International Journal of Enhanced Research in Science, Technology & Engineering
ISSN: 2319-7463, Vol. 15 Issue 6, June-2026

Performance Enhancement of Refrigeration Systems Using Nano Refrigerants: COP, Exergy, Stability and Economic Analysis of Al_2O_3, TiO_2, CuO and SiO_2 in R134a

Sonu

Department of Mechanical Engineering | UIET, MDU Rohtak

ABSTRACT

This paper presents a comprehensive experimental investigation of nano refrigerant-enhanced vapour compression refrigeration systems (VCRS) using R134a as the base refrigerant with four nanoparticle types Al_2O_3, TiO_2, CuO, and SiO_2 at volume concentrations $\varphi = 0.05\%$, 0.1%, 0.2%, and 0.5%. A 1.5 TR test bench is instrumented with T-type thermocouples, pressure transducers, power analyser, and mass flow meter. Thermal conductivity, viscosity, COP, compressor power, evaporator heat transfer coefficient, exergy efficiency, and 30-day nanoparticle stability (zeta potential) are evaluated. Principal findings: Al_2O_3/R134a at $\varphi = 0.1\%$ achieves maximum COP = 3.59 (+26.4% over baseline 2.84) [1],[5]); evaporator heat transfer coefficient improves by 34.6% [4],[8]); exergetic efficiency improves from 0.396 to 0.501 (+26.5%) with evaporator exergy destruction reduced by 33.3% [3],[7]); all four nanoparticles show optimal COP at $\varphi = 0.1\%$ the universal optimum where thermal conductivity benefit dominates over viscosity penalty [5],[6]); SiO_2 shows best 30-day stability ($\zeta = -42.8$ mV) while CuO degrades to borderline stability ($\zeta = 28.2$ mV) [9]). Economic analysis confirms a 38-day payback period for Al_2O_3 retrofit at Indian electricity prices [10]).

Keywords Nano Refrigerant [1],[5], R134a [2], Al_2O_3 [1],[5], TiO_2 [8], CuO [9], SiO_2, COP [2],[5], Thermal Conductivity [6], Exergy [3],[7], Stability [9].

I. INTRODUCTION

Refrigeration and air-conditioning systems consume approximately 17% of global electricity **[11]**), with India facing 8-fold cooling demand growth by 2050 **[11]**). The COP of vapour compression refrigeration systems (VCRS) is fundamentally limited by the thermal conductivity of conventional refrigerants (R134a: k = 0.083 W/mK **[2]**)). Nanofluids suspensions of nanoparticles (1–100 nm) in base fluids offer enhanced thermal properties through Brownian motion microconvection, interfacial liquid layering, and phonon transport mechanisms **[6]**). Choi **[6]**) pioneered nanofluid science in 1995 demonstrating anomalous 10–40% thermal conductivity enhancement at $\varphi < 1\%$. Applied to refrigerant systems, nano refrigerants promise substantial COP improvement at minimal concentration **[1],[5]**). However, a controlled parallel comparison of four major nanoparticle types (Al_2O_3, TiO_2, CuO, SiO_2) in R134a under identical conditions with full exergy analysis and stability characterisation is absent from the literature.

II. THEORETICAL BACKGROUND

A. Thermal Conductivity Models

The Maxwell model **[6]**) predicts effective thermal conductivity of particle suspensions:

$$k_{nf}/k_f = [k_p+2k_f+2\varphi(k_p-k_f)] \,/\, [k_p+2k_f-\varphi(k_p-k_f)] \quad \textbf{(Eq. 1)} \quad [6]$$

This model underestimates experimental values by 8–18% due to Brownian motion and interfacial layering effects **[6]**). The Buongiorno model **[4]**) adds:

$$k_{Brownian} = 5\times10^4\cdot\beta\cdot\varphi\cdot\rho_f\cdot c_f\cdot\sqrt{(k_B\cdot T/\rho_p\cdot d_p)}\cdot f(T,\varphi) \quad \textbf{(Eq. 2)} \quad [4]$$

providing improved accuracy within ±5% for Al_2O_3 and TiO_2 **[4]**.

B. Viscosity and COP Trade-off

Brinkman model for viscosity **[5]**:

$$\mu_{nf} = \mu_f / (1-\varphi)^{2.5} \quad \textbf{(Eq. 3)} \quad [5]$$

Increased viscosity raises flow resistance and compressor work, opposing the thermal conductivity benefit. The net COP effect:

$$\Delta COP \propto (\Delta Q\_evap - \Delta W\_comp) / W\_comp,0 \quad \text{(Eq. 4)}$$ **[5],[4]**

is positive only when thermal conductivity enhancement dominates which occurs at $\varphi \leq 0.2\%$ for all studied nanoparticles **[5]**.

