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Performance enhancement using appropriate mass charge of R600a in a developed domestic refrigerator

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Abstract: This paper presents performance analysis of a domestic refrigeration system using R600a as refrigerant. Investigation was conducted experimentally to select an appropriate refrigerant mass charge for the system and to compute the cooling system performance characteristics under ambient temperature of 29 °C. The choice of the hydrocarbon refrigerant (R600a) became so imperative due to notable influence of chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) on global warming and ozone depletion. UNFCCC and Montreal Protocol regulation have banned the use of halogenated refrigerants in cooling and heating systems. The paper reveals that the power consumed by the system using mass charge of 15 g refrigerant was reduced by 9.3 and 10.9% compared with the 10 and 25 g refrigerant mass charges respectively. In addition, the results show that the coefficient of performance (COP) of the refrigeration system while working with 15 g is 24.7 and 20.2% higher than when the system worked with 10 and 25 g refrigerants mass charge respectively. More so, the system attained an evaporator air temperature of -12 °C in 2 hours, which makes 15 g charge refrigerant appropriate for the running of the developed system that has a volume capacity of 68 liters.

1. Introduction

Refrigeration being a process of transferring heat from the refrigerating space to the surrounding required a working fluid which is referred to as refrigerant. The working fluid determines the rate of heat movement within a closed system. There are various classes of refrigerant, which are based on their chemical composition and safety [1]. Furthermore, the extensive effect of the greenhouse gas from the combustion of fossil fuel in generating power and emission of halocarbon refrigerants from the traditional refrigerator, mechanical heat pump and air-conditioning system has inflated the threat on ozone layers and in turns creating negative impact on the environment. In 1876, most of the cooling systems used inorganic refrigerants such as ammonia (R717), water (R718) and carbon dioxide (R744) as their working fluids but due to their toxicity and incompatibility with the materials used in the system, they were replaced with chloromethane (R40) and Sulphur dioxide (R764) [2-3]. More so, in 1931, halocarbon refrigerants (CFC_s and HCFC_s) were found to be better replacements for inorganic refrigerants [4]. Since the discovery of the harm that CFCs and HCFCs refrigerant produces



on the environment and climate, the American Household Manufacturers have endorsed HFC134a as a possible alternative refrigerant for CFCs refrigerant in traditional refrigerators [5]. The rising of the hydrofluorocarbon (HFCs) refrigerants with suitable thermodynamic and thermo-physical properties have made them admissible both for the commercial and consumer set up in 90's [6]. They found applications in domestic vapour compression refrigerator, air-conditioning and heat pump and other heating and refrigerating appliances. However, HFC134a refrigerant has high global warming potential of 1430, which makes it non-environmental friendly [7-9]. A few years ago, the discovery of their immense contribution to the change in climate has led to the researching and investigation of various performance of refrigerant starting with class A1, class A2, and class A3 refrigerants. In 1997, Kyoto protocol of United Nations Framework convention on climate change (UNFCCC) worked on drop-in replacement refrigerants to abolish the predominant greenhouse gases [10]. To achieve reduction in the GHG, eco-friendly and energy saving refrigerants are needed to be introduced into the refrigeration system. Hydrocarbons (HCs) have been widely found to be alternative to halocarbon refrigerants in heating, ventilation and air-conditioning system (HAVC) and they are organic compounds with composition of hydrogen and carbon atoms [11]; [17]. These working fluids do not have potential to deplete the ozone layer because they have zero ozone depletion potential (ODP = 0), non-poisonous, low global warming potential (GWP<5), low cost, lower total equivalent warming impact (TEWI), miscible with mineral oil and high efficiency with better coefficient of performance COP [12-14]. The refrigerant is not only good for environmental preservation but it can step down energy consumption of the system and likewise, improve the cooling speed by 3-10%. Hydrocarbon miscibility in mineral oil enabled a smooth running of the compressor and its high critical temperature enhances the efficiency of the refrigeration system [15]. Combustion of hydrocarbon does not just occur by having contact with air. There are definite conditions that must be attained and these include: (i) a surface temperature should exceed 440 °C (ii) release of hydrocarbon is essential (iii) the substance has to mix with the true proportion of air [16]. The classes of refrigerant are shown in Table 1.

