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EXPERIMENTAL INVESTIGATION OF THE EFFECT OF THE CHARGE AMOUNT ON THE POWER CONSUMPTION AND COOLING PERFORMANCE OF A REFRIGERATION SYSTEM

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ABSTRACT

Refrigeration systems are mechanical devices that transfer heat from a low-temperature region to a high-temperature region, effectively cooling a space or substance. They operate based on the principles of thermodynamics, utilizing refrigerants to extract heat from the area being cooled and then expelling it elsewhere. These systems play a crucial role in maintaining suitable temperatures for various applications across industries. The choice of refrigerant and system design significantly impacts efficiency, environmental impact, and overall performance. This study investigates the impact of refrigerant gas charge amounts on the performance of these systems. Two different charge amounts including 340 g and 425 g have been utilized in a refrigeration system that use R134a as refrigerant gas. The experimental process has been performed in a controlled environment. Analyzing the relationship between the quantity of refrigerant gas and system efficiency, this research aims to provide insights into optimizing charge levels to enhance the overall performance and energy efficiency of refrigeration systems. Experimental results showed that increasing the refrigerant charge amount from 340 g to 425 g reduced the hourly energy consumption from 0.322 kWh to 0.306 kWh. Moreover, the average coefficient of performance (COP) values were attained as 3.94 and 4.04, respectively for the charge amounts of 340 g and 425 g. The findings contribute to a deeper understanding of the intricate dynamics between refrigerant gas charge amounts and system functionality, offering potential strategies for improved system design and operation.

1. INTRODUCTION

The interplay between energy as a main parameter in scientific research and environmental safety is crucial as our energy choices notably impact air and water quality, as well as climate change, and also overall ecological balance and equilibrium [1]. Sustainable energy practices and renewable energy sources play a significant key role in mitigating environmental challenges, offering appropriate cleaner alternatives to traditional energy sources, and reducing our ecological footprint [2,3]. As the world transitions towards cleaner and more efficient energy systems, advancements in technologies like energy storage, decentralized generation, efficient heat exchangers, and solar energy are becoming pivotal in enhancing reliability, resilience, and sustainability in the global energy landscape [4]. In this context, heat pump systems are outstanding technologies that can efficiently transfer heat from one medium (generally lower temperature zone) to another (with higher temperature), offering both heating and cooling capabilities [5,6]. Operating on the mentioned principle of extracting heat energy from a low-temperature medium and releasing it at a higher temperature, heat pump devices can remarkably reduce energy consumption compared to traditional heating and cooling systems [7,8].

Considering studies presented in the literature, heat pumps are particularly effective in moderate climates, where the temperature differential is not extreme [9]. Additionally, these devices have an outstanding potential to contribute to environmental sustainability by utilizing renewable energy sources, such as geothermal or air-source heat pumps, to further

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decrease their carbon footprint [10]. Khanlari et al. [11] conducted an experimental investigation to evaluate capability of using building shower drain water in residential homes as a heat source for heat pump. It was revealed that heat loss inside homes can be extracted and reused as an energy source by utilizing heat pumps. In another work, Obalanlege et al. [12] developed a heat pump system with a hybrid solar collector system for electricity and useful heat generation. A hybrid photovoltaic-thermal (PVT) system has been utilized for performance enhancement in their work. The system's performance is examined in relation to the solar irradiation, water tank capacity, and PVT pipe water flow rate. A special emphasis is placed on the heat pump's coefficient of performance (COP) and PVT efficiency. The heat pump's minimum COP of 4.20 is indicated by the results, demonstrating the strong performance of the suggested hybrid system. An examination was conducted by Gilani et al. [13] on the energy efficiency and power production of a five-story residential structure in Cyprus that has a variable refrigerant flow (VRF) heat pump system integrated with photovoltaic technology. Photovoltaic (PV) arrays meet between 126 and 166% of the VRF's yearly energy needs. In addition, the PV system installation saves about 14 tons of $CO2$ annually. Li et al. [14] analyzed an air type heat pump system with latent heat storage unit. Their findings show that three hours after solar heating stops, the energy stored in the latent heat energy storage system may still be used to operate the heat pump effectively. By an average of 12.1%, the heat pump's energy efficiency is greatly increased. Another study revealed a direct-expansion heat pump system powered by the sun that uses micro-channel PVT modules as the evaporator [15]. The system's average COP in simulation and experimentation is 5 and 4.7, respectively. In the real-world testing conditions, the 150 m2 room's temperature may stay at 18.5 °C, which is high enough for space heating, thanks to the solar heat pump system's energy supply. Using a multi-function evaporator, Ran et al. [16] created a hybrid solar-air source heat pump with thermosiphon to benefit from solar and air thermal energy. The created heat pump has the ability to absorb heat from one heat source or from several. Additionally, it can operate in either the heat pump or thermosiphon mode based on the strength of the sun. To simulate the performance of the suggested system under various operating situations, a verified numerical model was created, and a comparison with traditional heating systems was also conducted. It demonstrates that the suggested heat pump has coefficients of performance of 3.12, 3.45, and 3.89 in the air source, solar-air source, and solar heat pump modes, respectively. Additionally, when solar energy is sufficient, it can provide heat in the solar thermosiphon mode without using any energy.

