

Performance Analysis of Refrigerants R22 and R290 in Vapour Compression Refrigeration Systems Under Different Operating Conditions

Vinay Dhende^{1*}, Abhishek Avhad¹, Rushikesh Jadhav¹, Aditya Amin¹, and C. S. Choudhari^{1*}

Department of Mechanical Engineering, AISSMS College of Engineering,

Savitribai Phule Pune University, Pune – 411 001, India

*dhendev03@gmail.com, cschoudhari@aissms.edu

Abstract – The global refrigeration and air-conditioning industry is under increasing pressure to use environmentally friendly working fluids that are in line with international climate agreements like the Kyoto and Montreal Protocols. R22 (chloro-difluoro-methane), which has been used in the industry for a long time, has a non-zero ozone depletion potential (ODP) and a global warming potential (GWP) of 1700, which means it should not be used. This study offers a systematic thermodynamic performance assessment of the natural hydrocarbon refrigerant R290 (propane) as a potential alternative to R22 in a standard vapour compression refrigeration system (VCRS). Analytical calculations were carried out over an evaporating temperature range of -25°C to $+10^{\circ}\text{C}$ and a fixed condensing temperature of 45°C , using thermodynamic properties from REFPROP 9.0. The key performance indicators looked at are the refrigerating effect, compressor work, coefficient of performance (COP), discharge temperature, volumetric refrigerating capacity (VRC), pressure ratio, and refrigerant mass flow rate. The results show that R290 has a discharge temperature that is about 11 K lower than R22 under the same conditions, a mass flow rate requirement that is almost 43% lower, and a COP that is slightly lower but still very competitive. The lower VRC of R290 means that the compressor's displacement efficiency is only slightly lower, but its almost-zero environmental indices offer strong ecological benefits. The results all point to R290 as a technically sound and better for the environment replacement for R22 in a wide range of refrigeration uses.

Keywords – R290, R22, coefficient of performance, natural refrigerant, thermodynamic analysis, propane, hydrocarbon refrigerant, operating conditions, and vapour compression refrigeration.

I. INTRODUCTION

Refrigeration and air conditioning systems are important parts of modern infrastructure. They help keep food fresh, store medicines, keep people comfortable, and cool down industrial processes. Since the early 1900s, the working fluids that power these systems have changed a lot. This is because of the need for better thermodynamic performance, safer operation, and more environmentally friendly practices.

In the early 1930s, the refrigeration industry changed forever when chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) became commercially available. Because they were chemically stable, did not catch fire, and had good pressure-temperature characteristics, compounds like R12 and R22 quickly replaced older natural refrigerants. R22 became the most popular fluid for air conditioning systems in homes and small businesses all over the world. However, the finding in the 1970s that chlorinated refrigerants speed up the loss of ozone in the stratosphere led to the Montreal Protocol of 1987, which required a gradual reduction and eventual removal of ODP-bearing

At the same time, the 1997 Kyoto Protocol brought attention to the role of high-GWP greenhouse gases in climate change caused by humans.

This category includes both HCFCs and their HFC replacements.

These two sets of rules have made scientists and businesses interested in natural refrigerants again. These include hydrocarbons, ammonia, carbon dioxide, and water. Propane (R290) has gotten a lot of attention among hydrocarbons. It only lasts in the atmosphere for 0.041 years, has an ODP of zero, and has a GWP of only 20 over a 100-year period, which is 99% less than R22. R290 has a latent heat of evaporation that is about 80% higher than R22 at atmospheric pressure. It also has a lower liquid density and better thermal conductivity. All of these factors affect how well refrigeration equipment works.

Even with these benefits, R290 has an ASHRAE A3 safety rating, which means it is very flammable and has a lower flammability limit (LFL) of about 2.1% by volume in air. This trait has historically prevented it from being widely used, especially in systems with a lot of charge. However, improvements in leak detection technology, smaller systems, and ways to lower charges have made its use less risky over time. This has led regulatory bodies in Europe, Asia, and North America to raise charge limits.

