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Thermodynamic Performance Analysis and Optimization of Domestic Refrigerator with Varying Refrigerant Charge and Capillary Tube Lengths

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Abstract

In this paper, thermodynamic performance analysis and optimization of a domestic refrigerator were experimentally carried out by simultaneously varying the refrigerant charge (w_r) and the capillary tube length (L). Continuous running and cycling tests were performed on a domestic refrigerator under tropical conditions using three refrigerants (R12, LPG and R600A) with different capillary tube lengths and various charges. The results show that the design temperature and pull-down time set by ISO for small refrigerator are achieved earlier using refrigerant charge 60g of LPG with 1.5m capillary tube length. The highest COP (4.8) was obtained using 60g charge of LPG with L = 1.5m. The average COP obtained using LPG was 1.14% and 15.09 % higher than that of R600a and R12 respectively. Based on the results of this study, R600a offered lowest power consumption. The compressor consumed 20 % less power compared to LPG and 32% less power than R12 in the system. In conclusion, the system performed best with LPG in terms of COP and cooling capacity. In term of power consumption R600a performed best. This shows that both LPG and R600A can be used as replacement for R12 in domestic refrigerator.

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Keywords: Cooling capacity, refrigeration system, COP, refrigerant charge, capillary tube length

1. Introduction

The energy consumption by household refrigerators depends on its components, the refrigerant charge and ambient conditions. It is well known that domestic refrigerators have highest efficiency when operating with certain combinations of capillary tube and refrigerant charge [1; 2]. Capillary tubes are used as expansion device in low capacity refrigeration machines such as domestic refrigerators, freezers and window type air conditioners. Usually, they have inner diameter (*d*) ranging from 0.5 mm to 2 mm

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and length (*L*) from 2 m to 6 m. Compared to other expansion devices, the capillary tubes are simple, cheap and cause the compressor to start at low torque as the pressure across the capillary tube equalize during the off-cycle. In order to enhance the system cooling capacity, the capillary tube and the suction line are usually placed together forming a counter-flow heat exchanger [3]. The heat exchanger may be of lateral or concentric type [4]. The flow inside the capillary tube is complex and pressure drop through the capillary tube has a strong influence on the performance of the whole system.

A number of experimental and numerical studies have been reported on the flow characteristics of refrigerant in a capillary tube, and the capillary tube dimensions and geometry, and their effect on the performance of vapour compression refrigeration system (VCRS) [4; 5; 6; 7; 8;9].

The literature reveals that most of the previous studies have focused on the independent variation of refrigerant charge (w_r)or capillary tube geometries (*L* or *d*), while study on the effect of simultaneous variation of these parameters is still lacking. Accordingly, in the present study, the thermodynamic performance of a household refrigerator was experimentally studied by simultaneously varying *refrigerant charge and capillary tube length.* The potential of replacing R12 with R600A and LPG was also explored. The prime objectives of the study were:

- To determine the best combination of *L* and w_r to give effective cooling.
- To compare the cooling capacities of R12, LPG and R600a under identical conditions
- To compare the COP and power consumption of the refrigerator with R12, LPG and R600a.

Nomenclature

w_r - Refrigerant charge
L – Capillary tube length
COP – Coefficient of performance
LPG – Liquidified Petroleum Gas
1,2 ,3 – Evaporator inlet, evaporator outlet, compressor outlet
P_R - Compressor pressure ratio
W_c - Compressor work (kW)
$\dot{m}$ - Refrigerant mass flow rate (kg/s)
h - *Specific enthalpies of refrigerant (Kj/kg)*
Q_E - Refrigerating capacity (kW)

2 Experiment and Analysis

The experimental setup (Figure 1) consisted of a domestic VCRS of 1 ton of refrigeration (TR) capacity designed to work with R12, an evaporator of 79 litre capacity, wire mesh air cooled condenser and a reciprocating compressor. The refrigerator was instrumented with two pressure gauges at the inlet and outlet of the compressor for measuring the suction and discharge pressure, and a power meter (with 0.01 kW h accuracy) for measuring the energy consumption. The test rig was thoroughly checked and commissioned before it was subjected to series of tests at various conditions. The specifications of the domestic refrigerator used in this study are shown in Table 1. Experiments were conducted with R12 and R600a, by varying *refrigerant charge* from 40g to 60g and *L* as 0.9m, 1.2m and 1.5 m, with dry bulb temperature of 32^{o}C. The temperature (- 30^{o}C to +90^{o}C), pressure (100 to 1300kPa) and compressor power (0 to 1100W) were measured with an uncertainty of ± 0.1 %.

