Experimental Performance Evaluation of R134a and Its Low GWP Hydrocarbon Alternatives in Domestic Refrigerator

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Abstract— According to Montreal Protocol it was decided to initiate the worldwide phase out of CFCs and HCFCs. Moreover in Kyoto Protocol even new developed HFCs refrigerants like R-134a should be gradually phased out due to their high global warming potentials (1430).The present work is to Explore performance evaluation of most promising drop-in replacements of R134a in domestic refrigerator with Zero ODP and low GWP refrigerants. The assessed refrigerants are R290, R600a, R430A, R436A.Basic cycle and performance comparison of all alternative refrigerants have been calculated for standard rating cycle, most commonly used condensing and evaporating temperatures 550C and -250C respectively. By performing the experiment we are come to know that the Charging amount is reduced by 59.25 and 55.5% for R290 and R600a respectively. COP of the domestic refrigerator working with R290 is improved by up to 2.09%, and compressor power is reduced by 2.06%. COP of the domestic refrigerator working with R600a is lower by up to 5.05%, and compressor power is increased by 5.29%. Pull down time for the R134a, R290, R600a are observed as 120, 104, and 109 min respectively. ON TIME ratio is reduced for R290 by 10.31% and for R600a it is increased by 6.89%. TEWI for R290 and R600a is reduced by 10.72% and 4% respectively.

Key words: Low GW, Hydrocarbons, CFCs, HCFCs, ODP

I. INTRODUCTION

HCFCs (hydrochlorofluorocarbons) and CFCs (chlorofluocarbons) have been applied extensively as refrigerants in air conditioning and refrigeration systems from 1930s as a result of their outstanding safety properties. However, due to harmful impact on ozone layer, by the year 1987 at Montreal Protocol it was decided to establish requirements that initiated the worldwide phase out of CFCs. By the year 1992, the Montreal Protocol was improved to found a schedule in order to phase out the HCFCs. Moreover in 1997 at Kyoto Protocol it was expressed that concentration of greenhouse gases in the atmosphere should be established in a level which is not intensifying global warming ozone layer. Subsequently it was decided to decrease global warming by reduction of greenhouse gases emissions. [4]

As a consequence of this protocol even new developed HFCs refrigerants like R-134a should be gradually phased out due to their high global warming potentials. Hence in order to meet the global ecological goals, conventional refrigerants should be replaced by more environmental friendly and safe refrigerants in a way the energy efficiency also improved. [3]

A. Fluid Selection:

In refrigeration and air conditioning systems selection of an appropriate working fluid is one of the most significant steps for a particular application. Low global warming potential has been inserted to the long list of desirable criteria of refrigerant's selection. In fact, environmental characteristics of refrigerants are becoming the dominant criteria provided that their thermodynamic behaviors and safeties are favorable as well. [7]

1) Environmental Impact and Safety Aspects:

Environmental effects are the main problems of common refrigerants so that non environmental friendly impacts of CFCs and later on HCFCs brought about them to be phased out despite of being stable, non-flammable and non-toxic (comparing to Sulfur Dioxide and other refrigerants used before the introduction of CFCs). Ozone depletion potential (ODP) and global warming potential (GWP) are the significant factors demonstrate the direct impact of refrigerants in case of any leakage or releasing to the surroundings. However, using low GWP refrigerants are not the only efficient way to reduce greenhouse gas emissions. In fact it is probable to choose a low GWP refrigerant but still raise total greenhouse gas emissions. When the low GWP refrigerant causes more energy use and fuel consumption actually there are larger indirect emissions. Therefore in developing the low GWP refrigerants always energy efficiency of the system must be studied and its indirect climate impacts should be considered besides its direct emissions.[8] Life cycle climate performance (LCCP) helps to consider overall potential of greenhouse gas emission of the system including materials, transportation, and operation, production, recycling, servicing and end-of-life. Furthermore, toxicity and flammability are the determining factors to select suitable refrigerant for any application. Low toxicity and flammability are the most desirable aspects in safety and health studies. [13]

2) Zero ODP and Low GWP Refrigerant:

Lots of studies are being processed and new blends and refrigerants are being developed to substitute conventional refrigerants. Mainly researches have focused on three groups of refrigerants; natural refrigerants, new blends and developing new refrigerants. Natural refrigerants got out of market with coming CFCs and HCFCs but now can be reconsidered. New blends are mixture of mostly natural refrigerants, dimethyl ether (DME) and HFCs in order to combine all advantages of them and achieve the best thermodynamic result and low GWP. Lastly developing a new refrigerant is another solution to overcome the environmental problem. [3][10]

