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Experimental investigation of the energy efficiency of a linear compressor and comparison with a reciprocating compressor in a small refrigeration system

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Abstract The conducted experimental studies of the linear compressor concerned the cooling capacity, efficiency, and Energy Efficiency Ratio (EER). Linear compressor performance tests were carried out for the supply voltage of 190–265 V and the supply frequency in the range of 45–65 Hz, which allowed the compressor to be tested outside its typical operating range. Modulation of the performance was achieved using an inverter. The full range of performance characteristics of a linear compressor was presented. The results were compared with a reciprocating compressor for similar displacement volume, which achieved lower EER values by an average of 38% for a pressure ratio above 1.7. The power consumption of a linear compressor is on average two times lower than that of a reciprocating compressor.

Keywords: Power Consumption; Linear compressor; Reciprocating compressor; Energy efficiency ratio; Energy saving compressor

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Nomenclature

CFD	–	computational fluid dynamics
EER	–	energy efficiency ratio
h_1	–	discharge enthalpy, kJ·kg^{-1}
h_4	–	suction enthalpy, kJ·kg^{-1}
h_3	–	inlet calorimeter enthalpy, kJ·kg^{-1}
h_7	–	outlet calorimeter enthalpy, kJ·kg^{-1}
$\dot{m}_{\text{ref}}$	–	mass flow of refrigerant, g·s^{-1}
N	–	number of elements on a sample
PR	–	pressure ratio
P_{suc}	–	suction pressure, kPa
p_1	–	discharge pressure, kPa
p_4	–	suction pressure, kPa
R	–	result of a calculation based on one or more measurements
$\dot{Q}_{\text{evap}}$	–	cooling capacity, W
W_{in}	–	electric power consumption, W
X_i	–	ith variable

Greek symbols

δR	–	uncertainty in the result
η	–	compressor efficiency

1 Introduction

In recent years, there has been a growing interest in energy-saving appliances in the heating and cooling energy sector, which accounts for a significant share of energy consumption. Today, in most types of small refrigeration system compressors (up to a cooling capacity of 1 kW), the market is dominated by different varieties of reciprocating compressors. Currently, there is an increasing interest in research into the use of energy-saving linear compressors in small refrigeration systems. The power consumed in the global dimension by small refrigeration systems occupies a significant part of it and increases year by year, Hovgaard [1].

Park *et al.* [2] conducted research on a linear compressor by dividing it into several control volumes. They analyzed the heat transfer for each volume. In the experiment, a calorimeter was used to determine the cooling capacity of a compressor. The energy efficiency ratio (EER) was estimated depending on the changes in the thermal properties of the compressor. The obtained experimental results coincided with the simulation within 5%. Liang [3] dealt with the issues related to the use of an oil-free linear compressor in small refrigeration systems. The oil-free operation will allow the use of mini/micro channel heat exchangers and increase the efficiency of the entire system. With a typical high-pressure ratio in domestic refrigeration, the key challenges are the development of large clearance losses, large piston displacement, and non-linear spring operation. The author made a thorough analysis of the above key issues, which will contribute to the implementation of an oil-free linear compressor for domestic refrigeration. The nonlinear spring model has been validated by experiments for lower pressures. The researcher observed that the gas leakage increases 2.5 times when the piston is fully eccentric in the cylinder. The gas leakage loss can be 27% of the power consumption at a pressure ratio of 13.6 when using R600a refrigerant. Two commercially available designs of linear compressors from LG [4] and Embraco Wisemotion [5] have been developed. Bezrodny *et al.* [6] tested the efficiency of the heat pump with the removal of excessive moisture, which can also contribute to energy efficiency.

An analysis of the possibility of controlling the efficiency of linear compressors and the impact of changes in efficiency on their operation was undertaken. Kim and Jeong [7] with Kim and Kim [8] determined the performance characteristics of a linear compressor for two ways of changing its efficiency (inherent capacity modulated and electronic resonance system). The experimental test conditions were selected to ensure the modulation of the compressor for the efficiency range from 50% to 100% at an evaporating temperature of –26°C and a condensing temperature of 36°C. The difference in the capacity of the refrigeration system for ICM (inherent capacity modulated) control and the electronic resonance system is within 1%. The results for conventional linear compressor control did not consider the power consumed by the electronic drive, so the ICM linear compressor had a potential improvement in energy savings. In another part of the research, they developed the characteristics of the linear compressor parameter change in response to the fluctuating evaporation and condensation temperature occurring in low-power refrigeration equipment. Based on the conducted experimental research, a numerical model and a compressor prototype were developed. The compressor prototype was tested for an evaporating temperature of –35°C to 15°C. For increasing the condensing temperature from 20°C to 50°C, the cooling capacity increased by 241 W and 50 W respectively.