Table: 1 shows the classification of refrigerants with their thermo-physical properties [1]

S/N	Refrigerant	Chemical Composition	Safety Classification	ODP	GWP
1	R12	CCl_2F_2	A1	1	10200
2	R22	CHClF_2	A1	0.055	8100
3	R134a	CH_2FCF_3	A1	0	1430
4	R32	CH_2F_2	A2	0	675
5	R143a	CH_3CF_3	A2	0	4470
6	R152a	CH_3CHF_2	A2	0	124
7	R170	CH_3CH_3	A3	0	6
8	R290	$\text{CH}_3\text{CH}_2\text{CH}_3$	A3	0	3
9	R600a	$\text{CH}(\text{CH}_3)_2\text{CH}_3$	A3	0	3

The refrigerant used in this vapour compression refrigeration system is isobutane gas (R600a) and its hydrocarbon refrigerant. It has found its application in refrigeration and air-conditioning industry. Parts of European countries have switched to hydrocarbons from conventional refrigerants which increase the greenhouse gas and influenced climate negatively [17-18]. However, the purpose of this research work is to investigate the appropriate refrigerant charge level that will serve as specification for the developed domestic refrigeration system.

2. Experimental Procedure

A traditional refrigeration system was developed from locally sourced materials and used as experimental test rig. It contains four essential components, which are, evaporator, single hermetic sealed compressor, capillary tube and natural cooled condenser. The system operated under room temperature of 29°C in a refrigeration and air-conditioning laboratory as shown in Figure.1.



Figure.1: Experimental test rig with attached measuring devices.

Furthermore, temperature sensors were connected to each of the essential points of the refrigeration system to measure their temperatures at an interval of 15 minutes for a period of 5 hours and likewise, power meter was used in determined the compressor power input. Pressure gauge was also, used to measure the pressure at the suction and discharge of the compressor as shown in Fig. 1. In addition, the compressor of the refrigeration system was charged with a natural refrigerant known as isobutane (R600a). The mass charge of refrigerants was varied from 10, 15 and 25 g to determine the performance characteristics of the system such as Coefficient of Performance (COP), Refrigerating Effect (RE) and power consumption. REFPROP software (Version 9.1) was applied to capture the thermodynamic properties of the system. The performance parameters were computed using equation (1) to (5) and the results are shown in Fig. 2 to 7. More so, materials used in the fabrication of the domestic refrigerator and details of the application of temperature sensors on the refrigeration cycle are displayed in Table 2 and 3 respectively.

Table 2: Materials used for the construction of the refrigerator.

S/N	Component	Specification
1	Marine board	Plywood
2	Aluminum	Tin foil(<0.2mm)
3	Styrofoam	EPS-Thermal
4	Hermetic sealed compressor	1/12 (60-70W)
5	Condenser	Air cooled type
6	Evaporator	1 1/4 Copper pipe
7	Capillary tube	Copper tube type
8	Pressure gauge	No:536G-A
9	Refrigerant	R600a
10	Temperature Sensor	K-Type (-50-1300) °C

Table 3: Details of the temperature measurement in degree Celsius

Temperature Sensor	Fixed point
T ₁	Temperature sensor fixed before compressor
T ₂	Temperature sensor connected after compressor
T ₃	Temperature sensor connected before capillary tube
T ₄	Temperature sensor connected after capillary tube
T ₅	Temperature sensor connected in the refrigerating space

The coefficient of performance was determined using the equation 1.

$$COP = \frac{Q_e}{W_c} = \frac{he_1 - he_4}{hc_2 - hc_1} \quad (1)$$

Where, Q_e is the latent heat absorbed in the evaporator and W_c is the work done by the compressor

$$Q_e = \dot{m}(he_1 - he_4) \quad (2)$$

Where Q_e is the latent heat absorbed in the evaporator, \dot{m} is the mass flow rate of refrigerant and $he_1 - he_4$ is the differential in enthalpies at the evaporator (kJ/kg).