Refrigerent	R134a	R290	R600a	R-430A	R-436A

Molecular weight [g/mol]	102	44.096	58.12	49.08	54.65
Critical Temp[°C]	101.1	134.67	134.67	120.3	130.1
Critical pressure [MPa]	4.59	4.23	3.65	3.23	3.39
Normal boiling	-26	-42.09	-11.67	-27.6	-34.3
Safety class	A1	A3	A3	A3	A3
ODP	0	0	0	0	0
GWP	1430	3	3	107	< 3

Table 1: Comparing Properties of Different Refrigerants.

3) Thermophysical Properties:

Generally, thermodynamic and transport properties of refrigerants are the key factors in refrigerant's selection as they determine the performance of the system. The desirable thermodynamic properties are a normal boiling point slightly less than target temperature and, thereby, an evaporating pressure higher than atmospheric pressure. The other favorable characteristics are, low liquid viscosity, high heat of vaporization, modest liquid density and slightly high gas density. It is worthwhile to mention that high heat of vaporization and gas density lead to higher capacity with a specific compressor in a refrigeration system. High liquid thermal conductivity intensifies heat transfer and results in smaller required heat exchangers. Low viscosity also causes low pressure drop in the heat exchangers. Smaller pressure ratio leads lower compression work and improve COP of the system. [7]

In view of the fact that boiling point and gas density are influenced by the pressure, operating pressure is a factor to choose a suitable refrigerant for a particular application. Selected refrigerant should be also chemically stable under operation condition while it shouldn't decompose nor react with material in the system.

B. Characteristics of R134a and New Proposed Refrigerants:

The properties of the refrigerants (such as vapor pressure, liquid density and liquid viscosity) for wide range of temperatures (between −50 and 60 °C) are compared in Figs.1.1 –1.3. Using Rafprop 9.0 all properties can be evaluate and their comparison as shown in graphs. Fig. 1.1 depicts the variation of vapor pressure of R134a, R290, R600a, R430A, R436A, R1234yf, R1234ze and DR11 against temperature. It was observed that R430A, R436A and R1234yf has approximately the same vapor pressure as R134A. Hence the compressors can operate relatively at lower pressures.

The liquid densities of R134a and other alternative refrigerants are compared in Fig. 1.2. The liquid density of R1234yf, R1234ze and DR11 are almost similar and the liquid density of remaining refrigerant was found to be lower than that of R134a, as the liquid density is low it will significantly reduce the refrigerant charge requirement. Thus we can expect that if we will proceed with R290, R600a, R430a, R436a it requires less charging amount as compare to that of the R134a.

