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ENERGY AND EXERGY ANALYSIS OF A DOMESTIC REFRIGERATOR: APPROACHING A SUSTAINABLE REFRIGERATOR

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ABSTRACT

In the perspective of reducing the household energy consumption, current research in conventional refrigeration is concentrating on introducing innovative designs and enhances the energy efficiency of the refrigeration system. This research work compares the performance of the domestic refrigerator by employing hot-wall air cooled and box type shell and tube water-cooled condenser. The energy and exergy analysis methods help to localize exergy losses in the refrigerator. The investigation is carried out according to ISO 15502:2005. Experimental studies were conducted in the same refrigerator unit operating with a different condenser to determine the coefficient of performance, exergy efficiency, and exergy loss in all components of the domestic refrigerator. The experimental result shows that COP is increased by 18-20% and the exergy efficiency of the refrigerator with water cooled condenser unit is found to be higher by 6.89-9.13% than the one with a hot-wall air cooled condenser. The per day energy consumption of a refrigerator with a water-cooled condenser reduces by 17% in comparison with conventional refrigerator. The irreversibility of the refrigerator with the water-cooled condenser is reduced by 34 % than that of the conventional system under similar operating conditions. The total equivalent warming impact of refrigerator working with the water-cooled condenser is 16% lower than that the refrigerator with air cooled condenser. The utilization of water-cooled condenser in household refrigerators enhances energy efficiency.

Keywords: *Refrigerator, Water-cooled Condenser, Hot-wall Condenser, Energy, Exergy*

INTRODUCTION

In the view of reducing household energy consumption, current research in refrigeration is focusing on improving energy efficiency, introducing innovative designs in compact condensers and evaporators. Among the domestic appliances, household refrigerator consumes about 15% of the worldwide energy, and about 40% of the world energy consumption is from the building sector [1, 2]. The development of an energy efficient refrigerator is one of the big challenges for the Heating, Ventilation, Air-conditioning and Refrigeration (HVAC&R) sector. The majority of the research since the 1980s focused on heat transfer enhancement in condensers and evaporators. Several studies were reported on the effect of ambient temperature, optimization of mass flow rate, use of eco-friendly refrigerant etc. to make the refrigerator more energy efficient [3]. All vapour-compression refrigeration systems utilize the condenser to reject the heat absorbed by the refrigerant in the evaporator. The condenser also rejects the heat equivalent of the work of compression to the cooling medium [10]. A well-designed condenser not only enhances the energy efficiency but also reduces the space and material of the refrigerator. In a refrigeration system, the condenser holds the maximum portion of the refrigerant charge, and therefore heat exchangers with the small internal volume on the refrigerant-side should be preferred [4]. Condensers commonly used in the domestic refrigerator are of wire and tube type. The condenser temperature decrement of approximately 8℃ and the corresponding decrement in power consumption of 10% are obtained by using a standard wire and-tube condenser, equipped with phase-change materials [5]. The study on spiral wire-on-tube condenser in a refrigerator shows that the decrease in condensing temperature can reduce the per day energy consumption of the refrigerator by 2.37%. This is due to the combined effect of a decrease in compressor ON time ratio and compressor power [6].

In modern refrigerators, the wire and tube condensers are replaced by the hot-wall air cooled condenser (HWAC); HWAC is often installed in the form of single serpentine tubes on the left, right and back sides. The single aluminium tube of length ranging between 20 to 25 m is fixed on the inner side of the wall of aluminium foil and gives off the heat absorbed by the refrigerant to the surrounding through walls [7]. In recent years, the bottom

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condenser is introduced near the compressor as a part of the HWAC to evaporate the drain water continuously in a domestic refrigerator. In all refrigeration components, condenser plays an imperative task to save energy consumption. It is also observed that a reduction of 1°C condenser temperature can reduce 2% of total energy consumption [3]. HWAC condenser normally dissipates heat by convection and radiation at the rate of 250W to 400W to the surroundings. In hot climatic conditions, such an arrangement leads to 25W to 35W of heat conducted into the refrigeration compartment through the insulating material which gives rise to the energy consumption of the refrigerator [8]. Despite the fact that HWAC consumes more power as compared to a water-cooled condenser, it is preferred in small systems due to its low cost and easy maintenance [9]. Hosoz and Kilicarslan [10, 11] Depending on the type of the cooling medium, condensers can be classified as air-cooled, water-cooled and the combination of the both known as the evaporative condenser. Hosoz et al. evaluated the use of air-cooled, water-cooled and evaporative condensers for refrigeration systems and found that the condensing pressure and compressor work is decreased, consequently increasing the refrigeration capacity and compressor's life. Shiochi et al. have simulated the effect of refrigerant flow in an air conditioning system with the water cooled condenser. The result shows that one can save 20% of energy with a water-cooled air conditioning system. Henceforth, in a densely populated country, increasing use of domestic appliances leads to demanding large energy supply. Therefore, researchers and industries have their attention oriented towards the implementation of the water-cooled condenser in domestic refrigerators and air conditioning systems [12].

According to the American Society of Heating, Refrigeration and Air conditioning Engineers (ASHRAE) standards, the plate-type heat exchangers have a better heat transfer coefficient than that of the shell and coil heat exchanger [13]. Ramezanizadeh, M., et al have experimentally investigated the thermal performance of a thermosyphon-based heat exchanger is by using Ni/Glycerol–water nanofluid. Since the effective thermal conductivity of thermosyphon depends on the temperature difference between a condenser and evaporator. Effects of mass flow rates of cold and streams and inlet temperature of the hot stream on heat transfer rate are evaluated. He concluded that an increase in the mass flow rates of the streams and inlet temperature of the hot stream lead to an increase in the heat transfer rate [14]. Aprea C [15] has reported that the exergy losses in condenser and evaporator are highly influenced by a change in condensing and evaporating temperatures in a vapour compression plant. This is due to the decrease in the difference in temperature between the condenser and cooling medium. Selladurai et al. [16] has compared the performance between R134a and R290/R600a mixture on a domestic refrigerator which is originally designed to work with R134a and found the similar result as highest irreversibility in compressor followed by the condenser, expansion valve and evaporator.

