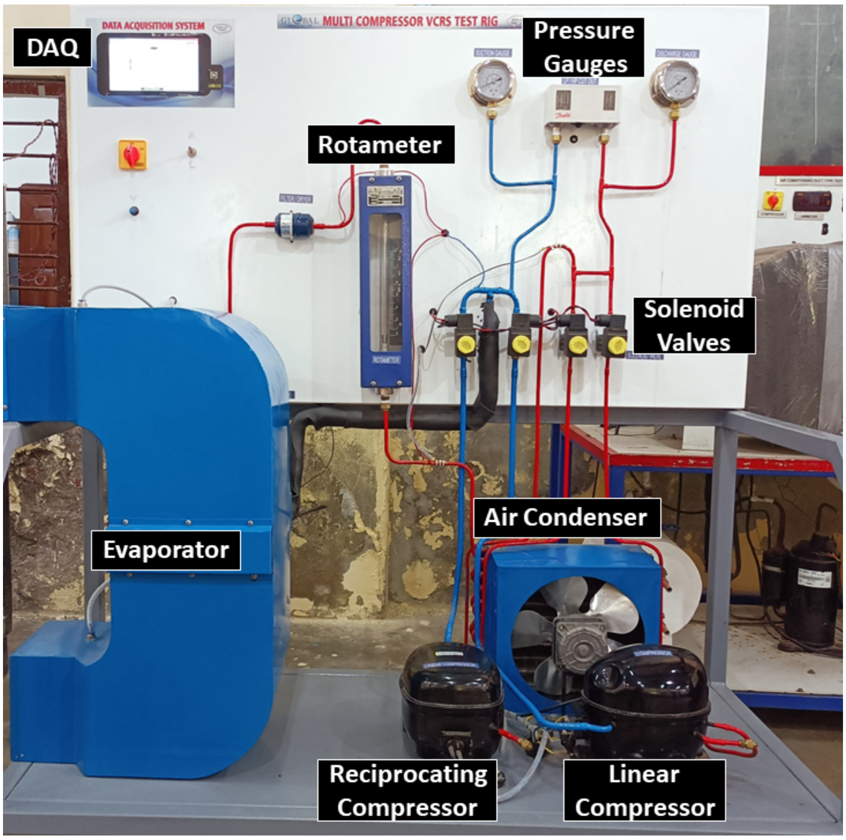


Fig. 1. Experimental setup of Multi-Compressor VCR system

In the initial stage of experimentation, the air flow controller's knob was calibrated to specific velocity settings, including values of 1 m/s, 1.5 m/s, 2.0 m/s and 2.5 m/s. Subsequently, the velocity was quantified using an anemometer and the obtained velocity measurement was subsequently input into the associated software. A time interval of 10 seconds was selected, during which data was systematically collected and recorded. Generally, a total of 25 data points were acquired. It is worth noting that the experimental system incorporated two distinct types of compressors: a linear compressor and a reciprocating compressor. The activation and deactivation of these compressors were facilitated through the manipulation of a dedicated control knob. The comprehensive dataset resulting from this experimental procedure was visually presented and stored utilizing a Data Acquisition System.

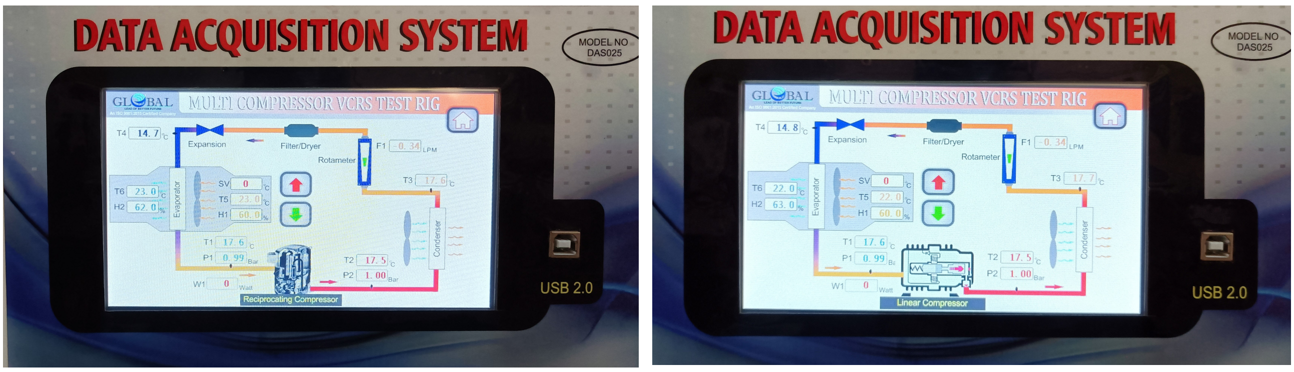
2.2 Specifications of the Experimental Setup

