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REVIEW

A critical review on the effect of nanorefrigerant and nanolubricant on the performance of heat transfer cycles

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Abstract

Nowadays, nanorefrigerants have been focused across the globe to improve the heat transfer characteristics of cooling units. Incorporating high thermal conductivity nanoparticles to the conventional refrigerants presented broad facts such as increased heat transfer coefficients, improved pool boiling inside closed cycles, enhanced COP, reduced compressor energy consumption of domestic refrigerators, and enhanced heat transfer rate during the two-phase flow of fluids. The present article focused on comprehensive experimental and numerical research reports of nanorefrigerants and nanolubricants. The heat and mass transfer and thermophysical characters such as viscous behavior, thermal conductivity, specific heat, and density have been discussed for various facts like flow condensation of fluids, evaporation, refrigerants pool boiling, and other related processes. The results showed that the volume concentration, diameter, and length of particles have a significant and crucial impact on the heat transfer rate and characteristics of pure refrigerants. Based on the available reports, it can say that the application of nanoparticles in pure refrigerants may enhance its features by about 50 – 60%. Further, the proposed correlations available in the literature for nanorefrigerants have been well discussed.

Nomenclature

A	Area (m^2)
C_P	Specific heat (J/kg K)
d	Diameter (mm)
F_{HT}	Nanoparticles impact factor
f	Friction factor
Fr	Froude number
g	Gram
h	Heat transfer coefficient (W/m^2 K)
I	Electric current (A)
G	Mass flux (kg/m^2 s)
R_p	Maximum roughness peak height (μm)
M	Molecular mass (kg/k mole)
Nu	Nusselt number
Pr	Prandtl number
q'	Heat flux (kW/m^2)
Re	Raynolds number
T	Temperature (°C)
V	Voltage (V)
We	Webber number
x	Vapor quality
X_{tt}	Martinelli number

Greek letter

Δ	Difference
λ	Thermal conductivity (W/m K)
ρ	Density (kg/m^3)
μ	Viscosity (Pa s)
φ	Mass fraction (%

Subscript

avg	Average
cr	Critical (thermodynamic critical point)
i	Inlet
o	Outlet
r	Refrigerant
n	Nanoparticles
nr	Nanorefrigerant
o	Oil
w	Water
wall	Wall temperature
t	Time
sat	Saturated
sup	Superheated
vol	Volume
gas	Gaseous state
nm	Nano meter
m	Meter

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p	Particles
l	Liquid
L	Litre

Abbreviations

Ag	Silver
Al_2O_3	Alumina oxide
ASHRAE	American society of heating, refrigeration and air conditioning engineers
CFC	Chlorofluorocarbon
CFD	Computational fluid dynamics
COF	Coefficient of friction
COP	Coefficient of performance
CuO	Copper oxide
EU	European union
F	Friction factor
GWP	Global warming potential
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbon
HFC	Hydro fluorocarbon
HTC	Heat transfer coefficient
HVAC	Heat ventilation and air conditioning
K	Kelvin
LPG	Liquid petroleum gas
MAC	Mobile air conditioning
MgO	Magnesium oxide
MO	Mineral oil
MWCNT	Multi wall carbon nano tubes
NH_3	Ammonia
NPs	Nanoparticles
ODP	Ozone depletion potential
PAG	Poly alkylene glycol
POE	Polyester
SAE	Society of automotive engineers
SDBS	Sodium dodecylbenzenesulfonate
SiO_2	Silica oxide
TiO_2	Titanium oxide
UV	Ultraviolet
ZnO	Zinc oxide
ZrO_2	Zirconium oxide

1 Introduction

Refrigerants are commonly used in commercial, industrial, and automotive industries for cooling and heating cycles. Chlorofluorocarbons (CFCs) have been widely used in cooling systems over the past few decades. However, CFC series fluids have been forbidden because of their toxic nature, which destroys the ozone protection of the earth. HFC series fluids like R134a have been successfully established and affected in automobile cooling systems for the past decade to fill the void created by the phase-out of CFCs. However, global warming problems have been addressed in the last two decades, and the Kyoto Protocol has moved to regulate greenhouse gases, including hydrofluorocarbons (HFCs) [1]. Table 1 elaborates the qualities of different fluids used in air conditioners, refrigerators, and chillers. As a result, HFC chain refrigerants had to be replaced as quickly as possible by environmentally friendly refrigerants. The replacement of HFC/134a was actively sought until this refrigerant was prohibited by the EU F-Gases Regulation and the MAC Directive. From 2011, the usage of HFC refrigerants in order to protect the atmosphere was banned from all automotive cooling systems of newly produced vehicles [2].

In particular, the MAC Directive also proscribed fluorinated greenhouse gases with a GWP greater than 150. The HFC refrigerants have been replaced with distinct kinds of refrigerants (such as R600a and R290 etc.), which have similar thermal properties, but GWP is low compared to HFC. Table 2 shows the different alternatives of HFC series refrigerants which are commonly used in air conditioners and refrigerators.

Maxwell [3] synthesized a nanofluid by dispersing small diameter particles (nanoparticles) in pure fluids to experience improved thermophysical characteristics. Nowadays, nanofluids have become a well efficient and suitable candidate in various disciplines and sectors such as pharmaceuticals [4, 5], automotive sector [6–8], atomic power [9, 10], lubrications of moving parts [11, 12], impinging technology [13, 14], micro-channels [15–17], heat transfer systems for electronic industries [18, 19], natural sources [20–22], cold storage and cooling sectors [23–28], combustion field [29, 30].

Nanorefrigerants and nanolubricants are proposed by dispersing the nanoparticles in a refrigerant and lubricant base. The three crucial merits of nanoparticles application in the coolants are as below [31]:

a) The nanoparticles increase the solubility rate within the coolant and the lubricant.
b) It boosts the thermophysical aspects and heat flow rate of the primary fluid.
c) The addition of nanoparticles in pure lubricant decreases the friction and wear/tear rate in compressors and other moving parts.

Nanorefrigerant studies have shown that the dispersion of nanoparticles into refrigerants will enhance the refrigerant heat transfer rate [32–34]. Nowadays, nanorefrigerant/nanolubricant plays a vital role in improving the heat transfer characteristics and energy efficiency of domestic or industrial refrigerators and air conditioners. Thus, employing a variety of nanoparticles with conventional working refrigerants is considered an outstanding fundamental reason to utilize nanorefrigerants in refrigeration and air conditioning

Table 1 The property characteristics of different refrigerants

Refrigerant	Name	Molecular Mass (g/mol)	Boiling point (°C)	Freezing point (°C)	Specific volume (m^3/kg)
R-11	Trichlorofluoromethane1	137.37	74.9	-168	0.001804
R-12	Dichlorodifluoromethane2	120.91	-21.8	-252	0.001792
R-13	Monochlorotrifluoro-methane	104.46	-114.6	-294	0.001729
R-13B1	Bromotrifluoromethane	148.91	-72	-270	0.001342
R-14	Tetrafluoromethane (Carbon tetrafluoride)	88.00	-198.2	-299	0.001598
R-22	Difluoromonochloromethane3	86.46	-41.3	-256	0.001904
R-40	Chloromethane (Methyl Chloride)	50.48	-10.7	-144	0.002834
R-113	Trichlorotrifluoroethane4)	187.39	118	-31	0.001735
R-114	1,2-dichloro-1,1,2,2-tetrafluoroethane	170.92	38.4	-137	0.001717
R-115	Chloropentafluoroethane	154.47	-38.0	-149	0.001629
R-134a	Tetrafluoroethane6)	102.03	-15	-142	0.00181
R-140a	Trichloroethane	133.04	165	–	–
R-142b	1-chloro-1,1-difluoroethane	100.50	14	-204	0.002297
R-170	Ethane	30.097	-127	-278	0.005182
R-218	Octafluoropropane	188	-36.4	–	–
R-290	Propane	44.09	-44	-309.8	0.004545
RC-318	Octafluorocyclobutane	200.04	22	-43	0.001611
R-500	Dichlorodifluoromethane	99.31	-28	-254	0.002016
R-600	n-Butane	58.12	31.2	-217	0.004382
R-600a	Isobutane (2-Methyl propane)	58.12	10.8	-229	0.004526
R-611	Methyl formate	60.05	89	-146	0.002865
R-717	Ammonia	17.02	-28	-107.9	0.004245
R-744	Carbon dioxide	44.01	-109.4	-70	0.002135
R-764	Sulfur Dioxide	64.06	14.0	-104	0.00191
R-1150	Ethylene	28.05	-155	-272	0.00437
R-1270	Propylene	42.08	-54	-301	0.004495

components. For the better enhancement in the performance of refrigerator and air conditioning components, nanoparticles with higher thermal conductivities have been used by researchers and scholars. The nanoparticles enhance the efficiency of cooling components by strengthening the internal thermophysical aspects [35, 36], like thermal property or conductivity and vapor quality of the selected fluid [37–40]. The thermal property (a thermal property known as thermal conductivity) of proposed nanorefrigerants provides a better result than the base refrigerant [41]. Most commonly, the improvement in thermophysical properties such as thermal property or conductivity, vapour quality, and dynamic viscosity is more responsible for enhancing any closed cycles such as air conditioners and refrigerators [42]. Many researchers