S. Joseph Sekhar et al. [17] has studied the energy and exergy analysis of a domestic refrigerator with a brazed plate heat exchanger as water cooled condenser. It is observed that the per day energy consumption of a refrigerator is reduced by 21% to 27% and COP improved by 52% to 68%, as compared to the conventional refrigerator with air cooled condenser. Based on experimental studies he reported that the exergy destruction and irreversibility is reduced with a water-cooled condenser. Raveendran et al. [3, 18] experimentally evaluated the performance of refrigeration with a brazed plate heat exchanger as a condenser and found that the electric energy requirement of a refrigeration system reduces from 21% to 27% and COP increases from 52% to 68%, as compared to the conventional system. Mahmood Joybari, et al. [19] has carried out an experimental exergy analysis of the vapour compression refrigeration system applied to the domestic refrigerator with R134a to improve its performance. With exergy analysis, the optimum requirement of refrigerant charge required for alternative refrigerant R600a is determined as 50 g. It is observed that the compressor has the highest exergy destruction followed by the condenser. The highest exergy destruction observed in R 134a compressor is 0.03095 kW, whereas in 0.03612 kW in R600a compressor. Hosseinzadeh-Bandbafha, H et al. have presented a study on the assessment of energy flow and greenhouse gas emission of peanut production in Guilan province, Iran, and then the application of data envelopment analysis to determine optimum energy use pattern for saving energy and reduction of greenhouse gas emission. This reduction in greenhouse gas emission can be realized by management of diesel fuel, nitrogen and machinery consumption according to optimized input rates introduced by the data envelopment analysis. [20]. Total equivalent warming impact (TEWI) has been defined which allows a comparison of for large size refrigeration systems in relation to their impact on the environment. The TEWI index takes into account not only the direct warming effect due to refrigerant losses but also the indirect effect due to the plant efficiency and CO_2 release by utility companies supplying power to the device in question [21].

It is seen from the literature survey that there is scope for development and comparing performances of refrigeration systems employing with thermosyphon-based Box type shell and tube water-cooled condenser (BSTWC) and air cooled condenser. This research study investigates the experimental performances of the domestic refrigerator operating with two different types of condensers. Each system with a different condenser was operated under the same condensing and evaporating temperatures, and environmental conditions. Then, the performance, Characteristics such as refrigeration capacity, energy consumption of compressor, the coefficient of performance, exergy efficiency etc., of the systems were compared with each other. The experimental investigation has focused on the energy saving opportunities with help of exergy analysis tool. Investigation results show that the use of BSTWC in domestic refrigerators enhances energy efficiency.

Exergy Analysis of Vapor-Compression Refrigeration Cycle

The second law of thermodynamics (exergy analysis) deals with the quality of energy. The degradation in the quality of energy is termed as exergy loss (irreversibility), and the analysis in the loss provides ample opportunities for improvement. The second law of thermodynamics has proved to be a very powerful tool in the optimization of complex thermodynamic systems [22]. The generalized exergy balance for a control volume can be expressed as given in equation 1,

$$\mathrm{Ex_D} = \sum(\mathrm{Ex})_{\mathrm{in}} - \sum(\mathrm{Ex})_{\mathrm{out}} + \left[\sum(\mathrm{Q}\left(1-\frac{\mathrm{T_0}}{\mathrm{T}}\right)_{\mathrm{in}} - \sum\left(\mathrm{Q}\left(1-\frac{\mathrm{T_0}}{\mathrm{T}}\right)_{\mathrm{out}}\right)\right] + \sum \mathrm{W_{in}} - \sum \mathrm{W_{out}} \quad (1)$$

where the exergy in any state is given by

$$\mathrm{Ex} = \mathrm{m_r}[(\mathrm{h}-\mathrm{h_o}) - \mathrm{T_o}(\mathrm{s}-\mathrm{s_o})] \quad (2)$$

where Ex_D is the exergy flow destruction and in general equation the first two terms are stream exergy flows, the next two terms are heat transfer exergy flows and the last two terms are work exergy flows. The domestic refrigerator is working on a vapour compression cycle as shown in Figure 1. The major components are a compressor, condenser, capillary tube, and evaporator. In this research work, the following assumptions are made:

- Steady state condition is prevailing in all the components.
- Pressure loses in the pipelines are neglected.
- Unnecessary heat gains and heat loses to and from the system are not considered.
- Kinetic energy, potential energy and energy losses are not considered.
- The mass flow rate of the refrigerant is considered to be unity.

