University POLITEHNICA of Bucharest

PhD Thesis

Theoretical and Experimental Performance Evaluation of Capillary Tube and Roll-Bond Evaporator in a Small-Scale Refrigeration System Using Alternative Refrigerants to Replace R134a

By

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1 Introduction

R134a is one of the HFCs that is still widely utilized in household refrigeration (HR), commercial refrigeration (CR) and automobile air conditioner (AAC) applications. This is because it possesses excellent thermodynamic properties, is chemically stable, does not promote flame propagation, and possesses the benefits of a low cost. Its global warming potential (GWP ≈1300), is a thousand times greater than those of CO_2 [3], [14]. The large increase in the use of HFCs in many domestic and industrial applications, along with an increase in greenhouse gas emissions, has contributed to an increase in energy consumption. In comparison to the overall amount of CO_2 emissions, HFC emissions are expected to hit 9-19 % by 2050 [15]. However, HFCs contribute significantly to the effect of global warming, which leads to an unbalance in the temperature of the earth's surface.

It is vital to develop eco-friendly refrigerants to replace halogenated refrigerants in order to accomplish this goal and completely eliminate the use of halogenated refrigerants

Furthermore, they must be able to operate efficiently in an existing system that uses R134a as a working fluid without the need to redesign the refrigeration system components or replace the lubricant, and it should not be less energy-efficient, safe, accessible, and cost-effective [24]. Environmental issues

The primary objective in the design of refrigeration systems is their efficient performance to save energy. Nevertheless, the environmental issues for safety and practical considerations must be taken into account [26]. Three indexes commonly used to determine the effect of refrigerants on the environment are ODP, GWP, and TEWI [3].

1.1.1 Ozone Depletion Potential (ODP)

1.1.2 Global Warming Potential (GWP)

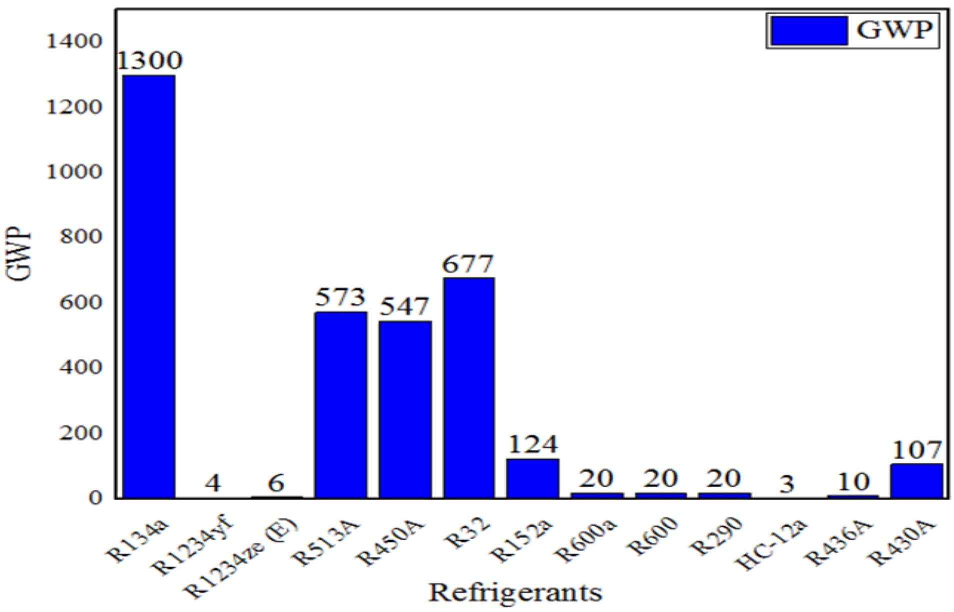

Figure 1.5 GWP of selected refrigerants [3]

1.1.3 Total Equivalent Warming Impact (TEWI)

1.2 The basic components of VCRS

A basic VCRS comprises four major components compressor, condenser, expansion device and evaporator which are connected in a closed loop. The basic components of a VCRS are described as shown below in figure 1.6.

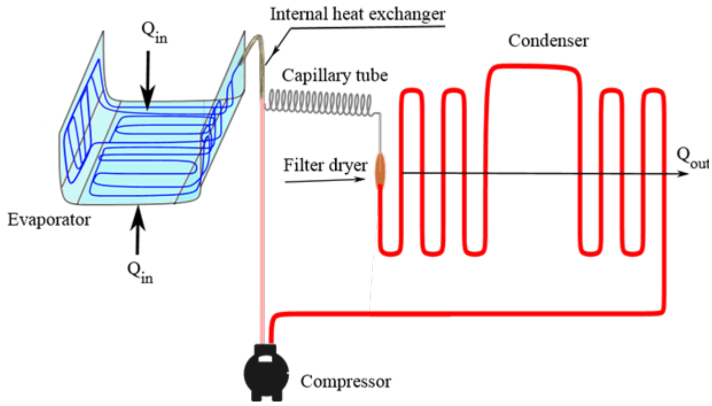

Figure 1.6 Major components of the VCRS

1.3 The problem statement

The environmental impacts are evident in Iraq through unpredictable climatic fluctuations throughout the seasons of the year, which led to a decrease in agricultural production and thus harm the economy, especially since Iraq is an important agricultural country. Many of the residential refrigeration, air conditioning and automotive air conditioning applications in Iraq are still working with fluorinated and halogenated refrigerants such as R12 as well as high GWP R134a refrigerant. In addition to the presence of large quantities of these gases stored in Iraqi universities for laboratory and educational purposes for undergraduate and postgraduate students. These refrigerants have a significant influence on ozone layer depletion and global climate change. Currently, can be noted the significant effect of these refrigerants on the global climate. Throughout recent years, Iraq had continuous dust storms as a result of the desertification phenomenon that affected large areas of the country and the noticeable rise in temperatures during the summer, which can reach more than 50 °C in the shade, according to daily weather forecasts.

In this context, the efficiency of the hydrocarbons (HCs) and hydro-fluoro olefins (HFOs) and their mixtures as alternative refrigerants for R134a and R12 should be investigated under different ambient temperatures. In order to accommodate the environmental conditions in Iraq, operational conditions were imposed. The effect of various working fluids on pressure drops and thermal efficiency in a small-scale refrigeration system also needs to be studied.

1.4 Objectives of the study

The main objectives of this thesis are as follows:

1. Provide a comprehensive literature survey of the available replacement possibilities of conventional refrigerants (R134a) with environmental friendliness in domestic and commercial refrigerators and automobile air conditioning. Thus, expanding the current knowledge and understanding of global warming phenomena resulting from these refrigerant emissions and their impact on climate change.
2. The development of a mathematical model to examine the effect of replacing refrigerant on the capillary tube's performance and hence the overall system's performance. The condition of the evaporator inlet corresponds to the capillary tube outlet.
3. Develop a steady-state mathematical model to investigate the influence of refrigerant replacement on the performance of the roll bond evaporator.
4. Conduct experiments on a simple VCR system using a small household refrigerator to evaluate the performance of R1234yf and R600a as alternative replacement refrigerants for R12 and R134a under steady-state conditions.
5. Assessment of the system performance by comparing the alternative refrigerants R600a and R1234yf to R134a.

2 Literature Review of R134a Replacement Possibilities in Different Refrigeration Applications

2.1 Refrigerants used in VCR system

2.2 Thermodynamic Properties of Refrigerants

The physical, harmlessly, environmental impact, and relevant regulations are fundamental factors in the adoption of new refrigerants [45]. The refrigerant mixture should have several thermo physical properties like high thermal conductivity, low gliding temperature, and low viscosity [3]. Several criteria must be considered when choosing refrigerants for HRs or AACs applications [46].

2.3 Refrigerants Replacement Scenarios

HFC, HFO, HC, and their blends have been the subject of several theoretical and experimental research as potential replacements for halogenated refrigerants in HR, CR, and AAC systems. As a result, various R134 refrigerant replacement possibilities, such as drop-in replacement, retrofit refrigerant, and new systems, were implemented.