Table 2 Relevant information on R-134a and potential R-134a alternatives

Refrigerant	Composition	Average Molar Mass (g/mole)	Dew Point (°C)	Critical Temperature (°C)	GWP	ASHRAE Classification
R-134a	R-134a(100)	102.0	-26.1	101.1	1300	Al
R0513A	R-134a/R-1234yf (44/56)	108.4	-29.2	96.5	573	Al
R-450A	R-134a/R-1234ze(E) (42/58)	108.7	-22.8	105.6	546	Al
R-515A	R-1234ze(E)/R-227ea (88/12)	108.7	-19.0	108.7	402	Al
R-1234yf	R-1234yf (100)	114.0	-29.5	94.7	< 1	A2L
R1234ze(E)	R-1234ze(E) (100)	114.0	-19.0	109.4	< 1	A2L
R-600a	R-600a (100)	58.1	-11.7	134.7	3	A3

reported that nanolubricants improve the tribological and rheological properties inside the compressor and rotary components used in refrigeration cycles [43–46]. Further, different factors such as size, shape, design dimensions, nanoparticles fraction, temperature aggregation, and surfactant usage also affect the performance of the closed two-phase system, as reported through many publications [47, 48]. These all mentioned factors affect the characteristics of the vapour compression cycle, whether it is domestic or industrial. A large study has been published on the application of nanofluids in different sectors, including transport, domestic and industrial [49–51], heat ventilation and air conditioning (HVAC) systems [52, 53], automotive air-conditioning cycles [54, 55], electronics [56], heat pump, heat exchangers, energy conversion systems, phase change materials, chemical, thermal processes, chillers in nuclear industries, and electrical applications [57], aerospace stations, transport systems [58], fluidic systems, and bio- engineering applications [59–62].

The objective of this review article is to discuss the role of developed nanorefrigerants (refrigerants using nanoparticles) and nanolubricants (lubricants using nanoparticles) inside the cooling channels, heat pumping components, heat exchangers, and pool boiling systems. At the initial stage, the study focuses on the preparation method of nanorefrigerants and nanolubricants. The second target is to discuss the role of different nanoparticles in domestic refrigerators, air conditioners, refrigeration compressors [63, 64], and other parts of closed-cycle such as condensation and boiling [65–69]. The study of the flow boiling heat transfer using nanorefrigerants is a significant area of research as many publication reports are available. Still, flow condensation has fewer references available in the literature.

2 Review reports available in the literature

The review reports on nanorefrigerants and nanolubricants have been published by several authors. Saidur et al. [70] published a review article explaining nanoparticles impact in conventional refrigerants and compressor lubricating oils. The author concluded that R134a with mineral oil and TiO_2 nanoparticles works safely and efficiently in the domestic refrigerating machine. Celen et al. [71] reviewed the flow properties of nanorefrigerants inside refrigeration appliances and air conditioners. The author clarified the influence of nanoparticle characteristics such as particle size and shaped on refrigerant pressure drop and heat transfer coefficient compared to conventional or pure refrigerants.

Further, the studies on thermophysical characteristics of nanorefrigerants and nanolubricants, pool boiling heat transfer, and usage of nanorefrigerants in domestic refrigerators and air conditioners were elaborated. In a review report of Alawi et al. [72], the influence of different nanorefrigerants and nanolubricants on heat transfer aspect and refrigerator compressor energy consumption focused. The applications of nanorefrigerants to specific appliances such as domestic refrigerating machines, heat pipes, and air conditioners were reviewed. The author highlighted that pool boiling heat transfer might improve or deteriorate through the usage of nanoparticles. Redhwan et al. [73] published a review report that mentioned that heat transfer coefficient augmentation purely depends upon the fractions and size of nanoparticles. The author suggested the usage of CFCs, HCFCs, and HFCs refrigerants with distinct metal/metal oxide nanoparticles to observe the heat transfer coefficient in heat transfer appliances. Azmi et al. [74] reviewed a study focused on nanorefrigerant and nanolubricant effect on energy saving of refrigeration and air conditioning appliances. One of their primary results is using R152a/ZnO nanorefrigerant, which saves 21% compressor energy compared to R152a. Yang et al. [75] focused on the cooling and heating process using nanoparticles dispersed in conventional refrigerants and lubricants in another review article. The heat transfer properties of nanorefrigerants and nanolubricants, thermophysical characteristics of synthesized nanolubricant, and nanorefrigerants (R113/CuO and R141b/Al_2O_3) have been reviewed. Yildiz et al. [141] published a review report focused on experimental investigations on nanorefrigerants and nanolubricants performance of refrigeration systems, flow condensation, and pool boiling process. The author reported an improved heat transfer rate using small diameter nanoparticles.

Further, the report concluded various factors affecting the performance of nanorefrigerant, such as long-term stability. In a recent review of Vamshi et al. [142], various nanorefrigerants and nanolubricants influence thermophysical characters, heat, mass flow rate, and pumping power of refrigeration system considered. The correlations developed to calculate thermal characters such as thermal conductivity, density and viscosity have been reported.

3 Synthesis of nanolubricant and nanorefrigerant

Generally, two categories of synthesis approaches are the step direct method, and the other is the step indirect method used in the synthesis of nanofluids. Nanorefrigerant is also a kind of nanofluid and prepared based onthe same approaches. In general, nanorefrigerant is prepared by mixing the nanoparticles either in a refrigerant or through the lubricant. It depends upon the phase-type of the refrigerant. Usually, many refrigerants (such as R134a, R152a, R600a, R290, etc.) used in domestic refrigeration components are vapor under atmospheric conditions. In such cases, the nanolubricants are synthesized by mixing technique, and further nanolubricant is appended with refrigerant to make a blend (refrigerant/nanolubricant) called nanorefrigerant. In other cases, the refrigerant (such as R113, R141b, etc.), which is usually used in the industrial sector for chiller plants, are in the liquid phase on atmospheric conditions, so the nanoparticles can directly be dissolved in the refrigerant to make a blend (refrigerant/nanoparticles) called nanorefrigerant. Citing an example, Lin et al. [76] defend a nanorefrigerant synthesis report on mixing TiO_2 nanoparticles in host refrigerant R141b. The primary fact of the study is that the selected refrigerant HCFC – 141b did not append with nanolubricant earlier to the process because of the unstable state of the fluid in the liquid state. On the other hand, to examine the structural effects, shape, size, and other characteristics of nanoparticles, many methods are available such as x-ray approach, energy diffusion x-ray spectroscope, transmission electron microscopy approach, vibration sample magnetometer, thermal test, UV spectroscopy, scanning electron microscopy and dynamic light scattering [77]. The stability examination of prepared nanolubricant is a significant parameter and would be followed before injection into the test rig [78]. For example, Yang et al. [79] synthesized a nanorefrigerant by dispersing MWCNT into R141b. The blend was prepared under a 30-min process of ultrasonication. After that, a visual method using spectroscopy was used to analyse the stability of the prepared nanorefrigerant.

Many reports state that the stability of nanofluid is a crucial parameter before injecting it into a working cycle. The most vital point is that the inspection of nanofluid stability must be of long tenure (average of 1 month). The result showed that the nanorefrigerant transparency increases concerning increment in the period (shown in Fig. 1). According to a study by Heris et al. [80], the prepared nanorefrigerant stability was better after 24 h from the synthesis process. The author also declared that density finding during the selected period is a easy technique to examine the mixing stability. In a study by Yang et al. [81], the ultrasonication process of half an hour and mechanical agitation process was used to prepare a stable nanofluid. The ZnO nanoparticles dispersed into a SAE50 lubricant.

In comparison with conventional methods of nanofluid synthesis, a post-treatment technique was proposed to enhance the mixing stability of nanorefrigerant. In some cases, very hard aggregates are present inside the nanorefrigerant, which is birthed in the synthesis process of dry particles. It is harder to fracture these aggregates through chemical and physical methods. The complex aggregates at the bottom were pulled out directly using the post-treatment technique [82, 83].