Many experimental and analytical studies have been performed in comparing the performance of R290 and R22. Devotta et al. compared R290 as a direct substitute to R22 in their study involving window-type air conditioning systems, finding that even though the cooling efficiency and energy consumption rate were lower in R290, its

efficiency was comparable to that of R22 in optimised conditions. Purkayastha and Bansal found R290's heat pump system to be 18% more efficient in coefficient of performance than R22 due to higher heat transfer coefficients for the evaporator and condenser. Chang et al. Studied the performance of R290 along with several other hydrocarbons in heat pump service and concluded that although the heating and cooling capacities were slightly lower, the energy efficiency ratio was better than that of R22. Zhou et al. studied the use of R290 and R22 in split type air conditioners and concluded that for a given energy efficiency ratio, R290 had a refrigerant charge that was 44% less than that of R22.

The contributions of this study to the scientific field lie in performing a detailed parametric thermodynamically analysis within a wide range of evaporation temperatures (from -25°C to $+10^{\circ}\text{C}$), in analysing a wide variety of performance parameters, and in summarising the results in order to provide practical recommendations related to the replacement of R22 with R290. Such an analysis is performed taking into account a vapour compression cycle with specified degrees of superheating and sub-cooling.

II. PROPERTIES OF REFRIGERANTS R22 AND R290

The choice of a refrigerant for an application requires a comprehensive consideration of factors, including environmental impact, thermo-physical properties, and safety. The following discussion provides an overview of the relevant properties of the two refrigerants.

IIa. Environmental Properties

Environmental properties of a refrigerant include ozone depletion potential, global warming potential, and atmospheric lifetime. These properties are provided in Table I.

Table I. Environmental Properties of R22 and R290

Refrigerant	Atm. Life (yr)	GWP*	ODP
R22	12.0	1700	0.055
R290	0.041	20	0.000

*Relative to CO_2 over 100-year horizon.

The differences in the two refrigerants are clear. R22 persists in the atmosphere for 12 years, and its ODP value is 0.055, which means that for every kilogram emitted, the damage to ozone is 5.5% as compared to R11. R290 is naturally occurring in the atmosphere and breaks down within weeks through oxidation in the troposphere without impacting ozone layer chemistry.

The total equivalent warming impact (TEWI) methodology takes this comparison a step further by considering not only the direct warming effect due to leakage of the refrigerant but also the indirect effect caused by the energy usage in

running the system. As already noted, since R290-based systems use significantly lower amounts of the refrigerant compared to R22-based systems, their direct emissions will be accordingly lower. The superior thermodynamic performance of R290 — demonstrated in subsequent sections — further curtails indirect warming contributions.

IIb. Physical and Thermo-Physical Properties

The primary physical constants of R22 and R290 are outlined in Table II. One of the key differences between these two is in the latent heat of vaporisation: R290 absorbs about 425 kJ/kg of energy during phase change, while R22 absorbs only 233 kJ/kg — an 82% advantage. The higher latent heat indicates that less mass of the substance will be needed to produce the same cooling capacity.

IIc. Safety Characteristics

According to ASHRAE Standard 34, R290 is an A3 refrigerant with a highly flammable hazard rating. A list of flammability parameters is provided in Table IV. The lower flammability limit by volume of R290 is 2.1%, meaning that R290 will not combust or sustain combustion if the concentration of the refrigerant is below this limit. ASHRAE Standard 15 stipulates that the maximum allowable concentration in an occupied space is 20% of the LFL, or 0.42% by volume. Newer sensor base safety systems have been developed that provide reliable detection of concentrations above this level.

TABLE II. Physical Properties of R22 and R290

Property	R22	R290
Molecular weight(kg/kmol)	86.47	44.1
Normal boiling point($^{\circ}\text{C}$)	-40.75	-42.2
Critical temp($^{\circ}\text{C}$)	96.2	96.7
Critical pressure (MPa)	4.99	4.25
Latent heat of evaporation (kJ/Kg)	233.7	425.4

This similarity in the normal boiling temperatures of R22 (-40.75°C) and R290 (-42.2°C) is important in practical retrofitting considerations, given the similarity in shape between the saturation pressure diagrams for both fluids. What this indicates is that the pressure range in which an R290 system works is not much different from that in which an R22 system works, reducing the redesign burden on components such as valves, receivers, and piping.