The basic components in the setup are as follow:

i. Evaporator: Air Cooled 9*9- 2 Row
ii. Compressor: In this setup we have two types of compressors, which can be switched on one at a time, these compressors are-
iii. Crank Drive Compressor: Hermetically Sealed Compressor, KCN411LAG, No. of cylinder= 1, Temp Range= -35°C to 6.7°C, 230 V, 50 Hz, 1 Phase, R-600a
iv. Linear Compressor: LG FMA102 NAMA, 230 V, 50 Hz, 1 Arm, 120 W, 2400-4500 rpm, R-600a)
v. Condenser: Air Cooled Condenser = 12*12 - 3 Row
vi. Expansion Device: Capillary Tube 0.44, 6 feet*2

2.3 Measuring Instruments

Data Acquisition System (DAQ) exhibits data on temperature and pressure for both inlet and outlet points of all components. Additionally, it presents information regarding refrigerant flow rates and power ratings. This system provides comprehensive monitoring of key parameters within the setup. Rotameter (Range: 0.1-1.2 LPM, Scale Length- 180mm, Accuracy: /-2% of FSD, Temperature: -20°C to 120°C) measures the refrigerant flow rate which being recorded in DAQ. Digital Anemometer (Range: 0-45 m/s, Temperature: -10°C to 50°C, Humidity: 40% RH – 85% RH, Accuracy: +-3% 0.1dgts) has been used to measure the air velocity.



(a) (b)

Fig. 2. DAQ Readings of (a) Reciprocating compressor (b) Linear compressor

2.4 Performance Parameters

The following parameters which have been used for the analysis of Linear and Reciprocating Compressor of VCR system have been shown in Eq. (1) to Eq. (5). The experimental data which has been recorded is taken at steady state.

i. Refrigeration Effect

$$q = (\boldsymbol{h_1} - \boldsymbol{h_4}) \tag{1}$$

ii. Refrigeration Capacity

$$\boldsymbol{Q} = \dot{m} \times (\boldsymbol{h_1} - \boldsymbol{h_4}) \tag{2}$$

iii. Compression Work

$$w_{\boldsymbol{c}} = (\boldsymbol{h_2} - \boldsymbol{h_1}) \tag{3}$$

iv. Power required for compressor

$$\boldsymbol{P} = \dot{m} \times \boldsymbol{W_c} \tag{4}$$

v. Coefficient of Performance

$$\boldsymbol{COP} = \mathrm{q} \div \mathrm{W}_{\boldsymbol{c}} \tag{5}$$

3. Results
3.1 Effect of Air Velocity on COP

In the context of Figure 3, air flow velocity plays a pivotal role in influencing the Coefficient of Performance (COP) of cooling systems, such as air conditioners or refrigeration units. Air flow velocity exerts a direct influence on the heat transfer efficiency within the cooling system. Elevated air flow velocities facilitate more efficient convective heat transfer between the cooling medium (air) and the cooling surface, such as the evaporator coils. This heightened heat transfer efficacy augments the cooling system's capacity, potentially leading to an increased COP.

Airflow velocity affects the temperature differential in cooling systems. Faster airflow reduces the temperature difference between the cooling medium and surface, boosting system efficiency and improving COP. The setup of fans or blowers significantly influences COP by optimizing heat transfer. However, the exact impact of airflow velocity varies with system design, operating conditions and cooling technology. Manufacturers typically provide recommended airflow rates and COP data for different conditions.