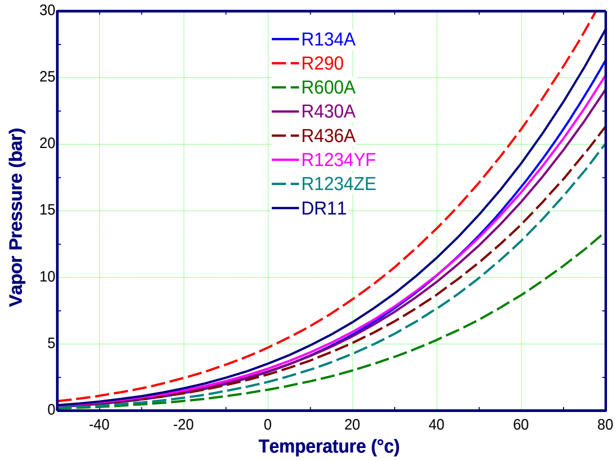

Fig. 1: Variation of Saturation Pressure with Temperature

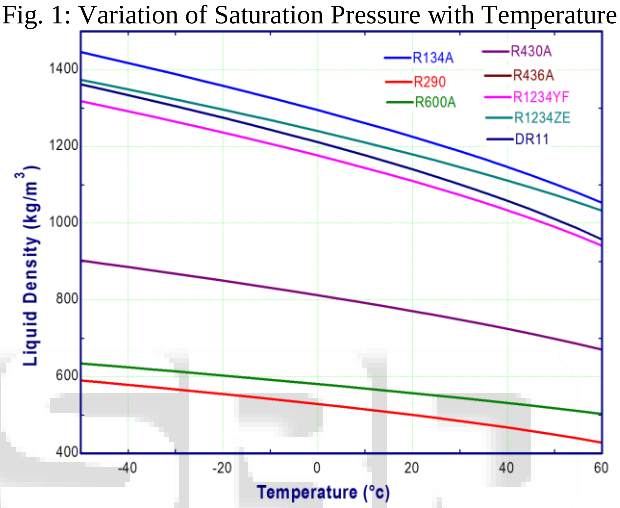

Fig. 2: Variation of Liquid Density with Temperature

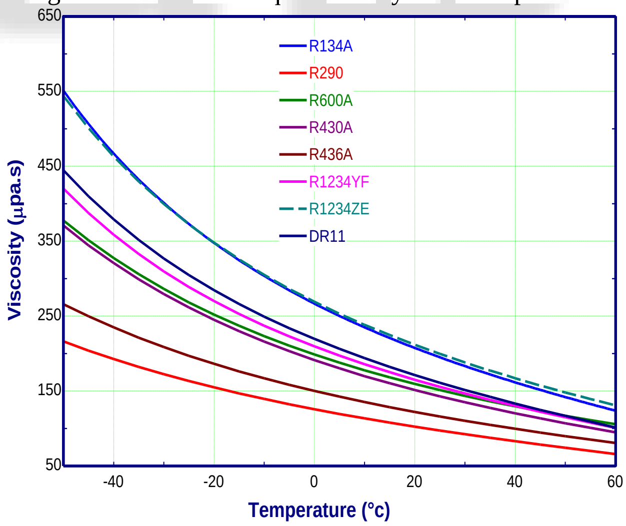

Fig. 3: Liquid viscosity Vs Temperature

The variation of viscosity of R134a and new proposed refrigerants against temperature is illustrated in Fig.1.3. It was observed that liquid viscosity of R1234ze was found to be almost similar to that of R134a over the wide range of temperature results in low friction (low irreversibility). But at the same time rest of the refrigerant lower viscosity than R134a, Hence less power can be expected with R290, R600a, R436A, R430A and R1234yf. The other properties such as critical temperature, critical pressure, boiling point, molecular weight, ODP and GWP of R134a and R430A are compared in Table 1.1.

1) *Experimental Setup:*

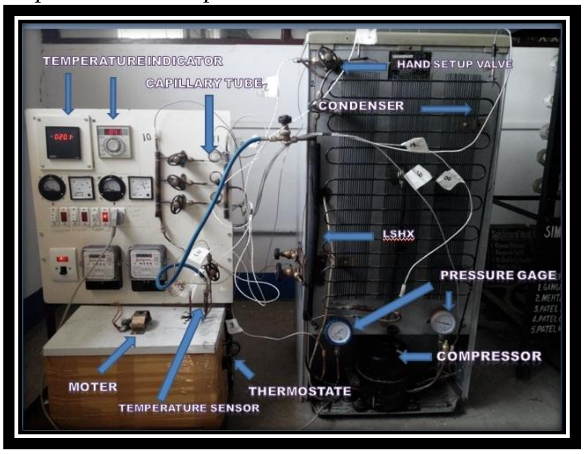

Fig. 4: Experimental Setup

II. EXPERIMENTAL PROCEDURE AND RESULTS

A. *Procedure:*

Initially, the system was flushed with nitrogen gas to eliminate impurities, moisture and other foreign materials inside the system, which may affect the accuracy of the experimental results. The experiments were conducted according to ISO 8187 [3]. To conduct no load pull down test, the door was kept open until temperature inside the refrigerator has reached the steady state condition with ambient. As per manufacturer's recommendation, 145 g of R134a was charged in the refrigerator for conducting baseline tests. During experimentation with R134a, 3.34 m capillary tube length was used. The continuous running tests were carried out by connecting the evaporator inside the calorimeter with the system. The pull down characteristics and cycling running tests were carried out by connecting the evaporator inside the refrigerator with the system. The actual refrigeration capacity and COP of the refrigerator were calculated as per the calorimetric test method. The heater load was adjusted by a dimmerstat to maintain a temperature of −12 ± 0.5 0C inside the calorimeter. The energy consumption of the compressor and heater were measured by separate energy meters. During continuous running tests, ambient temperature was maintained around 320C. All the experimental observations were made after attaining the steady state conditions (4 h). The cycling running tests were carried out at 32 ◦C ambient temperature with different freezer air temperature settings (−15,−12,−9,−6 ,−3 and 0 0C). After completing the base line reference test with R134a, the refrigerant was recovered from the system. Before experimenting with alternative refrigerants, the refrigerator was charged with 55g of R290 and ambient temperature was maintained at 32 ◦C. Then, the refrigerator was charged with 60 g of R600a and these tests were repeated. The variation in experimental values from the average value is within ±5%. Temperatures at different locations were recorded every ten minutes intervals. Pressure at compressor suction and discharge was measured every twenty minutes intervals. The instantaneous power consumption of the refrigerator during continuous running tests was measured after attaining the steady state condition. The measured values were used to study the performance characteristics of the refrigerator.