In a series of comprehensive experiments, researchers delved into the intricacies of heat pump systems, exploring various facets of their performance and efficiency. One notable investigation conducted by Afshari et al. [17] focused specifically on the compressor cooling fan within an air-to-water heat pump. The study aimed at optimizing this critical component, shedding light on ways to enhance the overall efficiency and functionality of the heat pump system. Building upon this work, the researchers extended their inquiries to predict the optimum charge for a heat pump system [18]. This endeavor underscores the ongoing efforts to refine and fine-tune the operational parameters of heat pumps, aiming for an optimal balance that maximizes energy efficiency and performance. Meanwhile, a separate experimental study conducted by Ceviz et al. [19] directed its attention towards water-to-air heat pumps. This research specifically evaluated the impact of source temperature on two crucial aspects: COP and the operational status of the compressor. By examining these factors, the study contributes notable results into the dynamics of water-to-air heat pumps, offering a nuanced understanding of how varying source temperatures can influence their overall efficiency and functionality. In another study Afshari et al. [20] experimentally investigate the effect of changing refrigerant gases in heat pumps. It was shown that different refrigerant gases can influence the energy performance and power consumption of a heat pump. Additionally, the impact of compressor lubricant and operating condition on overall performance of the system were analyzed. Coefficient of performance for the installed system was calculated for each experiment and comparative analyses were performed. Di Nicola et al. [21] explored the vapor-liquid equilibrium of binary systems containing environmentally friendly refrigerants with low global warming potential (GWP). Their study employed cubic equations of state to investigate the thermodynamic properties of these refrigerants. Pierantozzi et al. [22] continued the exploration of climate-friendly refrigerants, focusing on the thermodynamic properties of low-GWP fluids tailored for domestic applications. Additionally, their study delved into binary systems suitable for low-temperature options, contributing valuable insights to the ongoing efforts in sustainable refrigeration practices. Baskaran et al. [23] delved into the impact of capillary tube length on the performance of domestic refrigerators using the eco-friendly refrigerant R152a. This study aimed to understand how variations in capillary tube length influence the overall efficiency and functioning of refrigeration systems, providing practical considerations for optimizing domestic refrigerators with environmentally conscious refrigerants.

In this experimental work, two different refrigerant gas charge amount values including 340 g and 425 g have been tested to evaluate the effect of the refrigerant gas charge amount on the overall energy consumption and cooling performance of a refrigeration system.

2. MATERIALS AND METHODS

The experimental analysis has been performed in a controlled environment for attaining more accurate findings. In this regard, the R&D test room of Kristal Endüstriyel, Antalya, Türkiye has been utilized. The internal volume of the test room is 565 L. In the test room, temperature, pressure, humidity, and electrical parameters were measured. Schematic view and the photograph of the test room are presented in Figure 1a and 1b, respectively. Also, the dimensions of the test room and the photograph of the analyzed industrial refrigeration system are presented in Figure 2a and 2b, respectively.