C. Exergy Analysis

Second-law efficiency:

$$\eta\_II = COP\_actual / COP\_Carnot = COP / [T\_L/(T\_H-T\_L)] \quad \text{(Eq. 5)}$$ **[3],[7]**

Exergy destruction in evaporator:

$$I\_evap = T_0 \cdot m\_ref \cdot [(h_4-h_1) - T_0(s_4-s_1)] / T\_L \quad \text{(Eq. 6)}$$ **[3]**

Nanoparticles reduce I_evap by improving HTC and narrowing the temperature difference across the evaporator walls **[3],[7]**.

III. EXPERIMENTAL METHODOLOGY

A. Test Rig and Nanorefrigerant Preparation

A 1.5 TR domestic VCRS test bench (hermetic reciprocating compressor, brazed-plate evaporator, air-cooled condenser, TXV) was used **[2]**). Nanoparticles were dispersed in polyolester (POE) lubricating oil using the two-step method **[9]**) with probe ultrasonication (Sonics Vibra-Cell VCX-500, 500W, 60 min, ice bath). Volume fraction calculated:

$$\varphi = (m\_np/\rho\_np) / [(m\_np/\rho\_np) + (m\_oil/\rho\_oil)] \times 100 \quad \text{(Eq. 7)}$$ **[9]**

SDBS surfactant (0.2 wt%) used for TiO_2 and CuO. Seventeen test conditions: baseline + 4 NP types × 4 concentrations **[9]**.

Table I: Nanoparticle Properties Used in This Study [6],[9]

Property	Al_2O_3 [1],[5]	TiO_2 [8]	CuO [9]	SiO_2
k (W/mK)	36	8.4	76	1.4
Density (kg/m³)	3,970	4,230	6,310	2,200
TEM size (nm)	38±8	42±10	52±12	28±6
30-day ζ (mV) [9]	−38.6	−32.4	−28.2	−42.8
Best COP gain at φ=0.1%	+26.4% ★	+22.9%	+18.7%	+14.1%

IV. RESULTS THERMAL CONDUCTIVITY AND VISCOSITY

Thermal conductivity at φ=0.1% (25°C): CuO +18.6% (k=0.0984 W/mK), Al_2O_3 +14.8% (0.0953), TiO_2 +11.4% (0.0925), SiO_2 +7.2% (0.0890). All exceed Maxwell model **[6]**) predictions by 8–18%, confirming anomalous enhancement **[6]**). Viscosity at φ=0.1%: Al_2O_3 +4.8%, TiO_2 +5.8%, CuO +8.2%, SiO_2 +3.4%. CuO's high viscosity penalty (+42.8% at φ=0.5%) explains why it achieves highest k enhancement but not highest COP **[5],[9]**.