Figure 1: The experimental setup.

Table 1: Specification of the base line test unit

Item	Specification
Unit Type	Freezer
Internal Volume	69L
Refrigerant/Lubricant	R12/ Mineral Oil
Compressor	Reciprocating Compressor
Evaporator	Cross flow fin and heat exchanger
Condenser	Natural cooling hot plate type heat exchanger
Expansion Device	Capillary tube

The refrigerants were charged into the system with the digital charging system. Type K thermocouples were used to measure the temperature at inlet and outlet of the evaporator and outlet of the compressor. A temperature gauge was used for measuring the evaporator air temperature in order to obtain the pull-down time (the time required for changing the evaporator chamber air temperature from ambient temperature to the desired final temperature). Readings were taken five times for each value of w_r with an accuracy of ±0.05. The experiment was carried out under the average ambient temperature of 32°C at no load and closed door conditions. The *REFPROP* version 9.0 software was used to determine the enthalpy (h) of the refrigerant by using the temperatures from the readings as input data. The results were used to calculate the refrigerating capacity (Q_E), compressor pressure ratio (P_R), the compressor work (W_c), and the COP of the refrigerator, as defined in the following fundamental equations:

$$Q_E = \dot{m}\,(h_2 - h_1) \text{ in kW} \quad (1)$$

$$W_c = \dot{m}(h_3 - h_2) \text{ in kW} \quad (2)$$

$$P_R = \frac{P_{dis}}{P_{suc}} \quad (3)$$

$$COP = \frac{Q_E}{W} \quad (4)$$

where $\dot{m}$ = refrigerant mass flow rate (kg/s), h_1, h_2 and h_3 are specific enthalpies of refrigerant (kJ/kg) at evaporator inlet, evaporator outlet (compressor inlet) and compressor outlet respectively, and P_{suc} *and* P_{dis} are the compressor suction and discharge pressures (*kPa*) respectively.

3 Results and Discussion

The effects of w_r and L on thermodynamic performance parameters of domestic refrigerator were analysed for R12, R600A and LPG with objective of obtaining the best values of w_r and L for optimum performance of VCRS. The study also investigated feasibility of using R600A and LPG in a VCRS designed for R12.

Figures 2 and 3 show the effect of L on the system COP with 40g and 60g charges respectively. The COP increases with increase in L for all values of w_r. The highest COP of 4.8 was obtained with LPG at w_r = 60g and L = 1.5m, for R600a the highest COP of 4.76 was obtained at w_r = 60g and L = 1.5m, while for R12, the highest COP of 4.17 was obtained at w_r = 60g and L=1.5m. The average COP obtained using LPG is about 1.14% higher than that of R600a and about 15.09% higher than that of R12. Instantaneous power consumption is the main criterion to choose a right quantity of mass charge. Figures 4 and 5 show variation of the electric power consumption (W_c) with L and w_r. It is observed that W_c decreases with increase in L but increases with increase in w_r. This is mainly due to increase in mass flow rate of refrigerant through the compressor. The lowest W_c of 0.36 kW was recorded at w_r = 40g for R600a with L=1.5m, while the lowest W_c of 0.43 kW and 0.50 kW were recorded at w_r = 40g with L=1.5m for LPG and R12, respectively. The average power consumption for R600a is about 20% and 32% lower than that of LPG and R12, respectively.

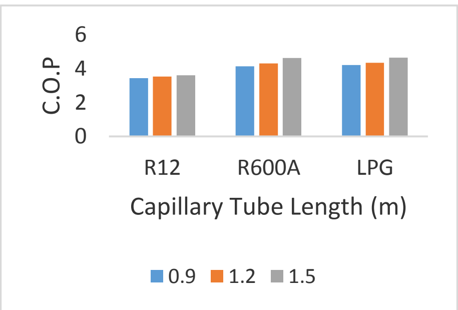

Figure 2: Effect of capillary tube length on the COP of the System at Refrigerant Charge of 40g.