Based on experimental research one-dimensional CFD model was created by Hwang and Lee [9]. The model simulated a temperature distribution inside the compressor and the resulting transitional flows. To shorten the calculation time, the temperature of the compressor solids was used as the boundary conditions of the wall. The obtained results for the simulation settings allowed us to obtain results with an accuracy of 5%, which improved the accuracy of the model compared to the previous one by 10%. An and Lee [10] developed a three-dimensional numerical CFD model that allowed the prediction of the cooling capacity of a linear compressor. To analyze the operating cycle of a linear compressor, experimental tests were carried out on two linear compressors, and the obtained results were consistent with the results of the numerical simulations. The accuracy of the simulation was increased by considering the detailed behavior of the valves.

This paper attempts to describe the influence of a linear compressor on the work of a refrigeration system also in extreme power supply cases and to compare it to a reciprocating compressor with a similar design displacement volume. The thermodynamic values of each of the elements of the refrigeration system were measured for various compressor power supply parameters. Experimental tests were carried out on a stand with a calorimeter. The article presents and discusses the characteristics of the impact of linear and reciprocating compressors on the refrigeration system. The motivation to undertake the research was the desire to extend the available experimental results in extreme cases of the operation of a linear compressor and to compare it with a reciprocating compressor in terms of energy efficiency. These experimental data will find application in industry and numerical research. The main purpose of the work, which is a novelty, is to determine and compare the energy efficiency of the linear and reciprocating compressors in a wide range of power supply parameters.

2 Materials and mmethods

2.1 Objects of study

The research object is a linear compressor (LG FLA 150NBMA), used in small refrigeration devices. It is one of the few linear compressors available commercially. The reciprocating compressor (Secop NLX15KK.3) used for the comparison has a similar volume compression to the linear one. The most important parameters of the tested compressors are presented in Table 1.

Table 1: Parameters of tested refrigeration compressors.

Compressor type	Linear compressor (LG FLA150NBMA)	Reciprocating compressor (Secop NLX15KK.3)
Voltage Range (V)	220–240	198–254
Frequency Range (Hz)	50–60	50–60
Resistance, main (Ω)	9	14.6
Displacement (cm^3)	15	14.65
Refrigerant	R600a	R600a

2.2 Experimental stand

The refrigeration system has been designed with a calorimeter to determine the cooling capacity of the compressor and EER of the refrigeration system in accordance with ANSI/ASHRAE 23.1 [11]. The test rig is equipped with an analyzer of electric network parameters (DMG 200, LOVATO ELECTRIC), which measures the electric power consumed by the heater in the calorimeter and the power consumed by the compressor. The temperature measurement was conducted with the aid of T-type thermocouples (OMEGA type T thermocouples). The pressure was measured by Danfoss transducers dedicated to refrigeration systems (Danfoss AKS 33). An electronic expansion valve was used for the control of the refrigerant mass flow (Carel E2V09) and a Coriolis-type mass flow meter (Endres + Hauser promass 83) for its measurement. A plate condenser (SWEP B5THx10) and flow meter (Kobold DUK 11G4HL443L) were utilized in the water cooling cycle. During the tests, the compressor performance was changed using an inverter (Sanyu SXE0015T2B). A multimeter (Fluke 8808A) was used to measure the compressor supply voltage. A calorimeter with an intermediate medium was used as the evaporator. In the steady state of heat transfer, the power supplied to the intermediate medium by the electric heater was equal to the power of the evaporator mounted in the top cover of the calorimeter. This power can be taken as the cooling capacity of the compressor. During the construction of the test stand, the experience gained during the stand for testing heat exchangers was used [12].

A diagram of the experimental rig of a refrigeration system is shown in Fig. 1. The pressure and temperature measurement points (P and T) have been marked on it. There are also detailed locations of the components of the refrigeration system. The high-pressure side is marked in a red line, and the low-pressure side in a blue line. Measurement uncertainties of power consumption, cooling capacity, and EER of the refrigeration system depend on the measured value of the electric power of the compressor and electric heater.