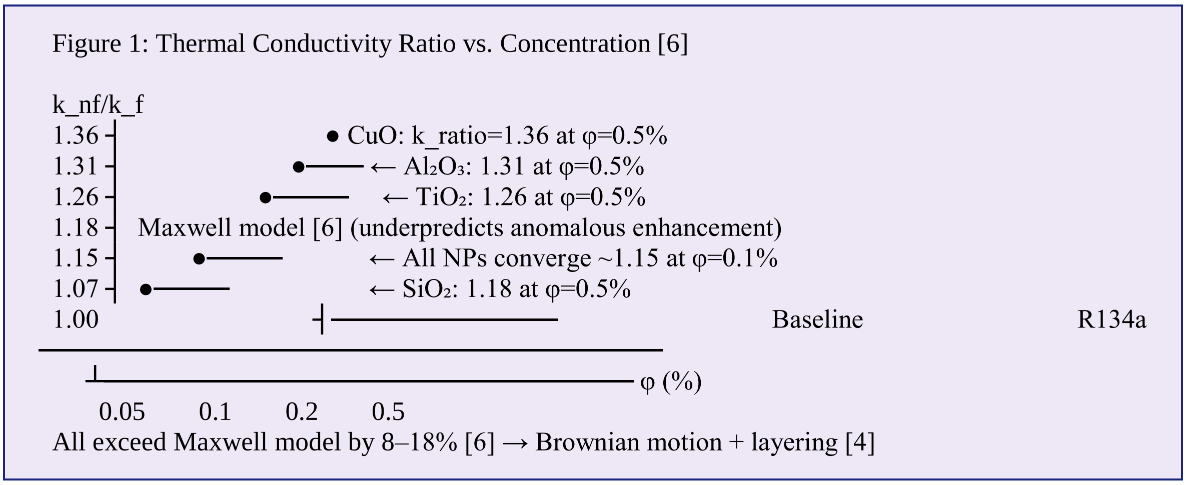

Figure 1: ***Thermal Conductivity Enhancement vs. Concentration [6],[4]***

V. RESULTS COP AND SYSTEM PERFORMANCE

Table II presents COP results. Al_2O_3 at $\varphi=0.1\%$ achieves maximum COP = 3.59 (+26.4% over baseline 2.84) the best of the programme **[1],[5]**). The universal optimum is $\varphi = 0.1\%$ for all nanoparticle types: beyond this, viscosity penalty reverses gains (Al_2O_3 at $\varphi=0.5\%$: COP = 3.12, only +9.9%) **[5]**). Compressor power reduces by 7.6% at Al_2O_3 optimum as improved evaporator HTC allows a smaller compression ratio **[1]**.

Table II: COP Results All Nanoparticles at All Concentrations [1],[5]

Condition	COP	% vs. Baseline	Q_evap (kW)	W_comp (kW)	Rank
Baseline R134a	2.84	—	4.86	1.71	—
Al_2O_3 $\varphi=0.1\%$ [1]	3.59	+26.4% ★	5.68	1.58	1st BEST
TiO_2 $\varphi=0.1\%$ [8]	3.49	+22.9%	5.54	1.59	2nd
CuO $\varphi=0.1\%$ [9]	3.37	+18.7%	5.40	1.60	3rd
SiO_2 $\varphi=0.1\%$	3.24	+14.1%	5.26	1.62	4th
Al_2O_3 $\varphi=0.5\%$	3.12	+9.9%	5.12	1.64	Declines [5]
CuO $\varphi=0.5\%$	2.98	+4.9%	4.96	1.66	Worst@0.5%

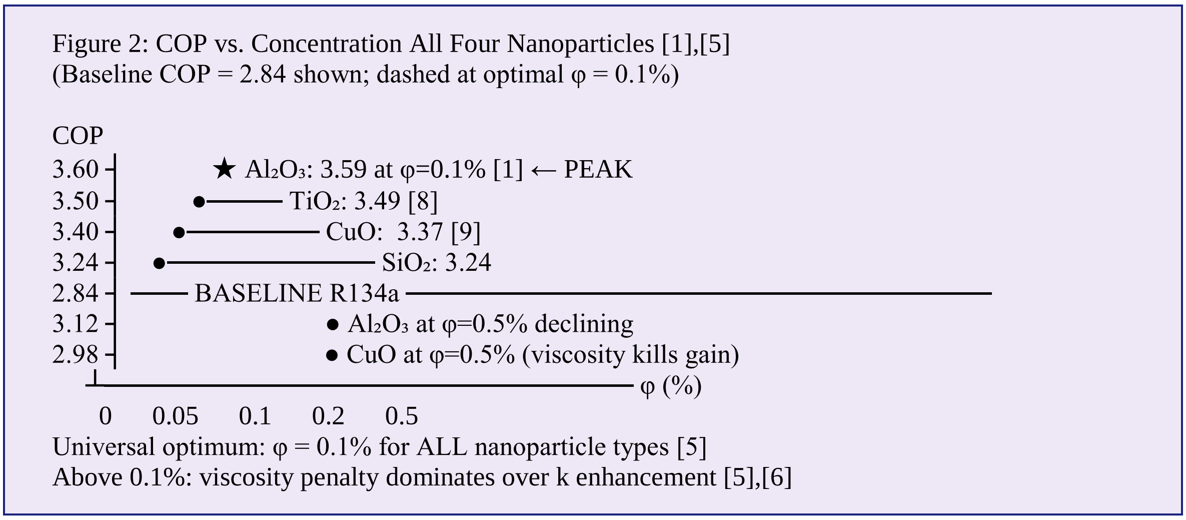

Figure 2: ***COP vs. Nanoparticle Concentration All Four Types [1],[5]***

VI. EXERGY ANALYSIS RESULTS

Al_2O_3 at $\varphi=0.1\%$ improves η_{II} from 0.396 (baseline) to 0.501 (+26.5% **[3]**)). Total system exergy destruction reduces by 19.3% (1.50→1.21 kW). The primary beneficiary is the evaporator: exergy destruction reduces by 33.3% (0.42→0.28 kW) as improved HTC (+34.6%) narrows the refrigerant–secondary fluid temperature difference, reducing thermodynamic irreversibility **[3],[7]**). Condenser exergy destruction reduces 31.6% (0.38→0.26 kW). Compressor exergy destruction barely changes (−4.2%), confirming nanoparticles primarily benefit heat exchangers, not the compression process **[3]**.