Fig. 1. a) Schematic view of the test room, **b)** A photograph of the test room

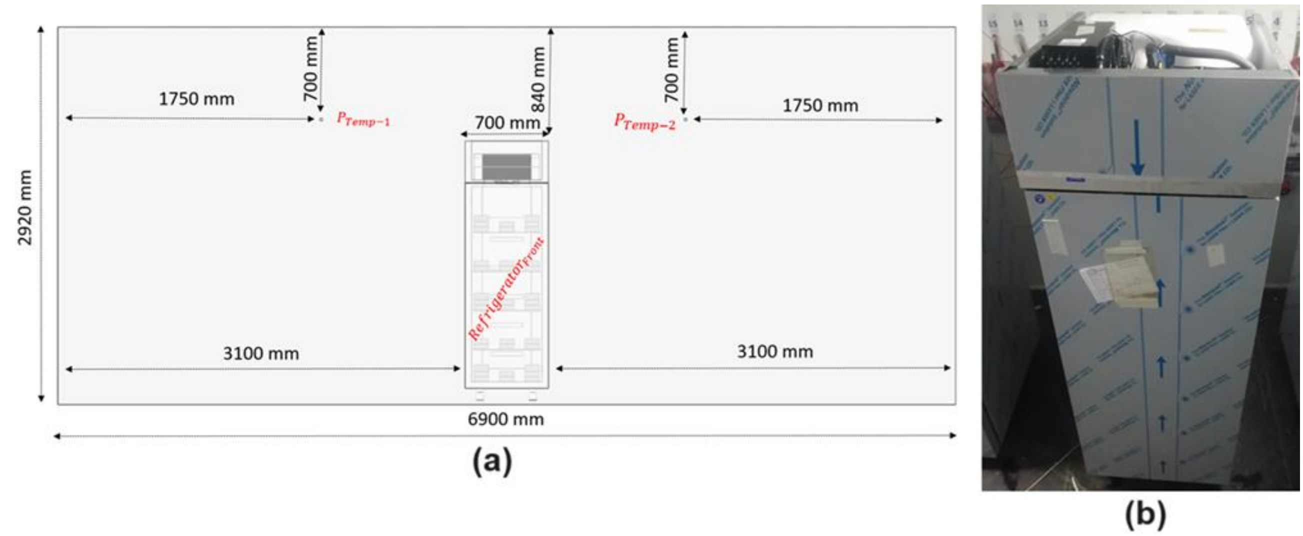

Fig. 2. a) Placement of the refrigeration system into the test room with dimensions, **b)** A photograph of the manufactured refrigeration system

It should be indicated the R134a has been utilized as refrigerant gas in the experimental process. Two different refrigerant charge amounts including 340 g and 425 g have been tested in this work. Temperature measurements have been done using appropriate apparatus with the measurement range of -100 ~ +400 °C and 0.1 °C accuracy. Additionally, measurement of electrical metrics was done using an energy analyzer with RS 485 Modbus communication. Accuracy values for electric current and voltage are both ±1%.

3. RESULTS AND DISCUSSION

In this experimental work, two different charge amounts including 340 and 425 grams have been tested in a refrigeration system. Time-dependent variation of inlet and outlet temperature values of the refrigerant gas in the evaporator are presented in Figure 3. When the inlet and outlet of the refrigerant are taken into account, it is seen that the outlet temperature rises. This is a sign of the refrigerant entering the superheated vapor zone at the evaporator outlet. Temperature change over time is seen in both input and output values. In addition, fluctuations in temperatures are observed as the compressor turns on and off. The reason for this is that the system is conditioned according to the set temperature value, and it performs its automation task according to the desired condition. By adjusting the system according to the given set value, it was found that the refrigerant inlet temperature in the evaporator decreased significantly. Moreover, when the compressor starts, instantaneous heating occurs because the hotter refrigerant at the outlet of the capillary tube passes through the evaporator inlet. This behavior can be seen in the small peaks on the inlet temperature curves in Figure 3.