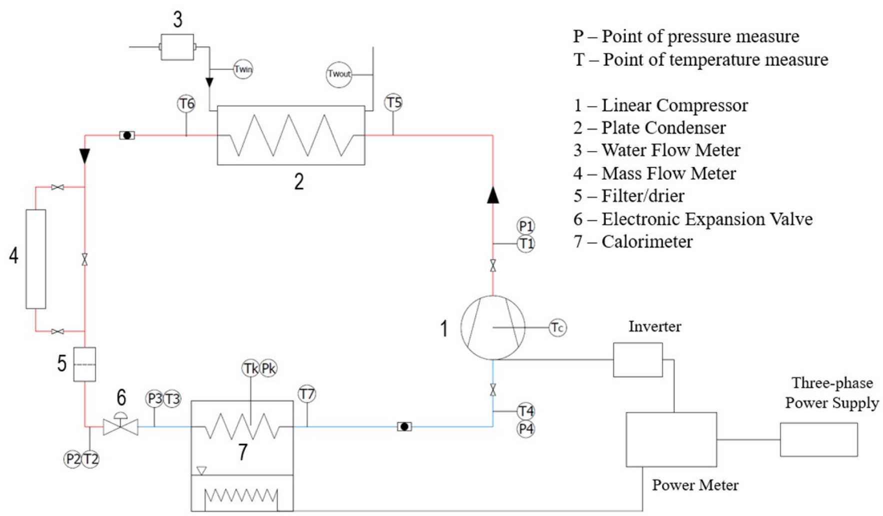

Figure 1: Scheme 2D of the experimental stand.

Compressors are dedicated by the manufacturers to the R600a (Isobutane) refrigerant that was used during the tests. The motivation to choose this refrigerant, despite a small pressure ratio, for the use of small compressors, was the mapping of working conditions in households (small refrigerators). They are powered by an inverter that allows changing the compressor power parameters and performance.

In the first stage of the research, the linear compressor was thoroughly tested in terms of determining its performance characteristics depending on the voltage and frequency of the power supply. The tests were carried out for supply voltage in the range of 190–265 V and current frequency in the range of 45–65 Hz. The temperature in the calorimeter was set to be equal to the ambient temperature, which eliminates heat losses to the environment. Under such conditions, the heater power in the calorimeter is equal to the cooling capacity of the tested compressor. The superheat of the refrigerant was kept at around 5 K.

In the second stage, a reciprocating compressor (Secop NLX15KK_3) with a similar volume displacement (declared by the manufacturer) to the tested linear compressor. The tests were carried out for a supply voltage of 200–250 V and a supply frequency of 45-55 Hz. The condition for comparison was the same pressure ratio. The adopted test conditions resulted in different parameters of evaporation and condensation temperatures and pressures (Fig. 2 and 3). As can be seen, these parameters are greater for the linear compressor than for a reciprocating one – evaporation parameters (temperature and pressure) by 9 K and 73 kPa on average, while condensation parameters by about 10 K and 140 kPa. This is a result of different mass flow rates generated in the tested devices.

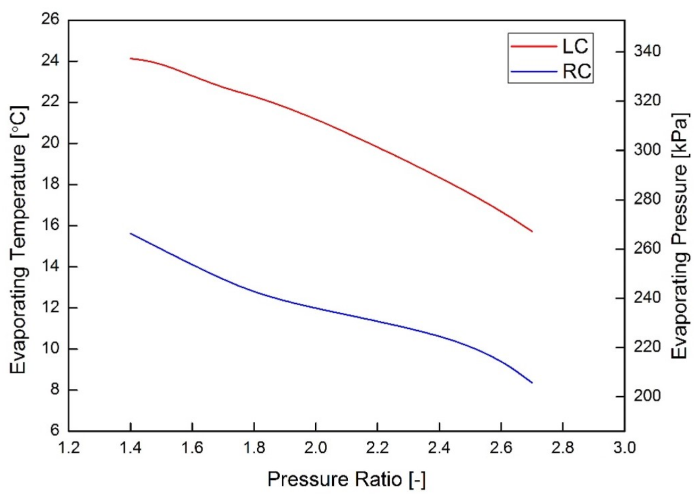

Figure 2: Compressors evaporation temperatures and pressures during the second stage of research.