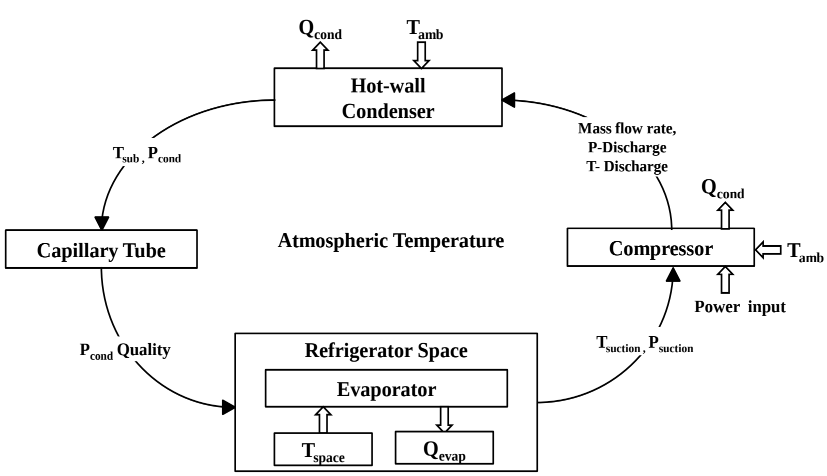

Figure 1. Schematic representation of vapour compression cycle

The exergy balance equation for each component is represented as below:

Compressor

$$(Ex_D)_{comp} = (Ex)_1 + W_{actual} - (Ex)_2 = m_r(T_o(s_2 - s_1)) \tag{3}$$

Electric power,

$$W_{actual} = \frac{m_r(h_2 - h_1)}{\eta_{mech} * \eta_{el}} \tag{4}$$

Condenser

$$(Ex_D)_{cond} = (Ex)_2 - (Ex)_3 = m_r(h_2 - T_0 s_2) - m_r(h_3 - T_0 s_3) \tag{5}$$

Expansion Device

$$(Ex_D)_{exp} = (Ex)_3 - (Ex)_4 = m_r\left(T_0(s_3 - s_4)\right) \tag{6}$$

Evaporator

$$(Ex_D)_{evap} = (Ex)_4 + Q_{evap}\left(1 - \frac{T_0}{T_r}\right) - (Ex)_4 \tag{7}$$

$$(Ex_D)_{evap} = m_r(h_4 - T_0 S_4) + Q_{evap}\left(1 - \frac{T_0}{T_r}\right) - m_r(h_1 - T_0 s_1) \tag{8}$$

The total exergy destruction in the system is the sum of exergy destruction in different components of the system and is given by

$$(Ex_D)_{Total} = (Ex_D)_{comp} + (Ex_D)_{Cond} + (Ex_D)_{exp} + (Ex_D)_{evap} \tag{9}$$

Exergy efficiency or rational efficiency computes the efficiency of a process taking the second law of thermodynamics into account.

$$\eta_{exergy} = \left(1 - \frac{(Ex_D)_{Total}}{W_{comp}}\right) \tag{10}$$

BSTWC Condenser

Nowadays the imminent need is to get the better energy efficiency of a vapour compression refrigeration system. The focus of the current research work is on the design and development of water-cooled condenser. The superiority of water-cooled condensers is his ability to absorb more heat and consume less energy. Depends on the availability of space, BSTWC condenser is designed as a box type shell and tube counter-flow heat exchanger with the consideration of refrigerant flow on the tube side and water flow on the shell side. There are distinct differences between tube configuration and geometry of BSTWC and HWAC condensers as shown in Figure 2.

Figure 2. The geometry of HWAC and BSTWC condenser

EXPERIMENTAL SET-UP

The experimental system is a household refrigerator which has an internal volume of the refrigerator is 284 litres. The eco-friendly R600a is used as a refrigerant with smart inverter compressor, HWAC connected in parallel with BSTWC and, the capillary tube used as an expansion device. The technical specifications of a refrigerator under test are specified in Table 3. A 4W DC pump is used to circulate the water through the water-cooled condenser. The circulated water is cooled in a mini cooling tower. The actual experimental set-up is shown in Figure 3.

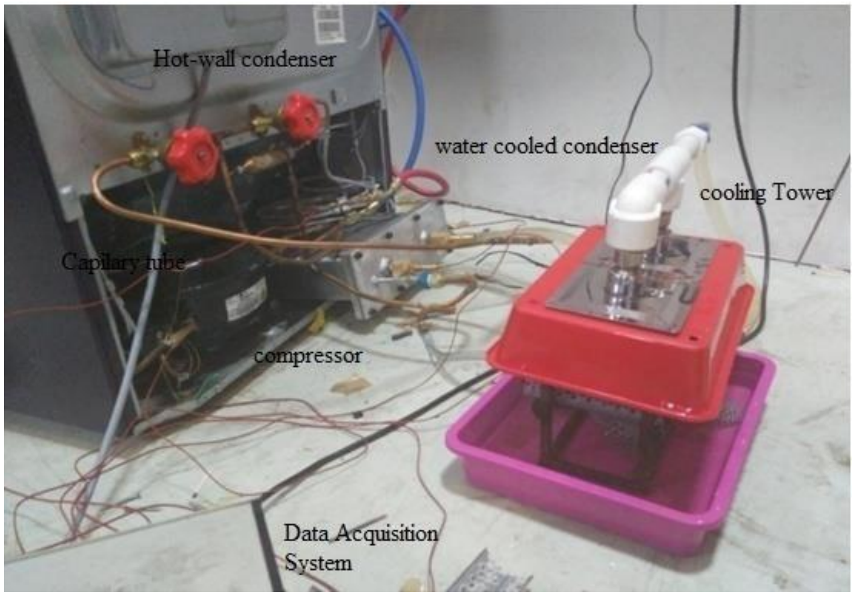

Figure 3. Experimental test set-up

The pressure gauges are used to measure compressor suction and discharge pressure with an accuracy of ±0.25%. The temperatures are measured at 16 potions with the help of K- thermocouples having an accuracy of ± 0.5°C. The thermocouples are mounted inside the freezer, food compartment, crisper compartments, compressor outlet, condenser outlet etc. as per ASHRAE refrigerator standard. The energy consumption of compressor and electrical devices is measured with a help of digital energy meter. The measuring instruments are calibrated before experimentation. The flow control valves are used to connect the refrigerator evaporator in parallel with external evaporator calorimeter. The heater is used to give a constant heating load on evaporating coils. The uncertainty analysis of the measuring instrument is presented in Table 4.