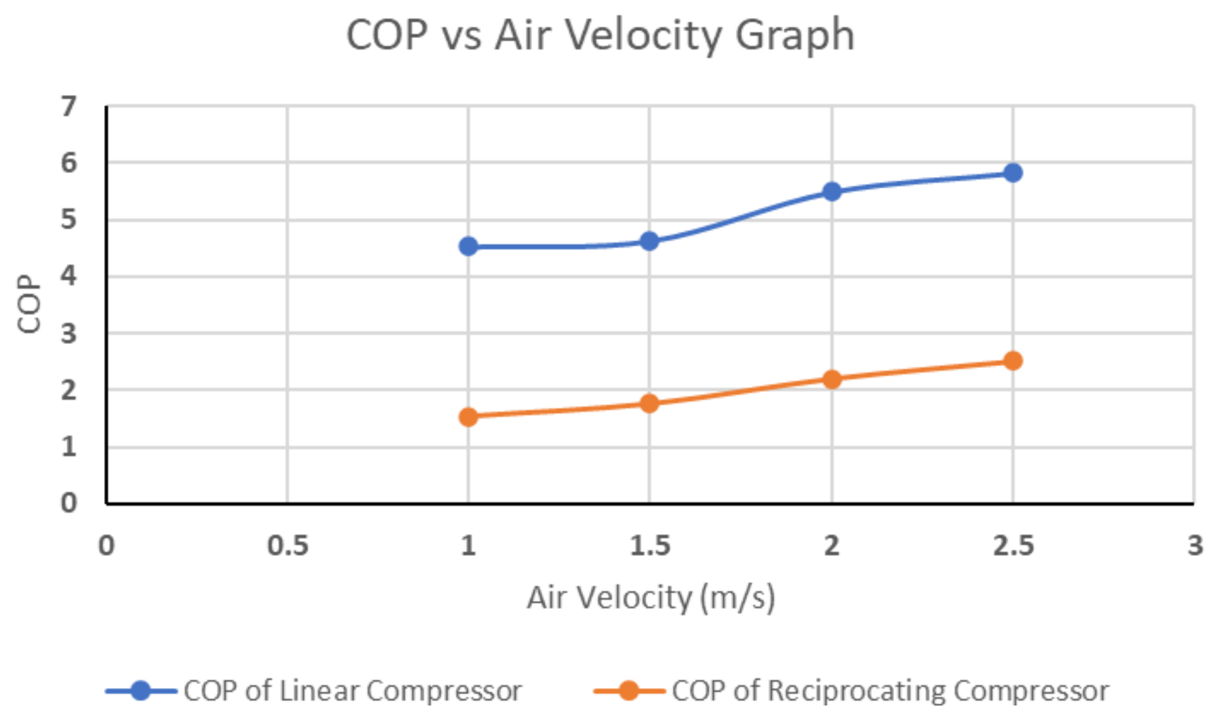


Fig. 3. Variation of COP with air velocity at ambient temperature= 34°C

3.2 Effect of Air Velocity on Refrigeration Capacity

In accordance with Figure 4, the refrigeration capacity of a given system is subject to the influence of several variables, among which the air flow rate holds significance. Several key considerations pertain to the fluctuation of refrigeration capacity in relation to air flow rate.

Airflow rate affects both sensible cooling (temperature reduction) and latent cooling (humidity removal). Increased airflow rates usually improve sensible cooling by enhancing heat transfer with cooling coils. Latent cooling, on the other hand, depends on system design and dehumidification capabilities.

The air flow rate wields influence over the available heat transfer surface area for heat exchange. Elevating the air flow rate can heighten convective heat transfer by facilitating superior contact between the air and the cooling surface. This, in turn, results in an increased refrigeration capacity.

Higher airflow increases refrigeration capacity but can reduce system efficiency. It requires more power for fans, raising energy consumption. An optimal airflow balance is crucial for efficiency.

It is important to emphasize that the specific relationship between refrigeration capacity and air flow rate is contingent upon the particulars of the system's design, the characteristics of the cooling coil and the operating conditions. Manufacturers often supply performance data or performance curves for their systems, aiding in the determination of how refrigeration capacity varies with air flow rate under different operational scenarios.