2.3.1 Replacement Scenario of Refrigerants as a Drop-in

Drop-in replacement is the case when the old refrigerant is taken out and the system is charged with the alternative refrigerant and sometimes with some slight changes to the control settings [66][67].

2.3.1.1 Household Refrigeration

Household refrigerators are the highest consumer of energy among refrigeration systems, where the residential electricity consumption by the refrigeration systems is approximately between 6%-30% of the energy produced worldwide [68], [69]. Many studies have been conducted to find an environmentally friendly alternative to replace R134a with a better coefficient of performance (COP), low energy consumption, low GWP, and zero ODP [3].

2.3.1.2 Automobile Air Conditioner System

Numerous researchers and investigators have researched the performance of alternative refrigerants in AAC systems.

2.3.1.3 Commercial Refrigeration System

2.3.2 Replacement Scenario as a Retrofit Refrigerant

The second option is the retrofit refrigerant, in which the cooling system is recharged with an alternative refrigerant after the original refrigerant has been removed with some minor adjustments. In order to improve system performance, enhance its energy efficiency, and prolonging its lifetime as well as reduce emissions [126]. The modifications of the system may include, the expansion devices, lubrication oil and some other specific components, to solve the compatibility issues that are facing the substitution process of new refrigerants [1].

2.3.2.1 The household refrigerator as a retrofit system

2.3.2.2 AACs as a retrofit system

2.3.2.3 The household refrigerator as the new system

2.4 Discussion Regarding the Literature Review

In this work, the results of the comprehensive review of all alternative refrigerants were compared with the R134a in three categories which are HR and CR and AACs, up to now. This comprehensive review has focused on several parameters in detail such as COP, cooling capacity, discharge temperature, mass flow rate, pull downtime and cooling capacity of the systems when employing alternative refrigerants to the high GWP refrigerants. A comparison of the results of various studies based on the percentage of the energy consumption (%), the reduction in the refrigerant charge (%) and improvement in COP (%), utilizing many refrigerants as replacement of R134a is shown in Figures 2.5 and 2.6.

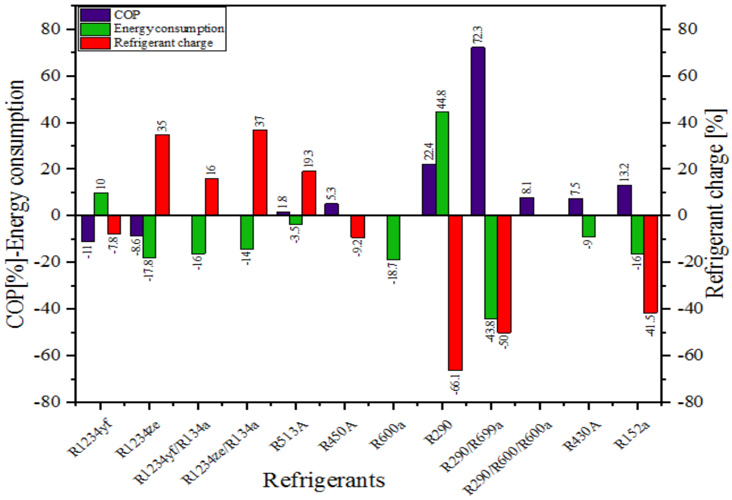

Figure 2.5 Percentage difference in COP, energy consumption and refrigerant charge of alternative refrigerants and their mixtures as a drop-in replacement.

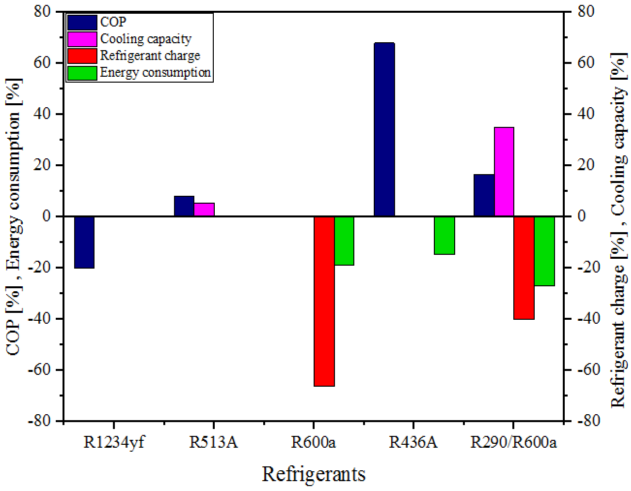

Figure 2.6 Percentage difference in COP, energy consumption and refrigerant charge of alternative refrigerants and their mixtures as Retrofit Refrigerant of R134a in an HR.

3 Description of Experimental setup

3.1 Experimental setup

The schematic diagram of the entire experimental setup is shown in Figure 3.2.

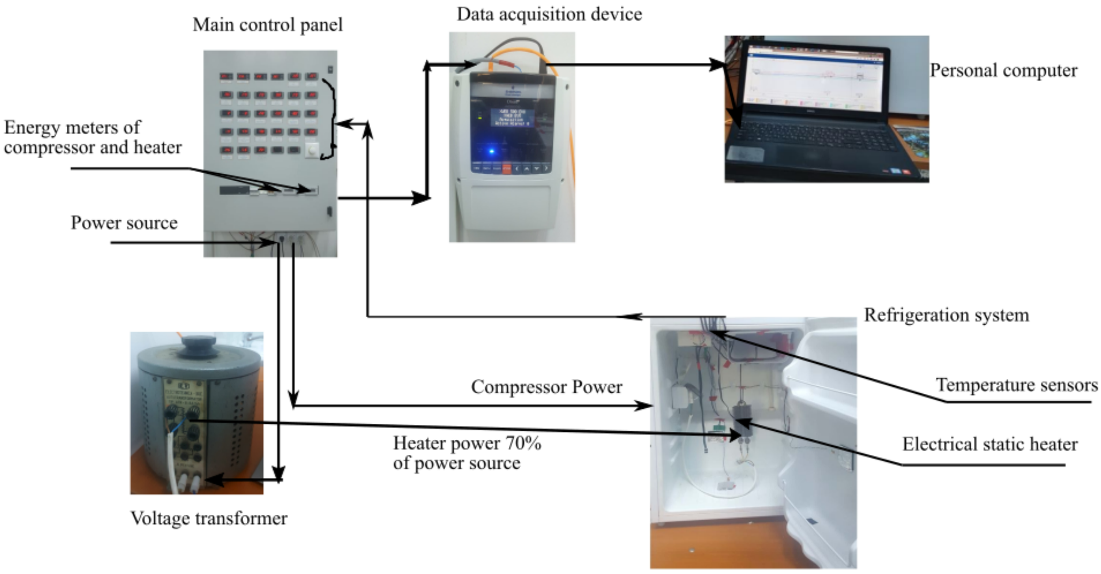

Figure 3.2 schematic diagram of the entire experimental setup

4 Steady-state performance of capillary tubes for small-scale vapour compression systems using different refrigerants

4.1 Introduction

The capillary tube (CT) being a key constituent of any VCR system needs precise design and control to achieve its high performance. All the SSR systems including household refrigerators and freezers, split air conditioners as well as heat pumps use the CT as an expansion device [156], [157].

To gain further insight into the effects of CT outlet parameters on the working performance of SSRSs, some model calculations were carried out with different refrigerants (R134a, R1234yf, R1234ze (E), R600, R600a, R152a and R513A). The model results were validated with the experimental outcomes. It is established that present systematic analyses of the CT outlet parameters may contribute to both drop-in and retrofit scenarios, especially for the environmental regulations regarding the use of refrigerants [169].

4.2 Model of capillary tube operation

A schematic of the VCRS with emphasis on the CT and its three main regions is given in Figure 4.1. The capillary tube has three main regions i) the straight region, ii) the helical region and iii) the suction line heat exchanger.