$$h_{cond} = \dot{m}(hc_2 - hc_3) \quad (3)$$

Where Q_c is the heat rejected at the condenser, \dot{m} is the mass flow rate of refrigerant and $hc_2 - hc_3$ is the differential in enthalpies at the condenser (kJ/kg)

$$W_c = \dot{m}(hc_2 - hc_1) \quad (4)$$

Where, W_c is the compressor work, \dot{m} is the mass flow rate of refrigerant and $hc_2 - hc_1$ is the differential in enthalpies at the compressor (kJ/kg).

$$\text{Mass flow rate } (\dot{m}) = \frac{\text{cooling load}}{he_1 - he_4} \text{ in (kg/s)} \quad (5)$$

Where \dot{m} is the mass flow rate of the refrigerant, $R.E$ is the refrigerating effect and $he_1 - he_4$ is the differential in enthalpies at the evaporator (kJ/kg).

3. Results and Discussion

Figure 2 shows that the coefficient of performance of the domestic refrigeration system when operating with 10, 15 and 25 g mass charge of refrigerant. However, the system performed better when working with 15 g refrigerant charge with 24.7 and 20.2% higher than when the system used 10 and 25 g refrigerants mass charge respectively. The refrigerating effect (R.E) of the domestic refrigerator was enhanced due to increase in the COP. Figure 3 revealed the energy saving trend of the cooling system, when working with different refrigerant mass charges of 10, 15 and 25 g. The energy consumed by the compressor when working with refrigerant charge of 15 g reduced below when the system was charged with 10 and 25 g by 9.3 and 14.0% respectively. This enables 15 g charge level to be appropriate refrigerants for the developed refrigerator as power consumption is one of the parameters to determine the performance characteristics of the system. The reduction in power input to the compressor, increases the COP and lowers the evaporator temperature of the system. Figures 4-6 displayed the variance of heat transfer within the natural cooled condenser and latent heat gained at the evaporator from the material to be cooled within the refrigerating space at an interval of 15 minutes for 5 hours. The thermal energy transfers in the condenser when the system was charged with 15 g of refrigerant was 7.4 and 14.8% higher than when the system was charged with 10 and 25 g and likewise the latent heat absorbed when the system was charged with 15 g of refrigerant was 11.5% and 3.8% higher than when the system was charged with 10 and 25 g of refrigerant respectively. More so, the rate of heat transfers within the evaporator and the condensing unit determine the overall performance of the refrigeration system.

The pull-down time is the time required for the system to attain its lowest temperature. Hence, the pull-down time for the 15 g mass charge achieved was 8.3 and 25.0% faster than when the system was charged with 10 and 25 g respectively. This enables the 15 g mass charge to have a better performance as displayed in Figure. 7.

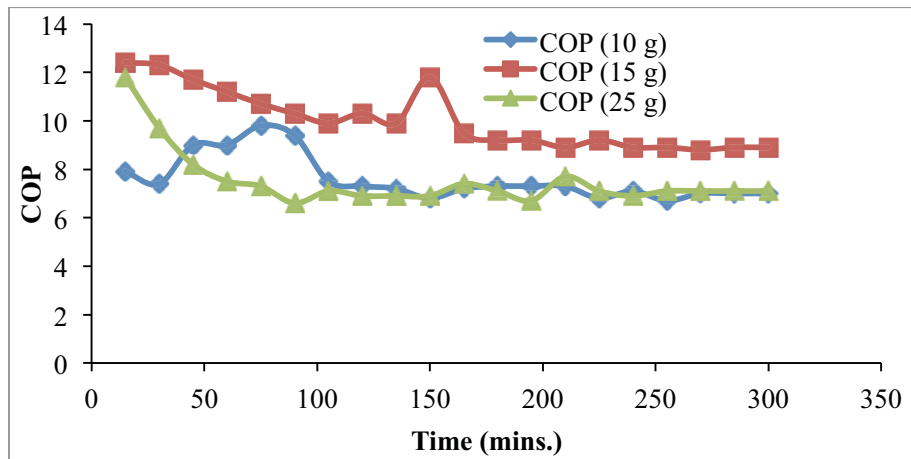


Figure. 2: Variation in COP with time when the system worked with 10 g, 15 g and 25 g refrigerant mass charge.

