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Experimental and Theoretical Assessment of Inverter-Operated Split Air Conditioner with Low GWP Alternative Refrigerants

Ashish Shivkumar Utage[1,*], Kundlik Vitthal Mali[1], Heramb C. Phadake[1]

[1] Department of Mechanical Engineering, Dr. Vishwanath Karad MIT World Peace University, Pune, 411038, India

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ABSTRACT

This article presents experimental evaluation and comparative analysis of low GWP alternative refrigerants, namely HC-290 (propane), HC-1270 (propylene), HC/HC-1270 blend, and HFC-32 (difluoro methane) as drop-in replacements for HCFC-22 (Chloro difluoro methane) in a typical 1.5 TR capacity inverter operated split type air conditioner (SAC). The experimental setup consisted of retrofitting an original HCFC-22 test unit following the soft optimization of the SAC system for each alternative refrigerant, followed by testing under controlled operating conditions as per the IS 1391, Part-1 standard at the half capacity and the rated capacity of inverter SAC. The results obtained were compared against the baseline HCFC-22 test unit. The optimized SAC gave EER_{IS} (Indian Seasonal Energy Efficiency Ratio) of 4.63 for HC-290, 4.71 for HC-1270 and 4.87 for HC-290/HC-1270 blend, respectively increased by 8.94 %, 10.82 % and 14.58 % compared to HCFC-22. HFC-32 delivered the maximum cooling capacity of 6.78 kW, 3.67 % higher than baseline unit at the rated capacity. HC-290/HC-1270 blend exhibited the lowest power consumption and discharge temperature amongst all the refrigerants considered. The charge of flammable refrigerants has been optimized below LFL satisfying EN378 standard for the safety of inverter SAC in domestic applications.

1. Introduction

Air conditioners have been widely used in domestic and commercial applications, but the refrigerants traditionally used, such as hydrofluorochlorocarbon (HCFC), contribute to global warming and ozone depletion. In RACHP industry, HCFC-22 has long been used as a refrigerant due to its favorable thermodynamic properties and high energy efficiency. However, HCFC-22 has a high global warming potential (GWP) of 2088, and ozone depletion potential (ODP) of 0.055 making it a subject of concern in terms of depleting the ozone layer and the adverse environmental impacts due to high GWP [1]. The need to mitigate the environmental impact of refrigerants has led to the search for potential substitutes for HCFC-22. Additionally, various international agreements and regulations, such as UNEP, Montreal Protocol and the Kigali Amendment, have started to phase out or phase down the use of high-GWP refrigerants and transition to more sustainable alternatives [1,2].

* *Corresponding author.*
E-mail address: ashish.utage@mitwpu.edu.in

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Consequently, the development and evaluation of potential substitutes for HCFC-22 have become a priority for researchers, manufacturers, and policymakers.

By carefully considering the factors, like thermodynamic properties, environmental impact, compatibility with existing components, safety considerations, availability and cost, several alternative refrigerants have been proposed, including hydrocarbon (HC) refrigerants such as propane (HC-290) and propylene (HC-1270), blend of HC-290/HC-1270 (50%/50% by weight) as a drop-in substitute to HCFC-22 in SAC APPLICATIONS [3]. Additionally, HFC-32 has emerged as a promising candidate due to its low GWP compared to HCFC-22. Many researchers investigated the HC-290 with both constant speed and inverter air conditioners and presented extensive analyses for its use as alternative refrigerant to replace R22 in SAC. A few researchers also proposed HC-1270 and its blend in different composition as an alternative to HCFC-22. The choice of these alternative refrigerants is based on their low GWP, and compliance with international regulations such as the Montreal Protocol and the Kyoto Protocol. Nugroho *et al.,* [4] tested the performance enhancement and optimization of residential air conditioning systems with a novel functionalized Al_2O_3 (FAl_2O_3)-Polyolester (POE) nanolubricant. It was discovered that FAl_2O_3-POE nanolubricant had higher heat absorption than pure POE. When using R32, the COP increases across all concentrations of FAl_2O_3-POE nanolubricant. FAl_2O_3-POE/R32 exhibits a higher COP range of 3.12%-32.26%. The findings indicated that using a new FAl_2O_3-POE nanolubricant with R32 can lower electrical power consumption by 13.79% to 19.35%.