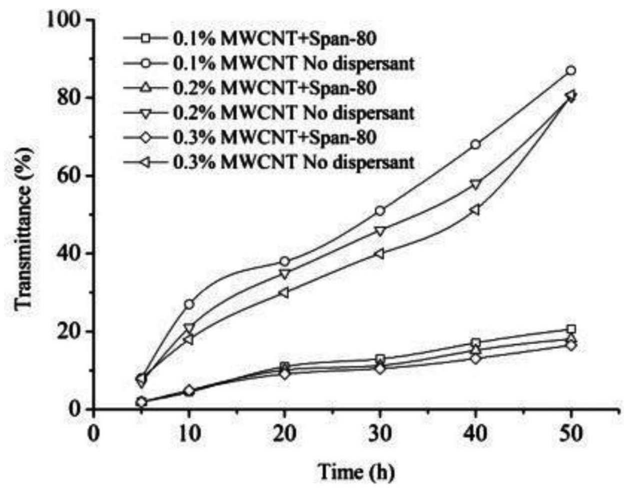


Fig. 1 Transparency status of synthesized nanorefrigerant [79]

4 The role of nanorefrigerant and nanolubricants within the heat transfer cycle

4.1 Effect of CuO nanoparticles

Behabadiet al. [84] published a well-defined experimental report on flow condensation heat mass transfer properties of HCR600a/lubricant/CuO blend flowing inside horizontally dimensioned smooth copper pipe. Three fluids (HCR600a, HCR600a/polyester oil blend, and HCR600a/lubricant/CuO nanorefrigerant) were synthesized with distinct CuO fractions of 0.5, 1, and 1.5 wt. % and tested within a horizontal smooth tube test section. Several parameters such as mass velocities (range 154.7 to 265.3 kg/m^{2}s), vapor quality (within 10–80%), heat fluxes (range 17 to 20 kW/m^2), and condenser pressures (range 0.51 to 0.62 MPa) were selected to observe the effect on HTC. The study reported 83% heat transfer rate enhancement at 1.5 wt.% particles fraction compared to the base fluid of R600a (shown in Fig. 2). Sanukrishna et al. [85] studied the influence of CuO-based nanolubricant inside a cooling cycle in performance improvement. A poly-alkylene/CuO nano-refrigerant was tested inside a designed experimental rig. Results showed that the application of 0.1 vol. % fraction of copper oxide particles enhanced the efficiency of the domestic refrigerator, like COP, Freezing capacity, and power consumption. The heat transfer rate at the freezer and air-cooled condenser was also enhanced.

Further, the thermophysical property (such as thermal conductivity) of poly alkylene lubricant using CuO particles observed a 12.67% increment compared to base lubricant. Tashtoush et al. [86] proposed a study and modeled a

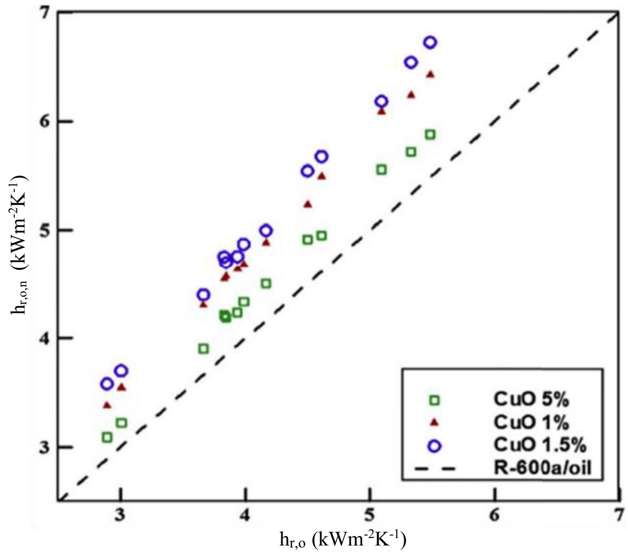


Fig. 2 Heat transfer coefficients for pure R600a and synthesized R600a/CuO [84]

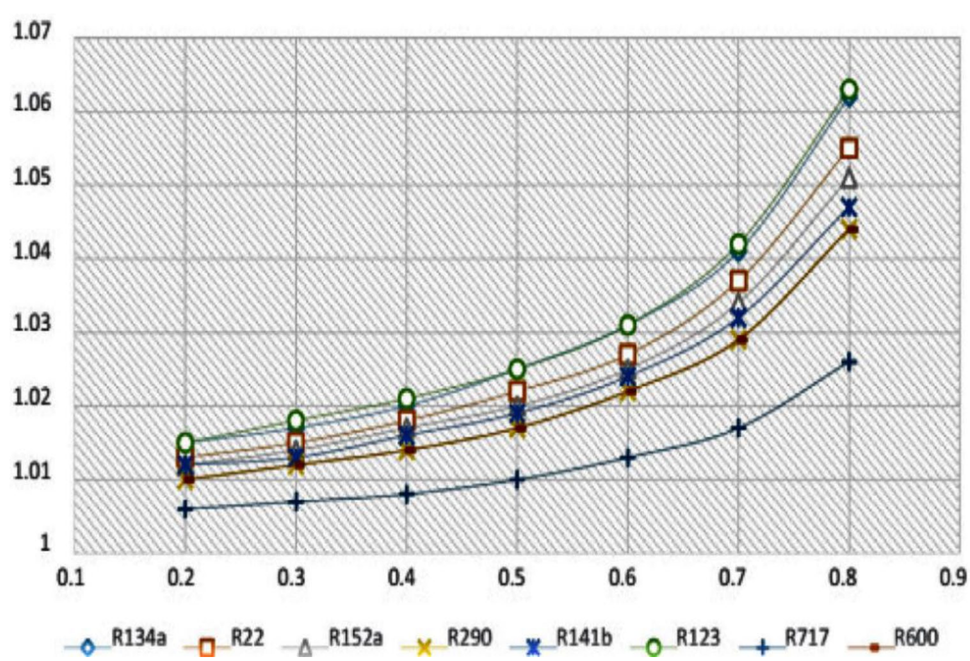
flow boiling inside an ejector-based refrigeration cycle using distinct nanorefrigerant, namely the mixtures of Al_2O_3 and CuO nanoparticles with R134a, R22, R141b, NH_3, R123, R290, R600, and R152a. The reaction of particle diameter, shape, mass, and temperature was tested on the HTC and performance. The study focused on resisting the migration of nanoparticles to the vapor phase of refrigerants. The author published a hypothesis that indicated a good validation with the available facts, with an approximate deviation of 10%. Further, the enhancement in the HTC of both R123 and R134a was found upto 7% (Fig. 3).

Similarly, another experimental research by Sun et al. [87] considered distinct nanoparticles with refrigerant R141b (copper/R141b, copper oxide/R141b, alumina/R141b, and alumina oxide/R141b) target pool boiling heat flow study during a horizontal pipe. The author declared copper/R141b as a better-performed nanorefrigerant. Various variables including nanoparticles fractions of 0.10, 0.20, and 0.30 wt. %, the mass flux of 120, 210, and 330 kg/m^{2}s and vapor class from 0.3 to 0.8 tested to collect the heat transfer performance inside the tube. The HTC increased using investigated variables, specifically a particle's weight fraction. Finally, Cu/R141b at mass velocity or flux of 120 kg/m^{2}s using 0.3 wt.% particles fraction observed the highest HTC of 49% compared to other selected blends (graphical data shown in Fig. 4).

Some other experimental studies targeted flow condensation of cooling processes, such as Sheikholeslami et al. [88], to experimentally define the heat flow rate and frictional pressure reductions of R600a/POE/CuO nano-refrigerant condensation inside a tube. It reported that the presence of nanoparticles during condensation observed a destructive result as an increment in the friction pressure drop.

Kaushik et al. [143] experimentally observed the effect of varying concentrations (1.2 to 1.5 wt.%) of CuO nanoparticles inside the R134a based vapor compressed cycle. They found that the overall performance coefficient using nanorefrigerant is better than pure refrigerant. Yalmiz [144] mixed Cu (II) oxide and Cu/Ag hybrid nanoparticles mixed in R134a flowing inside a refrigerating unit. The author studied various characteristics such as friction coefficient, energy consumption, and performance coefficient. The results showed that using Cu/Ag and CuO nanorefrigerant,

Fig. 3 Heat transfer coefficient results at 0.5 wt. % fraction of CuO nanoparticle [86]