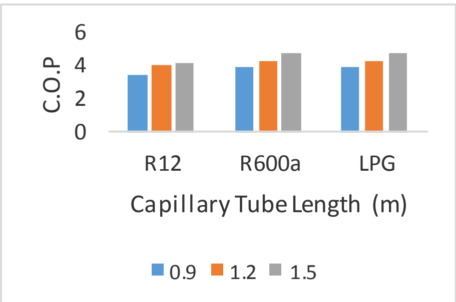

Figure 3: Effect of capillary tube length on the COP of the System at Refrigerant Charge of 60g.

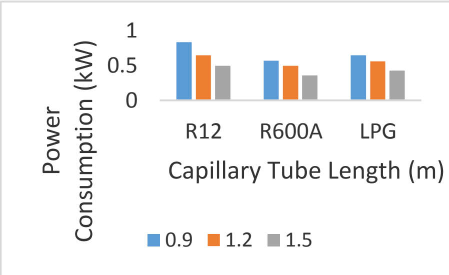

Figure 4: Effect of capillary tube on power consumption of the system at Refrigerant Charge of 40g

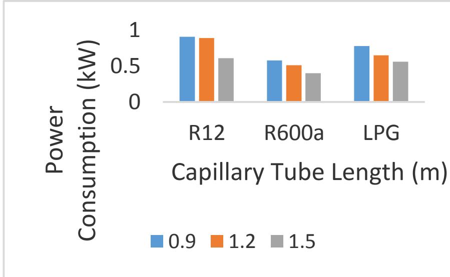

Figure 5: Effect of capillary tube on power consumption of the system at Refrigerant Charge of 40g

Figures 6 to 11 show comparison of cooling capacity for 40g and 60g charges of R600a, R12 and LPG respectively with capillary tube lengths 0.9m, 1.2m and 1.5m. At 40g charge, the cooling capacity of R12 varies from 1.6854 kJ/s (L=0.9m) to 6.1324 kJ/s (L=1.5m), that of R600a varies from 3.095 kJ/s (L=1.5m) to 5.7752 kJ/s (L= 0.9m) while that of LPG varies from 3.105 kJ/s (L= 1.5m) to 5.8752 kJ/s (L= 0.9m). At 60g charge, cooling capacity of R12 varies from 1.6317 kJ/s (L=0.9) to 5.3735 kJ/s (L= 1.5m) while that of R600a varies from 2.005 kJ/s (L=1.5m) to 6.5779 kJ/s (L =0.9m) and that of LPG varies from 2.015 kJ/s (L=1.5m) to 6.6779 kJ/s (L = 0.9m). Based on this study, the cooling capacity of LPG is about 1.59% and 7.51% higher than that of R600a and R12, respectively.

The pull-down time is the time required for changing the evaporator chamber air temperature from ambient condition (32ºC) to the desired final temperature (-12ºC) according to ISO-8187 standard for the considered refrigerator class [10]. Figures 12 and 13 show the comparison of pull-down time of R12, R600a and LPG in the refrigerator for 40g and 60g charges, respectively.

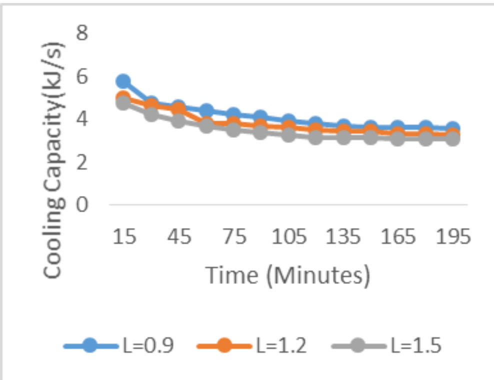

Figure 6: *Cooling Capacity for 40g charge of R600a at capillary tube length 0.9m, 1.2m and 1.5m*

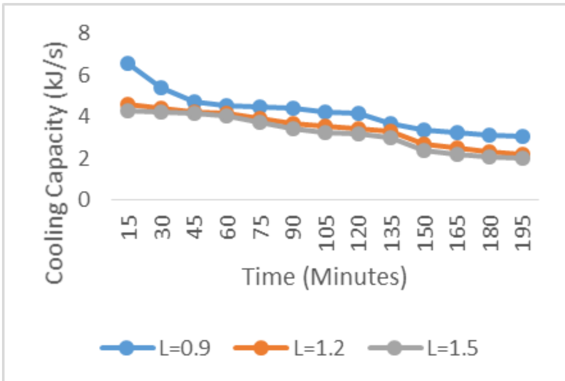

Figure 7: *Cooling Capacity for 60g charge of R600a at capillary tube lengths 0.9m, 1.2m and 1.5m*