Mali *et al.,* [5] evaluated HC-290 and HC-290/HC-1270 blend as possible alternatives to HCFC-22 for inverter room AC. These refrigerants being highly flammable, charge optimization calculation was done to develop the safe and energy efficient SAC. HC-290 demonstrated the greatest ISEER of 5.11, which was 20.2% greater than HCFC-22. Park and Jung [6] assessed the performance of HC-290 in 3.5 kW AC. Under drop-in conditions, HC-290 provided 5% to 15% less cooling capacity and 1% to 12% higher energy efficiency. Devotta *et al.,* [7] evaluated the performance of a room AC using low GWP refrigerants HC-290, HC-1270, HFC-161, HFC-32, and HFC-1234yf in a drop-in approach. Performance simulation was accomplished by optimizing system components for the highest EER. HC-290 was also tested by Devotta *et al.,* [8] and Padalkar *et al.,* [9] in a window AC with a constant speed compressor. The EER of the HC-290 was 7.9% higher and 2.8% higher for lower and higher operating conditions, respectively. Salman *et al.,* [10] developed correlation to determine flow boiling properties of an R290/R1270 (65%/35% w) mixture and pure R290 in an embedded plate heat exchanger with offset strip fins. The results discovered that HTC value of R290/R1270 blend was higher than R290. The further investigation is recommended to optimize the composition of the blend for improved performance. Choudhari and Sapali [11] investigated the feasibility and performance of R290 in refrigeration systems as a replacement for R22. R290 had a lower discharge temperature and required only half of the charge. In response to environmental concerns and legal constraints, the study determined that, due to its lower GWP value, R290 is a feasible alternative to R22 in terms of cooling efficiency, energy consumption, and environmental impact. Wu *et al.,* [12] modified 2.4 kW R22 wall room air conditioner with a 20% larger displacement compressor to charge R290 and R1270 for performance testing. Experimental investigations showed 2.4% more cooling capacity and 0.8% higher EER for R1270, using a higher viscosity mineral lubricant and for R290, using a larger displacement compressor compared to the original R22 system under normal conditions. Saravanan *et al.,* [13,14] investigated and developed strategies for reducing the refrigerant charge when transitioning from R22 to R290 due to its high flammability, with a focus on maintaining or improving the system's performance. Pramudantoro *et al.,* [15] analyzed the performance changes caused by R22 to R32 drop-in replacement in a domestic AC at 0°C with the liquid density ratio between R32 and R22 as 0.82. The refrigerant charge of R32 varied from 90% to 105% by mass with a 5% increment for each measurement. At 95% optimal refrigerant charge, mass ratio of R32 to R22 was 77.9%, where cooling capacity increased by 7.7% while COP declined by 12.1%. Shaik and Setty [16] studied the thermodynamic performance of a window air conditioner employing various sustainable R290/RE170 and R1270/RE170 refrigerant mixtures as R22 alternatives. The refrigerant mixture RM7 (R1270/RE170 95/5 by mass %) exhibited the highest coefficient of performance (COP) among the twelve refrigerants studied, with a 0.23% improvement compared to R22. RM7 also had a 7.49% lower pressure ratio than R22, indicating potential energy efficiency benefits. All twelve investigated refrigerants, including RM7, showed lower compressor discharge temperatures compared to R22, suggesting improved durability and lifespan of the compressor motor.

These studies revealed that the performance of HC-290, HC-1270, HC-290/HC-1270 blend, and HFC-32 have emerged as promising alternatives due to their lower GWP and comparable thermodynamic properties. However, comprehensive experimental evaluations are required to assess their performance including cooling capacity, power consumption, energy efficiency ratio (EER_{IS}), compressor discharge temperature and refrigerant charge to validate their suitability as a drop-in replacement for HCFC-22 and promote sustainable practices in the RACHP industry. This research article presents the experimental findings obtained through performance tests on original test unit followed by system optimization of SAC system for the selected alternative refrigerants satisfying the standards for the use of HC refrigerants in SAC [17]. The results and discussion section will highlight the thermodynamic performance comparison, energy efficiency analysis for HC-290, HC-1270, HC-290/HC-1270 blend, and HFC-32, providing a comprehensive assessment of their potential as alternative refrigerants for HCFC-22.