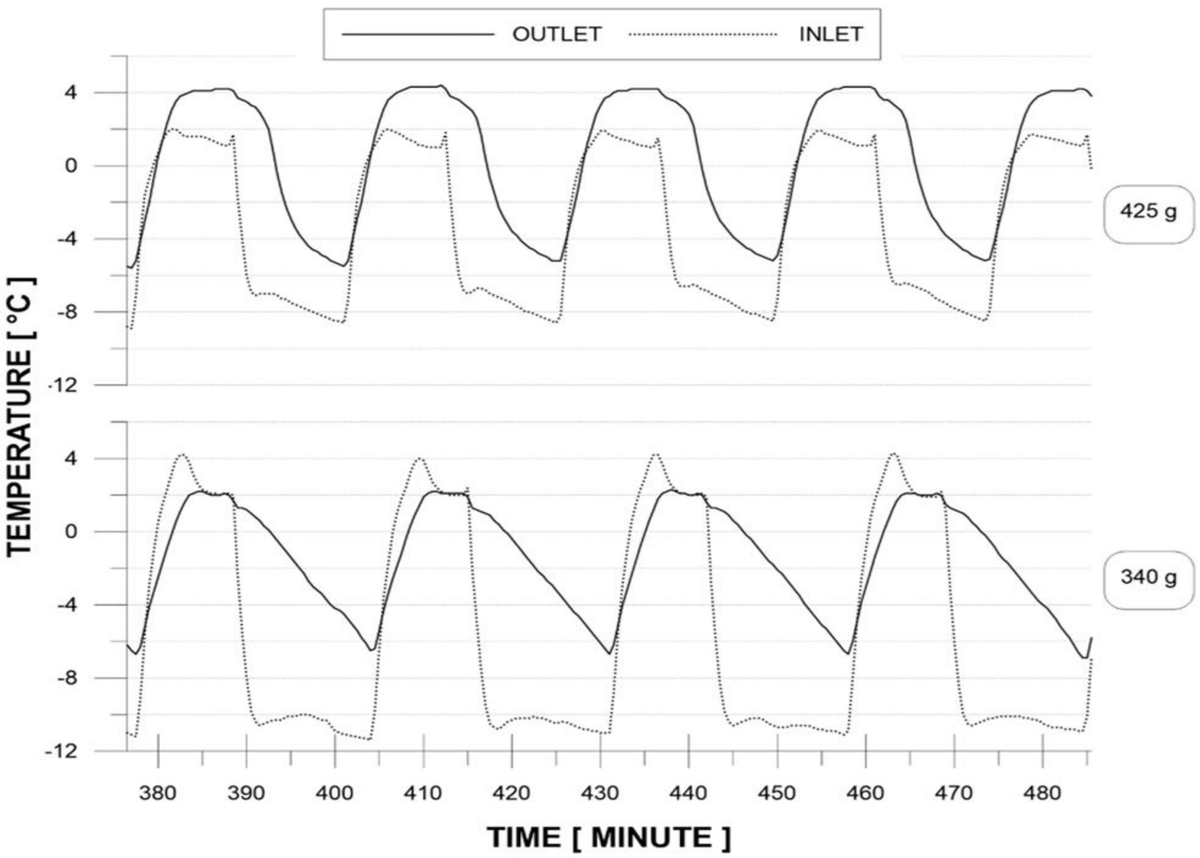

Fig. 3. Time-dependent variation of refrigerant gas temperature in the evaporatör at two different charge amounts

Figure 4 illustrates the change in air temperature over time in the evaporator with two different charge amounts. A key distinction exists between the current diagrams and the previous presented in Figure 3. When the air flows through the evaporator, it undergoes a temperature change, experiencing a drop caused by heat transfer, and in this process, there is no phase change, similar to the behavior of the refrigerant. It should be noted that typically, air or other fluids such as water used in evaporator are termed secondary fluids. In all the results obtained, it is evident that temperatures fluctuate, remaining consistently below approximately 0 °C. Additionally, average cabin temperature values for the charge amount of 340 and 425 grams were found as 0.29 and -2.92 °C, respectively. Moreover, average hourly energy consumption for the cases that utilized 405 and 425 grams of refrigerants were attained as 0.322 and 0.306 kWh, respectively. As can be seen, utilizing 425 grams of refrigerant gas reduced the hourly energy consumption of the refrigeration system.