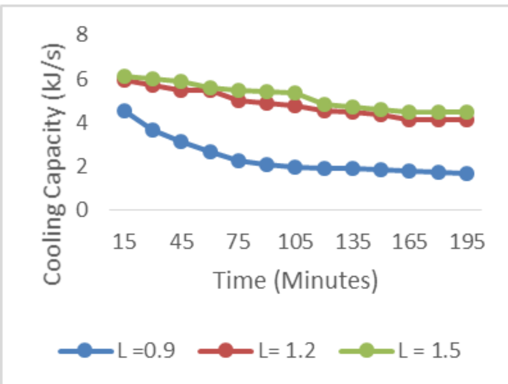

Figure 8: *Cooling Capacity for 40g charge of R-12 at capillary tube lengths 0.9m, 1.2m and 1.5m*

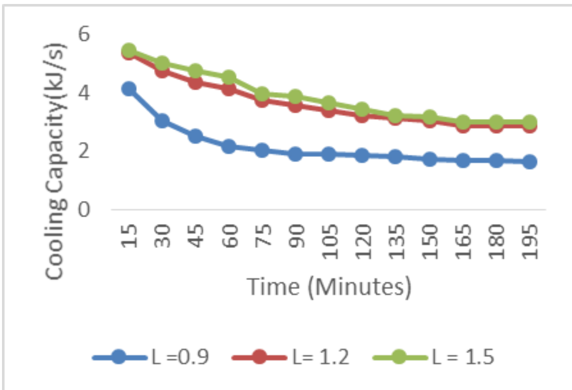

Figure 9: *Cooling Capacity for 60g charge of R12 at capillary tube lengths 0.9m, 1.2m and 1.5m*

According to ISO standard, the design temperature (-12ºC) and pull – down time of 135 minutes were achieved in the refrigerator system using 60g of R600a with capillary tube lengths 1.2m and 1.5m (Figure 13). Using 60g of LPG, the design temperature (-12ºC) was achieved at pull down time of 120 minutes with capillary tube length of 1.5 m, while for R12, the design temperature of (-12ºC) was at pull – down times of 165 minutes and 180 minutes using refrigerant charges of 40g and 60g with capillary tube lengths of 0.9m and 1.5m (w_r= 40g, Figure 12) and 0.9m (w_r= 60g, Figure 13). These results show that the design standard set by ISO for refrigerator system was achieved with refrigerant charge of 60g and capillary tube length of 1.5 m using LPG at lower time (120 minutes) compare to R600a and R12.

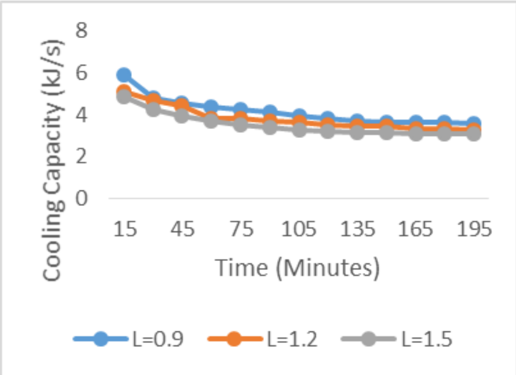

Figure 10: *Cooling Capacity for 40g charge of LPG at capillary tube lengths 0.9m, 1.2m and 1.5m*

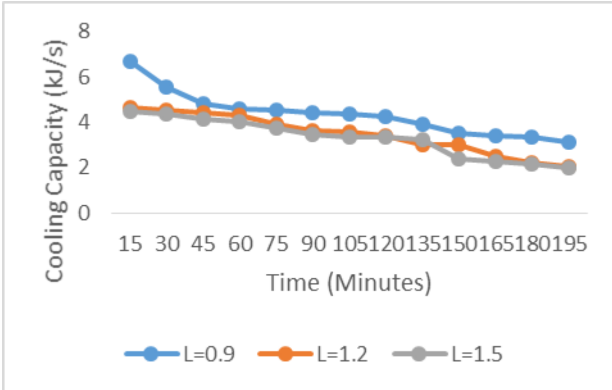

Figure 11: *Cooling Capacity for 60g charge of LPG at capillary tube lengths 0.9m, 1.2m and 1.5m*