2. Methodology

The thermodynamic cycle of HCFC-22 was first modelled in IMST ART software tool (Corberan, 2002) and its performance was assessed and validated against the experimental results. IMST-ART is a computer-aided engineering design system that provides superior performance simulation [18]. IMST-ART is a software program that models vapour-compression refrigeration systems with various refrigerants and secondary fluids. It includes accurate and quick algorithms, an easy-to-use graphical interface, and strong analysis tools.

Figure 1 shows the approach and a methodology used for the study. The input data for the AC system simulation, as well as the variable speed performance data of the inverter compressor, were obtained from the original equipment manufacturers (OEM) at half and rated capacity, respectively.

The soft optimization process for the inverter operated SAC system involved a systematic parametric analysis of geometrical and operating parameters to enhance the performance of the system before retrofitting with each alternative refrigerant.

Table 1 presents simulation cases matrix for developing the HC-290 SAC system. The various operating and geometrical parameters have been soft-optimized for SAC system to achieve maximum EER and maintain the original capacity. The subsequent design of experiments (DoEs) was analyzed for various performance metrics, including cooling capacity, power consumption, EER, compressor discharge temperature, and refrigerant charge quantity.

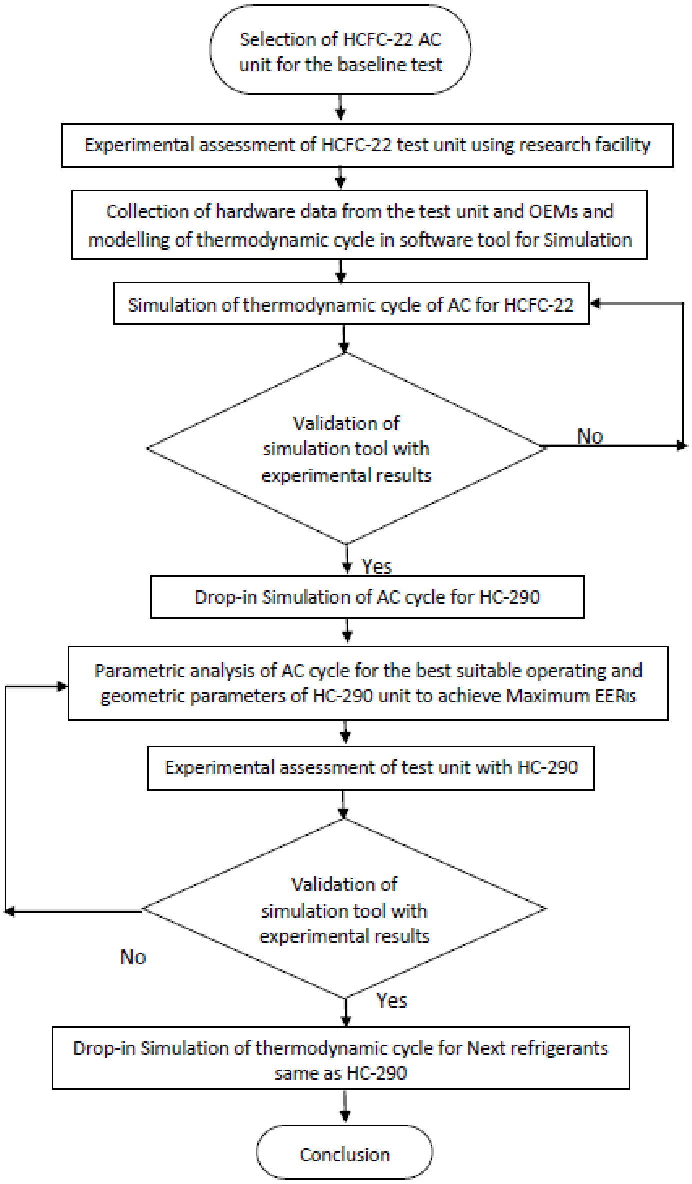

Fig. 1. Research Methodology

Table 1
Simulation case matrix for operating and geometric parameters of HC-290 system