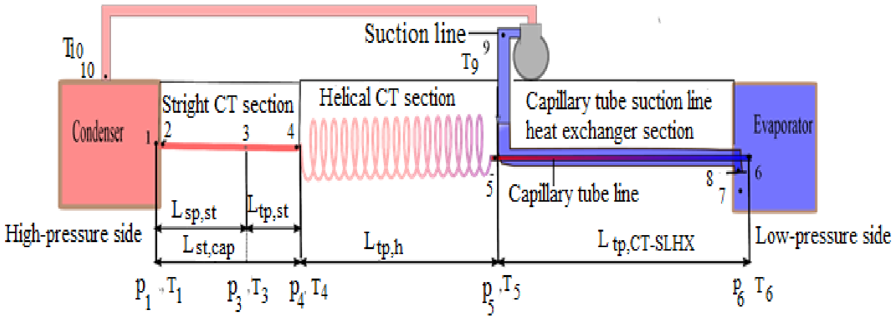

Figure 4.1 Schematic of the VCRS with emphasis on the CT and its three main regions [155]

The flowchart presented in Figure 4.8 has been implemented in the Engineering Equation Solver program (EES)[60]. Based on the program developed in EES and the experimental setup, the validation of the model has been conducted.

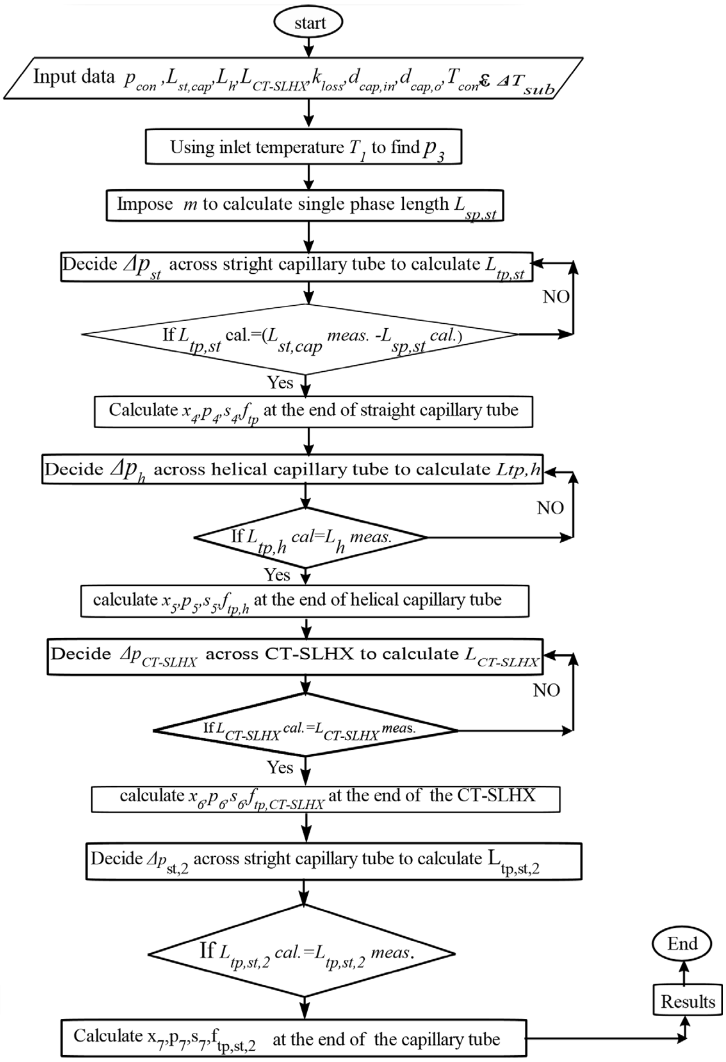

Figure 4.8 The flow-chart of the EES program [155]

4.3 Experimental Validation of capillary tube Mathematical Modelling

4.3.1 Model validation

The model validation is conducted as follows: experimental data is inserted in the EES program; the value obtained for the pressure in point 7 is compared with the value for the evaporating pressure measured on the experimental setup, as presented in figure 4.9.

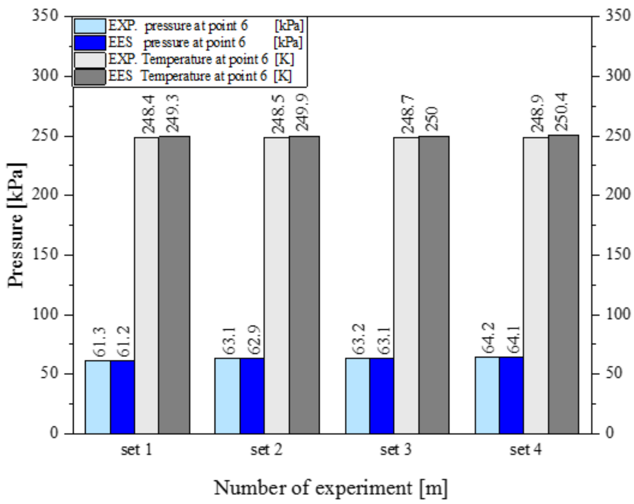

Figure 4.9 Comparison between experimental data and the results obtained with the program developed in EES.

4.4 Results and Discussions

In order to better study, the behavior of the working fluid flowing in the capillary tube which consists of three shapes connected in a single formation, and according to the state of the refrigerant at the inlet of the capillary tube, the three shapes are taken into account and the relevant correlations for each of the three shapes were solved then the results were analyzed. The results are presented in Figures 4.10, 4.11, 4.12, and 4.14, respectively.

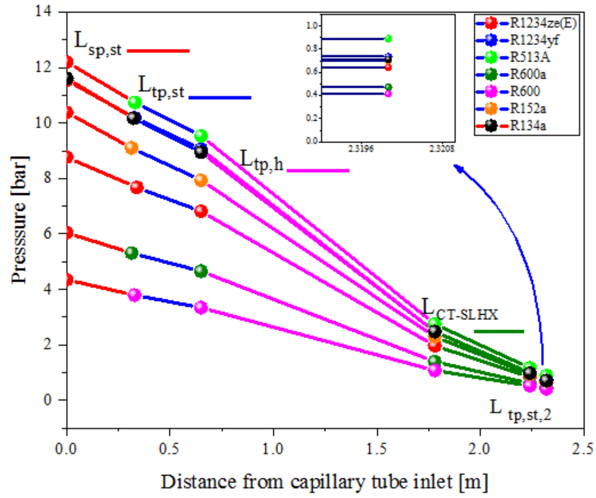

Figure 4.10 pressure distribution along with the CT.