Experimental Procedure

A refrigerator test set-up is incorporated with two condensers, initially, the test set-up is flushed with nitrogen gas to check the leakage and to remove impurities from the system. The system is charged with refrigerant R-600a. According to the methodology used in the literature [3], the experimentation is carried out as per ISO 15502:2005 household refrigerating appliances test guidelines [23]. The experimentation is carried out in a test room. The test room conditions are maintained and controlled with help of an air conditioning system. In the evaporator calorimeter test setup, the calorimeter temperatures vary between −20°C to 6°C (±0.5°C). The calorimeter is an insulated chamber consists of evaporator coils, a heater connected with dimmerstat and ethylene glycol solution. The dimmerstat is needed since temperature is one of the variable parameters. The temperature of the glycol solution is varying by changing current and voltage with help of dimmerstat. The refrigeration load applied by the heater is evaluated by using Q_{evap} = VI, where voltage and current measurements for the heaters. This method is adapted to perform the experimentation at different evaporator temperatures. The dimmerstat is used to provide a heating load which acts as an equivalent evaporator capacity. Other parameters like voltage, current, power consumption, relative humidity, water inlet and outlet temperatures are recorded with help of a data acquisition system. The energy consumption is monitored for 8 hrs at no load condition using a digital energy meter and calculated the energy consumption for 24 hours operation. The experimental test conditions during the test are presented in Table 1. The % RH is measured and is observed in the range of 50% to 75%. The pressure and temperature readings are monitored with help of data acquisition system. During experimentation, the ambient temperature is maintained at 32°C ± 0.5°C. The refrigeration system with BSTWC condenser under test is set to keep the inlet cooling water temperature 30°C. The COP is calculated by considering the compressor work, pump work and heater load.

Table 1. Operating test condition of the refrigeration system

Factors	HWAC	BSTWC
Cooling water temperature	NA	30°C
Evaporator temperature	-20°C to 6 °C	-20°C to 6°C
Ambient temperature	32°C ± 0.5°C	32°C ± 0.5°C
Relative humidity	50% to 75%	50% to 75%
Capillary tube length	l =1800 mm	l =1800 mm

Uncertainty Analysis

If you are comparing the uncertainties in the values of two quantities, then by analyzing the absolute uncertainty you cannot tell which of the measurements is more accurate because the units of the measured quantities are different. In order to resolve this issue, the relative uncertainty which is the ratio of the absolute uncertainty and the average is determined by using weakest link rule [24]. Weakest Link Rule is used to determine the absolute uncertainty of the refrigeration system, the largest relative uncertainty from all measured relative uncertainties is considered as systems uncertainty. As shown in Table 2, the largest relative uncertainty is 1.45% for a set of sample observation. This justifies the reliability of the experimental study

Table 2. Instrument specifications

Measured Parameter	Measuring device	Make	Range	Accuracy	Relative Uncertainty %
Temperature	K- Type Thermocouple	EUREKA	-10 to 200 °C	0.5 °C	0.833
Evaporator Pressure	Pressure Gauge with Glycerine	MASS	-30 to 200 psi	1.6 %	1.16
Condenser Pressure	Pressure Gauge with Glycerine	MASS	0 to 200 psi	1.6 %	1.38
Energy Consumption	Energy Meter	Selec: EM368	1, VV I5 A	0.01kWh	0.67
Flow rate	Rotameter	EUREKA	0 to 138 kg/hr	2% of full flow	1.45

RESULTS AND DISCUSSION

The performance analysis of a refrigerator is carried out experimentally at various operating conditions with HWAC and BSTWC condenser using R600a as a refrigerant. As per the energy user guide, in order for a refrigerator to be environmentally friendly, it should contain refrigerant that won't contribute to ozone depletion or global warming. R600a also claims better energy efficiency. One of the downsides of R600a is that it's flammable, unlike R134a; however, the small quantities used in refrigeration make this a very low risk. The test results are used to analyze the variation of performance parameters such as energy consumption, the coefficient of performance (COP), exergy loss in the compressor, total exergy loss & exergy efficiency at various system components at different operating conditions. The variation of COP of a refrigerator for different evaporating temperatures is presented in Figure 4. The investigation results show that the COP increases with an increase in the evaporator temperature for both the condensers. The refrigeration capacity is measured and the COP is calculated using the following Equation (11):

$$COP = \frac{heater\ load + heat\ infiltration}{compressor\ work + pump\ work} \tag{11}$$

The BSTWC has enhanced the COP of the system in the range of 18% to 22 % as compared to a refrigeration system with HWAC due to its lower compressor work and higher evaporator capacity. In the systems with a BSTWC, the heat absorbed by the water at the condenser is rejected to the ambient air by means of a cooling tower. This lowers condenser pressure and power requirement, thus increasing the coefficient of performance and compressor life. The high heat transfer properties of the BSTWC affect on pressure ratio. The BSTWC lowers the condensing pressure; as a result, the pressure ratio reduces. It is observed that the temperature lift is small in a refrigerator with BSTWC condenser as compared with a refrigerator with HWAC.