Simulation cases	Input parameters						
	Condenser temperature	Evaporator temperature	Compressor capacity	Sub-cooling	Super heat	Capillary diameter and length	HC-290 Charge
S1	√						
S2	√	√					
S3	√	√	√				
S4	√	√	√	√			
S5	√	√	√	√	√		
S6	√	√	√	√	√	√	
S7	√	√	√	√	√	√	√

In above simulation matrix, √ represents the parameter(s) of HC-290 SAC system undertaken for a parametric study keeping other variables constant with an effort to maximize EER_{IS}. Finally, most effective parameters were developed for the HC-290 system from the simulation case 7 (S7) after the subsequent simulation cases were analysed using previously optimized parameters.

2.1 Experimentation

To establish the baseline test, the experimental assessment was carried out in a well-equipped psychrometric test facility, as described by Utage *et al.,* [19] as shown in Figure 2.

(a) Indoor and outdoor chamber (b) Indoor unit of HCFC-22 AC

(c) Outdoor unit of HCFC-22 AC (d) Instrumentations

Fig. 2. Experimentation test facility with HCFC-22 SAC unit

The psychrometric chambers are specifically designed to simulate the operating conditions of a typical split air conditioner arranged with indoor and outdoor unit of same size. As specified in Table 2, following are the details of the components and configuration of the HCFC-22 SAC test unit for the baseline experimentation.

Table 2
Specifications of original HCFC-22 test unit [19]

SAC Components	Parameters	Value
Compressor	Cooling capacity (W)	5090
	EER (W/W)	3.25
	Displacement (m^3/rev)	28.8
Condenser	Frontal area (m^2)	0.422
	Number of tube rows per pass	18
	Fin spacing/thickness (mm/mm)	1.6
	Air flow (m^3/h)	1600
Evaporator	Frontal area (m^2)	0.316
	Number of rows/circuits	15
	Fin spacing/thickness (mm/mm)	1.3
	Air flow (m^3/h)	900
Capillary	Numbers	1
	Diameter (mm) x Length (mm)	1.91 x 500

According to IS-1391 part-1 standard, the capacity rating test (CRT) was performed for evaluating cooling capacity, energy consumption and the energy efficiency of SAC [20]. This standard also specifies the test conditions for indoor and outdoor units of AC as given in Table 3 below. The obtained DBT and WBT values are used to calculate enthalpy and corresponding mass flow rates of air.

Table 3
Test conditions as per IS 1391- Part 1 [20]

Parameters	DBT (°C)	WBT (°C)	Cooling capacity test	Power consumption test
			At 35°C	
Indoor Room Conditions	27	19	Standard cooling at full capacity	Standard cooling at full capacity
Outdoor Room Conditions	35	24	Standard cooling at 50% capacity	Standard cooling at 50% capacity

The simulation tool was fine-tuned against the experimental results of the baseline test and validated within 6 % accuracy after soft optimization of the original AC unit. Table 4 shows the validation of the IMST ART software tool for the key performance parameters of HCFC-22 unit at the rated capacity.

Table 4
Validation of software tool with baseline test at the rated capacity

Performance Parameters	Simulation results	Experimental results	% Deviation
Cooling capacity (kW)	6.91	6.78	1.88 %
Power Input (kW)	2.20	2.26	2.72 %
EER_{IS}	4.54	4.25	6.38 %
Discharge temperature (°C)	68	72	5.88 %
Charge quantity (g)	1200	1200	Nil

Following the baseline test with HCFC-22, parametric analysis of the AC system was performed with an aim to achieve maximum EER_{IS} using different combinations of system configuration such as compressor capacity, capillary tube length and diameter etc. As the vapor pressures of HC-290, HC-1270, and HC-290/HC-1270 are similar to HCFC-22, drop-in performance tests with optimum charges were performed for these refrigerants. Due to the inability of retrofitting HFC-32, compressor was sized to meet the requirements and heat exchanger circuitries were changed. The capillary size was also adjusted to maintain the necessary superheat at the compressor suction. The condenser area is modified primarily by altering tube diameters to achieve better energy efficiency while retaining the original cooling capacity [6].