Table III presents the thermo-physical properties under the nominal operating conditions of $T_e = 10^\circ\text{C}$ and $T_c = 45^\circ\text{C}$. The value of liquid viscosity for R290 is $115.69 \mu\text{Pa}\cdot\text{s}$, while that of R22 is $197.97 \mu\text{Pa}\cdot\text{s}$, resulting in a decrease of 42%, which reduces frictional pressure drop and enhances convective heat transfer coefficients. The thermal conductivity of liquid R290 ($0.101 \text{ W/m}\cdot^\circ\text{C}$) exceeds that of R22 ($0.0911 \text{ W/m}\cdot^\circ\text{C}$), further augmenting evaporator and condenser performance. The specific heat of R290 at the liquid state ($2.53 \text{ kJ/kg}\cdot^\circ\text{C}$) is more than twice that of R22 ($1.18 \text{ kJ/kg}\cdot^\circ\text{C}$), which is the primary reason for the substantially lower compressor discharge temperatures observed with R290.

TABLE III. Thermo-Physical Properties at $T_e = 10^\circ\text{C}$, $T_c = 45^\circ\text{C}$

Property	State	R22	R290
Sat.pressure (Mpa)	Liquid (10°C)	0.640	0.601
	Vapour (45°C)	1.729	1.534
Density(kg/m^3)	Liquid	1253.8	517.56
	Vapour	75.45	34.14
Viscosity ($\mu\text{Pa}\cdot\text{s}$)	Liquid	197.97	115.69
	Vapour	13.69	9.13
Therm.cond($\text{W/m}\cdot^\circ\text{C}$)	Liquid	0.0911	0.101
	Vapour	0.0135	0.0224
Spec. heat ($\text{kJ/kg}\cdot^\circ\text{C}$)	Liquid	1.1836	2.5318
	Vapour	1.0487	2.3714

III. THERMODYNAMIC FRAMEWORK AND SIMULATION METHODOLOGY

IIIa. Cycle Description

The theoretical performance evaluation is based on the standard vapour compression refrigeration cycle with superheating in the evaporator and sub-cooling in the condenser, as shown in Figure 1 on the pressure-enthalpy ($P-h$) diagram.

1. State points are defined as: superheated vapour at compressor inlet;
2. superheated vapour at compressor outlet (after isentropic compression);
3. sub-cooled liquid entering the condenser;
4. saturated vapour leaving the condenser;
5. two-phase mixture at the end of isenthalpic expansion;
6. saturated vapour leaving the evaporator;
7. superheated vapour from the evaporator.

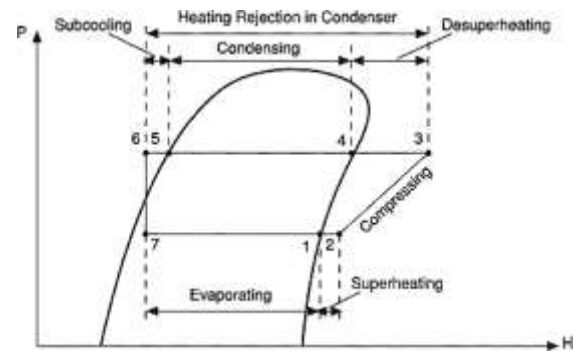


Fig. 1 Schematic $P-h$ Diagram for the VCRS Cycle with Superheating and Sub-Cooling.

IIIb. Simulation Assumptions

The following assumptions govern the theoretical analysis:

- Steady-state operation with negligible pressure drops in connecting pipework and heat exchangers.
- No heat exchange between the refrigerant lines and the surroundings (adiabatic piping).
- Compression process is isentropic (100% isentropic efficiency).
- Expansion across the throttle valve is isenthalpic.
- Fixed superheating of 10°C in the evaporator.
- Fixed sub-cooling of 5°C in the condenser.
- Cooling capacity basis: 1 ton of refrigeration (TR) = 3.5 kW.
- Thermodynamic properties evaluated using REFPROP 9.0

IIIc. Performance Equations

The governing equations for each performance parameter are as follows.