The $\log p{-}h$ chart of the cycle created from the characteristic points obtained during the tests of the linear compressor, for a selected measurement run (Voltage 230 V and frequency 60 Hz of supply current) is shown in Fig. 4. The achieved evaporation and condensation temperatures, as well as the level of refrigerant subcooling and superheating, are marked on it.

In Table 2, there is a list of devices utilized in the experimental rig along with their respective measurement errors. The error analysis of the individual calculated parameters was carried out in accordance with Moffat [13]. Uncertainties were calculated using the formula

$$\delta R = \left\{ \sum_{i}^{N} \left(\frac{\partial R}{\partial x_i} \delta X_i \right)^2 \right\}^{\frac{1}{2}} . \qquad (1)$$

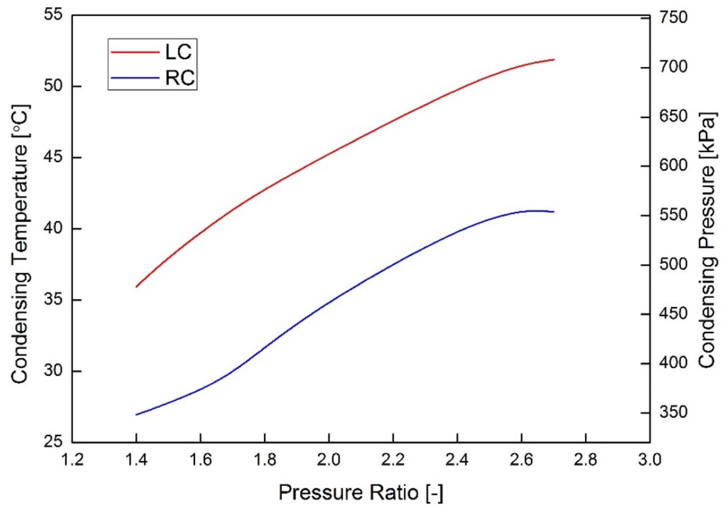

Figure 3: Compressors condensing temperatures and pressures during the second stage of research.

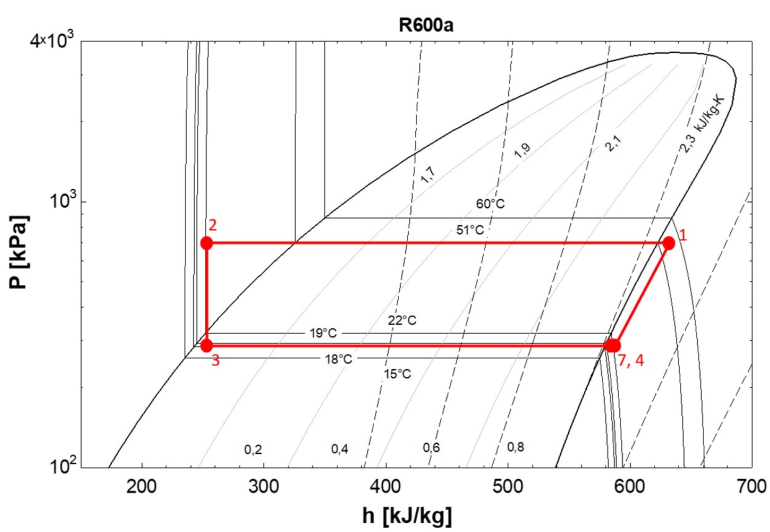

Figure 4: Refrigeration cycle of the tested system in the p–h coordinate system.

The analysis was conducted for the parameters used in further elaboration of the results. The ranges of the uncertainties obtained from calculations are presented in Table 3.

Table 2: List of elements used on the experimental rig with measuring accuracy.

Element Name	Type	Operating rate	Measurement uncertainty
T – Thermocouple	OMEGA type T	73.15–623.15 K	±0.2 K
P – Pressure Transducer	Danfoss AKS 33	–100–3400 kPa	±0.8% of the measured value
Power Meter	Lovato Electric, DMG 200	1.5–1380 W	±1% of the measured value
Inverter	Sanyu SXE0015T2B	10–400 Hz	–
Mass Flow Meter	Endres+Hauser promass 83A	0–0.125 $\mathrm{kg\,s^{-1}}$	±1% of the measured value
Water Flow Meter	Kobold DUK 11G4HL443L	0.08–20 $\mathrm{l\,min^{-1}}$	±0.7% of the measured value
Electronic Expansion Valve	Carel E2V09	–	–
Plate Condenser	SWEP B5THx10	0–2000 W	–
Multimeter	FLUKE 8808A	0–300 V	±0.015% of the measured value
Calori Tank	–	0–1000 W	±1% of the measured value
Filter/drier	Danfoss Eliminator 023Z450191	–	–
Sight glass	Carel	–	–

Table 3: Uncertainties of the parameters.