Later, experimentation was carried on optimized/modified AC unit as per the best possible parameters obtained using corresponding alternative refrigerants HC-290, HC-1270, HC-290/HC-1270 blend, and HFC-32 one-by-one referring the standards. The data collected was analyzed and compared to the baseline performance of HCFC-22 as presented in the result and discussion section.

2.2 Uncertainty in the Measurement

The recorded parameters during experimentation including air flow, cooling capacity, power consumption, EER etc were analyzed for uncertainty for all the selected replacements. For airflow rate computation, the air pressure difference across the nozzle and specific volume of air were recorded. Pressure difference was measured with pressure transducers. The values of air-water mixture enthalpies, associated density and specific volume were obtained from REFPROP 10.0 version property database [21]. The accuracy of these values assumed was ±1%; hence the error is 0.01.

The maximum percentage error in measurement of cooling capacity is 4.99. The electronic power meter was used to measure power input (W) to the system with an accuracy of ±10 W in the measuring range 0 to 5000 Watts. The maximum error in measurement of power is 10 W. The maximum percentage error in measurement of EER is 5.10%.

3. Results and Discussions

The experimental evaluation aimed to assess thermodynamic performance and energy efficiency of selected four alternatives' refrigerants HC-290, HC-1270, HC-290/HC-1270 blend, and HFC-32 based on major key parameters of SAC, including cooling capacity, power consumption, energy efficiency ratio (EER_{IS}), discharge temperature and refrigerant charge as reported below.

3.1 Cooling Capacity

When the SAC unit was investigated under baseline testing, HCFC-22 demonstrated a cooling capacity of 6.54 kW at full load and 3.26 kW at half-load. When compared to the baseline test, under drop-in condition HFC-32 delivered the maximum cooling capacity of 6.78 kW and 3.35 kW at the rated and half capacity respectively, increased by 3.67 % and 2.76 % as shown in Figure 3.

The highest capacity achieved for HC-290 was 5.72 kW and 2.83 kW at the rated and half capacity respectively. HC-1270 delivered a moderate cooling, 5.96 kW and 2.95 kW respectively at the rated and half capacity making it suitable for small capacity air conditioners. The blend of HC-290/HC-1270 (50%/50% by weight) offered an improved cooling capacity delivering 6.14 kW and 3.06 kW at the full capacity and half capacity respectively compared to each hydrocarbon alone.

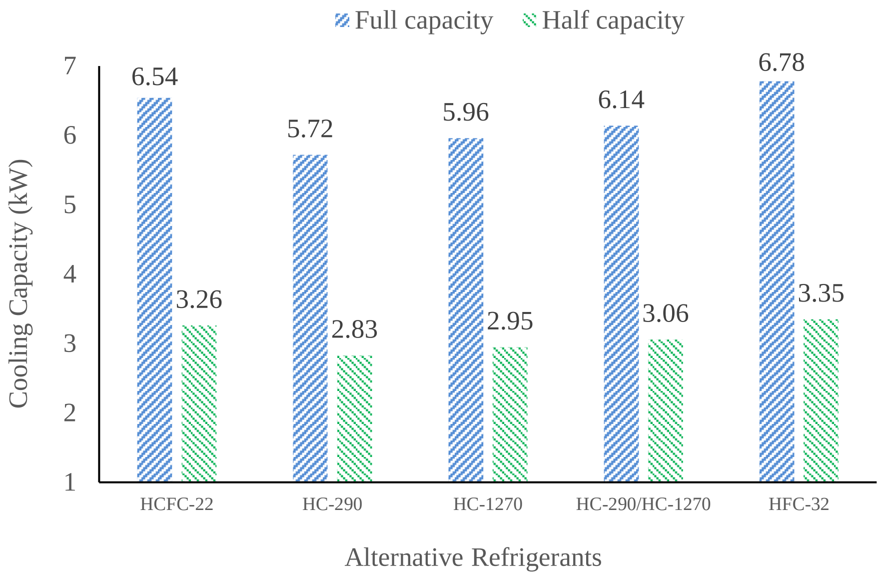

Fig. 3. Variation of cooling capacity for selected alternative refrigerants at full and half capacity

3.2 Power Consumption

The power input required for the baseline unit was 2.26 kW at full load. Subsequently, the same unit tested at half capacity by decreasing the compressor frequency and consequently, the compressor's RPM. Remarkably, there was a significant reduction in power consumption, recorded to be 0.78 kW as presented in Figure 4.