The pressure ratio (PR) quantifies the pressure lift across the compressor

$$PR = \frac{P_c}{P_e} \quad (1)$$

$$PR = \frac{P_c}{P_e} \quad (1)$$

The isentropic compression work per unit mass (kJ/kg):

$$W_{\text{comp}} = h_2 - h_1 \quad (2)$$

The refrigerating effect (RE) per unit mass (kJ/kg):

$$RE = h_1 - h_6 \quad (3)$$

The coefficient of performance:

$$\text{COP} = \frac{\text{RE}}{W_{\text{comp}}} = \frac{h_1 - h_6}{h_2 - h_1}$$

The volumetric refrigerating capacity (VRC, kJ/m³):

$$\text{VRC} = \rho_1 \cdot \text{RE} \quad (5)$$

The refrigerant mass flow rate per unit refrigerating capacity (kg/s per TR):

$$\dot{m}_r = \frac{\text{RE}}{3.5} \quad (6)$$

7) The power per ton of refrigeration (kW/TR):

$$\frac{\text{Power}}{\text{TR}} = \frac{3.5 \cdot W_{\text{comp}}}{\text{RE}}$$

8) The discharge temperature T_d is determined from the isentropic end-state

$$s_2 = s_1, \quad T_d = T(P_c, s_2)$$

IV. Results and Discussion

Performance parameters were evaluated for evaporating temperatures spanning -20°C to $+20^\circ\text{C}$ across four discrete condensing levels ($T_c = 30, 35, 40$, and 45°C) for both R22 and R290 fluids. The collected data points are consolidated within Tables V, VI, and VII.

TABLE V
Refrigerating Effect (kJ/kg) at $T_e = -10^\circ\text{C}$

and $T_e = +10^\circ\text{C}$

$T_c (^\circ\text{C})$	$T_e = -10^\circ\text{C}$		$T_e = +10^\circ\text{C}$	
	R22	R290	R22	R290
30	162	285	172	308
35	158	275	168	293
40	153	265	163	280
45	148	255	157	265

TABLE VI
Compressor Work (kJ/kg) at $T_e = -10^\circ\text{C}$ and $T_e = +10^\circ\text{C}$

$T_e = -10^\circ\text{C}$ $T_e = +10^\circ\text{C}$

$T_c (^\circ\text{C})$	R22	R290	R22	R290
30	27	48	22	38
35	29	51	25	42
40	31	57	27	47
45	36	63	32	59

TABLE VII
COP at $T_e = -10^\circ\text{C}$ and $T_e = +10^\circ\text{C}$

$T_c (^\circ\text{C})$	$T_e = -10^\circ\text{C}$		$T_e = +10^\circ\text{C}$	
	R22	R290	R22	R290
30	6.4	6.4	7.5	8.5
35	5.5	5.5	6.5	7.0
40	4.5	4.5	5.8	6.0
45	3.5	3.2	5.0	4.7

IVa. Refrigerating Effect

As shown in Figure the refrigerating effect (RE) changes depending on the evaporating temperature with respect to the four condensing temperatures for both R22 and R290.

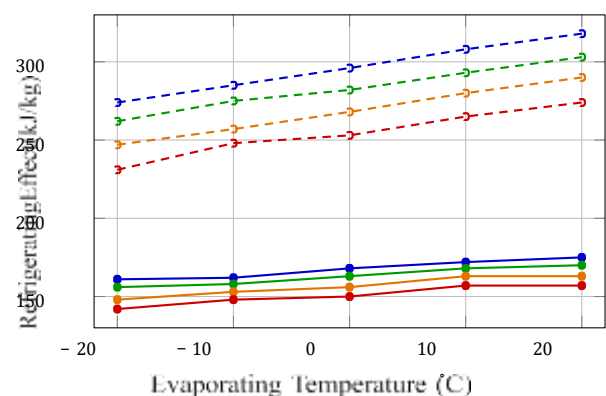
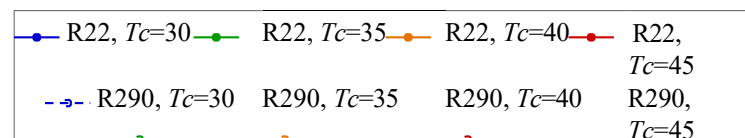


FIGURE II

Refrigerating Effect vs. Evaporating Temperature for R22 (Solid) and R290 (Dashed) at $T_c = 30, 35, 40, 45^\circ\text{C}$

Two clear bands are apparent in Figure II. The lower band (R22) ranges from approximately 140–175 kJ/kg, while the upper band (R290) ranges from approximately 230–320 kJ/kg, having the same characteristics described by the lower band based on evaporating temperature and T_c .