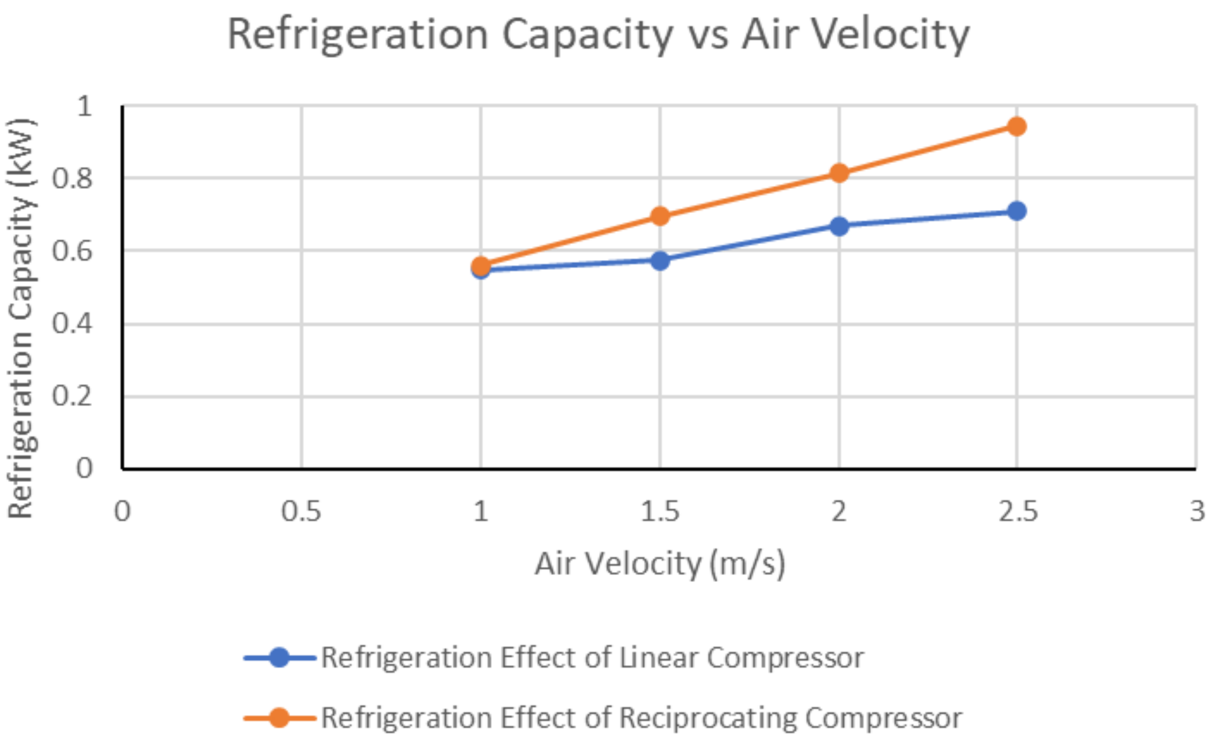


Fig. 4. Variation of refrigeration capacity with air velocity at ambient temperature= 34°C

3.3 Effect of Air Velocity on Compressor Work

In context of Figure 5, the impact of air velocity on compressor work in a refrigeration system is primarily associated with the condenser and evaporator coils, as these components are where air velocity plays a significant role.

In the evaporator coil, increased air velocity can enhance the heat transfer between the warm air in the space being cooled and the refrigerant inside the coil. This improved heat transfer allows for more efficient cooling, reducing the load on the compressor and, consequently, its work. Higher air velocity in the evaporator typically leads to a reduction in compressor work.

If the air velocity decreases in the evaporator coil, the heat transfer rate decreases and the evaporator may struggle to absorb heat efficiently. This can result in the compressor needing to work harder to maintain the cooling effect, as it has to circulate the refrigerant more and evaporate it at a slower rate. Compressor work increases when air velocity is reduced in the evaporator.