B. *Calorimetric Test:*

- Fill up sufficient water in the evaporator so that coil is fully immersed in water.
- Connect mains supply to the unit.
- Depending upon expansion device to be used, open inlet and outlet valves for capillary and close.
- Check time required for compressor energy meter disc to make 10 revolutions.
- Adjust heater input so that heater energy meter disc to make about 18-20 revolution during above measured time.
- Observe evaporator temperature, if the temperature is dropping, increase the heater input and if temperature is rising, then reduce the heater input. Try to keep the temperature of water as for as possible near ambient, so that it will reduce the heat losses from/to atmosphere.
- As the evaporator temperature remains steady, note down the reading and fills up observation table.

1) *Calculation:*

1) Refrigerating effect is balanced by heater so,

Heater input=refrigerating effect

$$R.E = \frac{(n * 3600)}{t_h * EMC_h} \quad (1)$$

Where,
n=No. of revolution of disc=10,
t_h=time for 10 rev.
EMC_h=heater energy meter constant=1200 rev/Kwh

2) Compressor work,

$$W = \frac{(n * 3600)}{t_c * EMC_c} \quad (2)$$

Where,
t_c=time for compressor energy meter disc, sec
EMC_c=compressor energy meter constant=1200 rev/Kwh

3) Actual $COP = \frac{R.E}{W}$ (3)

C. *Experimental Results and Discussion:*

Experimental results obtained for continuous operating modes with different freezer air temperature settings at 32 ◦C ambient temperature are discussed in this section. Table 6.1 shows the performance comparison of R134a and its low GWP alternatives.

Parameters	Experimental		
Refrigerant	R134A	R290	R600a
Charging amount(g)	145	55	60
Condenser temperature(°C)	49	46	53
Ambient Temperature(°C)	32	32	32
Evaporator temperature(°C)	-15	-15	-15
Refrigeration effect(kJ/kg)	142.1	267.3	245.8
COP	2.591	2.645	2.46

Actual Compressor outlet temperature(°C)	64	58	67
Volumetric efficiency	0.4553	0.3107	0.5848
Pressure ratio	8.37	5.658	9.18
Compressor work(W)	34.35	33.64	36.17

Table 2: Experimental Results and Discussion

1) Performance Characteristics:

The discharge temperature is an important parameter considered for choosing an alternative. The discharge temperature influences the stability of the lubricants and compressor components. Fig.6.1. reveals that discharge temperature of R290 was found to be lower than that of R134a and discharge temperature of R600a is comparatively higher due to its lower specific heat ratio. Hence R290 has lower impact on compressor components and stability of lubricants. Hence, longer compressor life time can be expected when R290 is used as an alternative. It is seen that charging amount of refrigerant is also reduced by 62%.

Power consumption of R134a and alternatives were shown in Fig.6.2. It is observed that power consumption increases with increase in refrigerant mass charge. This is mainly due to increase in mass flow rate of refrigerant through compressor. Power consumption of R290 found to be lower than that of R134a. It was showed that power consumption of R600a was higher than that of R134a. The power consumption of the refrigerator increases with increase in ambient temperature due to increase in condensing temperature and pressure.