The refrigerating effect of R290 is higher than R22 by approximately 70–80% throughout the full range of operating conditions, due largely to propane having a much higher latent heat of vaporisation. R290's RE is imposed by the condensing condition. At $T_c = 45^\circ\text{C}$, R290 creases as the condensing temperature decreases. For compressor work falls from 83 kJ/kg at $T_e = -20^\circ\text{C}$ to example, at $T_c = 30^\circ\text{C}$, the RE of R290 at $T_e = 20^\circ\text{C}$ is 59 kJ/kg at $T_e = 20^\circ\text{C}$, a 29% reduction — underscor318 kJ/kg, while the RE of R22 is only 175 kJ/kg — an ing the strong benefit of operating at higher evaporating advantage of 82%. At the extreme condition ($T_c = 45^\circ\text{C}$, temperatures. $T_e = -20^\circ\text{C}$). While R290 specific compressor work is roughly twice the RE of R290 is still much higher than R22 at 231 kJ/kg versus 142 kJ/kg, an advantage of 63%. that of R22 at identical conditions, this must be interpreted alongside the proportionally higher refrigerating and $T_c = 45^\circ\text{C}$ RE curves for R290 (approximately effect of R290. The ratio of RE to

compressor work — 40–45 kJ/kg) as compared to R22 (approximately 18– i.e., the COP — is what determines practical energy ef20 kJ/kg) for any given evaporating temperature. This efficiency, and this ratio remains close for both fluids as indicates that the RE of R290 is more sensitive to the shown in the following section.

IVb. Compressor Work

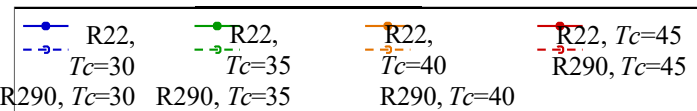
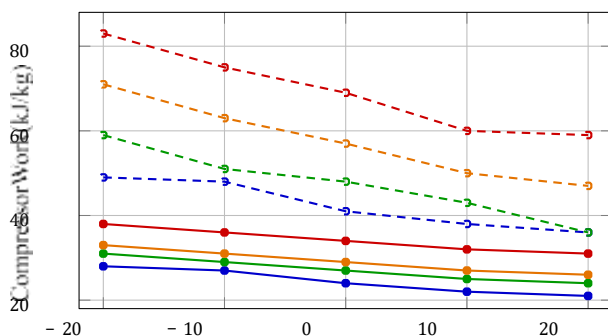
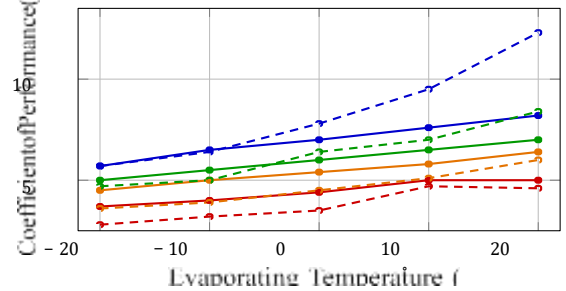


Figure plots the isentropic compression work per unit mass as a function of evaporating temperature across all for condensing temperature

IVc. Coefficient of Performance parameter to take into consideration when designing a system for particular ambient temperature



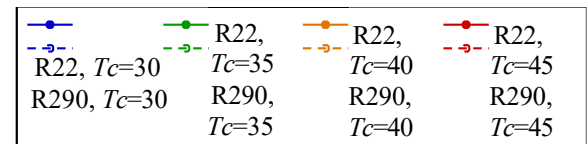
Compressor Work vs. Evaporating Temperature for R22

(Solid) and R290 (Dashed) at $T_c = 30, 35, 40, 45^\circ\text{C}$ The

COP graph shows a sophisticated and important narrative.