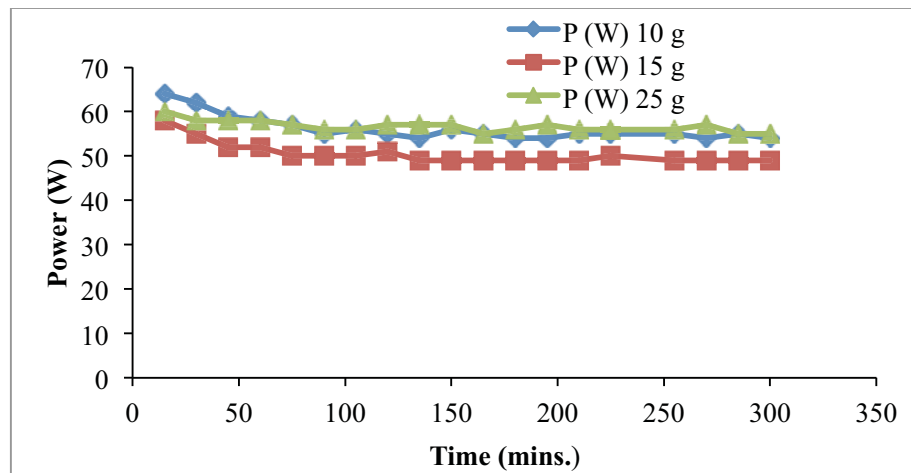


Figure. 3: Variation of power input to the compressor with time.

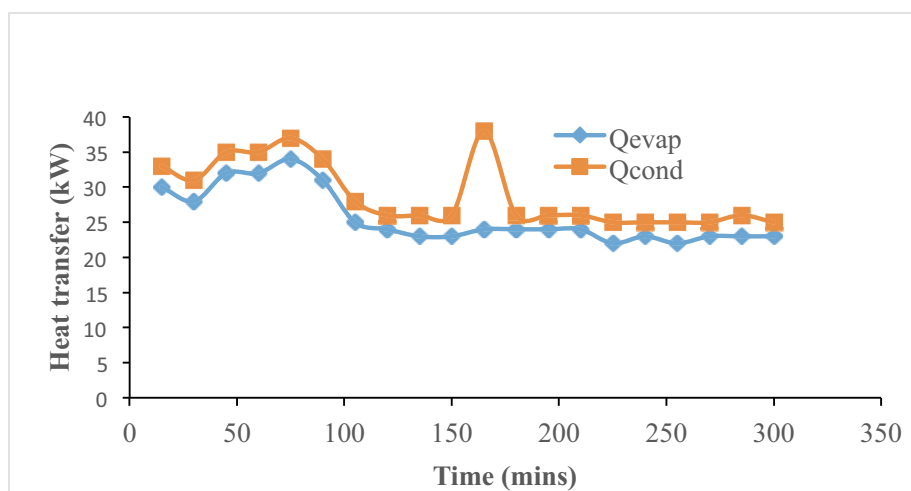


Figure. 4: Variation of heat transfer in the evaporator and condenser for 10 g of R600a.

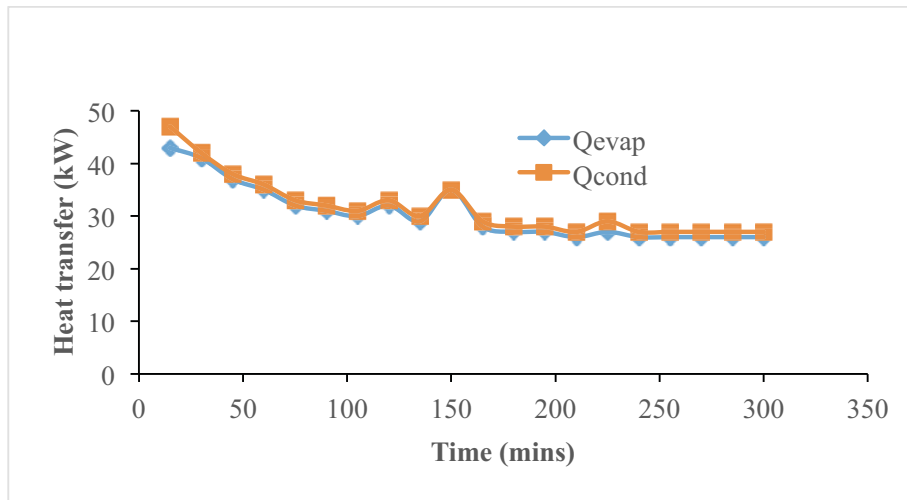


Figure. 5: Variation of heat transfer in the evaporator and condenser for 15 g of R600a.