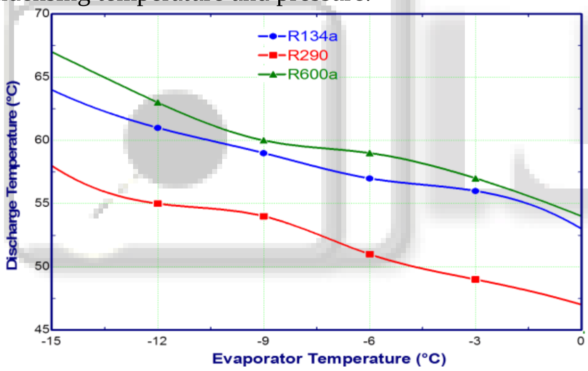

Fig. 5: Experimental Compressor Discharge Temperature Comparison

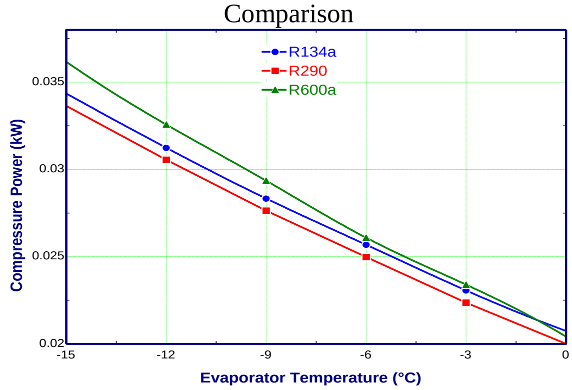

Fig. 6: Experimental Compressor Power Comparison

The COP variation comparison of R134a and hydrocarbons are compared in Fig.6.3 with variation of evaporator temperature. The COP of the R290 were higher than that of R134a, COP of R600a is lower than that of R600a, at ambient temperatures 320C.

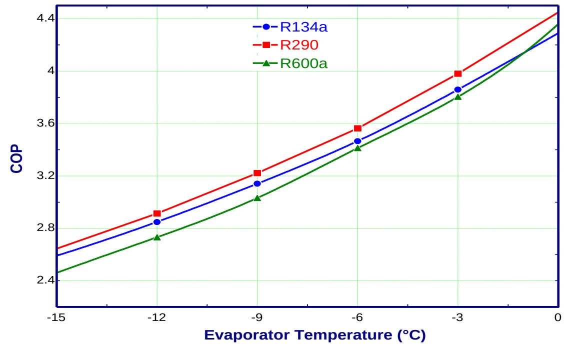

Fig. 7: Experimental COP Comparison

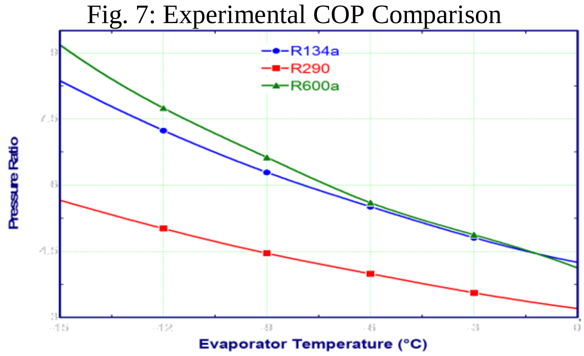

Fig. 8: Experimental Pressure Ratio Comparison

Fig. 6.4 shows the variation of Pressure Ratio with respect to change in evaporator temperature. The Pressure ratio for the R600a is higher than that of R134a, and it is lower than R134a for R290. Composure power is increases as the pressure ratio is increases. As the evaporator temperature is low, pressure ratio is increases.

2) Pull Down Characteristic:

Pull-down time is the time required to reduce the air temperature inside the refrigerator from ambient condition to the desired freezer and cabin air temperatures of -12 and 60C in the freezer and cabin, respectively, according to ISO8187 [3]. Pull down tests were carried out at 32 0C ambient temperature. The no load test is performed by adjusting the thermostat position corresponding to an average cabinet temperature of 70C. The purpose of this test is to find the pull-down period, the no-load power consumption, and the percentage running time. The pull-down period is the time required to reach the specified temperatures inside the cabinet after switching on the unit. Fig.6.5 and 6.6 shows the freezer and cabin pull down characteristics for R134a, R290 and R600a.

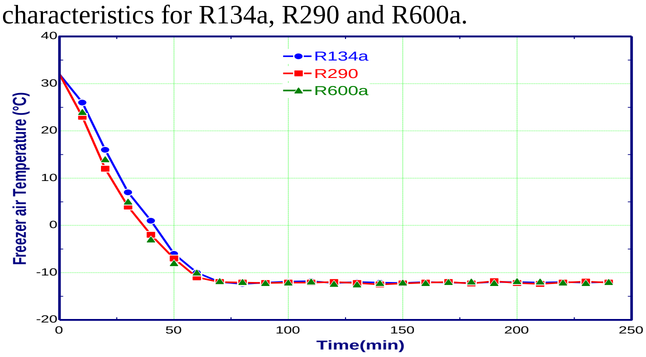

Fig. 9: Pull Down Time Vs. Freezer Air Temperature At 32 ◦C Ambient Temperature

The pull-down time of about 120 min was required to reach the desired freezer air temperature (−12 ◦C) for R134a. The time required for R290 and R600a was about 104 and 109 min. The pull down time was reduced by about 13.33 and 9.16% for R290 and R600a respectively compared to R134a due to its high latent heat of vaporization.