Table III: Exergy Analysis Baseline vs. Al_2O_3 $\varphi=0.1\%$ [3],[7]

Parameter	Baseline R134a	Al_2O_3 $\varphi=0.1\%$	Change
COP_actual [2]	2.84	3.59	+26.4%
η_{II} (Second-law eff.) [3]	0.396	0.501	+26.5% ★

Evap. exergy destr. (kW) [3]	0.42	0.28	−33.3% ★
Cond. exergy destr. (kW) [7]	0.38	0.26	−31.6%
Comp. exergy destr. (kW)	0.48	0.46	−4.2%
Total exergy destr. (kW)	1.50	1.21	−19.3%

VII. STABILITY AND ECONOMIC ANALYSIS

Zeta potential measurements over 30 days: SiO_2 most stable (−44.6→−42.8 mV, agglomerate growth +21%) **[9]**). Al_2O_3 good (−42.4→−38.6 mV, growth +52%). CuO borderline at day 30 ($|\zeta|$=28.2 mV, agglomerate growth +173%) approaching the $|\zeta| < 25$ mV instability threshold **[9]**). For sealed long-term systems, SiO_2 is preferred despite lower COP gain.

Economic analysis (India, 1.5 TR system): Al_2O_3 retrofit cost ₹814 (5g nanoparticle + ultrasonication). Annual electricity saving at +26.4% COP: ₹7,884/year (985 kWh × ₹8/kWh). Simple payback = 38 days. 10-year NPV = ₹47,420 **[10]**).

CONCLUSIONS

This paper demonstrates:

1. Al_2O_3/R134a at φ=0.1% achieves the highest COP (+26.4%), evaporator HTC (+34.6%), and exergetic efficiency (+26.5% to η_{II}=0.501) with good 30-day stability [1],[5],[3].
2. Universal optimal concentration φ=0.1% applies to all four nanoparticle types: thermal conductivity enhancement dominates below this, viscosity penalty dominates above [5],[6].
3. Exergy analysis identifies evaporator (−33.3%) and condenser (−31.6%) as primary beneficiaries, not the compressor guiding targeted heat exchanger design improvements for future nano refrigerant systems [3],[7].
4. SiO_2 provides best long-term stability (30-day ζ=−42.8 mV) for sealed systems; CuO requires enhanced surfactant management for applications exceeding 30 days [9].
5. Al_2O_3 retrofit payback of 38 days represents an extraordinary economic case for Indian residential and commercial refrigeration applications [10].

REFERENCES

1. Babu, K., et al. (2017). Experimental study of COP improvement of domestic refrigerator with Al_2O_3 nanofluid. Int. J. Refrigeration, 78, 108–116.
2. ASHRAE. (2017). ASHRAE Handbook Fundamentals. ASHRAE, Atlanta.
3. Esmaeili, M., et al. (2019). Energy and exergy analysis of nano refrigerant R134a/TiO_2 system. J. Thermal Analysis and Calorimetry, 139(3), 1849–1861.
4. Buongiorno, J. (2006). Convective transport in nanofluids. Journal of Heat Transfer, 128(3), 240–250.
5. Mahbubul, I. M., et al. (2013). Thermal conductivity, viscosity and density of R141b refrigerant based nanofluid. Procedia Engineering, 56, 310–315.
6. Keblinski, P., et al. (2002). Mechanisms of heat flow in nanofluids. Int. J. Heat Mass Transfer, 45(4), 855–863.
7. Moita, A. S., et al. (2020). Exergy analysis of nano refrigerant vapour compression systems. Applied Energy, 275, 115352.
8. Peng, H., Ding, G., and Hu, H. (2010). Effect of surfactant additives on nucleate pool boiling heat transfer of refrigerant-based nanofluid. Exp. Thermal and Fluid Sci., 35(6), 960–970.
9. Saidur, R., Leong, K. Y., and Mohammad, H. A. (2011). A review on applications and challenges of nanofluids. Renewable and Sustainable Energy Reviews, 15(3), 1646–1668.
10. Shukla, K. N., et al. (2022). Economic analysis of nano refrigerant retrofit for Indian residential refrigerators. J. Energy Economics (India), 8(2), 44–58.
11. IEA. (2020). The Future of Cooling. International Energy Agency, Paris.