Parameter	Uncertainty
Cooling capacity, $\dot{Q}_{\mathrm{evap}}$	1.0–2.1%
Overall efficiency, η	1.2–3.9%
Pressure ratio, PR	1.7–1.8%
Energy efficiency ratio, EER	0.7–2.0%

3 Results and discussion

Several parameters were chosen for the reduction of the experimental data and their respective characteristics were presented. The parameters originate from the refrigeration system energy balance and can be used for comparison of refrigeration compressors. The values shown in the following characteristics (Figs. 5–12) were calculated according to the following formulas:

1. Cooling capacity (validation of calorimeter measurement) – the amount of heat that the evaporator can extract from the refrigerated space:

$$\dot{Q}_{\text{evap}} = \dot{m}_{\text{ref}}(h_7 - h_3). \tag{2}$$

2. Overall efficiency of a compressor – power corresponding to the shaft work of the refrigeration cycle to the electric power consumed by the refrigeration system:

$$\eta = \frac{\dot{m}_{\text{ref}}(h_1 - h_4)}{W_{\text{in}}}\,. \tag{3}$$

3. Pressure Ratio – discharge to suction pressure:

$$\text{PR} = \frac{p_1}{p_4}\,. \tag{4}$$

4. Energy efficiency ratio – the amount of heat absorbed by the evaporator to the electric power consumed by the refrigeration system:

$$\text{EER} = \frac{\dot{Q}_{\text{evap}}}{W_{\text{in}}}\,. \tag{5}$$

3.1 Linear compressor performance characteristics

The first characteristic (Fig. 5) shows the change in mass flow rate of the linear compressor (LG FLA150NBMA) as a function of the supply frequency. The mass flow rate for the linear compressor is in the range of 0.14–1.56 gs^{-1}. The trend of the characteristics for each tested voltage increases with the frequency of the supply current. An analogous increase is seen in relation to the rising voltage. This is expected as the voltage is proportional to the length of the piston stroke in a linear compressor.

Compressor regulation carried out by means of a linear motor ensures high precision of mass flow rate setting depending on the needs. This gives a definite advantage over a piston compressor, where the crank system is a limitation.

The characteristic shown in Fig. 6 relates to the cooling capacity of the linear compressor depending on the frequency and the supply voltage. Analyzing the cooling capacity of the tested linear compressor (Fig. 6), one

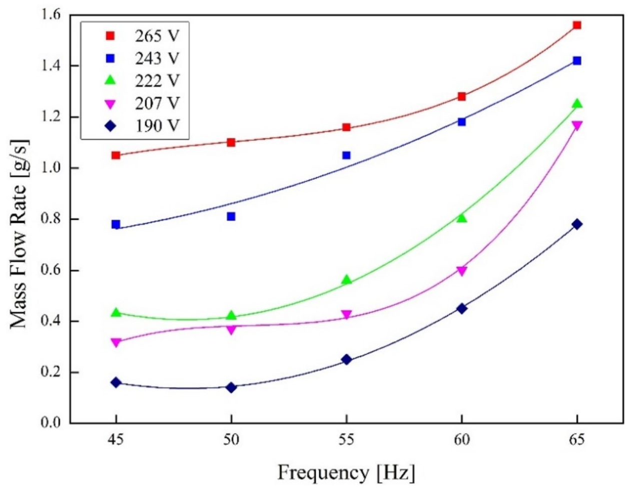

Figure 5: The mass flow rate of a linear compressor against the frequency of the supply current.