At low condensing temperature ($T_c = 30^\circ\text{C}$),

The two-band pattern seen in Figure III resembles R290 is very close in performance to R22 across the range that described for the RE graph. At $T_e = 20^\circ\text{C}$ and $T_c = 30^\circ\text{C}$,



(dashed line) curves occupy a significantly higher range of R290 has a COP of approximately 12. The R22 (solid line) -20°C to -5°C , but when the evaporating temperature curves occupy a much lower range of approximately 21– temperature exceeds 0°C , it shows a substantial performance 38 kJ/kg forming a tight lower grouping, while the R290 advantage over R22.3 compared to 8.2 approximately 36–83 kJ/kg. In general, for both refrigerator- with R22, which is a 50% improvement in performance., increasing evaporation temperature causes com- The dramatic difference in performance at high compressor work to decrease steadily while increasing con- rating temperatures can be attributed to the better condensing temperature causes compressor work to increase enthalpy properties of R290 at low pressure ratios, where significantly the high latent heat and low density of R290 produce.

The effect of condensing temperature is especially much higher refrigerating effects relative to compressor pronounced for R290: the spread between the $T_c = 30^\circ\text{C}$ energy. Conversely, at the highest condensing temperature and $T_c = 45^\circ\text{C}$ curves reach approximately 34 kJ/kg ($T_c = 45^\circ\text{C}$), R290's COP drops below R22's COP at $T_e = -20^\circ\text{C}$, compared with only about 10 kJ/kg for over the entire evaporating temperature range, with the R22.

This indicates that R290 compressor work is con-greatest shortfall occurring at low evaporating temperature considerably more sensitive to the lift (pressure ratio) immatures. At $T_e = -20^\circ\text{C} / T_c = 45^\circ\text{C}$, R290 yields a COP of 2.8 versus 3.7 for R22 — a 24% shortfall. This region corresponds to high pressure ratio condition where R290's larger specific compressor work is not fully compensated by its higher refrigerating effect.

At intermediate condensing temperatures ($T_c = 35^\circ\text{C}$, 40°C), the two refrigerants track each other closely in efficiency.

IVd. Effect of Condensing Temperature

Across all three performances metrics, the condensing temperature exerts a stronger influence on R290 than on R22. The data shows that across the full range of evaporating temperature, R290 is only slightly trailing R22 at lower evaporating temperatures and only slightly leading R22 at higher evaporating temperatures.

As the condensing temperature increases, the crossover point moves higher in evaporating temperature. From this, one can conclude that the best application range for R290 is for moderate to high evaporating temperature refrigeration and air conditioning (e.g., $T_e > -10^\circ\text{C}$), and low to moderate condensing temperatures ($T_c \leq 40^\circ\text{C}$), which makes up a large percentage of the applications associated with comfort cooling and food retailing at medium temperature.

The spread between the $T_c = 30^\circ\text{C}$ and $T_c = 45^\circ\text{C}$ curves demonstrate a greater extent of variability for R290. This variation occurs in the system designer's selection of the proper size of condenser and in their management of the surrounding ambient conditions. Properly sizing the condenser and managing ambient conditions for R290 will result in much higher levels of performance from R290 as opposed to R22, offering an additional reason to operate R290 with a thorough preventative maintenance program.

IVe. Practical Performance Summary

The crossover dynamics of COP indicate that R290 has lower COP than R22 when the condensing temperature is high; however, R290 has a higher COP than R22 at low condensing temperatures and high evaporating temperatures. This establishes the operational envelope in which R290 should be able to replace R22. A comparison of performance at both extremes is contained in Table VIII.

TABLE VIII
Performance Comparison at Boundary Conditions

Parameter	Favourable		Demanding	
	R290		R22	
RE (kJ/kg)	175	318	142	231
W_c (kJ/kg)	21	36	38	83
COP	8.2	12.3	3.7	2.8

There are some key engineering issues to consider when replacing R22 with R290. Performance-wise, there is a considerable benefit to the moderate-lift operating conditions in the vast majority of comfort cooling and medium-temperature refrigeration systems using R290. R290 operates at approximately 11 K lower discharge temperature than R22, which is beneficial to compressor reliability. In addition, the significantly lower R290 refrigerant charge requirement contributes to the simplicity of system sealing and reduced liability for environmental leaks.