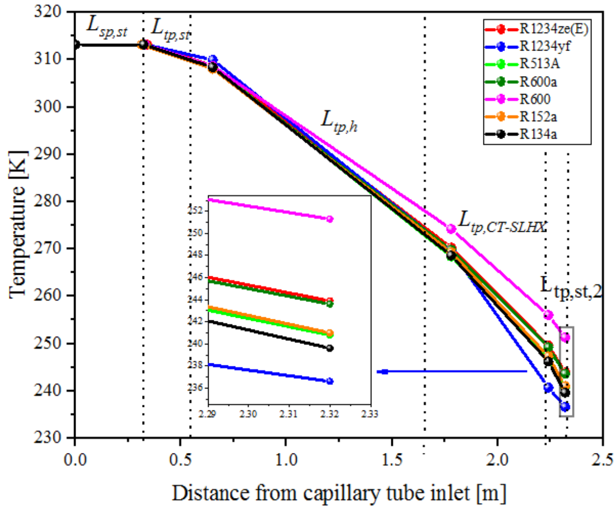

Figure 4.11 The temperature distribution along with the CT

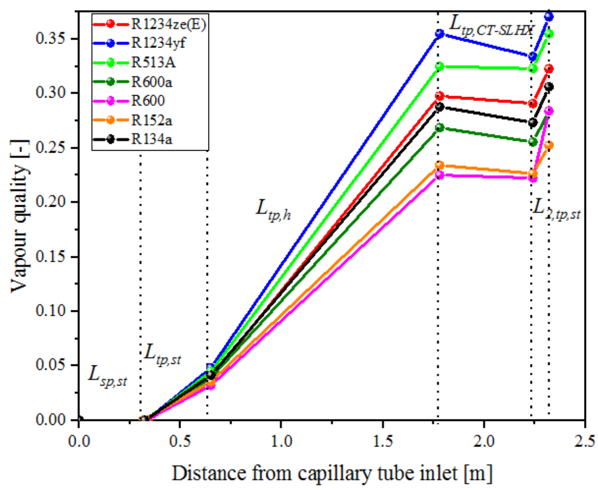

Figure 4.12 Variations of vapour quality along with CT

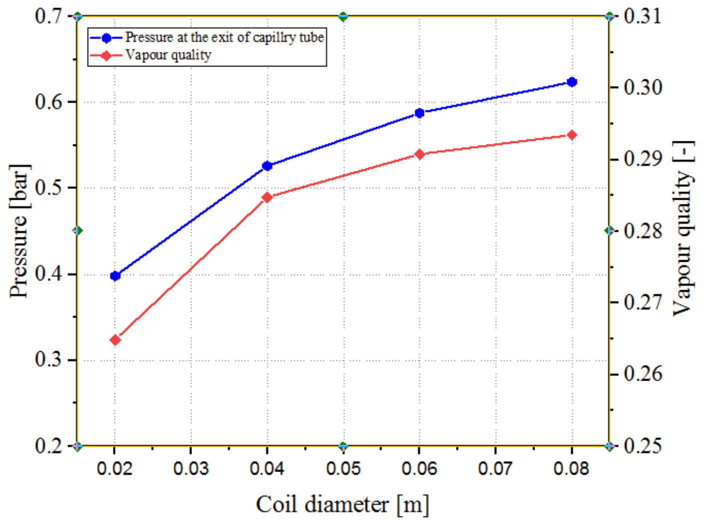

Figure 4.14 The effect of change of coil diameter on pressure and vapour quality at the CT outlet.

From Figure 4.16 it can be noticed that the expansion process displays the same pattern for all investigated refrigerants. The enthalpy of the refrigerant along the straight and helical CT is constant. The enthalpy during the expansion process in CT-SLHX is not constant due to the heat transfer process between the refrigerant flowing in the suction line and the refrigerant flowing through the CT. The CT outlet state 6 will move to the left towards lower enthalpy and vapour quality values. Lower vapour quality values will determine the higher enthalpy difference between the outlet and inlet of the evaporator.

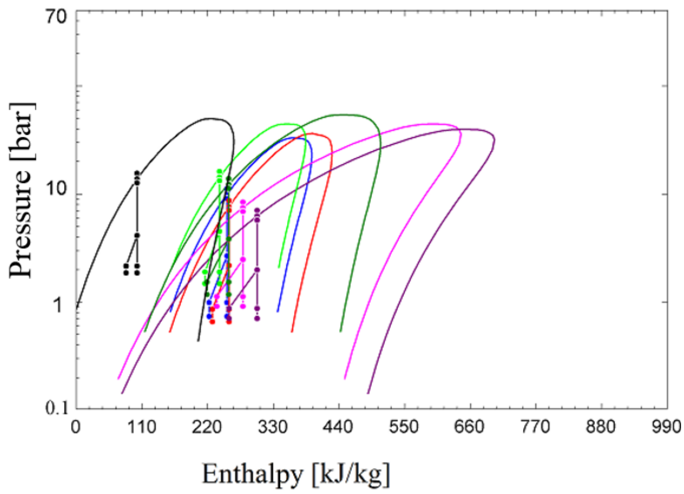

Figure 4.16 Expansion process in the CT on the p-h diagram [60]

The capillary tube inlet diameter is the most influential factor. Due to reduced frictional effects, the mass flow rate increases with increasing capillary tube diameter.

5 A mathematical model of the roll bond evaporator operating with a different refrigerant in a small-scale household refrigerator

5.1 Introduction

The roll bond evaporator (RBE) is one of the most used heat exchangers in the domestic refrigeration industry due to the excellent efficiency of its heat transfer, thus it has now been fitted in more and more mini-refrigerators, wine cabinets, freezers and iceboxes.

The heat transfer performance of evaporators greatly affects the household refrigerators' efficiency, so their improvement can greatly enhance the performance of the refrigerator [218].

5.2 Mathematical model

A mathematical model is developed to evaluate the heat transfer performance of the RBE that can be used for both steady-state and transient simulations, under different operating conditions of the refrigeration system. The mathematical model proposed in this study was divided into three sub-models: (i) the evaporator channels, (ii) inside the evaporator plate cabinet, and (iii) the refrigerated compartment.

5.2.1 Correlations of heat transfer coefficients within evaporator channels (refrigerant side)

Based on the refrigerant thermodynamic state, the evaporator is divided into two sequential heat exchangers which are the two-phase region and the superheating region of the evaporator. For the two-phase and superheating regions, a special evaporator model was designed to predict the heat transfer coefficients utilizing specific correlations for each region, as shown in Figure 5.3.

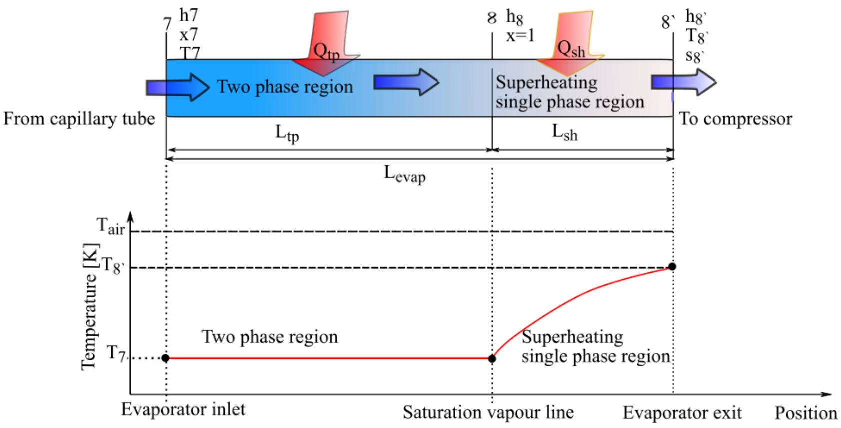

Figure 5.1 Single-phase (superheated), and the two-phase regions.

5.2.1.1 Two-phase heat transfer rate

5.2.1.2 Single-phase heat transfer rate

5.2.1.3 Computation of convection heat transfer rate between the evaporator and the air inside the refrigerator compartment.

A schematic of the refrigerated enclosure corresponding to the experimental setup is given in Figures. 5.7 and 5.8. The following is a calculation of the heat exchange between the exterior vertical evaporator surface, the horizontal evaporator surface pointing downward, and the air within the refrigerator compartment:

$$\dot{Q}_{conv,1} = \dot{Q}_{v,out} + \dot{Q}_{hor,down} \tag{5.29}$$

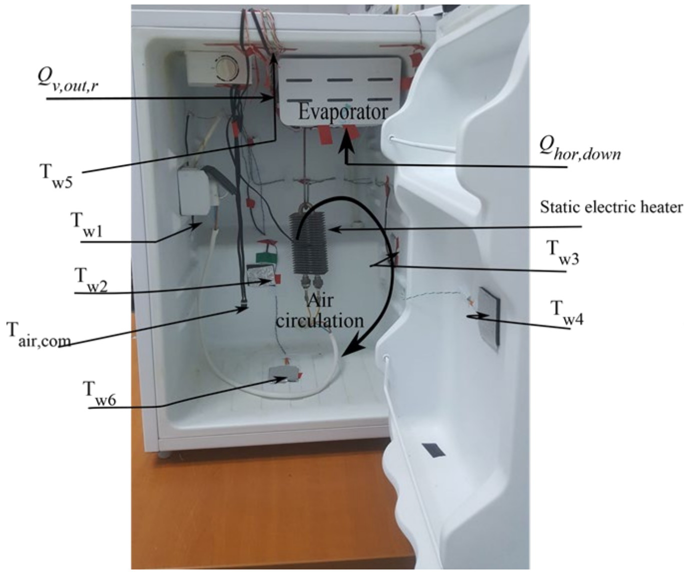

Figure 5.7 The sensors' locations to measure the refrigeration system walls' temperature