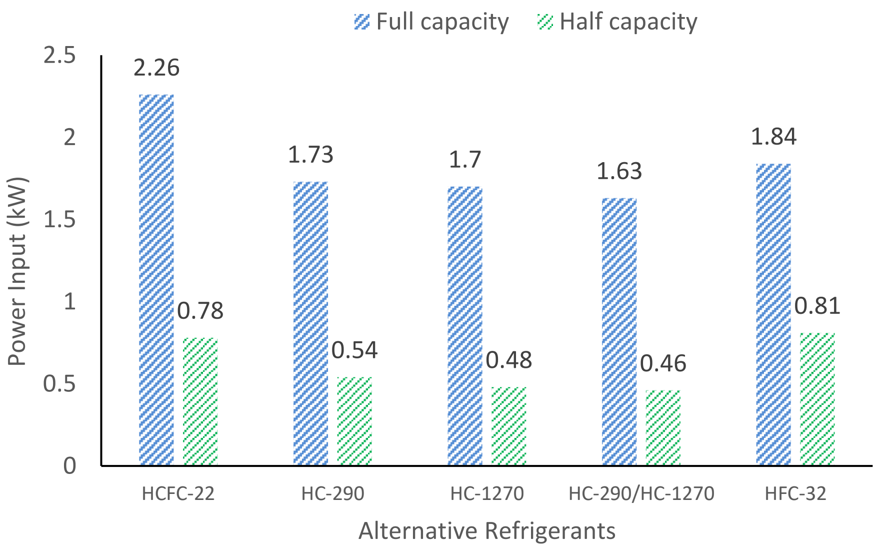

Fig. 4. Variation of power consumption for selected alternative refrigerants at full and half capacity

HC-290 being a hydrocarbon refrigerant with its excellent thermodynamic properties demonstrated good energy efficiency and low power consumption compared to HCFC-22 and HFC-32. The power consumption of HC-1270 was 1.7 kW and 0.48 kW at the rated and half capacity of the SAC. HC-290/HC-1270 blend showed significantly lower power consumption similar to or slightly better than HC-1270 and HC-290, but safety measures are essential due to the presence of flammable components. HFC-32 have the highest power consumption compared to all selected refrigerants due to its higher pressure ratio. SAC unit with HFC-32 consumed 1.84 kW and 0.81 kW at the rated and half capacity respectively.

3.3 Indian Seasonal Energy Efficiency Ratio (EER_{IS})

The investigation of original SAC gave EER of 2.99 and 5.06 respectively at the full and half capacity demonstrating the EER_{IS} to be 4.25. Under drop-in test, even though cooling capacity was marginally lowered, but EER_{IS} achieved for HC-290 was 4.63, 8.94 % higher than the baseline test as shown in Figure 5.