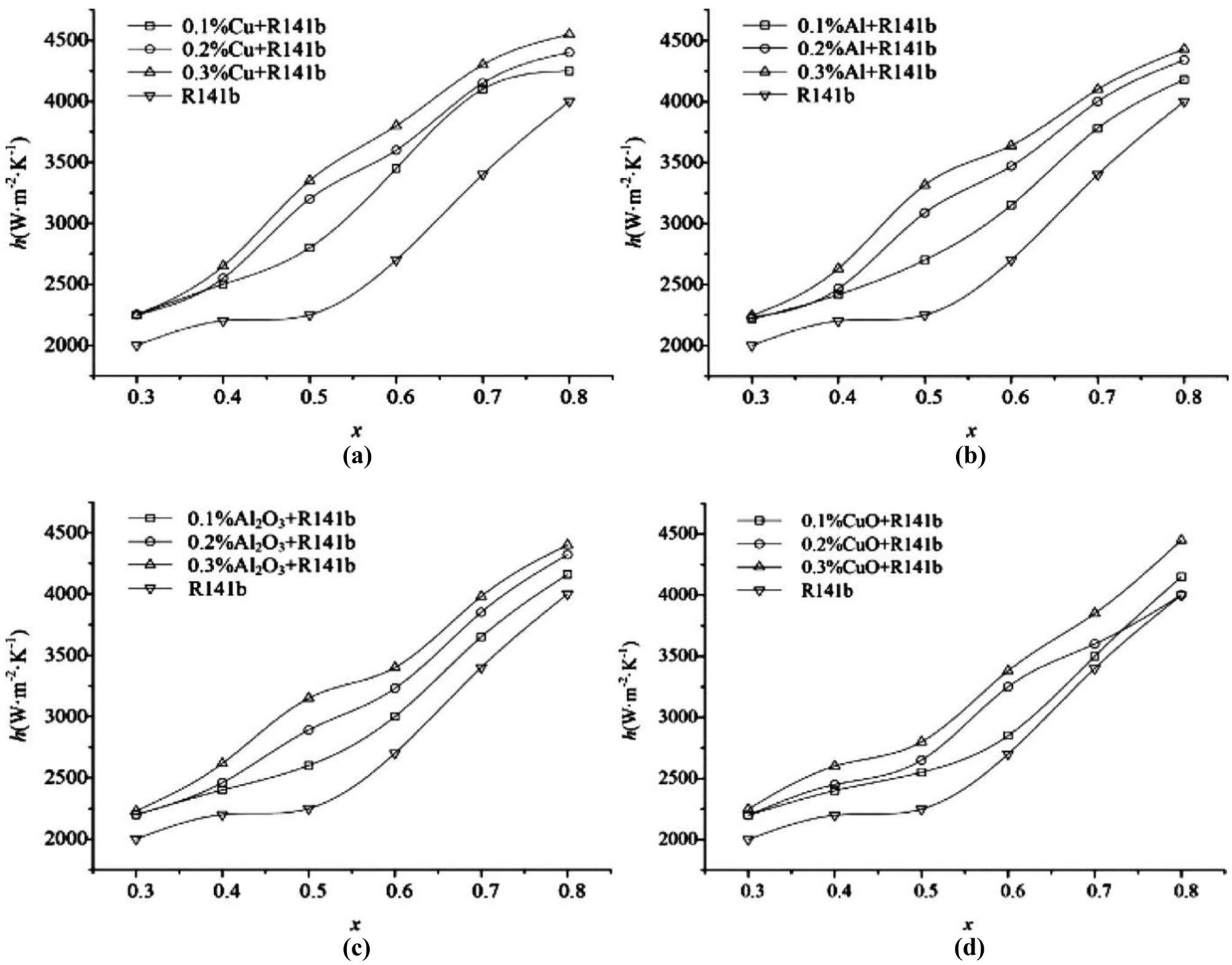


Fig. 4 Heat transfer coefficients of nano-refrigerants at a mass flux of 120 kg/m^2s [87]

significant improvements in COP about 20.8% and 15.7%, respectively, were observed.

4.2 Effect of SiO_2

Silicon oxide nanoparticles are a classic variety of nanomaterial. However, the studies related to the usage of SiO_2 particles in refrigeration and air conditioning systems are not much widely available in the literature. Krishna et al. [89] study the character of silicon dioxide particles on heat transfer improvement and lubricant tribology properties inside a heat and mass transfer closed cycle. The blend of R134a/poly-alkylene/SiO_2 was synthesized to define the heat transfer characteristics using different variables such as particle fraction, vapor quality, mass velocities, and heat flux. The author reported a maximum outcome of 163% for the HTC with a 0.4% nanoparticle fraction. It was noticed in various reports that a minor increment in pressure drop is common using nanorefrigerant instead of base refrigerant. In another work targeting thermal characteristics and heat transfer efficiency, Nawi et al. [90] used silica particles and hydrofluoro-ether based Newtonian nanorefrigerant to study flow boiling in a smooth horizontal pipe. The ideal volume fraction 0.02 vol. % of SiO_2 helped increase thermal conductivity by about 27% and an increment in refrigerant viscous behavior and boiling HTC. The author also reported that the rise in selected nanorefrigerant temperature reduced fluid conductivity and dynamic viscosity.

4.3 Effect of TiO_2

Bi et al. [91] examined a study related to the domestic VCR cycle using R600a/TiO_2 nanofluid. Two parameters, cooling capacity, and compressor work, investigated experimentally. Considering TiO_2 fractions of 0.10 g/L and 0.50 g/L in R600a, the compressor work retained about 5.90% and

9.56%, respectively. Further, an outstanding variable, namely freezing velocity of R600a/TiO_2 system, also expressed a good outcome compared to the conventional R600a based refrigerator. The author found similar outcomes when R134a/TiO_2 nanorefrigerant was used in the same refrigerator. Thus, the use of nanorefrigerant in domestic refrigerators as working fluid is discussed as a suitable candidate for better improvements in performance.

Jiang et al. [92] designed a well small-scale NH_3 – water absorption refrigeration cycle to study the blend of TiO_2/SDBS. Synthesized nanofluids with distinct mass concentrations of TiO_2 nanoparticles of 0.1, 0.3, and 0.5 wt.% were employed, and the highest increased value of COP, about 27%, was observed with 0.5 wt. % of titanium particles using 0.02 wt. % fraction of selected surfactant.

Jatinder et al. [78] published a research report explaining a domestic refrigeration system's thermal conductivity and good performance. The author considered three candidates (TiO_2, R600a, and MO) to contrast with primary refrigerant LPG. Refrigerant R600a mass fraction of 40 g and TiO_2 fraction of 0.2 g/L were reported as optimum values of the whole study. Results showed a significant reduction in compressor work, compressor discharge temperature, and cooling time. Moreover, an increment of 62.54% in the coefficient of performance was reported.

4.4 Effect of Al_2O_3

Aktas et al. [93] investigated COP, compressor power, and evaporator heat rate concerned to compressor discharge and freezer temperatures, using five distinct synthesized nanorefrigerants containing aluminum oxide nanoparticles. The five various refrigerants (name: R134a, R430a, R12, R436a, R600a) were utilized to synthesize the selected nanorefrigerant. The author proposed a good enthalpy calculation approach rooted in nanofluid density. The results discussed as the highest value of COP was achieved with R600a/Al_2O_3 blend. With this, refrigerants R12 and R134a showed the lowest value of compressor energy compared to others. Mahbubul et al. [94] experimentally determine the effect of thermal conductivity, viscosity, and density on COP of the cooling cycle. Al_2O_3 with a volume fraction of 5% mixed in R134a is considered to make the nanorefrigerant. At a temperature of 308 K, thermophysical properties such as density, λ, and μ of the synthesized nanorefrigerant enhanced about 27.50%, 10.9%, and 13.6%, respectively (shown in Fig. 5). Also, the improved thermal property of the selected nanorefrigerant increased the performance coefficient of the cycle by about 15%, while density and specific heat improved by 3.1% and 2.5%, respectively.

Eid et al. [95] fabricated a refrigerator to target the study of the heat flow behavior of nucleate evaporation using

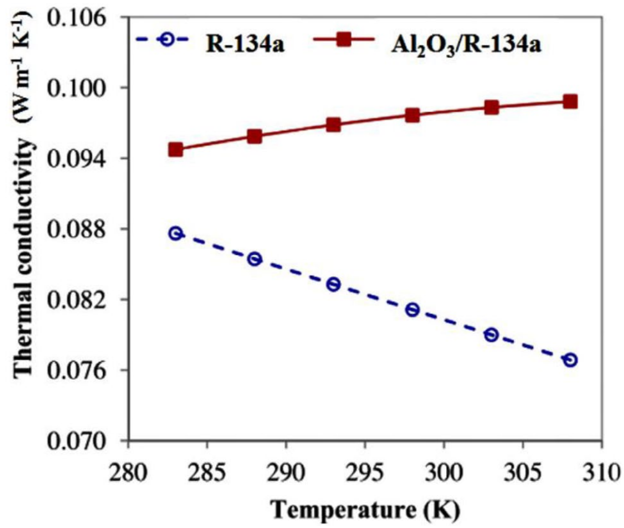


Fig. 5 Thermal conductivity of pure R134a vs. R134a/Al_2O_3 nanorefrigerant as a function of temperature [94]

refrigerant R141b and Al_2O_3 particles. The designed system contained a well-covered evaporator cabin with a steel material horizontal in the shape of around surface, a cooling unit, a condenser, and a control switchboard.