5.2.1.4 The convective heat flow rate ($\dot{Q}_{conv,2}$) occurs between the evaporator and the internal air in the evaporator cabinet

The convective heat flow rate that occurs between the evaporator and the internal air in the evaporator cabinet can be calculated the Eq. 5.39, as presented down:

$$\dot{Q}_{conv,2} = \dot{Q}_{v,in} + \dot{Q}_{hor,in,up} \tag{5.39}$$

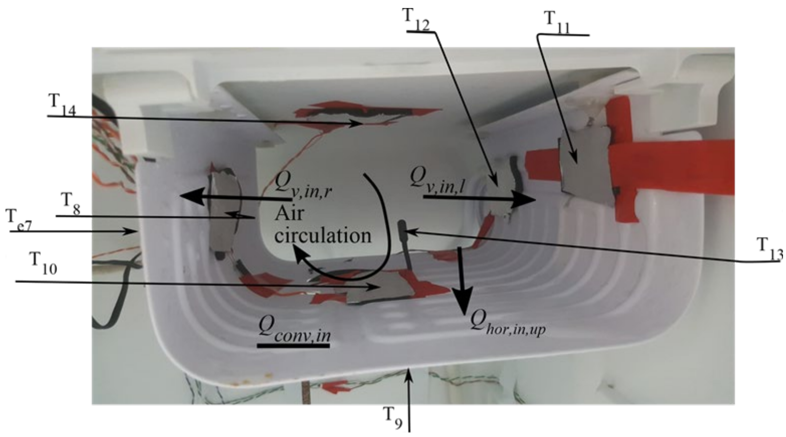

Figure 5.8 The heat is transferred between the air within the evaporator and the internal walls of the evaporator.

5.2.1.5 The radiation heat flow rate $\dot{Q}_{rad}$ between refrigerator walls and the outside evaporator wall

Radiation energy is the energy transferred from a hot body to another body whose temperature is lower than the temperature of the hot body in the absence of matter. The radiant energy is transferred at light speed by photons.

5.3 Validation of evaporator Mathematical Model

To validate the experimental results, the cooling capacity coming from the compression cycle-based cooling capacity (enthalpy differences, refrigerant side) equation (5.3) was compared to the cooling capacity emerging from the energy balance of the heat sources equation (5.26). The comparison of the cooling capacities that were achieved by employing the energy balance equation for heat sources (radiation, convection and the SEH) as well as the enthalpy differences of the refrigerant state at the inlet and outlet of the evaporator and multiplying them by the mass flow rate is shown in Figure 5.16.

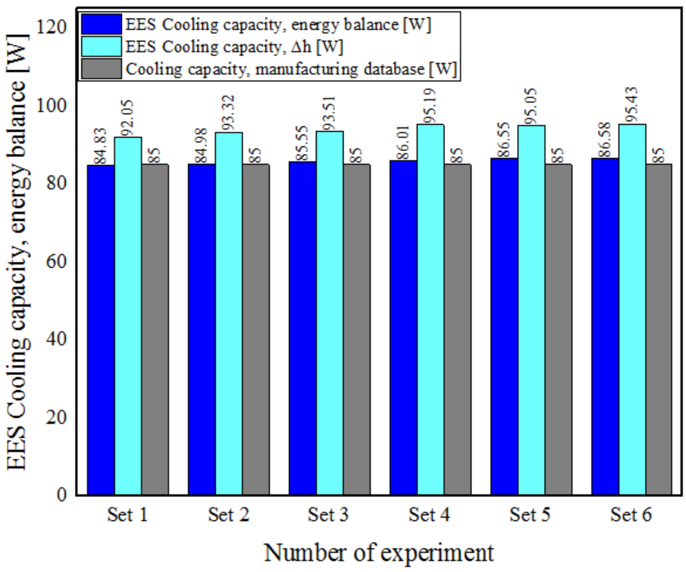

Figure 5.16 Comparison of the model results with the manufacturing database.

5.4 Results and Discussions

5.4.1 Heat transfer evaluation

Because of the small size of the refrigerator and evaporator, the amount of heat transferred by radiation has a large effect on the total amount of heat transferred from the walls and internal air in the refrigerator compartment and the evaporator cabin which is absorbed by the working fluid (refrigerant) through the evaporator walls. It can also be remarked that when the ambient temperature rises, the heat radiation and the amount of heat emitted by the SEH increase significantly. Convection, on the other hand, provides a relatively consistent amount of heat.

5.4.2 Convective heat transfer coefficient

The convective heat transfer coefficient (CHTC) of the vertical and horizontal evaporator walls was shown in Figure 5.17. Vertical walls have a larger CHTC than horizontal walls. The CHTC of internal vertical walls is lower than that of exterior walls. Due to the influence of the heat from the SEH and the heat passed through the refrigerator walls from the environment. The horizontal walls facing down have a substantially larger CHTC than the horizontal walls facing up.

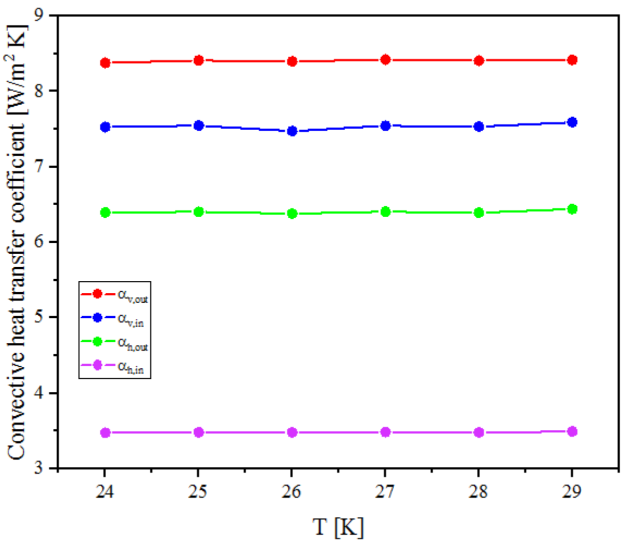

Figure 5.17 The CHTC of the evaporator walls.

5.4.3 Effect the ambient temperature on cooling capacity

The cooling capacity of the evaporator can be calculated by using two methods, The first method is to determine the differences in enthalpy between the inlet and outlet of the evaporator multiplied by the mass flow rate, and the second approach involves applying the energy balance equation to determine the amount of heat absorbed by the refrigerant through the evaporator walls. The cooling capacity variation as a function of ambient temperature for R600a in an SSR system is depicted in Figure 5.19.

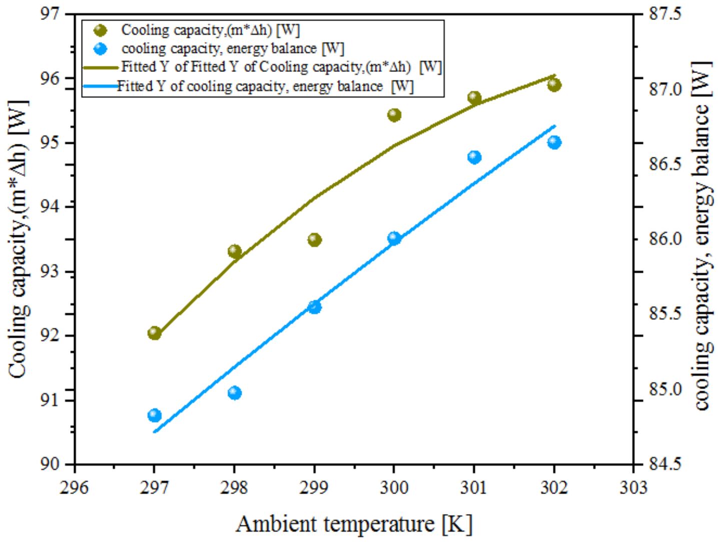

Figure 5.19 The cooling capacity variation as a function of ambient temperature.

It has been discovered that as the ambient temperature rises, the cooling capacity increases as well. This is owing to the significant challenges experienced throughout the experimental procedure in terms of controlling the ambient temperature due to the enormous size used of the experimental room and the cost of building the specific climate chamber.