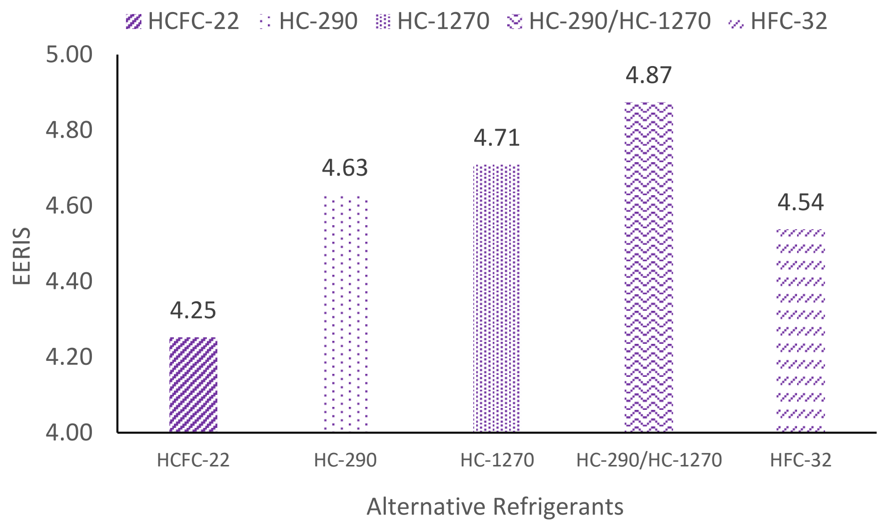

Fig. 5. EER_{IS} of selected alternative refrigerants for inverter SAC

EER_{IS} achieved with HC-1270 was 4.71, 10.82% higher compared to HCFC-22. In full capacity test, the EER_{IS} achieved for HC-290/HC-1270 blend was 4.87, increased by 14.58 % compared to baseline performance. This was highest amongst all tests conducted in this study. A blend of HC-290/HC-1270 exhibited a balanced combination of energy efficiency and reduced flammability risk. HFC-32 gave ISEER 4.54 just 6.8 % higher than HCFC-22 at full capacity.

3.4 Discharge Temperature

As shown in Figure 6, HC-290 and HC-1270 have better favorable combination of lower discharge temperature and moderate pressure ratio, which contributed to better system performance and efficiency. HC-290/HC-1270 blend also tends to have a lower discharge temperature and moderate pressure ratio, similar to HC-290 which falls within acceptable limits at the full and half capacity. HFC-32 exhibited higher discharge temperatures leading to concerns about compressor overheating and therefore compressor and system components need to be designed to handle this pressure ratio for system safety and efficiency.

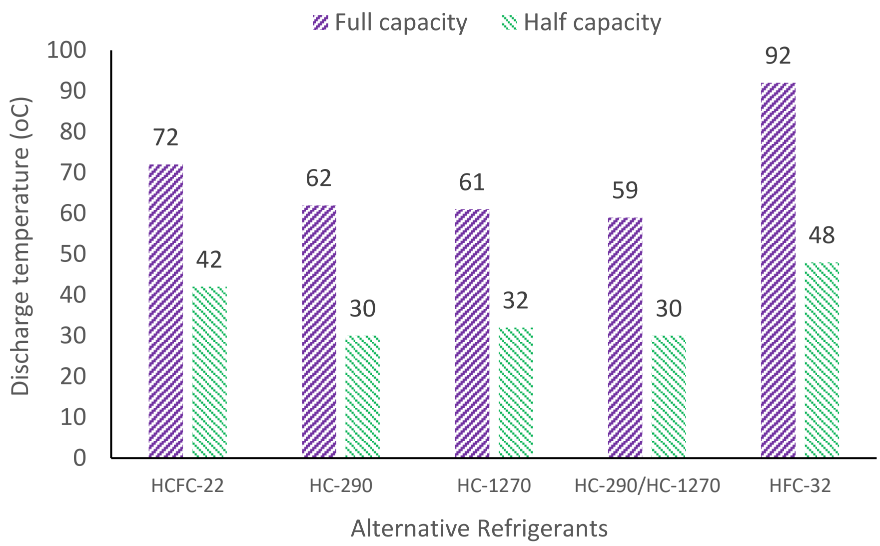

Fig. 6. Variation of discharge temperature for selected alternative refrigerants at full and half capacity

The low to moderate pressure ratio for HC-290/HC-1270 blend compared to HFC-32 is beneficial for compressor and system efficiency however, it required special compressor design considerations due to its flammability characteristics. Blending helped to mitigate the high discharge temperature issue associated with individual refrigerants like HFC-32.

3.5 Refrigerant Charge

The charge for original HCFC-22 unit was 1200 g. As the molecular mass of HC-290 is lower, the optimum charge required for HC-290 is around 52 % of that required for HCFC-22 as presented in Figure 7. When compared to HCFC-22, HC-290 and HC-1270 have significantly higher latent heat. As a result, mass flow rate for these refrigerants will be smaller than HCFC-22 system. It was seen that for the half-capacity test, there was a decrease in subcooling and an increase in compressor suction superheat. Table 5 demonstrates the optimum charge calculation for the maximum EER of SAC.