The author considered Al_2O_3 nanoparticles with distinct fractions of 0.001%, 0.005%, 0.01%, 0.03%, 0.05%, and 0.1% with pure fluid R141b. The results showed that a maximum HTC of about 124% was achieved using a 0.05% fraction of Al_2O_3 (Fig. 6). Further, the author observed that HTC achieved an increment only up to a volume fraction of 0.05%, and after that, a reduction was collected up to 0.1% volume fraction. The author reports this interesting matter is that employing more nanoparticles may resist the heat transfer as a layer deposited

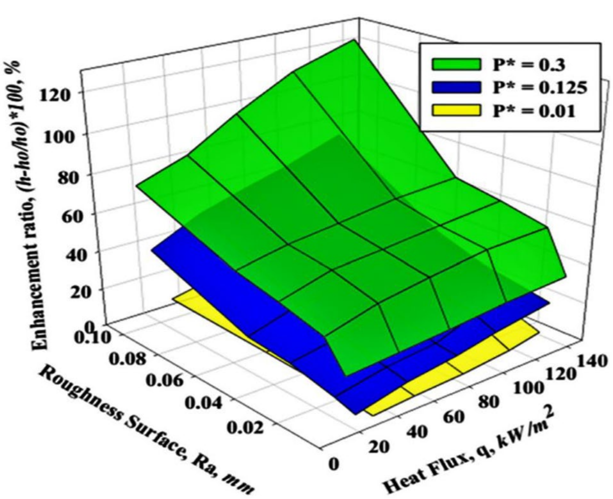


Fig. 6 The enhancement ratio vs. heat flux and surface roughness at distinct normalized pressures using Al_2O_3 particles [95]

above the heating surface. The author also drew a correlation based on 165 experimental tests performed in his study:

$$h = \frac{4(IV)}{\pi d^2 \delta T} \tag{1}$$

I refer to electric current, V as voltage, and δT is temperature variation. Further, it validated with the work of Cooper's proposed correlation [96]:

$$q^{0.67}(55)\left[\frac{p}{p_{cr}}\right]^{(0.12-0.2logR_p)}\left[-log\frac{p}{p_{cr}}\right]^{-0.55} M^{-0.5} \tag{2}$$

The literature shows very few studies on air conditioning cycles compared to domestic refrigerators. Considering Al_2O_3 nanoparticles at fractions of 0.1, 0.2, 0.3, 0.5, and 1 wt%, Hady et al. [97] performed a thermal energy characteristics test on an H_2O chilled cooling unit. Al_2O_3/H_2O nanofluid was synthesized and used inside the cooling coil of the system. The author reported that the usage of Al_2O_3 nanoparticles significantly enhanced the cooling capacity of the air conditioner unit. For instance, the highest value of COP, about 17%, was achieved with 1 wt.% applied mass fraction.

4.5 Effect of multiwall carbon nanotubes (MWCNTs)

MWCNTs, referred to as multiwall carbon nanotubes, have high thermal conductivity compared to other metal oxide nanoparticles, making them a suitable candidate for efficient nanorefrigerant. According to a literature survey, MWCNTs based nanorefrigerant shows tremendous improvements in thermal property and flow boiling HTC compared to pure refrigerants [98].

Yang et al. [99] performed experimental research to study flow heat transfer properties of MWCNT/R141b nanorefrigerant, using distinct weight conc.of 0.10, 0.20 and 0.30 wt. %, Nusselt number, and Re number inside a channeled pipe. The report significantly received a heat transfer boost using MWCNTs in pure refrigerant, along with Nu number enlargement. The highest increment of the Nu number was reported by 41%. Also, the author observed an increment in fluid viscosity and pressure drop with the addition of nanoparticles and surfactants. The author proposed a correlation for flow boiling of a single-phase forced convection HTC. The range of Reynolds number was mentioned of approximately from 9000 to 15000.

$$h = Re_l^{0.7} Pr_l^{-1.22}(1+\varphi)^{0.23\frac{\lambda l}{d}} \tag{3}$$

Re_l refer as Reynold number, Pr_l known as Prandtl number for liquids only, φ known as particle fraction, λ_l represents as thermal conductivity for liquids, and d is the diameter. The above correlation achieved through modified well-known correlation developed by Winterton [100]:

$$S = \frac{1}{(1 + 0.55E^{0.1}Re_l^{0.16})} \tag{4}$$

S is the sheltering factor, h refers as heat transfer coefficient (HTC), E represents strength factor for two-phase flow, h_{pool} defines the pool boiling HTC, q known as heat velocity, x is vapor grade, P and P_σ stands for fluid normal stress/pressure and critical stress, M stands for molar mass, ρ_l stands for density for pure liquid and ρ_v refers as the density of vapors. Two correlations given by Jung and Radermacher in 1991 for flow boiling heat transfer phenomena have been written as below:

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_{gas}}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_{gas}}\right)^{0.7} \tag{5}$$

X_{tt} stands for Martinelli number, g is gravitational acceleration, ρ_g refers as density for the gaseous state, μ_l and μ_{gas} are the dynamic viscosities for pure liquid and gaseous states, respectively. Fr represents Froude number, and G is the mass velocity.

$$h = 3.9Fr_l^{0.24}\left(\frac{x}{1-x}\right)^{0.64}\left(\frac{\rho_l}{\rho_v}\right)^{0.4} \tag{6}$$

$$Fr_l = \frac{G}{\rho_l^2 gd} \tag{7}$$

In a similar study performed by Lin et al. [101], the author published a report representing the outcomes of employing MWCNTs in R141b using the surfactant SDBS (sodium dodecylbenzene sulfonate). The application of nanoparticles in R141b efficiently improved the thermophysical properties, as reported by the author. The refrigerant R141b is a well suitable fluid with low GWP and ODP values for the refrigeration unit. Further, Kumar et al. [102] experimentally studied heat transfer characteristics of MWCNT/H_2O blend inside a tubular heat exchanging design. MWCNTs were distributed in the blend of H_2O and ethylene glycol (ratio of 70:30). In terms of results, the observed convective HTC was increased about 160% using 0.45 vol.% fraction of multi-walled CNT at temperature range 40 °C. Also, an increment of 19.37% was achieved for the thermal property of the MWCNT/H_2O-ethylene glycol blend. Moreover, the study mentioned that a small reduction in the Reynolds number at entire temperatures with a minor increment in the friction was observed. Finally, at a higher velocity and temperature range, the optimum value of 0.15% of multi-walled CNT addition worked better.

Peng et al. [103] practically conducted research to see the outcome of CNTs in R113/oil-based nucleate pool boiling design. The study considered different weight fractions of 0 to 30 wt.% for CNTs. The author used four kinds of carbon nanotubes which were categorized via different outer diameters range 15 to 80 nm and distinct length range within 1.4 to10 μm. The results showed the most remarkable improvement of 61% for nucleate pool boiling HTC by reducing the outer nanotube diameter and increasing the particle length. The author formulated a new equation for nucleate pool boiling HTC by conducting approximately 300 experimental tests. The heat flux (range:10 to 80 kW/m^2) and the saturated pressure was 0.10 MPa. The author used the correlation given by Rohsenow in 1952 for heat transfer of the nucleate boiling flow [104]:

$$q_{nucleate} = \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{0.5} \left[\frac{c_{pl}(T_s - T_{sat})}{c_{sf} h_{fg} Pr_l^n} \right] \quad (8)$$

$q_{nucleate}$ represents the boiling heat flux, C_{sf} stands for hypothetical constant, T_{sat} stands for saturated temperature and subjects to a combination of surface and fluid, n is also hypothetical constant.

Sun et al. [105] conducted an experimental work inside a pipe by the usage of two blends of multi-walled CNT-carboxylic acid /R141b and MWCNT- hydroxide /R141b. Different variables such as thermal conductivity, mass flux, particle fraction, viscosity, and vapor quality at inlet conditions were studied to focus on the outcomes of boiling HTC and the effect factor. The author declared that the maximum improvement about 23.5% for synthesized multi-walled CNT – carboxylic acid/R141b nanofluid and 15.17% for multi-walled CNT-hydroxide/R-141b using 0.175% of particle concentration, mass flow of 120 kg/m^2/s^1 and vapor quality range of 0.5 (graphical data shown in Fig. 7). The author used the below-mentioned method to find out the flow boiling HTC:

$$h_{pool} = 55(Pr)^{0.12}\left(-l_g Pr\right)^{-0.55} M^{-0.5} q_{exp}^{0.66} \quad (9)$$

q_{exp} representsexperimental heat flux ranges from 5 – 25 kW/m^2.

Peng et al. [61] did a study on nucleate boiling heat flow rate using pure metallic copper nanoparticles inside R113/ester oil blend. The author reported an excellent heat transfer improvement using Cu nanoparticles and also proposed a correlation of HTC of nucleate heat boiling phenomena by 93% in accordance with the entire available practical record.

Choi et al. [148] investigated the performance of MWCNT particles in the R134a refrigerator. The author reported that power consumption of compressor was reduced by about 17% using nanorefrigerant compared to a refrigerant with which the COP of the refrigerator improved around 28%.