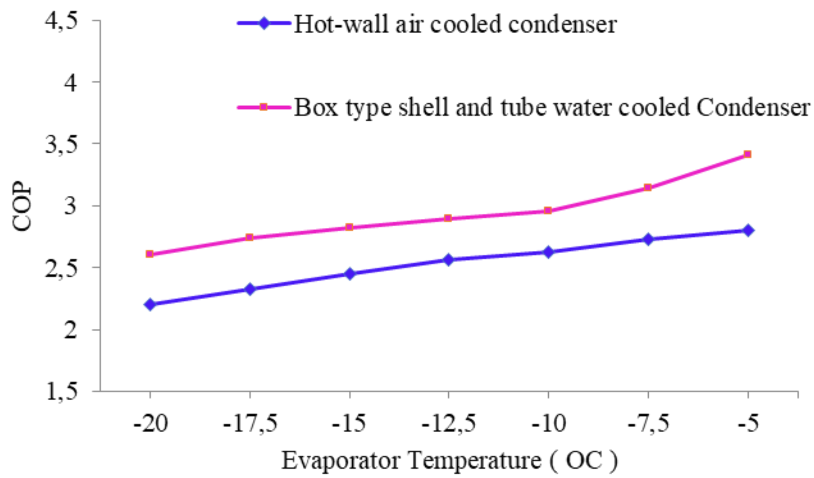

Figure 4. Variation of COP with different evaporator temperature

The energy consumption of the compressor during pull down with BSTWC with respect to time is shown in Figure 5 and Figure 6. It is observed that the pull-down time of the refrigerator is 95 minutes with BSTWC and 125 minutes with HWAC. Thus the desired set temperature is achieved faster with BSTWC than the refrigerator with the HWAC.

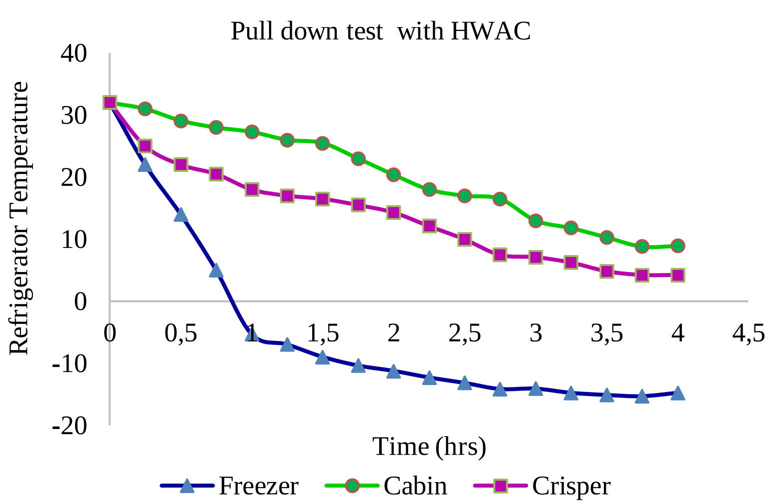

Figure 5. Variation of pull-down speed of a refrigerator with HWAC

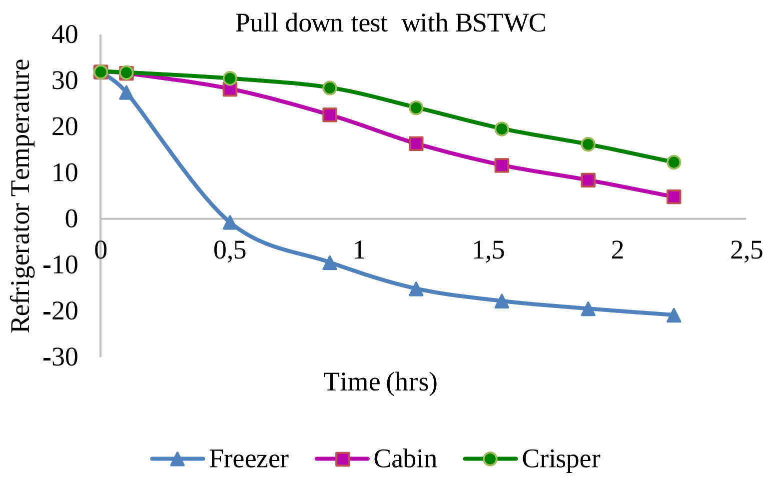

Figure 6. Variation of pull-down speed of a refrigerator with BSTWC

The effect of this reduces the energy consumption by 17% for the refrigerator working with BSTWC condenser at the no-load condition as compared to the conventional refrigerator.

The variation of compressor work with evaporator temperature is represented in Figure 7. The figure shows that compressor work increases with the evaporating temperature. The energy consumption of refrigerator working with BSTWC as a condenser is reduces by 10% to 20%, as compared to the refrigerator with the HWAC.

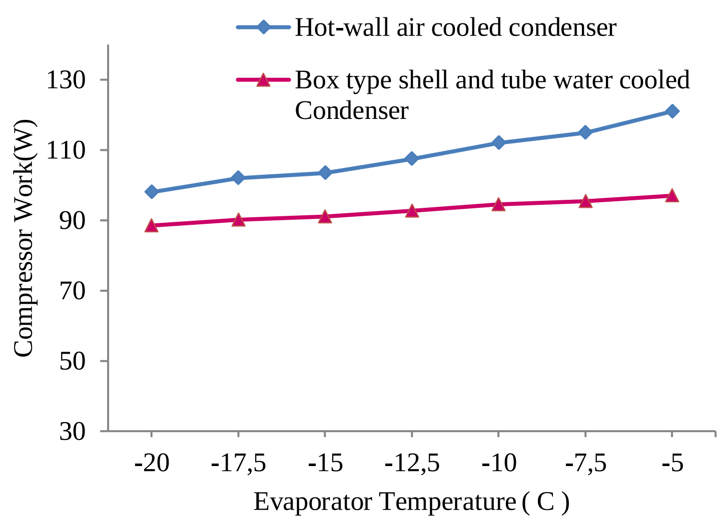

Figure 7. Variation of compressor work with varying evaporator temperature

The variation in compressor work and discharge temperature affects the performance of a refrigerator; the increase in the compressor discharge temperature affects lubricating properties. The result indicates that the compressor discharge temperature of the refrigeration system with BSTWC condenser is lower by about 29% than a refrigerator with the HWAC. The BSTWC condenser with the cooling water should be operated with water temperature below 30 ℃.