While there are still concerns about R290's flammability, the industry has produced a mature set of risk mitigation technologies, including hermetically sealed compressors, charge limits defined by the latest editions of ISO 5149 and IEC 60335-2-89, and commercially viable leak detection sensors for residential applications. Several leading compressor manufacturers have started delivering R290-compatible compressors, while well-known international brands such as Unilever, Coca-Cola, and PepsiCo have implemented considerable fleets utilising R290 refrigerant globally with strong safety records.

V. Comparative Summary and Practical Implications

Table IX provides a quantitative comparison of the performance characteristics of R22 and R290, as well as qualitative comparisons of attributes which can be used in selecting designs.

TABLE IX

Comparative Assessment of R22 and R290

Criterion	R22	R290
ODP	0.055	0.000
GWP (100-yr)	1700	20
Refrigerating effect	Lower	Higher (+70–82%)
Compressor work	Lower	Higher (+50%)
(specific)	Lower	Higher ($\approx 2\times$)
COP (low T_c /high T_e)		
COP (high T_c /low T_e)	Higher	Lower
COP (moderate conditions)	Comparable	(Comparable–24%)
Discharge temperature	Higher	Lower ($T_{\text{Lower}} \approx -11$
Pressure ratio	Higher	K)
VRC	Higher	
Mass flow rate /	Higher	Lower (T_{Lower}
charge	Non-flam.	(Flammable (A3) $\approx$
Flammability		$\approx -15_{43}\%$)
Toxicity	Low	Very low
Regulatory status	Phase-out	Permitted/growing

At the most favourable operating point ($T_e = 20^\circ\text{C}$, $T_c = 30^\circ\text{C}$), R290 delivers a COP 50% higher than R22, making it an excellent option for use as a low-lift refrigerant in air conditioning systems designed for temperate climates.

Under extreme operating conditions ($T_e = -20^\circ\text{C}$ and $T_c = 45^\circ\text{C}$), R290 COP is 24% lower than R22. However, R290 remains an environmentally sound refrigerant with low refrigerant charge requirements, which justifies its use. It will also be possible to increase the COP of R290 through improvements to the design of heat exchangers and compressor valves, making use of the lower refrigerant charge of R290.

VI. Conclusions

A systematic thermodynamic performance analysis of natural refrigerant R290 (propane) and synthetic refrigerant R22 was performed in a standard vapour compression refrigeration cycle at evaporating temperatures ranging from -20°C to $+20^\circ\text{C}$ and condensing temperatures ranging from 30 to 45°C . The following conclusions were drawn:

1. The refrigerating effect of R290 is consistently 63–82% larger than R22 throughout the entire operating range. This makes propane's higher latent heat of vaporisation the defining characteristic of R290 and the reason for its lower mass flow rate and charge requirements.
2. R290 requires approximately twice as much compressor work compared to R22 for the same temperature and

pressure, with this difference being greater at higher condensing temperatures. Even so, the higher refrigerating effect of R290 offsets the higher work at moderate condensing temperatures.

3. The COP of R290 at low condensation temperatures gives it an advantage compared to R22. At $T_c = 30^\circ\text{C}$ and $T_e = 20^\circ\text{C}$, R290 achieves a COP of 12.3, approximately 50% higher than that of R22 (8.2) at the same temperatures. Therefore, R290 is an ideal refrigerant for moderate ambient temperature comfort cooling applications requiring low lift.
4. Under high condensation temperatures ($T_c = 45^\circ\text{C}$) with low evaporating temperatures, R290 COP falls up to 24% below R22. High-lift, high-ambient applications remain the primary domain where R22 retains a thermodynamic advantage. System redesign for R290 (optimised compressor, enhanced condensers) is expected to reduce this gap substantially.
5. R290 performance metrics, including refrigerating effect, compressor work, and COP, show much greater sensitivity to the condensing temperature than those of R22. This highlights the crucial need for proper condenser sizing and ambient management when designing R290 systems.
6. R290 has zero ozone depletion potential (ODP = 0) and a global warming potential (GWP) of 20, providing it with a clear environmental superiority over R22 (GWP = 1700, ODP = 0.055), and is fully in accordance with the international agreements set forth by the Montreal and Kyoto Protocols.
7. The lower discharge temperature (≈ 11 K), lower pressure ratio, and lower refrigerant mass flow rate (43% less per TR) for R290 all contribute to reduced maintenance requirements and reduced refrigerant emission due to leakage.
8. Although R290 requires multiple engineered safety features due to its A3 flammability classification, the existence of established standards, charge minimisation, and leak detection methods makes the commercial and residential refrigeration industry able to design safe R290 systems for the majority of applications.