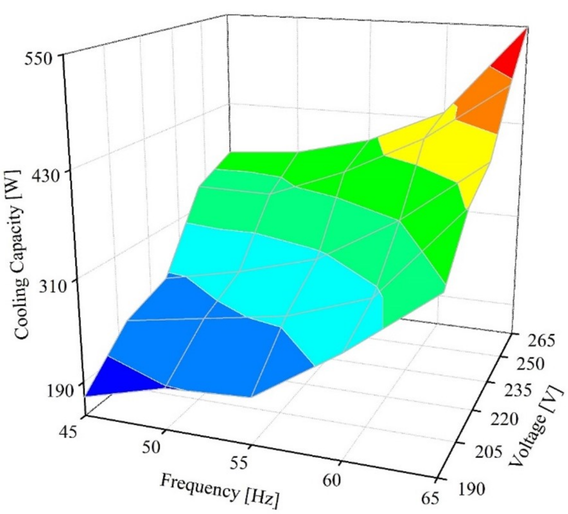

Figure 6: The cooling capacity of a linear compressor against the frequency and voltage of the supply current.

can observe the achieved values of cooling capacity, which is in the range of 172–551 W. The maximum values are achieved for the highest voltages and power supply frequencies. The cooling capacity in the entire range is growing moderately, with a sharp increase which occurs after exceeding the operating conditions declared by the manufacturer (220–240 V, 50–60 Hz). It is an indication that the operating conditions are close to the inherent frequency of the piston spring system in the linear compressor. This allows modulation of compressor power supply conditions for sudden demands on the refrigeration system during e.g. extra load increases.

The overall efficiency of the linear compressor depending on the change of frequency and the supply voltage is shown in Fig. 7. The trend of changes and the compressor operating points for which it achieves the greatest efficiency are visible.

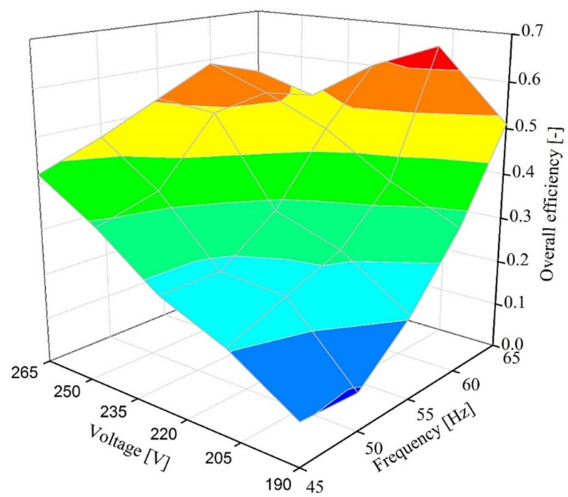

Figure 7: The overall efficiency of a linear compressor against the supply frequency and voltage.

The achieved overall efficiency is in the range of 0.08–0.66. Similar efficiency values were noted by Zhang *et al.* [14]. Local minima in the data at the highest values of the input parameters are probably due to the overlapping of several phenomena occurring in the linear compressor, where the achievement of the maximum operating parameters of the compressor is dominant (large clearance losses – a phenomenon resulting from leakage between the cylinder and the piston, which increases with the pressure ratio, piston drift – a phenomenon occurring during a significant pressure difference between the compressor body and the compression chamber. As a result of the pressure difference, an axial force is created, which is counteracted only by the springs. During large pressure differences, this force affects the position of the piston, which can then hit the head of the cylinder, and cause non-linear work of the spring – a phenomenon related to piston drift, which results in a change of the piston position). At the highest voltages and frequencies, the compressor may have reached its top dead centre as well (loud compressor operation with high vibration). For lower supply voltage and current values, there is a sharp drop in compressors efficiency.

The last characteristic (Fig. 8) relating to the linear compressor shows the obtained values of the energy efficiency coefficient of the refrigeration system. The energy efficiency ratio of the refrigeration system (Fig. 8) is in the range of 2.2–6.6. In terms of energy efficiency (EER value above 4), the most favorable operating range of the compressor is within the range of power supply parameters of 220–265 V and 50–65 Hz. For the highest values of independent parameters, there is a decrease due to the possible reaching of the top dead center of the compressor. Despite the limitations, the linear compressor is definitely more energy efficient than the commonly used reciprocating compressor, which is described later in the discussion.

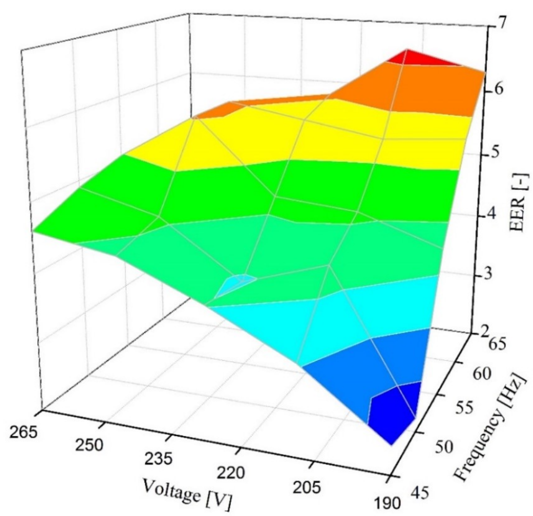

Figure 8: EER of the refrigeration system against the supply frequency and voltage of the linear compressor.