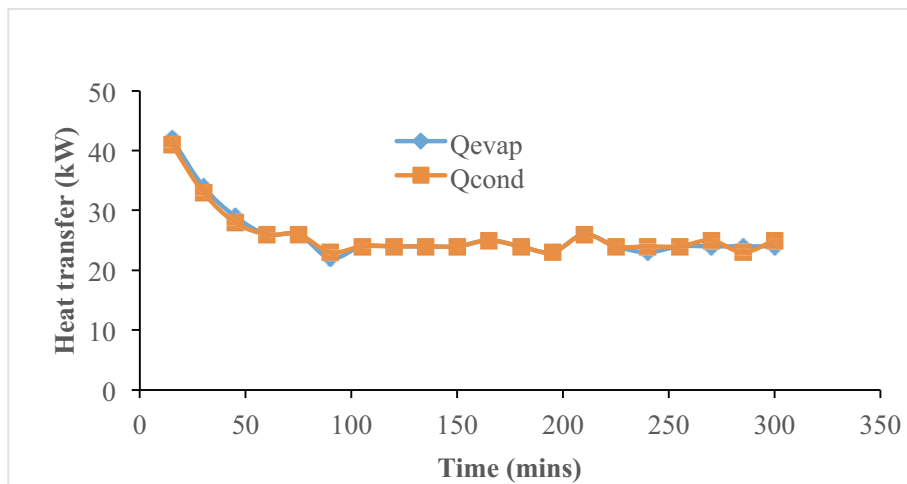


Figure. 6: Variation of heat transfer in the evaporator and condenser for 25 g of R600a.

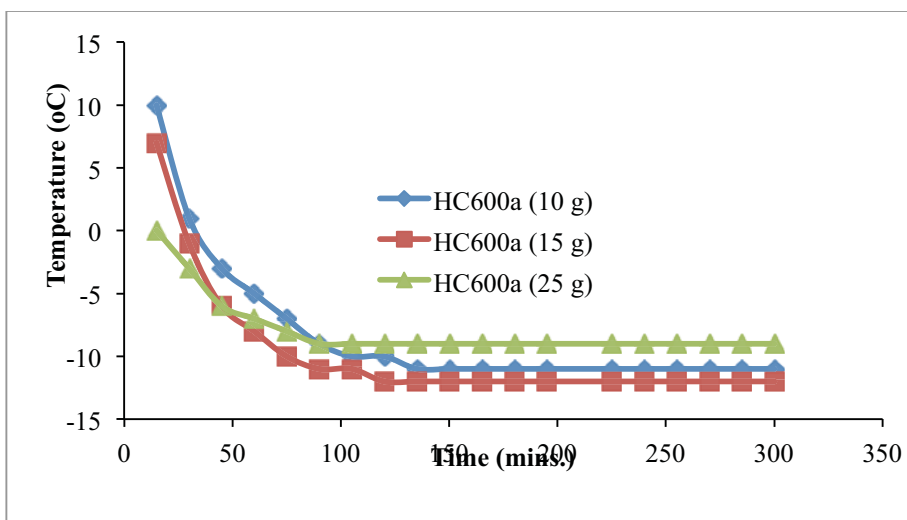


Figure. 7: Variation in pull-down time for the 10, 15 and 25 g of refrigerant mass charges.

4. Conclusion

From this experimental evaluation, effect of refrigerant mass charge was investigated using performance characteristics which include coefficient of performance, refrigerating effect and compressor work input. The selected hydrocarbon refrigerant (R600a) is an environmental friendly type with zero ozone depletion potential, miscible with mineral oil, negligible global warming potential and compatible with system materials. It was feasible from the experimental test results that refrigerant charge of 15 g was suitable to run the developed vapour compression refrigeration system (VCRS) efficiently under a normal room temperature in a tropical region.

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