5.4.4 Variation of SEH power with ambient temperature

5.4.5 Effect the ambient temperature on COP

The COP of SSR systems falls as the ambient temperature increases. At the selected operating condition of the ambient temperatures ranging from 296 to 302 K, the average COP was 1.55, while it was 1.37 in the manufacturing database with a relative error was 11.6%. The effect of the ambient temperature with respect to COP is depicted in figure 5.21.

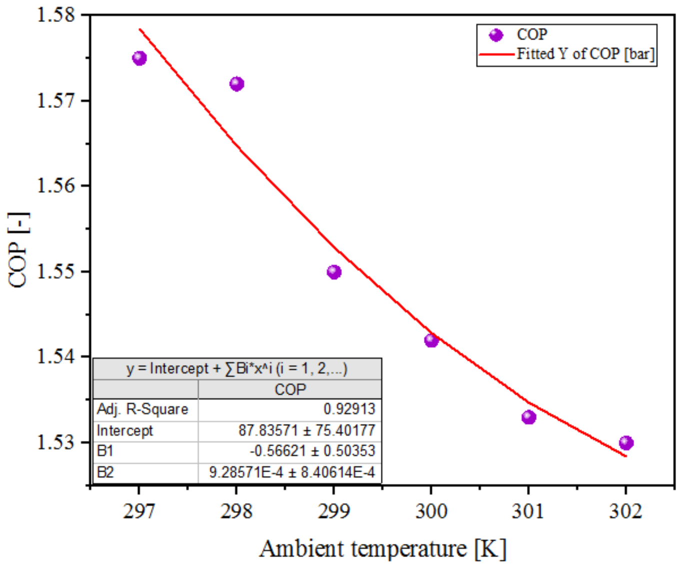

Figure 5.21 Effect of the ambient temperature variation on the COP

5.4.6 Variation of compressor power with ambient temperature

It can be seen that as the ambient temperature rises, the power consumed by the refrigerator's compressor rises as well. It was observed that when the refrigerator works with R600a refrigerant, its efficiency decreases with the increase in the ambient temperature. When the refrigerator compartment temperature exceeds 10 °C due to the increase in ambient temperature, the heat load generated by the SEH overcomes the capacity of the compressor, and thus the SEH is switched to the off state. Figure 5.22 highlights the correlation between the compressor's power consumption and the variation in ambient temperature.

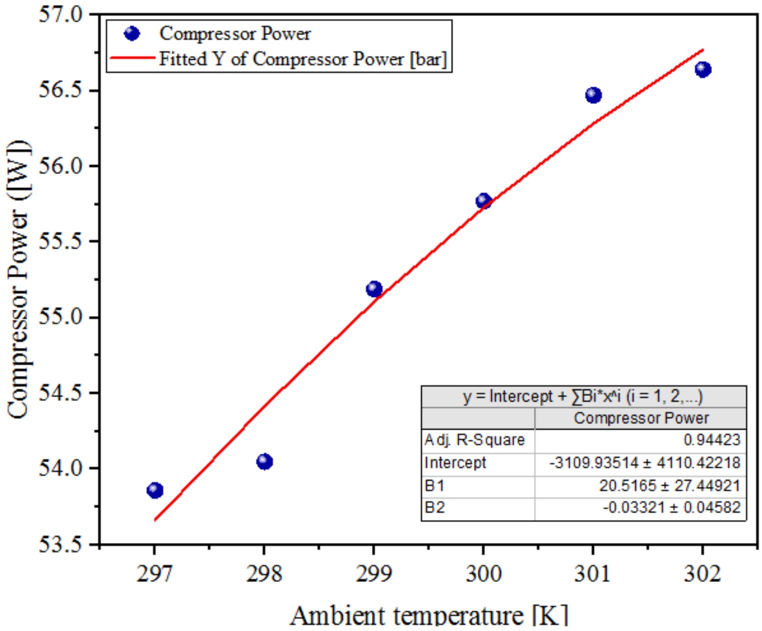

Figure 5.22 Effect of the ambient temperature variation on the power consumption

6 Comparison of the performance evaluation of the SSR system employing R600a and R1234yf as R134a substitutes

6.1 Introduction

6.2 Results and discussion

6.2.1 The heat generated by the electric static heater

6.2.2 Comparison of tested refrigerants' cooling capacities, $\dot{Q}_{e,ref} = \dot{m} * \Delta h$

The cooling capacity of any refrigeration system typically decreases as the ambient temperature rises. Figure 6.2 in this work shows that as the ambient temperature rises, the cooling capacity of the refrigerator increases. This is due to the continuous heat generated by the static electric heater, which requires an increase in the mass flow rate, consequently causing an increase in the amount of heat absorbed by the flowing refrigerant inside the evaporator channels.

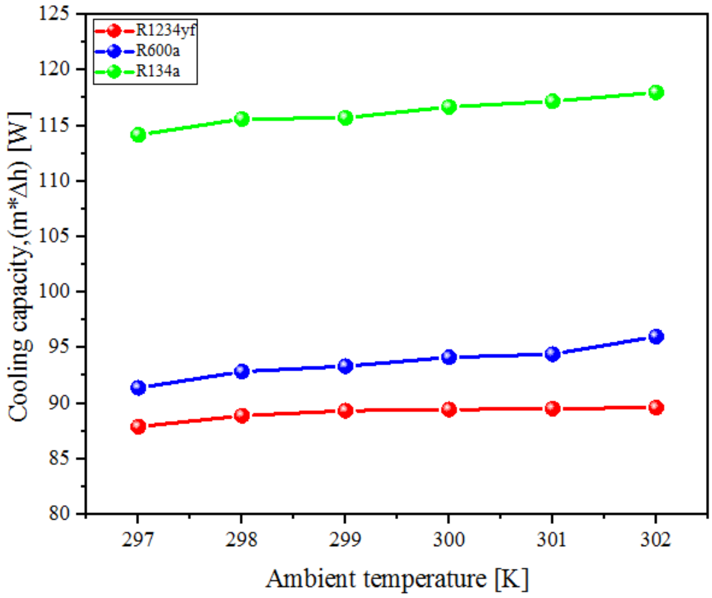

Figure 6.2 variations of the cooling capacity ($\dot{m}_{ref} * h$) with the ambient temperature of R123yf, R134a and R600a as a baseline

6.2.3 Comparison of Cooling Capacity Applying Energy Balance Equation

The experimental facility is a SSR originally designed to work with R600a. From figure 6.3 and table 6.2, when the main refrigerant was replaced with R134a and R1234yf, it was discovered that R134a and R1234yf have a 4.59 % and 3.67 % higher cooling capacity than R600a, respectively, in the ambient temperature ranging between 297 and 302 K.

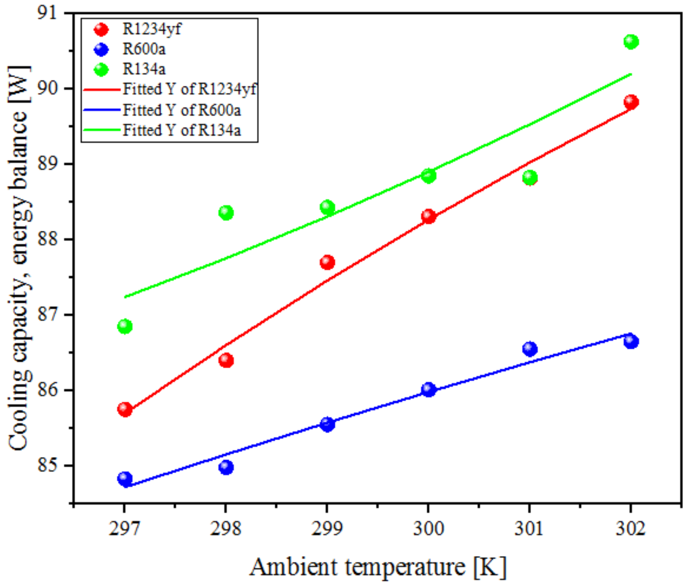

Figure 6.3 variations of the cooling capacity (energy balance equation) with the ambient temperature of R123yf, R134a and the refrigerant R600a as a baseline.