4.6 Other Nanoparticles

Maheshwary et al. [106] investigated the ZnO particles shape effect on heat flow and thermophysical character of R134a flowing inside an air-conditioning and refrigeration cycle. The study considered the cubic and spherical shape of particles. The outcomes reported a significant growth in thermal conductivity of nano-refrigerant, about 42.5% for cubic and 25.26% for spherical shape, respectively (Fig. 8).

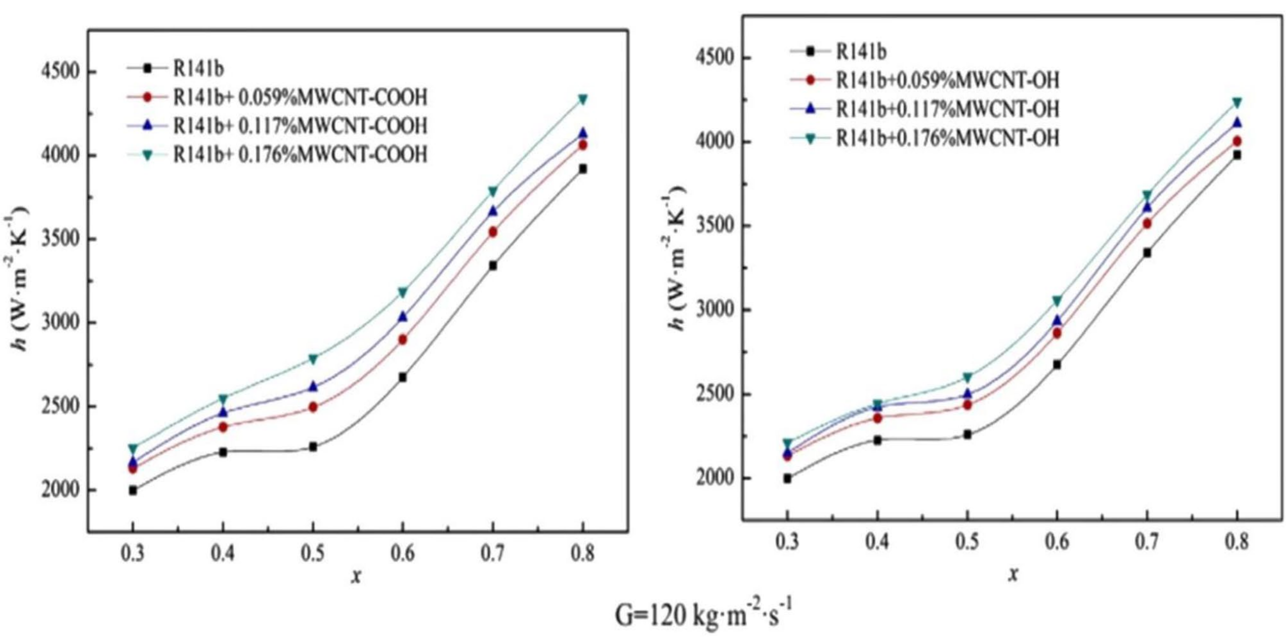


Fig. 7 Heat transfer coefficient variations of the particle at distinct fractions using MWCNT/R141b nanorefrigerant [61]

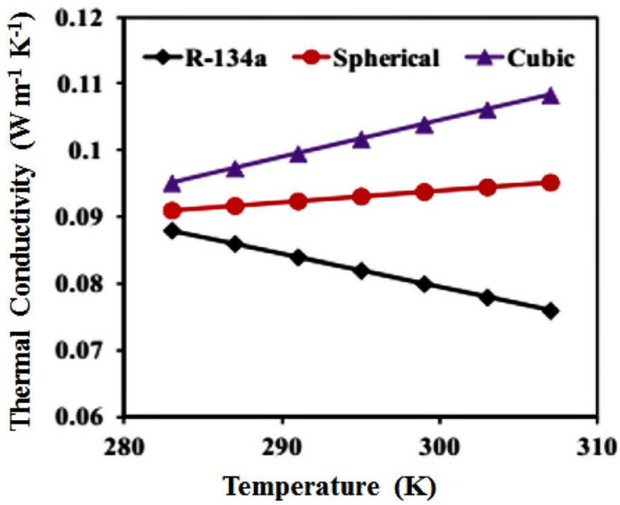


Fig. 8 Thermal conductivity of 134a using spherical and cubic shaped ZnO nanoparticles [106]

Also, an increment in dynamic viscosity and heat capacity decrement was observed. Peng et al. [107] used diamond nanoparticles and published an experimental report. The author synthesized an R113/diamond/VG68 nanorefrigerant to notice the heat transfer properties of nucleate boiling. The outcomes showed an improved HTC of 63.5% compared to the base refrigerant. Some researchers studied the effect of nanoparticles employing inside heat transfer systems appended with renewable energy sources such as solar energy. For example, Ghafurian et al. [108] published a research report representing the influence of carbon-based nano-size particles on fluid evaporating rate enhancements inside solar connected generator type cycle.

Citing a few examples of the efficient results of heat exchange rate and thermal augment using nanorefrigerants inside solar-driven systems, Kumaresan et al. [102] used a blend of multi-walled carbon nanotubes in an H_2O-ethylene glycol mixture. The nanoparticle diameter ranges 30–50 nm in 10–20 µm in long with 0.45% fraction was used. In terms of results, a 19.36% increase was received in thermal conductivity. Eid et al. [109] dispersed Al_2O_3 particles having 40 nm size and 0.001–0.10 vol. % in pure R141b fluid. The result showed a 124% improvement in the pool boiling HTC. Finally, most of the studies related to MWCNT, CuO, and Al_2O_3 based nanofluids are the most efficient and suitable for practical applicability. Karthick et al. [145] studied the performance and exergy characters of the refrigerating unit using various nanoparticles ZnO, TiO_2, and Al_2O_3 with R600a. The author mentioned 14.6% COP enhancement and 7.5% improvement in exergy efficiency using nanorefrigerants. Sarrafzadeh et al. [146] published a thermodynamic and energy analysis study of R134a/Al_2O_3 refrigerators. The author mixed 0.05, 0.1, and 0.3 vol. % fractions of alumina particles in refrigerator one by one and found 2.69% reductions in compressor power at 0.1% Al_2O_3 and 20% increment in an evaporator temperature gradient. Deokar et al. [147] investigated the heat transfer coefficient and pressure drop characters of flow boiling inside a smooth tube using R410a with ZnO and gamma-alumina nanoparticles. The author declared that thermal conductivity and viscosity have higher values using NPs in R410a and lower pressure drops. The overall heat transfer coefficient also had higher values in the case of nanorefrigerant (Table 3).

A new caste of nanofluid has been developed called io – nanofluids. These high thermal behavior nanofluids should be considered for application in HVAC&R systems [110].

5 Numerical reports on nanorefrigerants/ nanolubricants

According to the literature survey, few numerical reports represent nanorefrigerant performance of refrigeration and air conditioning cycles (Table 4 and 5). Helvaci and Khan [111] did a numerical investigation and studied the heat flow rate and entropy inception of selected refrigerants using Al_2O_3, CuO, silica oxide,and MgO nanoparticles. The selected particles were utilized in pure HFE7000 (lubricant). The study considered particles fraction of 0 – 6 Vol. %, and the fluid flow was laminar flow. The author reported the study as 2D and stable state inside around pipe. The heat flux throughout the test was constant (1000 W/m^2) and subjected to an upper surface of the tube. The work used an FVSF. The study resulted in the entropy inception ratio showing reduction with an increment in applied particles volume fraction (Fig. 9).

Further, MgO-based nanorefrigerant showed the least entropy inception ratio compared to other nanorefrigerants. The author proposed some equations for Nu number and frictional factor of selected nanorefrigerants using NRA.