3.2 Comparison with the reciprocating compressor

The first comparative characteristic (Fig. 9) shows the mass flow rate of a given compressor as a function of the pressure ratio. Comparison of compressors was carried out for the pressure ratios in the range of 1.4–2.5. As one can see, the mass flow rates achieved by the reciprocating compressor are much higher than by the linear one. For a linear compressor, it is in the range of 0.15–1.32 gs^{-1}, while for a reciprocating compressor, it is in the range of 1.53–2.62 gs^{-1}. These differences result from the construction of the linear compressor, which, due to the lack of a crank system, and thus a free piston, achieves a smaller stroke than a reciprocating compressor. For maximum power supply parameters (265 V, 60 Hz), the linear compressor achieves a mass flow value similar to that achieved by a reciprocating compressor for minimum power conditions (230 V, 18 Hz).

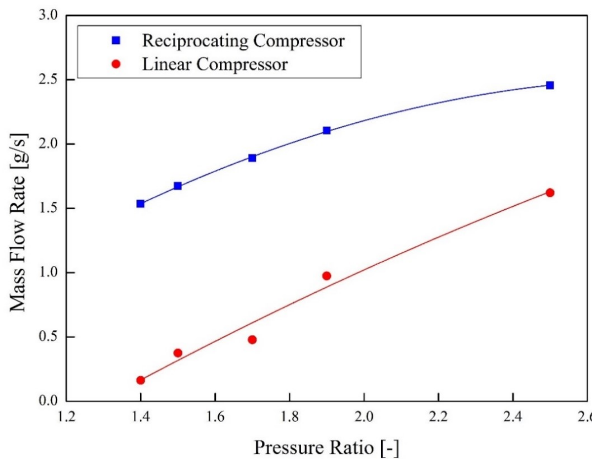

Figure 9: The mass flow rate of a linear compressor and reciprocating compressor against the pressure ratio.

Figure 10 shows the electrical power consumption of a given compressor as a function of the pressure ratio. The electric power consumption (which has a large impact on the energy efficiency ratio) of the linear compressor achieves much lower values of 23–96 W, while the reciprocating compressor for the same pressure ratio reaches values of 95–226 W. This shows, on average, two times lower power consumption to achieve the same pressure ratio. This is mainly due to the lack of flexibility when modulating the reciprocating compressor with a crank system. In addition, the reciprocating compressor has four points of friction compared to the linear compressor and a less energy-efficient motor. This makes the electricity consumption much higher for it.

The third comparative characteristic (Fig. 11) shows the overall efficiency of a given compressor as a function of the pressure ratio. The overall

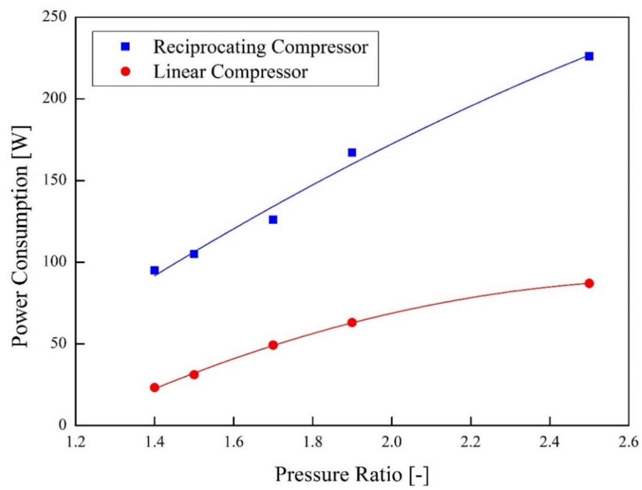

Figure 10: Electric power consumption of the compressor against the pressure ratio.