6.2.4 The influence of ambient temperature on the power consumption

In this study, it is possible to note that the amount of power generation consumed by a small-scale refrigerator powered by the refrigerant R1234yf is greater than the amount of power required by a similar refrigerator working with R600a and R134a. Figure 6.4 showed that as the temperature rises, so does the power consumption. In the ambient temperature range of 297 to 302 [K]. According to the findings the compressor that is driven by the refrigerant R600a consumes about one-half of the power that is consumed when it is driven by R134a and R1234yf.

Regarding the terms of energy consumption, R600a is an excellent replacement for the refrigerant R134a in small-scale refrigerators, provided that the disadvantage associated with its flammability has been eliminated.

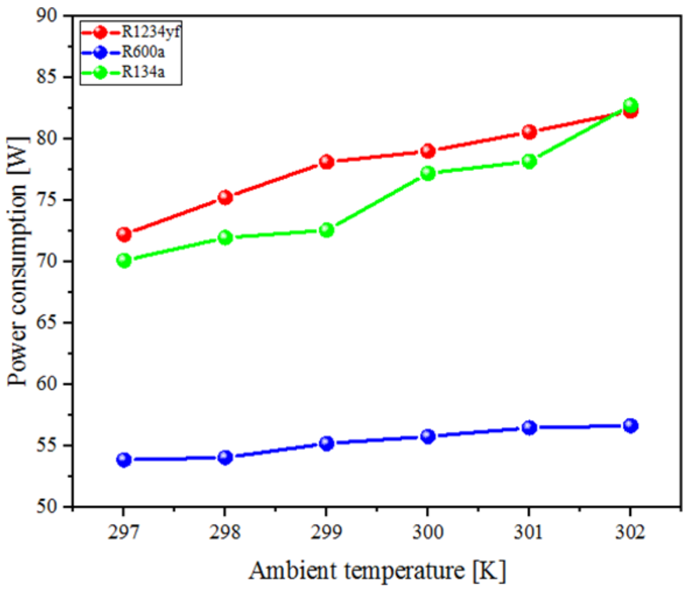

Figure 6.4 variations of the power consumption with the ambient temperature of R123yf, R134a and R600a as a baseline.

A reduction in the amount of electrical energy that is consumed by the refrigerator compressor leads to a reduction in the amount of direct harmful emissions that are produced as a result of the burning of fossil fuels in order to generate the electrical energy that is required to run refrigeration systems, which in turn leads to a reduction in the impact that refrigeration systems have on the overall rate of climate change.

6.2.5 Coefficient of performance (COP) of the refrigeration system

Figure 6.5 illustrates the influence of ambient temperature variation on the COP of a refrigeration system operating with the refrigerants R1234y, R600a, and R134a. According to the findings obtained, the COP of the SSR system goes down whenever there is an increase in the ambient temperature. It can be demonstrated that the COP of the refrigerants R1234yf and R134a were lower than those of R600a by -29.02 % and -28.43 %, respectively. This result depicted that the performance of R600a is the best in terms of COP, and it can be used as an alternative refrigerant to replace R134a in the SSR system.

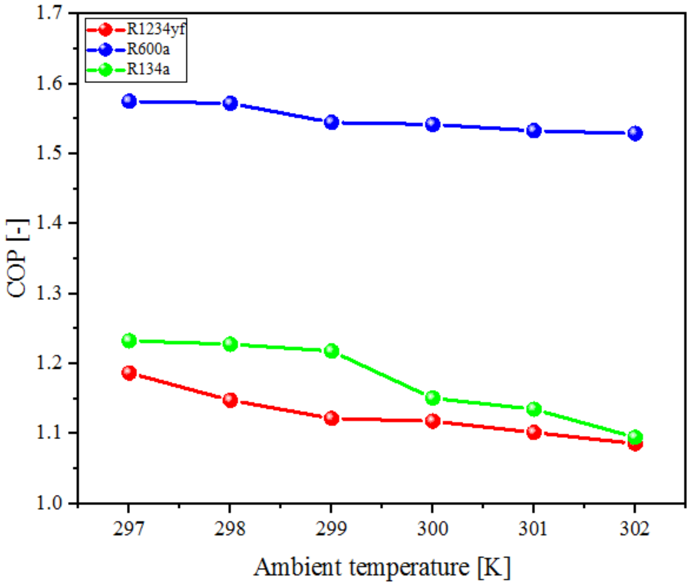

Figure 6.5 variations of the COP with the ambient temperature of R123yf, R134a and R600a as a baseline.

6.2.6 The radiation and convection heat transfer rate concerning ambient temperature

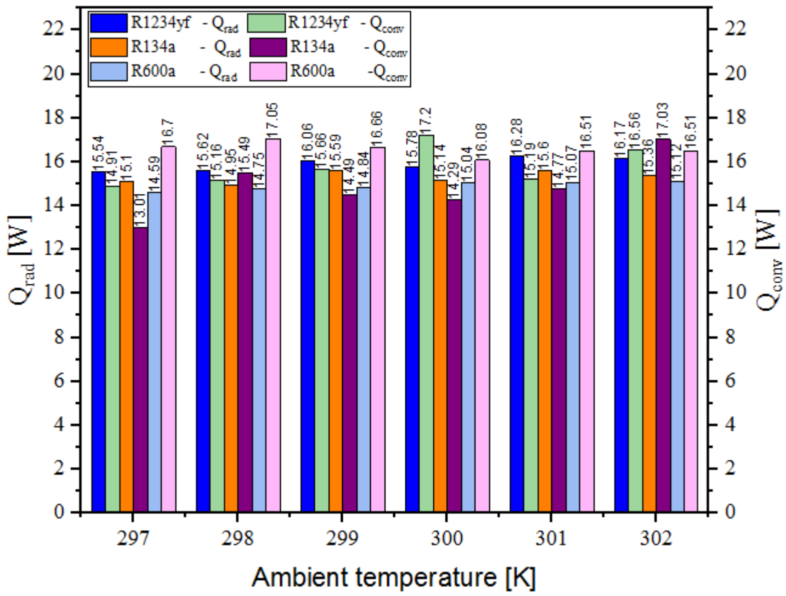

Figure 6.7 The radiation and convection heat transfer rate viz. the ambient temperature

It is possible to report that the rate of heat transfer by radiation and convection has roughly the same values, with minor variations, under the selected working conditions for ambient temperatures ranging from 297 to 302 K.

In terms of the rate of convective heat transfer, it was discovered that the lowest and highest convective heat transfer rate values with the R1234yf were -11.08 % and 6.96 %, respectively, and for R134a, the value ranged from its lowest point, which was -22.09 %, to its greatest point, which was 3.15 %, in comparison to R600a. Therefore, the radiation heat transfer rate of systems with low cooling capacity is intriguing and should be considered.

In conclusion, the findings that are presented in table 6.6 indicate that, from the perspective of the natural refrigerant, the R600a refrigerant is a good replacement for the R134a refrigerant in a cold climate, provided that some modifications are made to the system equipment and find a solution for the flammability problem. As a consequence, the issue of flammability prevents the use of this refrigerant in a hot climate such as that of Iraq, where the temperature during the summer months typically reaches more than 50 ^{o}C. As a matter of fact, it is not recommended to use this refrigerant in household appliances in a hot and humid climate in order to keep people safe. Furthermore, due to its low flammability and similar thermodynamic properties, the synthetic refrigerant R1234yf can be used as a drop-in replacement for R134a in household refrigerators in hot climates. It behaves similarly to R134a with 0% ODP, negligible GWP, and a short atmospheric lifetime.