For Nu number:

$$Al_2O_3 - HFE7000 : Nu_{ave} = 0.576(RePr)^{0.28}(1 + \varphi)^{3.016} \quad (9)$$

$$CuO - HFE7000 : Nu_{ave} = 0.591(RePr)^{0.278}(1 + \varphi)^{2.658} \quad (10)$$

$$MgO - HFE7000 : Nu_{ave} = 0.571(RePr)^{0.281}(1 + \varphi)^{3.143} \quad (11)$$

$$SiO_2 - HFE7000 : Nu_{ave} = 0.567(RePr)^{0.282}(1 + \varphi)^{2.737} \quad (12)$$

For friction factor:

$$Al_2O_3 - HFE7000 : f = 48.492Re^{0-0.984}(1 + \varphi)^{0.033} \quad (13)$$

Table 3 Summary of experimental studies on nanorefrigerants and nanolubricants

Authors	Nanorefrigerant/Nanolubricant	Type of study	Evaluation	Remarks
Behabadiet al. [84]	R600a/POE/CuO	Flow condensation	Nanorefrigerant reported 83% heat transfer rate enhancement by 1.5 wt% particles fraction compared to pure refrigerant	Contour plot for flow visualization of nanorefrigerant to understand the flow behavior is not included
Sanukrishnaet al. [85]	Poly – alkylene/CuO	Domestic refrigeration system	Application of 0.1 vol. % fraction of copper oxide particles enhanced the efficiency of the domestic refrigerator, like COP, Freezing capacity, and power consumption	The size of CuO nanoparticles and visual evidence of sedimentation of synthesized nanolubricant is not shown
Tashtoush et al. [86]	R134a, R22, R141b, NH_3, R123, R290, R600,R152a/ Al_2O_3 and CuO	Ejector type refrigeration cycle	The highest heat transfer coefficient, about 7%, was enhanced using R123 and R134a	The HTC is not studied at different sizes and shapes of selected nanoparticles
Sun et al. [87]	CuO/R141b, Al_2O_3/R141b, Cu/R141b and Al/R141b	Flow boiling inside a horizontal tube	The substantial maximum HTC around 49% was observed using 0.3 wt.% of Cu with R141b at a flux of 120 kg/ m^2/s	The flow visualization of nanorefrigerant to understand the flow behavior is not included
Sheikholeslami et al. [88]	R600a/POE/CuO	Flow condensation	The presence of nanoparticles during condensation observed a destructive result as an increment in the friction pressure drop	The effect of shape and size of CuO particles on friction pressure drop inside the tube is not studied
Krishna et al. [89]	R134a/PAG/SiO_2	Heat and mass transfer	The author reported a maximum outcome of 163% for the HTC with a 0.4% nanoparticle fraction	The visual evidence of sedimentation of SiO_2/PAG is not explored
Nawi et al. [90]	Hydrofluoroether/SiO_2	Flow boiling (Thermal conductivity)	The ideal volume fraction0.02 vol. % of SiO_2helped to increase thermal conductivity by about 27%	The thermophysical properties of selected nanofluid are not studied at different SiO_2 shapes and sizes
Bi et al. [91]	R600a/TiO_2	Domestic refrigerating unit	Considering TiO_2 fractions of 0.10 g/l and 0.50 g/L in R600a, the compressor work was retained at about 5.90% and 9.56%, respectively	The shape of TiO_2 nanoparticles was not described
Jiang et al. [92]	TiO_2/SDBS	NH_3 – water absorption refrigeration unit	The highest increased value of COP, about 27%, was observed with 0.5 wt. % of TiO_2 particles using 0.02 wt. % fraction of selected surfactant	The size and shape of TiO_2 nanoparticles are not described
Jatinder et al. [78]	TiO_2/R600a/MO	Domestic refrigerator	An increment of 62.54% in coefficient of performance was reported using nanorefrigerant	The compressor suction temperature using selected nanofluid is not studied
Aktas et al. [93]	(R134a, R430a, R12, R436a, R600a) + Al_2O_3	Refrigeration cycle	The highest value of COP was achieved with R600a/Al_2O_3 blend	The performance of the system is not studied at different shapes and sizes of Al_2O_3 particles

Table 3 (continued)

Authors	Nanorefrigerant/Nanolubricant	Type of study	Evaluation	Remarks
Mahbubul et al. [94]	Al_2O_3 + R134a	Thermal conductivity, viscosity, and density	Density, thermal conductivity, and viscosity of the synthesized nanorefrigerant enhanced about 27.50%, 10.9%, and 13.6%, respectively	Thermophysical characteristics of Al_2O_3/R134a nanofluid are not studied at different particle shapes and size
Eid et al. [95]	R141b and Al_2O_3 particles	Nucleate boiling system	Maximum HTC about 124% was achieved using a 0.05% fraction of Al_2O_3	The nucleate boiling for different orientations and geometry is not studied
Hady et al. [97]	Al_2O_3/water	Air conditioning unit	The highest value of COP, about 17%, was achieved with a 1 wt% applied mass fraction	The compressor energy performance of modified AC unit is not studied
Yang et al. [99]	MWCNT/R141b	Heat transfer properties inside a channelized pipe	The highest increment of the Nu number was reported by 41%	The boiling performance of MWCNT/R141b at different aspect ratios is not studied
Lin et al. [101]	MWCNTs/R141b + surfactant SDBS	Dispersion stability	The stable dispersion quality of MWCNTs in R141b was observed using SDBS	The dispersion stability of MWCNTs at different aspect ratios is not described
Kumar et al. [102]	MWCNT/H_2O-ethylene glycol (70:30)	Heat transfer characteristics of tubular heat exchanging design	The convective HTC was increased about 160% using 0.45 vol. % fraction of MWCNT	The visual evidence of dispersion stability of MWCNT/H_2O-ethylene glycol (70:30) is not explored
Peng et al. [103]	CNTs/R113	Nucleate pool boiling	The results showed the greatest improvement of 61% for nucleate pool boiling HTC by reducing the outer nanotube diameter and increasing the particle length	The nucleate boiling of CNT/R113 at different aspect ratios was not studied
Sun et al. [105]	MW CNT- carboxylic acid /R141b, MWCNT- hydroxide /R141b	Heat transfer properties inside a tube	The maximum improvement is about 23.5% for synthesized MWCNT – carboxylic acid/R141b nanofluid and 15.17% for MWCNT- hydroxide/R-141b using 0.175% of particle conc. was reported	The flow boiling HTC of selected nanorefrigerant inside the rough surface tube is not studied
Peng et al. [61]	Cu/R113/ester oil	Nucleate boiling	The author reported an excellent heat transfer improvement using Cu nanoparticles and also proposed a correlation of HTC of nucleate heat boiling phenomena by 93% in accordance with the entire available practical record	The nucleate pool boiling of Cu/R113/ester oil at different shapes and sizes of Cu particles is not studied

Table 3 (continued)

Authors	Nanorefrigerant/Nanolubricant	Type of study	Evaluation	Remarks
Maheshwary et al. [106]	R134a + ZnO	Thermophysical properties	The outcomes reported a significant growth in thermal conductivity of nano-refrigerant, about 42.5% for cubic and 25.26% for spherical shape, respectively	The effect of size on thermophysical characteristics of R134a/ZnO is not studied
Peng et al. [107]	R113/diamond/VG68	Nucleate boiling	An improved HTC of 63.5% compared to the base refrigerant was reported	The pool boiling of R113/diamond/VG68 at different aspect ratios is not investigated
Kumaresan et al. [102]	MWCNT/H_2O-ethylene glycol	Thermal conductivity	In terms of result, a 19.36% increase was received in thermal conductivity	The effect of the aspect ratio of MWCNTs on thermal conductivity is not studied

$$CuO - HFE7000 : f = 48.197Re^{-0.984}(1 + \varphi)^{0.899} \quad (14)$$

$$SiO_2 - HFE7000 : f = 48.696Re^{-0.984}(1 + \varphi)^{0.401} \quad (15)$$

$$MgO - HFE7000 : f = 48.056Re^{-0.983}(1 + \varphi)^{0.398} \quad (16)$$

Alawi et al. [112] conducted a numerical study to understand the reaction of alumina/R141b nanorefrigerant on heat flow performance inside a high-temperature concentric annulus cylinder using the CFD approach. The study involved the MG and Brinkman models in approximating the influence of thermal conductivity and dynamic viscosity of selected nanorefrigerant. The alumina/R141b nanorefrigerant achieved the most significant improvement in heat flow rate compared to other particles. The author reported physics behind this achievement is that alumina particles have the largest thermal conductivity compared to other particles. Also, the report represented that the maximum heat flow rate achieved at a high range of particles fraction and smaller particle diameters (20 nm) received the most remarkable heat exchange rate compared to large ones (30 nm). The study also reported that the heat flow rate of the selected nanorefrigerant improved by increasing the ΔT of the cylinders, as per increment in Rayleigh number.