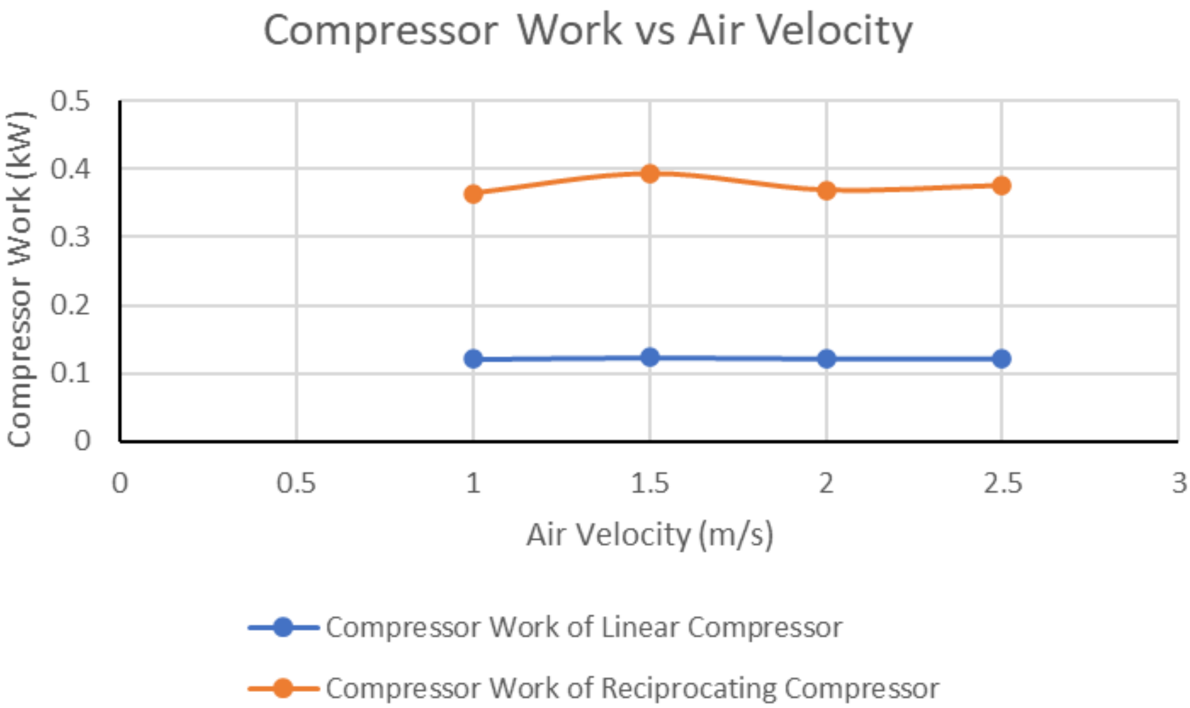


Fig. 5. Variation of compressor work with air velocity at ambient temperature= 34°C

In Figure 6 and Figure 7, the VCR cycle with crank-drive compressor and linear compressor is shown respectively on the pressure-enthalpy chart at air velocity of 2.5 m/s.

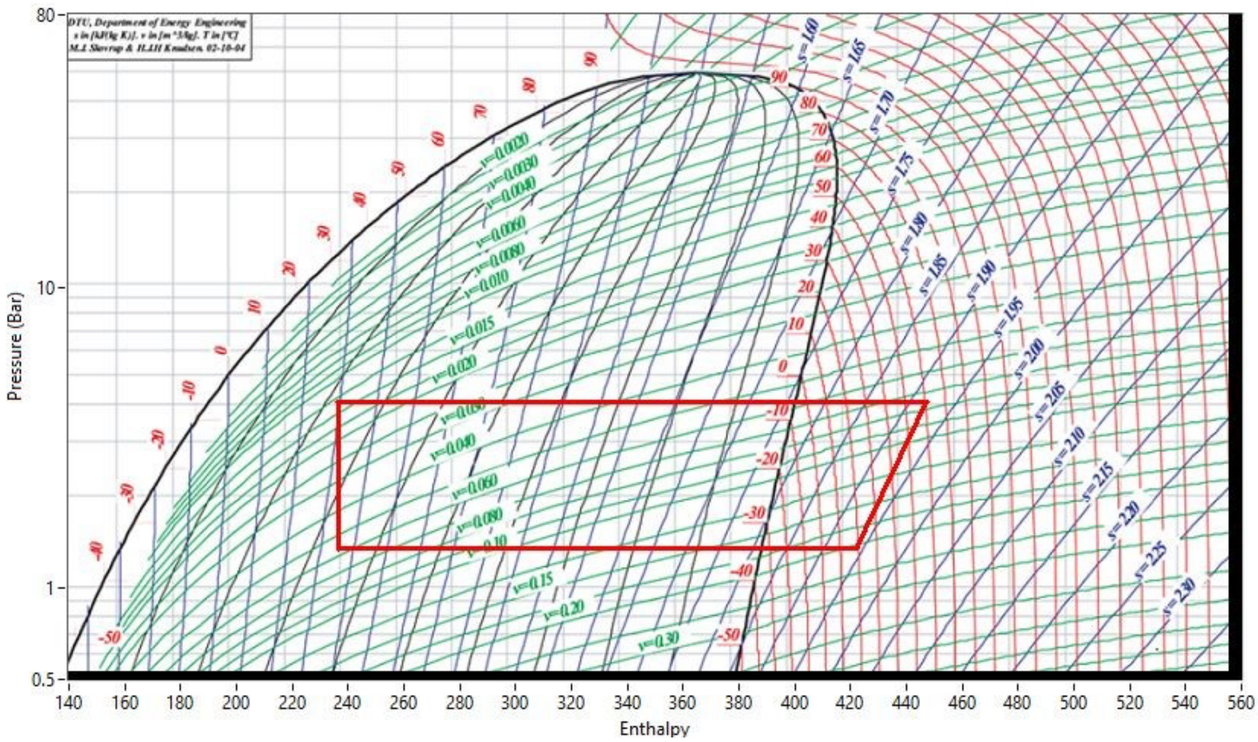


Fig. 6. Pressure-Enthalpy chart with crank-drive compressor at air velocity 2.5 m/s