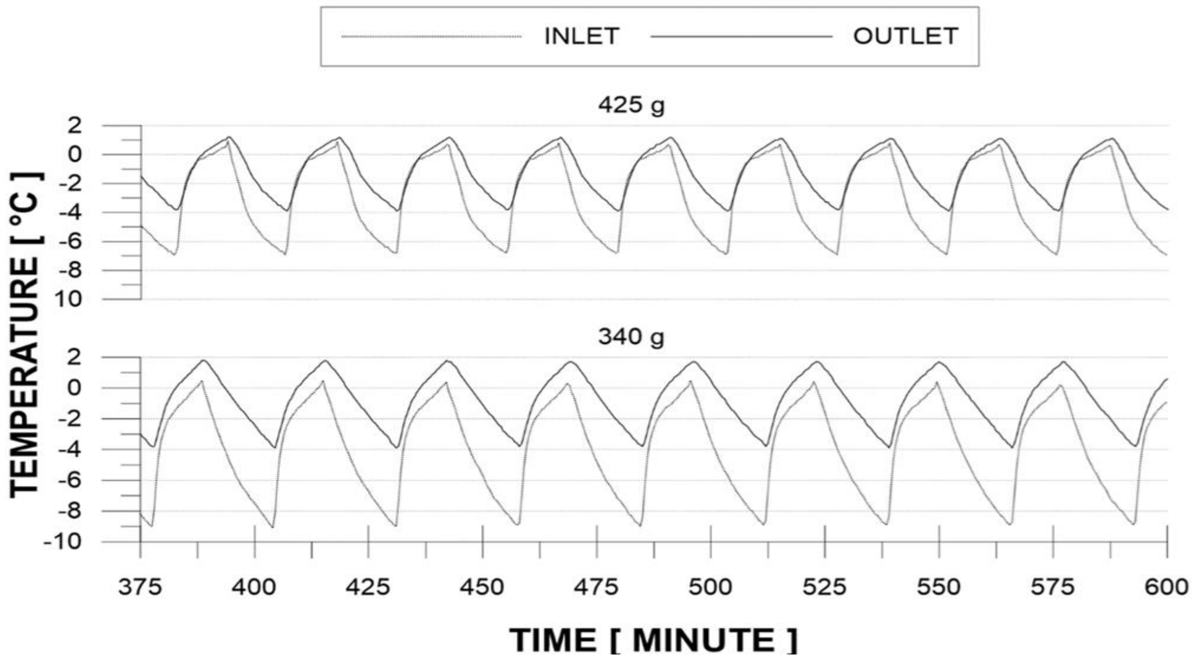

Fig. 4. Time-dependent variation of air temperature in the evaporatör at two different charge amounts

A Temperature-Entropy (T-s) diagram of heat pumps and refrigerators is a graphical representation of the thermodynamic process of a vapor compression cycle, illustrating changes in temperature and entropy at different stages and working conditions. Any minor alterations in the operating conditions are identifiable in the Temperature-Entropy diagram. In this context, T-s chart of the system has been presented for two different charge amounts of 340 g and 425 g in Figure 5. In the T-s diagram for the cycle, the compressor is represented by an upward-sloping line as it increases the temperature and pressure of the refrigerant by doing work on the refrigerant. In cooling machines, the evaporator plays a crucial role in extracting thermal energy and creating a cool environment. The evaporator is depicted by a horizontal line on the T-s diagram, representing the phase change of the refrigerant from a liquid to a vapor as it absorbs heat from the external source which is air in the present study. On the other hand, the condenser is shown as a downward-sloping line in the T-s diagram, indicating the release of heat to the surroundings as the refrigerant transitions from vapor to liquid, completing the heat pump cycle. By comparing two different charge amounts, it can be stated that by increasing refrigerant charge the cycle has been moved upside on the T-s diagram which means that the cycle has been operated in higher temperature and pressure values.