Exergy analysis provided some useful information about the system such as total irreversibility distribution of the components and this analysis helps determine which component plays a key role to raise the system efficiency. Figure 8 and Figure 9 shows the variation of exergy loss in refrigeration system components with respect to an increase in evaporator temperature. The values of exergy destructions in components of the refrigeration system for both condensers are represented in table 5.

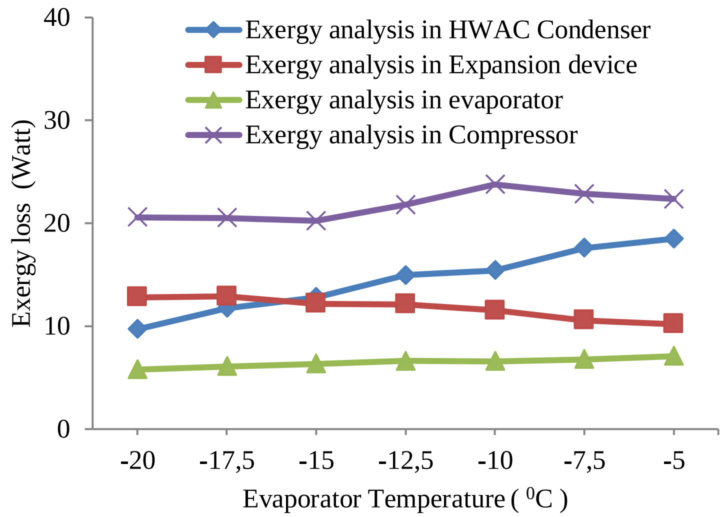

Figure 8.Variation of exergy loss in refrigerator components with HWAC condenser

In capillary tube due to a drop in pressure with an increase in evaporator temperature, tends to reduce the irreversibility with an increase in evaporator temperature. The irreversibility in the refrigeration system reduces by 8.5 % when the system operated with water cooled condenser. The exergy loss of evaporator increases with an increase in evaporator temperature when the system operated with both condensers. The exergy loss in the evaporator is 7% less when the system works with BSTWC. The irreversibility of the condenser increases with evaporator temperature. The increase in heat transfer rate due to water in BSTWC results in a reduction in exergy loss by 58% as compared with exergy loss in HWAC. The results show that the maximum exergy losses in the compressor are 26.52 W followed by the capillary at 14.65 W, condensers at 7.86 W and at the evaporator is 7.21W when the system operated with BSTWC.

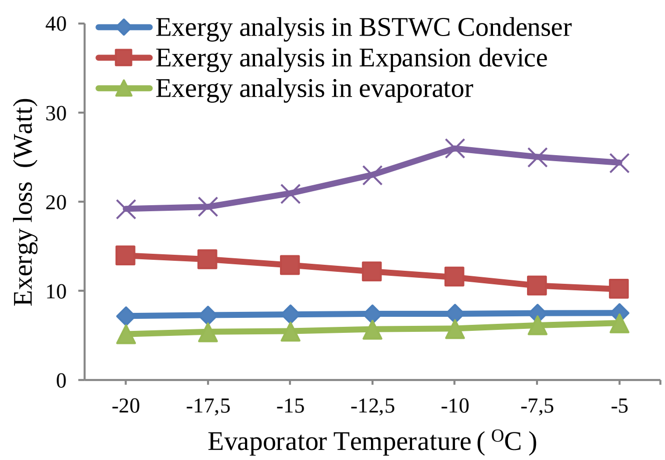

Figure 9. Variation of exergy loss in refrigerator components with BSTWC condenser

The irreversibility in compressor increases with an increase in evaporator temperature. Due to the higher temperature difference between the internal compartment and the ambient was high. The higher the temperature difference, the higher the load imposed on a refrigerator. For this reason, the ambient temperature is a significant determinant of energy consumption and so the exergy loss of the compressor was also observed. Due to an increase in work and low outlet pressure the irreversibility in the compressor when the system adopted with BSTWC is 15- 17 % more as compared to HWAC condenser.

Table 3. Exergy analysis of refrigeration components

Type of Condenser	Temperature	$(Ex_D)_{COMP}$	$(Ex_D)_{COND}$	$(Ex_D)_{EXP}$	$(Ex_D)_{EVAP}$
HWAC	-20	20.58	9.69	14.01	5.78
	-17.5	20.51	11.74	13.53	6.08
	-15	20.24	12.80	12.03	6.34
	-12.5	21.80	14.96	11.13	6.61
	-10	23.77	16.14	11.34	6.59
	-7.5	22.86	18.04	10.53	6.77
	-5	22.34	19.77	9.79	7.07
BSTWC	-20	19.20	7.18	13.97	5.15
	-17.5	19.46	7.26	13.53	5.38
	-15	20.91	7.37	12.88	5.46
	-12.5	23.01	7.41	12.13	5.69
	-10	25.98	7.45	11.55	5.76
	-7.5	25.01	7.49	10.58	6.16
	-5	24.39	7.52	10.19	6.40

The Figure 10 shows the variation of exergy efficiency with an increase in evaporator temperature. The exergy efficiency decreases with the increase in irreversibility in components at different evaporator temperature. A similar trend is reported in the literature [17, 18] when the brazed plate type of heat exchanger is used as a water-cooled condenser for the domestic refrigerator. This means that an increase in evaporator temperature affects the system positively. Comparatively, the refrigerator with BSTWC has 32% to 38% more exergy efficiency than the HWAC.