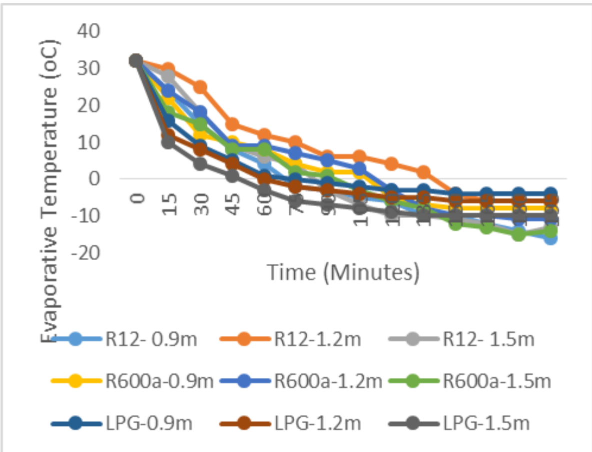

Figure 12: Pull down time for 40g charge of R12, LPG and R600a

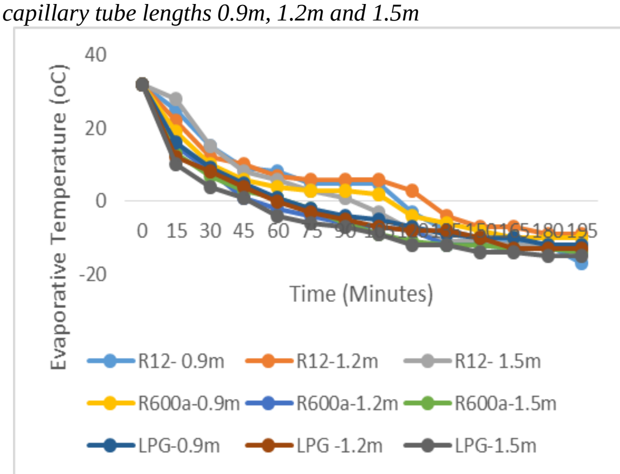

Figure 13: Pull down time for 60g charge of R12, LPG and R600a

In order to accept a refrigerant as a drop-in replacement, similar or better cooling capacity and power consumption should be achieved [11]. Based on pull-down time and COP, the appropriate combination of capillary tube length and refrigerant charge as a drop in refrigerant for R12 is LPG with L=1.5m and w_r = 60g, on the basis of cooling capacity, the best combination of LPG refrigerant is L=0.9m and w_r = 60g, while from power consumption per day perspective, the appropriate combination of capillary tube length and refrigerant charge is R600a with L=1.5 m and w_r = 40g.

CONCLUSION

In this study, the performance of LPG and R600a which are environmentally friendly refrigerants with zero ozone depletion potential (ODP) and low global warming potential (GWP) was studied experimentally in a domestic refrigerator and compared with the performance of the R12 refrigerant in the same system using different capillary tube lengths and refrigerant charges. After carefully investigated experimentally the performances of LPG, R600a and R12 in a domestic refrigerator, the following conclusions can be drawn out based on the results obtained:

- The pull-down time set by ISO for small refrigerator was achieved earlier using refrigerant LPG than using R600a and R12.
- The average COP obtained using LPG is about 1.14% and 15.09% higher than that of R600a and R12, respectively.
- R600a offers lower power consumption. The compressor consumed about 20% and 32% less power than LPG and R12, respectively in the system.
- The cooling capacity of LPG is about 1.59% and 7.51% higher than that of R600a and R12, respectively in the system.

In conclusion LPG and R600a is an appropriate long-term candidate to replace R-12 in the existing domestic refrigerator in terms of power consumption, cooling capacity and COP criteria.

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Biography

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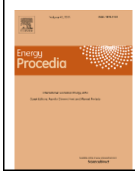

Optimization, Energy management and Energy conversion systems, Exergy and Exergo-economic Analysis, Renewable Energy Technologies, Heat Transfer Analysis, Turbo-machinery, etc.