In summary, R290 is strongly recommended as a drop-in and redesigned substitute for R22, especially in moderate-lift and air-conditioning applications. Where high-lift performance is paramount, targeted system design modifications for R290 will be necessary to fully realise its environmental and practical benefits.

Nomenclature

h	Specific enthalpy (kJ/kg)
P	Pressure (MPa)
T_c	Condensing temperature ($^\circ\text{C}$)

T_e	Evaporating temperature (°C)
T_d	Discharge temperature (°C)
$\dot{m}_r$	Refrigerant mass flow rate (kg/s)
RE	Refrigerating effect (kJ/kg)
COP	Coefficient of performance
VRC	Volumetric refrigerating capacity (kJ/m ³)
PR	Pressure ratio
W_{comp}	Isentropic compression work (kJ/kg)
GWP	Global warming potential
ODP	Ozone depletion potential
TEWI	Total equivalent warming impact
LFL	Lower flammability limit
TR	Ton of refrigeration (= 3.5 kW)

Acknowledgment

The authors thank the Department of Mechanical Engineering at AISSMS College of Engineering, Pune, for access to computational resources and REFPROP 9.0.

References

- [1] United Nations Environment Programme, Montreal Protocol on Substances that Deplete the Ozone Layer, UNEP, Nairobi, 1987.
- [2] United Nations Framework Convention on Climate Change, Kyoto Protocol to the United Nations Framework Convention on Climate Change, UNFCCC, Bonn, 1997.
- [3] E. Granryd, "Hydrocarbons as refrigerants — an overview," *International Journal of Refrigeration*, vol. 24, pp. 15–24, 2001.
- [4] B. Palm, "Hydrocarbons as refrigerants in small heat pump and refrigeration systems — a review," *International Journal of Refrigeration*, vol. 31, pp. 552–563, 2008.
- [5] S. Devotta et al., "Performance assessment of HC-290 as a drop-in substitute to HCFC-22 in a window air conditioner," *International Journal of Refrigeration*, vol. 28, pp. 594–604, 2005.
- [6] B. Purkayastha and P.K. Bansal, "Experimental study on HC290 and a commercial liquified petroleum gas mix as suitable replacement for HCFC-22," *International Journal of Refrigeration*, vol. 21, pp. 213–217, 1998.
- [7] Y.S. Chang et al., "Performance and heat transfer characteristics of hydrocarbon refrigerants in a heat pump system," *International Journal of Refrigeration*, vol. 23, pp. 232–242, 2000.
- [8] G. Zhou et al., "Performance of a split type air conditioner matched with coiled adiabatic capillary tubes using HCFC-22 and HC-290," *Applied Energy*, vol. 24, no. 4, pp. 870–885, 2010.
- [9] E.W. Lemmon, M.L. Huber, and M.O. McLinden, NIST Standard Reference Database 23: REFPROP, Version 9.0, National Institute of Standards and Technology, Gaithersburg, 2010.
- [10] J.M. Calm, "Emissions and environmental impacts from air conditioning and refrigeration systems," *International Journal of Refrigeration*, vol. 25, pp. 293–305, 2002.
- [11] A. Miyara, "Condensation of hydrocarbon a review," *International Journal of Refrigeration*, vol. 31, pp. 621–632, 2008.
- [12] A.S. Dalkilic et al., "A performance comparison of vapour compression refrigeration systems using various alternative refrigerants," *International Communications in Heat and Mass Transfer*, vol. 37, pp. 1340–1349, 2010.

Author Information

Vinay Dhende, Co-Author, Department of Mechanical Engineering, AISSMS College of Engineering, Pune – 411 001, India.

C S Choudhari, Professor and Head, Department of Mechanical Engineering, AISSMS College of Engineering, Pune – 411 001, India.