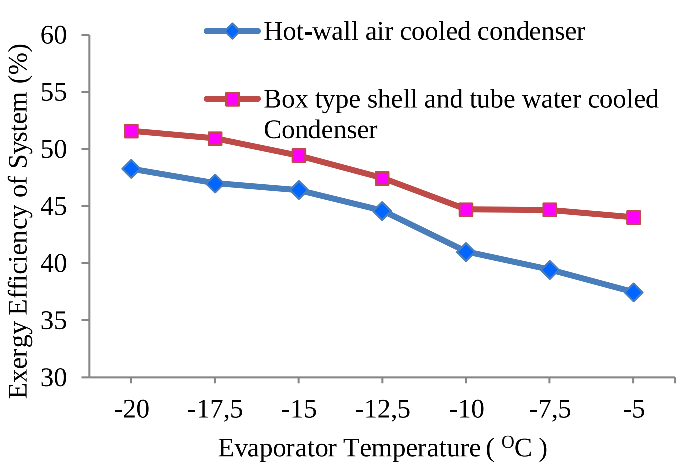

Figure 10. Variation of exergy efficiency in refrigerator components with evaporator temperature

TOTAL EQUIVALENT WARMING IMPACT

Based on the increasing contribution of refrigeration systems to climate change it is necessary to use environmentally friendly refrigerants to mitigate global warming. Three conventional environmental metrics - global warming potential (GWP), total equivalent warming impact (TEWI) and life cycle climate performance (LCCP) are used as tools to select the most environmentally friendly refrigerant. LCCP is a holistic metric to quantify the effect of the refrigerant on the total lifetime system emissions. However, in practice, the LCCP is more complex than TEWI and the contribution of additionally accounted for emissions is negligible. GWP is a useful metric to compare different refrigerants. However, it may overestimate the benefits of low GWP refrigerant to the environment, as it does not take into account many other affecting factors [21, 23]. TEWI is an important environmental index. This index is calculated using the summation of direct impact and indirect impact according to the following Equation (12) [21]:

TEWI = GWP (direct; refrigerant leaks incl. EOL) + GWP (indirect; operation)

$$\text{TEWI} = (\text{GWP}\ x\ m\ x\ L_{\text{annual}}\ x\ n) + \text{GWP}\ x\ m\ x\ (1-\alpha_{\text{recovery}})) + (E_{\text{annual}}\ x\ \beta\ x\ n) \quad (12)$$

Global warming potentials (GWPs) express the extent to which a greenhouse gas directly contributes to radiative forcing. Table 4 shows that the TEWI of refrigerator working with BSTWC is lower than that of the refrigerator with HWAC condenser by about 16 %.

Table 4. TEWI of refrigerator

PARAMETER	HWAC	BSTWC
Refrigerant	R600a	R600a
GWP = Global Warming Potential of refrigerant, relative to CO_2	10	10
L annual = Leakage rate per year (kg)	0.066	0.066
n = System operating life (years)	15	15
Refrigerant charge (kg), m	0.058	0.058
α recovery = Recovery/recycling factor	0.8	0.8
Energy consumption per year (kWh), E	462	398
Indirect emission factor, β	0.47	0.47
TEWI Direct effect	0.5742	1.188
TEWI Indirect effect	4244.1	2806
TEWI	3257.67	2807.1

It is also observed that due to the lower refrigerant charge required in HWAC, the direct impact which is related to refrigerant leakage is less in HWAC as compared to BSTWC.

CONCLUSION

The energetic and exergetic experimental performance analysis of a domestic refrigerator with HWAC and BSTWC condenser is studied to check the possibility of energy conservation and exergy efficiency. A significant improvement in system performance and reduction in energy consumption and exergy destruction and irreversibility of a refrigerator is observed with BSTWC condenser. Following conclusions are drawn based on experimental results.

- The energy consumption of conventional domestic refrigerator is significantly reduced with BSTWC condenser. The per day energy consumption in the BSTWC condenser refrigeration system is almost 10% to 20% less than the conventional HWAC refrigeration system.
- The exergy efficiencies of the refrigerator with the BSTWC unit are found in a range of 6.89% to 9.13 %, which is more than a conventional refrigerator.

- The COP of the domestic refrigerator using BSTWC and HWAC were evaluated. COP is increased by 18-20 % with the BSTWC condenser in comparison with a refrigerator with the HWAC.
- The irreversibility of the proposed system is 34 % less than that of the conventional system under similar operating conditions.
- The societal benefit of this technology is the enhancement of energy efficiency, which leads to a reduction in energy cost. This further modification also creates new avenues for research in heat recovery in the residential building sector.

NOMENCLATURE

HWAC	Hot-wall air cooled condenser
BSTWC	Box type shell and tube water cooled condenser
COP	Coefficient of performance
HVAC&R	Heating, Ventilation, Air-conditioning and Refrigeration
ASHRAE	American Society of Heating, Refrigeration and Air conditioning Engineers
TEWI	Total equivalent warming impact
IS	Indian standard
TR	Tons of refrigeration
OD	Outer diameter
ID	Inner diameter
DC	Direct current
kWh	Kilowatt-hour
ISO	International Organization for Standardization
RH	Relative humidity
Lph	Litre per hour
Greek symbols	
h	Enthalpy ($J\ kg^{-1}$)
I	Irreversibility (W)
l	length of heat exchanger
m	mass flow rate
Q	Heat transfer Rate(W)
s	Entropy ($J\ kg^{-1}\ K^{-1}$)
T	Temperature (°C)
W	Work of compressor(W)
Ex_D	Exergy destruction
Ø	Tube diameter
η	Efficiency
Subscripts	
comp	Compressor
cond	Condenser
Exp	Expansion device
evap	Evaporator
in	inlet
out	outlet

REFERENCES

[1] Geppert, J., and Stamminger, R. (2013). Analysis of effecting factors on domestic Refrigerator's energy consumption in use, Energy Conversion and Management, 76, 794-800.