Table 5
Charge calculation for HC-290 under drop-in condition [4]

Charge of HC-290 (g)	580	600	620	640	665
Cooling capacity (W)	5588	5713	5728	5798	5806
Power input (W)	1749	1772	1731	1833	1876
EER (W/W)	3.20	3.22	3.31	3.16	3.09

Considering density and suction volume for the blend of HC-290/HC-1270, optimize charge selected was 580 g (290 g of HC-290 + 290 g of HC-1270) according to optimum charge calculations. The charge was adjusted to balance efficiency and safety lower than using pure HC-290 or HC-1270.

R-32, being a HFC refrigerant, has lower flammability compared to hydrocarbons and therefore typically has a lower refrigerant charge. It has a higher density and better thermodynamic properties. HFC-32 is not suited for existing HCFC22 systems since it requires considerable system redesign. HFC-32 has been reported to have a higher EERIS than HCFC-22. The mass flow rate of HFC-32 is relatively lower compared to hydrocarbons, as it can achieve similar cooling capacity with a smaller charge due to its higher efficiency. Additionally, safety considerations related to flammability should not be overlooked when assessing the suitability of hydrocarbon refrigerants like HC-290 and HC-1270 [22].

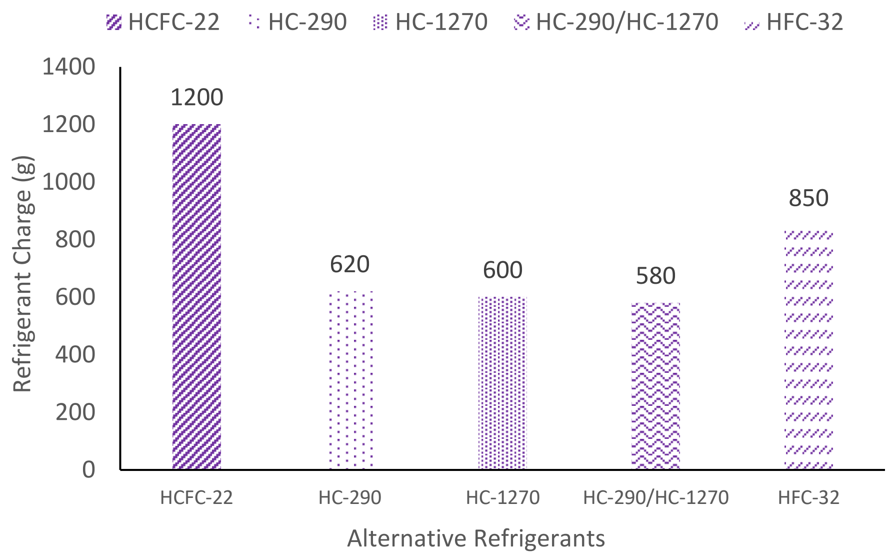

Fig. 7. Required charge for selected alternative refrigerants

4. Conclusions

The experimental study investigated low GWP alternative refrigerants as possible substitutes for the harmful HCFC-22 in 1.5 TR capacity inverter-operated SAC. After optimization, HC-290, HC-1270, and HC-290/HC-1270 blends outperformed HCFC-22 in terms of energy efficiency and discharge temperatures. HFC-32 demonstrated the highest cooling capacity of 6.78 kW, 3.67 % higher than baseline unit at the rated capacity, however exhibited a higher discharge temperature (92 °C). In full capacity test, HC-290/HC-1270 blend achieved the highest EER_{IS} rating of 4.87, increased by 14.58 % compared to HCFC-22, due to the least power consumption compared to all. The discharge temperature for HC-290/HC-1270 blend was lowered in the range 18 °C to 20 °C compared to HCFC-22. While these alternatives proved effective, their safety and system compatibility must be considered for implementation. Further research is recommended to explore their long-term performance and suitability for a wider range of SAC systems.

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