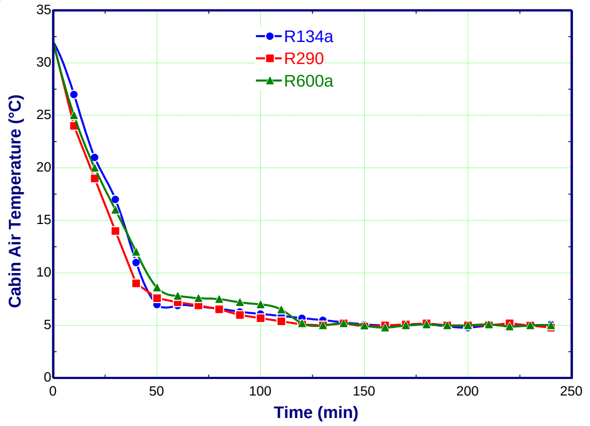

Fig. 10: Pull Down Time Vs. Cabin Air Temperature At 32 ◦C Ambient Temperature

3) Cycling Running (ON/OFF) Tests:

In order to study the actual operating conditions, the refrigerator was subjected to cycling running tests. ON time ratio and energy consumption per day were determined for normal running condition. Based on the ON time ratio and energy consumption per day. The ON time ratio of R134a was 0.58. The ON time ratio of R290 was found to be lower than that of R134a by about 10.34% due to high latent heat of vaporization. R600a has higher ON time ratio by about 6.9% compared to that of R134a due to lack of refrigerant quantity.

Refrigerant	R134a	R290a	R600a
Pull-down time (min)	120	104	109
ON-time (min)	81	75	98
OFF-time (min)	59	69	60
ON-time ratio	0.58	0.52	0.62

Table 3: Comparison Pull down Time and on Time Ratio for R134a and Assessed Refrigerants

4) Total Equivalent Warming Impact (TEWI):

TEWI is an important environmental index. This index is calculated using summation of direct impact and indirect impact according to the following equation:

TEWI = Direct impact +Indirect impact

$$TEWI = (m*l*S_l*GW_{100}) + (E*S_l*r) \quad (4)$$

Where; m, l, S_l, r, and E are refrigerant charge (kg), leakage rate (%), service life (yrs), CO2 generation emission (kg CO2/kWh), and energy consumption (kWh), respectively. GWP100 is the GWP which is evaluated based on a time horizon of 100 years and is referenced to the unitary value of CO2.[12] Table shows calculated TEWI for the case study refrigerator with different refrigerants. The results showed that TEWI of R290 and R600a are 10.72% and 4% lower than R134a. In addition, the results showed that the direct impact is negligible compared to the indirect one.

Refrigerant	R134a	R290a	R600a
Refrigerant charge (kg), m	0.145	0.055	0.060
Leakage rate per year (% yr^{-1}),L	0.066	0.066	0.066
Service life (yr), Sl	15	15	15
Global warming potential, GWP_{100}	1430	3	3
TEWI, Direct effect, ($m*L*Sl*GWP_{100}$)	205.27	0.1633	0.1782
Energy consumption (kWh), E	301	294.68	316.84
CO2 generation emission (kgCO2/kWh), r	0.47	0.47	0.47
TEWI, Indirect effect, (E*Sl*r)	2122.05	2077.49	2233.86
TEWI	2327.32	2077.65	2234.04

Table 4: TEWI for the Refrigerator with R134a and Assessed Refrigerants

III. CONCLUSION

In this work, low GWP refrigerants like R290, R600a, R430A, R436A have been studied as promising drop-in replacements for the common high global warming potential refrigerants R134a Conclusion made from the actual experiment conducted at ambient temperature 320C:

- Charging amount is reduced by 59.25 and 55.5% for R290 and R600a respectively.
- COP of the domestic refrigerator working with R290 is improved by up to 2.06%, and compressor power is reduced by 2.06%.
- COP of the domestic refrigerator working with R600a is lower by up to 5.05%, and compressor power is increased by 5.29%.
- Pull down time for the R134a, R290, R600a are observed as 120, 104, and 109 min respectively.
- ON TIME ratio is reduced for R290 by 10.31% and for R600a it is increased by 6.89%.
- TEWI for R290 and R600a is reduced by 10.72% and 4% respectively.

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