[2] Aprea, C., Greco A. and Maiorino, A. V (2012). An experimental evaluation of the greenhouse effect in the substitution of R134a with CO2, Energy, 45 (1), 753-761.

[3] Raveendran, P. Saji, and Sekhar, S. Joseph, (2016). Experimental studies on domestic refrigeration system with a brazed plate heat exchanger as condenser, Journal of Mechanical Science and Technology, 30 (6), 2865-2871.

[4] Palm, B., (2007). Refrigeration systems with a minimum charge of refrigerant, Applied Thermal Engineering, 27, 1693-1701.
[5] Sonnenrein G, Elsner A, Baumhogger E, Morbach A, Fieback K, Vrabec J(2015). Reducing the power consumption of household refrigerators through the integration of latent heat storage elements in wire-and tube condensers, International Journal of Refrigeration; 51:154–60.
[6] Zhang Z, Huang D, Zhao R, Leng Y. (2017). Effect of airflow field optimization around spiral wire-on-tube condenser on a frost-free refrigerator performance. Applied Thermal Engineering; 114:785–92.
[7] Ameen, A., Seetharamu, K.N., Mollik, S.A., Mahmud, Khizir, Quadir, G. A (2006). Numerical analysis and experimental investigation into the performance of a wire-on-tube condenser of a retrofitted refrigerator, International Journal of Refrigeration, 29,495–504.
[8] Shikalgar N. D., and Sapali, S. N., (2017). Numerical and Thermal Analysis of Condensers applied to domestic Refrigerator, Journal of International Review of Mechanical Engineering, Vol. 11 N7, PP 81- 84.
[9] Bansal, P. K., (2003). Developing new test procedures for domestic refrigerators: harmonization issues and future R&D needs—a review, International Journal of Refrigeration,26,735–748.
[10] Hosoz M., and Kilicarslan, A, (2004). Performance evaluations of refrigeration systems with air-cooled, water-cooled and evaporative condensers, International Journal of Energy Research, 28, 683-696.
[11] Hesselgreaves, J. E., The impact of compact heat exchangers on refrigeration technology and CFC replacement, International Refrigeration and Air Conditioning Conference, 135-139, 1990.
[12] Li, Y., Wu J., and Shoichi, S., (2009). Modelling and energy simulation of the variable refrigerant flow air conditioning system with a water-cooled condenser under cooling conditions, Energy and Buildings, 41, 949-957.
[13] ASHRAE Handbook, (2008). HVAC Systems and Equipment, ASHRAE
[14] Ramezanizadeh, M., et al., (2019). Experimental and Numerical Analysis of a Nanofluidic Thermosyphon Heat Exchanger, Engineering Applications of Computational Fluid Mechanics 13 (1): 40-47.
[15] Aprea C, Greco A. (2002). An exergetic analysis of R22 substitution Applied Thermal Eng.; 22:1455–69.
[16] Saravanakumar, R., and Selladurai, V.(2013). Exergy analysis of a domestic refrigerator using eco-friendly R290/R600a refrigerant mixture as an alternative to R134a, Journal of Thermal Analysis and Calorimetry, 115,933-940.
[17] S. Joseph Sekhar, Raveendran, P. Saji (2017).Exergy analysis of a domestic refrigerator with a brazed plate heat exchanger as condenser, Journal of Thermal Calorimetry, 127:2439–2446.
[18] Raveendran, P. Saji, Sekhar, S. Joseph, (2017). Performance studies on domestic refrigerators retrofitted with building-integrated water-cooled condenser, Energy and Buildings,134, 1–10.
[19] Mahmood Mastani Joybari, Mohammad Sadegh Hatamipour, Amir Rahimi, Fatemeh Ghadiri Modarres (2013). Exergy analysis and optimization of R600a as a replacement of R134a in a domestic refrigerator international journal of Refrigeration, 36,1233-1242.
[20] Hosseinzadeh-Bandbafha, H. (2018). Application of data envelopment analysis approach for optimization of energy use and reduction of greenhouse gas emission in peanut production of Iran, Journal of Cleaner Production 172: 1327-1335.
[21] Pavel Makhnatcha, Rahmatollah Khodabandeha(2014). The role of environmental metrics (GWP, TEWI, LCCP) in the selection of low GWP refrigerant, The 6th International Conference on Applied Energy – ICAE2014, Energy Procedia 61, 2460 – 2463.
[22] Ahamed, J.U., R. Saidur, H.H. Masjuki (2011). A review on exergy analysis of vapour compression refrigeration system, International Journal of Renewable and Sustainable Energy Reviews, 15, 1593–1600.
[23] Davies, Thomas W., and Caretta, Ottone,(2004). A low carbon, low TEWI refrigeration system design, Applied Thermal Engineering, 24, 1119–1128.
[24] Coleman, H.W. and Steele, W.G., (1999). Experimentation and Uncertainty Analysis for Engineers, 2nd Edition, John Wiley & Sons, Inc., New York, NY.
[25] ISO 15502: 2005, Household refrigerating appliances.