7 General Conclusions, Personal Contributions and Future Work

7.1 General Conclusions

- The usage of R1234yf increased the amount of electrical energy consumed which was between 1.6 and 10% more than the power consumed by R134a.
- Hydrofluoroolefins (HFOs) (among them R1234yf) are synthetic refrigerants that have been offered as potential candidates to replace R134a in various refrigeration applications with minimum system adjustments. Natural refrigerants such as hydrocarbons (HCs) and their mixes can be used to replace R134a in current refrigeration systems. Because of their numerous attractive features, HC refrigerants (including R600a) have resurfaced.
- If the safety issue is solved concerning flammability, the HC and their mixtures could be considered the best long-term alternative to HFC134a.
- The refrigerant vapour quality was increased along the CT sections up to the inlet of the SLHX and thereafter it got decreased due to the heat exchange between the expanding hot and cold refrigerant.
- The decrease in the density of the refrigerant along the capillary tube was responsible for the observed increase in the velocity of the refrigerant as the evaporation process continued along the capillary tube. However, once the refrigerant entered the SLHX section of the CT, the velocity of the refrigerant dropped because of the increase in its density.
- Utilizing an internal heat exchanger at the end of the CT sections will enhance the overall performance of the system. Our technology may increase the cooling effect of SSR systems by decreasing the quality of refrigerant vapour.
- At the CT outlet and the evaporator inlet, increasing the coil diameter led to an increase in evaporating temperature and pressure, as well as an increase in enthalpy and vapour quality.
- Actually, higher vapour quality implied a lower amount of liquid refrigerant and thus lower cooling capacity.
- R600 and R1234yf achieved the highest and lowest temperatures at the CT outlet, respectively.
- The vapour quality produced by R1234yf was found to be the highest, whereas R600 produced the lowest vapour quality.
- Because of the small size of the refrigerator and the evaporator, the amount of heat that is transferred by radiation has a significant impact on the total amount of heat that is transferred from the walls and internal air in the refrigerator compartment and the evaporator cabin.
- Internal vertical walls have a lower convective heat transfer coefficient than outside walls. Because of the heat from the SEH and the heat from the environment that flowed through the refrigerator walls.
- Using many temperature sensors (14 thermistor sensors, in addition to two pressure transducers) in various positions on the walls of the refrigerator and evaporator leads to a measurement inaccuracy that lowers the average cooling capacity obtained using the energy balance equation to 85.76 [W] from the more accurate 94.09 [W] obtained using enthalpy differences multiplied by the refrigerant mass flow rate.
- In this study, the R600a refrigerant was the reference to compare numerous parameters that can give good information for selecting the replacement refrigerant, due to the experimental facility is originally built to operate with it.
- The refrigerator's cooling capacity becomes more effective as the ambient temperature continues to rise. In point of fact, this is because the SEH continues to produce heat, which necessitates an increase in the mass flow rate for the refrigerant (working fluid) to absorb the extra heat while it is flowing inside the evaporator channels.

- A refrigerator with an RBE and R134a refrigerant has a higher cooling capacity than one with R1234yf or R600a. In ambient temperatures ranging from 297 to 302 K, it was revealed that R134a and R1234yf have a 4.59 % and 3.67 % better cooling capacity than R600a, respectively.
- An SSR using the refrigerant R1234yf consumes more energy than one using R600a or R134a. The power utilized by the compressor when running with R1234yf and R134a refrigerants were greater than when operating with R600a. In SSRs, R600a is an excellent replacement for the refrigerant R134a in terms of energy consumption, provided the disadvantage of flammability has been overcome.
- The COP of the refrigerator decreased as the ambient temperature increased, and the COP of the refrigerant R600a is greater than that of R1234yf and R134a. This is due to the fact that the compressor running with R600a consumes less power than the one running with R1234yf and R134a.
- The radiation heat transfer rate inside the refrigerator compartment and evaporator cabinet is about half of the total heat transfer rate of the investigated mini-refrigerator, indicating that it has a substantial impact on the overall heat transfer rate. As a result, the rate of radiative heat transfer in systems with low cooling capacity is intriguing and must be taken into account.

Finally, the R600a cannot be utilized in a hot climate like that of Iraq due to the flammability concern, therefore, R1234yf, a synthetic refrigerant, is the best candidate to fulfill this task as a replacement for R134a in household appliances.

7.2 Personal contributions

The present work provides several noteworthy contributions, was summarized below:

- With reference to alternative refrigerants, the literature review followed the directions: types of alternative refrigerants available; the possibilities of replacing alternative refrigerants in automotive refrigeration and air conditioning applications, and the advantages and challenges of alternative refrigerants. Therefore, the replacement possibilities were divided into three categories: Drop-in replacement, retrofit refrigerant, and new systems.

- An original analysis approach to CT was adopted as compared to other publications accessible in the literature. This analysis takes into consideration the reality of CTs found in small-scale refrigerators, where the CT consists of three sections: straight CT section, helical CT section and CT-SLHX section. This analysis approach is an original contribution to this thesis.

- For the CT analysis approach, the following contribution to the fields are presented below:

  - ❖ The original graphs offer information about the influence of replacing the refrigerants on the performance of the many parameters at the CT outlet.
  - ❖ I have studied the effect of changing the coil diameter of the CT, increasing the coil diameter increased the refrigerant pressure, temperature and vapour quality. Higher vapour quality is the lower cooling capacity of the system.
  - ❖ From the findings of the CT analysis approach, we may deduce that R1234yf behaves similarly to R134a, R600a has the largest cooling effect, and R513A produces the least. Because of this, we now have two viable alternatives to R134a: R1234yf and R600a.
  - ❖ The CT analysis approach also provided the possibility to analyze the distribution of pressure and temperature along the capillary tube. The pressure and temperature decrease as the CT length increase and this may be useful in determining the required CT length if we decide on the required evaporator temperature for the systems.
  - ❖ The CT approach shows that refrigerant velocity increases as refrigerant vapour decreases and vice versa.

- ❖ The CT analysis approach contributes to determining the effect of the condensation pressure variation. The higher the condensing pressure, the higher the pressure at the outlet of the CT and the inlet of the evaporator. As a result, both the evaporation temperature and enthalpy increased, resulting in a lower cooling capacity.
- ❖ Also, the CT model may contribute figure out the quality of the refrigerant vapour. R1234yf had the highest vapour quality (0.3132) while R600 had the lowest (0.2124). The higher quality of the vapour at the CT outlet and the evaporator inlet led to different cooling capacities, which helps to choose a desirable alternative of R134a.

- An original heat transfer analysis approach of a roll bond evaporator in a small refrigerator enclosure was done. This RBE analysis approach was used to evaluate the heat transfer performance in small refrigerators. For the RBE analysis approach, the following contributions to the fields are presented below:
  - ❖ Two methodologies to validate the model have been used, the first methodology was comparing the cooling capacity obtained by applying the energy balance equation and the enthalpy differences with mass flow rate to the manufacturing database, and the second was computing the length of RBE of a single and two-phase region and compare it to the measured length.
  - ❖ The heat transfer approach by radiation and convective has been studied in SSR, and the results of the RBE heat transfer analysis approach showed that the radiant heat transfer rate is nearly half of the total heat absorbed by the refrigerant, so it should be taken into account for SSRs.
  - ❖ I have studied the effect of variation in ambient temperature on energy consumption. Energy consumption increased with increasing ambient temperature.
  - ❖ The calculated mass flow rate using the CT model for refrigerants R134a, R1234yf and R600a were applied in the RBE model and the effect of ambient temperature variance was examined. The mass flow rate increased with the increase in ambient temperature, R134a had a higher value while R600a had a lower value due to the refrigerant charge of R134a being the highest value (43 g) and R600a having the lowest value (19 g), an increase in the refrigerant charge leads to increase the mass flow rate.
  - ❖ The CHTC of the refrigerator and evaporator walls of R600a SSR has been computed along with a variety of ambient temperatures. The vertical wall had CHTC higher than the horizontal wall, and the horizontal wall facing the cooled surface was lower than the wall facing the hot surface.
  - ❖ This study focused on operating conditions in cold rooms in hotels to obtain experimental operating conditions similar to the case of Romania as much as possible. Since the temperature in Iraq in summer is more than 50°C, the research case is compatible with that of refrigerated hotels in Iraq. Where small rooms, offices and hotels frequently use mini-refrigerators.
  - ❖ Based on my research comparing R134a, R1234yf, and R600a, I can say that R1234yf is an excellent drop-in replacement for R134a, especially in warm climates where R600a is unsuitable due to its flammability.

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