The results obtained in this research reveal that the COP for the 425 g charge is slightly higher than that for the 340 g charge. Increasing the charge amount of the system increased the COP values from 3.94 to 4.04. The results of this study show us the effect of refrigerant charge amount on performance. It is aimed to increase the charge amounts analyzed in this experimental study in future studies. In addition, it is aimed to optimize comprehensive experimental investigations using appropriate techniques.

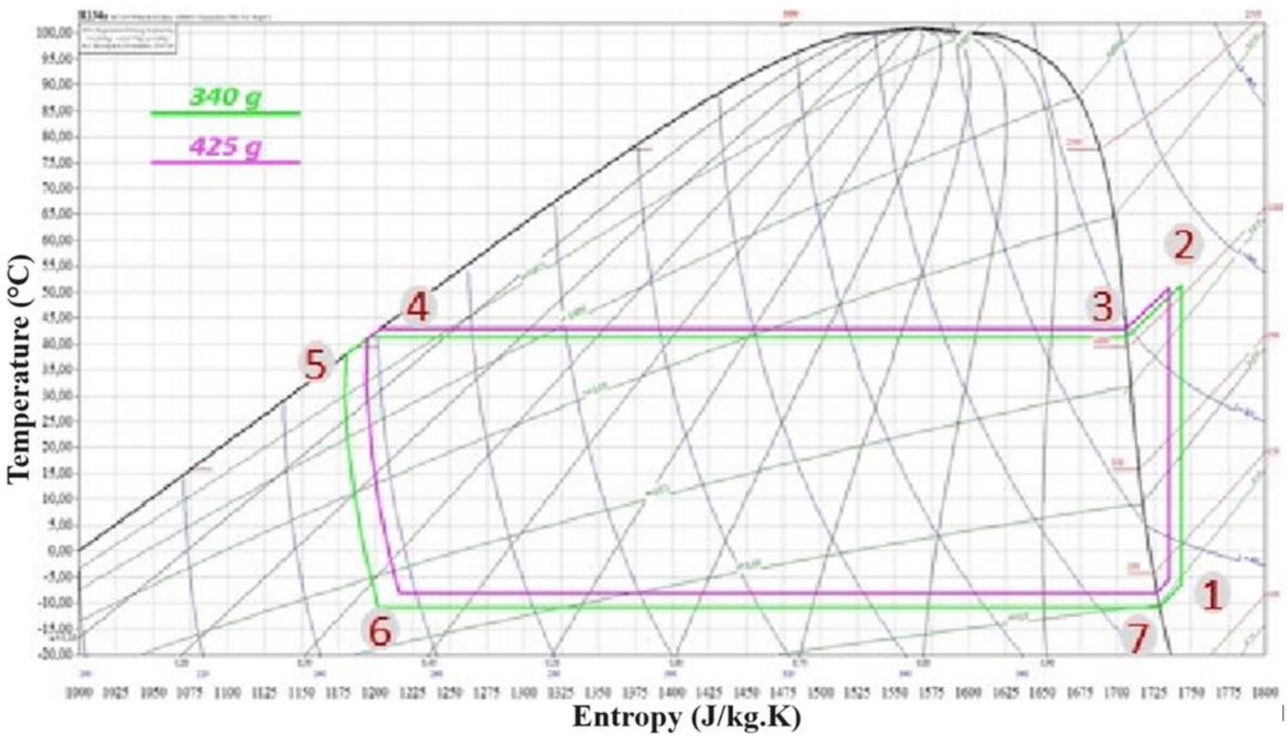

Fig. 5. T-s diagram of the test system operated in different charges

4. CONCLUSIONS

In the present work, two different refrigerant charge amounts have been experimentally analyzed in a refrigeration system and the effect of utilizing different amounts of refrigerants on the cooling performance have been experimentally surveyed. The experimental investigation into varying refrigerant charge amounts within the refrigeration system has provided crucial insights into the complex relationship between charge levels and system performance. Experimental results showed that increasing the refrigerant charge amount from 340 g to 425 g improved the coefficient of performance from 3.94 to 4.04. The findings gleaned from this study shed light on the intricate interplay of refrigerant quantities and their direct impact on the system's efficiency, capacity, and overall functionality.

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