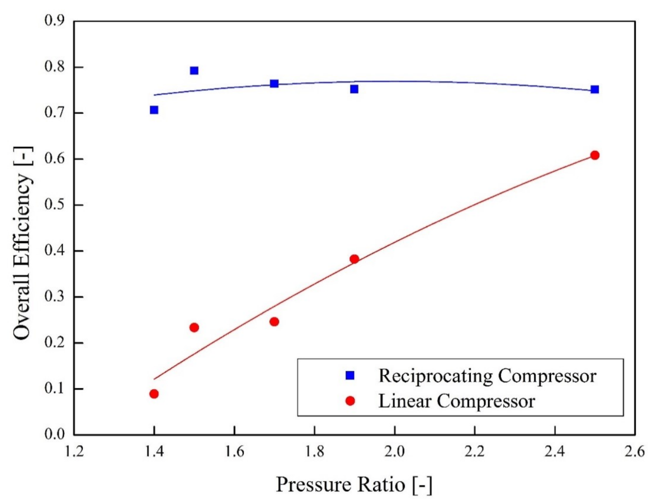

Figure 11: Compressor efficiency against the pressure ratio.

efficiency characteristics show a slight growth for the reciprocating compressor with increasing discharge-suction pressure difference, in the range of 0.71–0.79. The linear compressor, due to its construction, achieves lower efficiency values in the initial phase, to reach its maximum value for the highest value of the pressure ratio. The linear compressor overall efficiency ranges from 0.09–0.61. The achieved values are mainly a result of the construction of both compressors, where the reciprocating compressor has a constant piston stroke. The results show the possibility of increasing the efficiency of linear compressors. Future research should focus on leak sealing, piston drift prevention, new flow geometry and valves.

The last characteristic (Fig. 12) shows the obtained energy efficiency of the refrigeration system depending on the tested compressor. Regarding EER, a decreasing trend can be seen for the reciprocating compressor with the increasing pressure ratio, where the values fall in the range of 5.6–3.7. This is due to the increasing power consumption, with a disproportionate lower increase in cooling capacity. The linear compressor is characterized by a different trend, where for the low pressure ratios it reaches low values, then as the pressure ratio increases, the EER values grow sharply. The obtained EER is in the range of 2.2–5.6. This proves a proportionally greater increase in cooling capacity in relation to power consumption. For pressure ratios greater than 1.7, a linear compressor is approximately 35% more energy efficient than a reciprocating compressor.

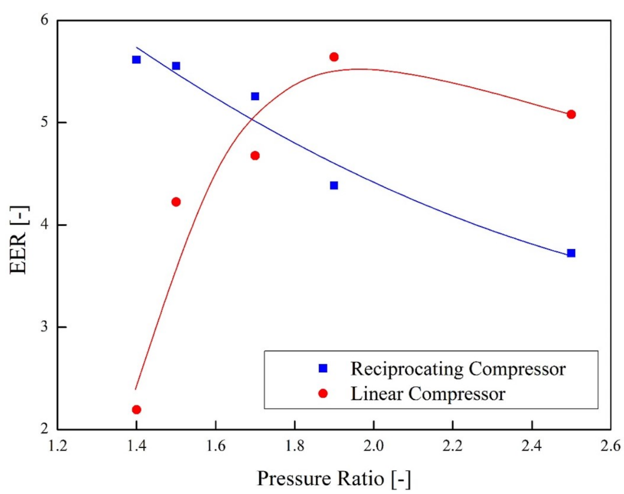

Figure 12: EER of the refrigeration system against the pressure ratio.

4 Conclusions

The tests carried out on a linear compressor, going beyond the scope of its typical operation declared by the manufacturer, allowed us to determine the possible, full range of performance characteristics. Subsequent comparative studies with a reciprocating compressor allowed us to determine its greater energy efficiency and the legitimacy of its use in small refrigeration systems.

- Experimental tests were carried out on a test rig designed in accordance with the ANSI/ASHRAE 23.1-2010 standard.
- A series of characteristics related to a linear compressor have been determined, showing its performance, efficiency and achieved EER values. They have been designated beyond the scope of the operation range declared by the manufacturer.
- Research on a reciprocating compressor was carried out, comparing it with a linear compressor for the same pressure ratio. As a result of the tests, the linear compressor is more energy efficient by an average of 38% compared to the tested piston compressor for a pressure ratio above 1.7. The power consumption of an electric linear compressor is on average two times lower than that of a reciprocating compressor.
- The results can be used for further research on its design and be a guideline for the industry.

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