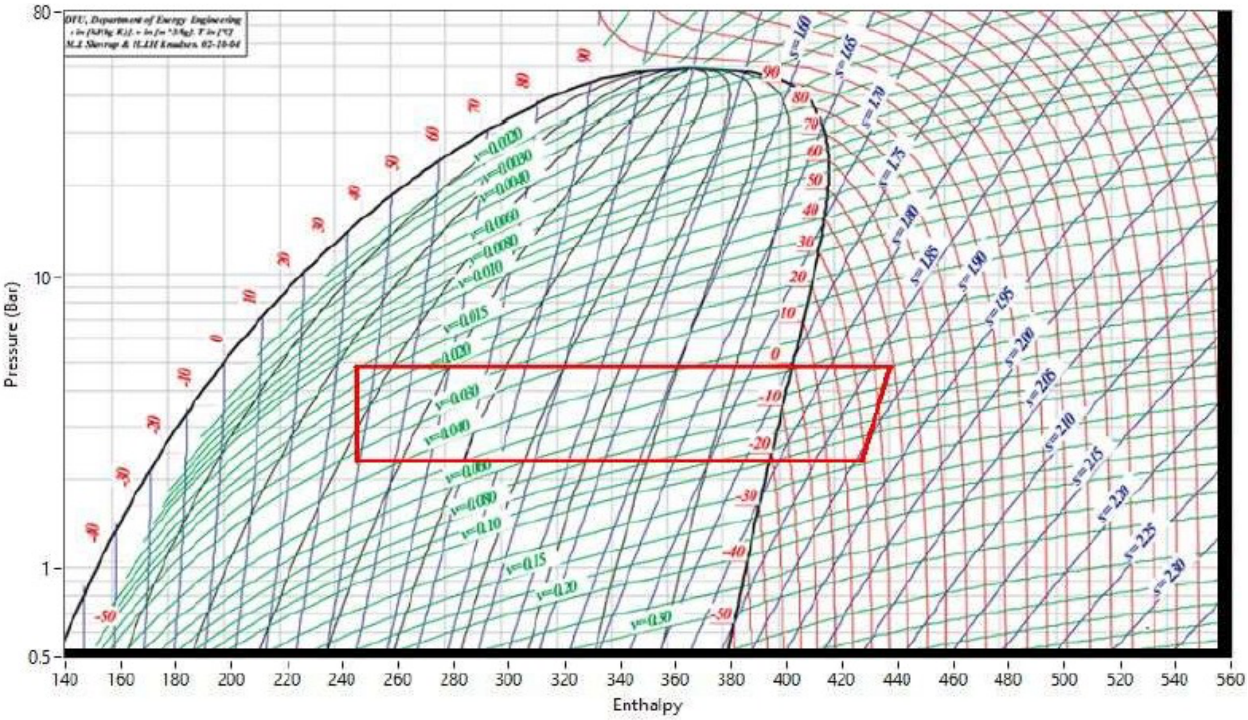


Fig. 7. Pressure-Enthalpy chart with linear compressor at air velocity 2.5 m/s

4. Conclusions

The prime objective of our experimental work was to analyse the performance of linear compressor of VCR system. In addition to this, our work also emphasis on the comparison between linear and reciprocating compressor. The following conclusions were drawn which are follows:

i. Elevating fan speed enhances the COP for compressors in a general context. However, results can vary when considering the cooling coil's bypass factor. Linear compressor has an increased COP of around 160% when compared to reciprocating compressor at same air velocity.
ii. Increasing air velocity in the evaporator coil of both linear and reciprocating compressors improves heat exchange efficiency, enhancing the refrigeration effect. It enhances heat transfer, leading to better cooling performance and increased system efficiency.
iii. The input power for specific compressors remains relatively consistent; approximately 120 watts for linear compressor and 380 watts for reciprocating compressor.
iv. Linear compressor outperforms reciprocating compressor, chiefly due to their lower power consumption of about 38% of power consumption of reciprocating compressor for approximately same refrigeration effect. This advantage translates to significant energy savings.

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