In their other report, Mahbubul et al. [113] published a simulation report on heat flow rate and pressure drop of synthesized alumina/R134a nanorefrigerants. The authors considered nanoparticle fractions in a range of 1 vol. % to 5 vol. %, at constant velocity (5 m/s) and a uniform mass velocity (100 kg/m^2s). The study was conducted on temperature variations from 300 to 325 K to count the effect of change in temperature on the thermal conductivity of selected nanorefrigerants. The results showed that thermal conductivity and pressure drop of R134a refrigerant increases by increasing particles volume fractions. A method developed by Peng et al. [33] was used to define the flow boiling HTC and the equationis mentioned as below: (Eq. 17):

$$h_{nr} = F_{HT} \cdot h_r \quad (17)$$

Here, h_{nr} known as flow boiling HTC of nanorefrigerant and h_r refers to flow boiling HTC of pure refrigerant. F_{HT} represents a nanoparticle impact factor, and it can be calculated through the below-mentioned equation:

$$F_{HT} = exp\left\{ \varphi \left[0.8\frac{\lambda_p}{\lambda_r} - 39.94\frac{(\rho C_p)_p}{(\rho C_p)_{r,l}} - 0.028G - 733.26x(1-x) \right] \right\} \quad (18)$$

where φ is nanoparticle volume concentration, x refers as vapor quality of fluid, G is mass velocity, λ_p and λ_r known as the thermal conductivity of nanoparticles and refrigerant, respectively, $(\rho C_p)_p$ known as multiplication of density and

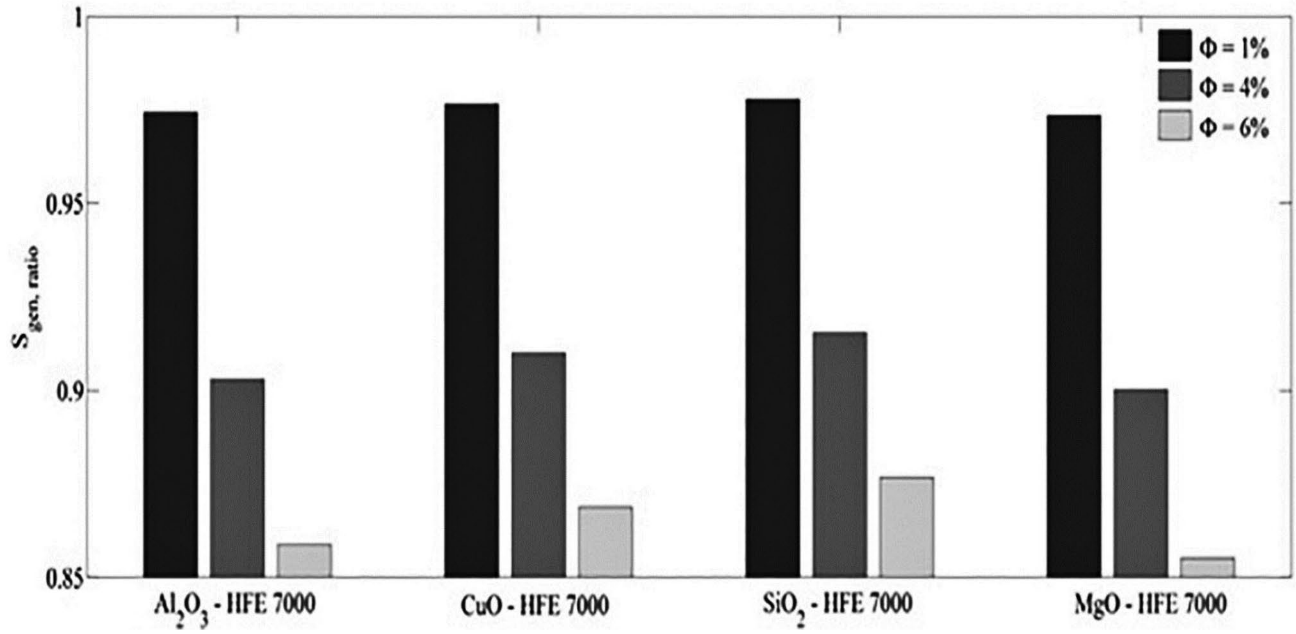


Fig. 9 Entropy generation of synthesized nanofluids (at Re = 800) [111]

heat capacity of the particles and $(\rho C_p)_{r,l}$ refers to the density multiplication of pure liquid refrigerant. At a temperature range of 300 K and nanomaterial fraction of 1.0 vol. %, the outcomes showed that λ improved only up to 4%, the lowest of other temperature ranges (Fig. 10).

Peng et al. [114] did a well-simulated work on the pool boiling heat flow rate of selected nanorefrigerants. The study considered the reaction of heating on particle movements through both physical testing and numerical testing. The author noticed that the movement of particles migration mechanism from a liquid state to vapor state in nanorefrigerants boiling is categorized into various activities such as bubble migration from the heating surface, bubble capturing the nanoparticles, movement of particles and bubbles in a liquid state. The study concluded that the nanoparticle fraction during liquid state changes with respect to tenure, which leads to the compact bubble motion, and the movement of particles changes with respect to time.

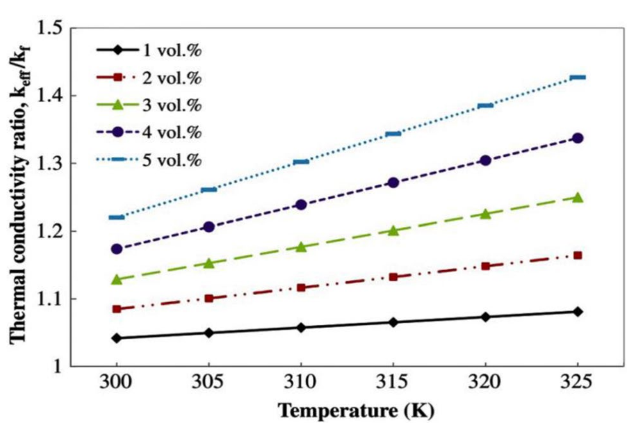


Fig. 10 Thermal conductivity ratio of nanofluid as a function of temperature [33]

Turgut [115] reported a numerical study that represents applications of R134a/Al_2O_3 nanorefrigerant inside a well-designed shell and tube-type evaporator. The study considered various objectives for optimization such as the diameter of the shell, baffle spacing, nanoparticle fraction, particles diameter, number of pipes, number of pipe passes, length of pipe, fabrication cost, and cost of the condenser. The author concluded that the heat transfer rate greatly improved via appending Al_2O_3 nanoparticles into pure R134a refrigerant. Also, the maximum overall HTC was increased by about 18%, and the total value of the heat exchanger device was reduced by 5% using alumina particles in R134a.

In another well-designed study, Alawi et al. [116] conducted a heat exchange study of copper oxide/R134a nanorefrigerants using simulation. The authors considered particles fraction and temperature in a range from 1 – 5% and 300 – 320 K, respectively. The study results that nanoparticle fraction and temperatures have efficient impacts over thermophysical properties of the selected nanorefrigerants. The results found that the fluid's viscosity increases with the increment in nanoparticle fraction. On the other hand, viscous behavior and density of fluid reduce with the increment in temperature. It was also found that the thermal conductivity of nanorefrigerant was improved by about 10% and 8.13% for 1 vol. % and 5 vol. %, respectively.

Zohud et al. [117] performed a well-defined numerical study that focused on seeing the impact of selected nanorefrigerants on heat flow properties inside a round pipe using a constant heat flux. The study considered four kinds of nanorefrigerants such as ZnO/R1270, CuO/R1270, Al_2O_3/R1270, and SiO_2/R1270. The author used ANSYS fluent for simulation and compared the outcomes of nanorefrigerants with those of base refrigerant. The Re number ranged from 20000 – 100000, and the fluid flow pattern was turbulent. The particle's volume fraction is considered within 0 to 5 percent. The author proposed two equations for the average Nu number and frictional factor of selected nanofluids flow inside the round pipe with turbulent flow. The diameter particle is fixed at 30 nm. In terms of outcomes, the author observed an enhancement in convective heat exchange coefficient with the increment in Re number and the nanoparticles fraction. The correlations are mentioned below:

$$Nu_{avg} = 0.027Re^{0.792}Pr^{0.475}(1+\varphi)^{-0.308} \quad (19)$$

$$f = 0.38Re^{-0.266} \quad (20)$$

Ajayi et al. [118] investigated a simulation study related to copper/R134a and copper/R600a nanorefrigerants flowing inside an expansion valve (capillary) of domestic VCR cycle using the computational domain. The results received from the simulation demonstrated that only R134a and R600a have more isotherms. It indicates that refrigerants can prevent heat transfer very quickly. Furthermore, adding a 0.10% fraction of selected particles can improve the thermophysical behavior such as thermal conductivity, specific heat, density, and viscosity of the pure fluid.

Coumaressin and Palaniradja [119] conducted a thermal energy study of a domestic refrigerator based on R134a/copper oxide nanorefrigerant, both experimental and numerical. The particle's volume fraction, diameter, and heat flux are considered in a range as 0 – 1%, 10 – 70 nm, and 10 – 40 kW/m^2, respectively. The author concluded that the evaporating HTC improves with the increment in particles fraction up to 0.5% and then reduces for all the values of heat velocity.

Hernandez et al. [120] numerically investigated the thermal performance of the refrigeration cycle through different nanorefrigerants using a 2D approach in ANSYS. The author studied the heat transfer behavior of R113/CuO, R123/CuO, and R134a/CuO nanofluids with a nanoparticle fraction range from 1 to 5 vol. %. Two methods are available to incorporate the 2D process. Firstly, the Lagrangian–Eulerian approach is implemented when the particle volume concentration is less than 10%. Second, the Eulerian approach is used when nanoparticle volume fractions are higher. In his published report, Akhbari et al. [121] write that the nanoparticles dispersed in nanofluids are in considerable amounts

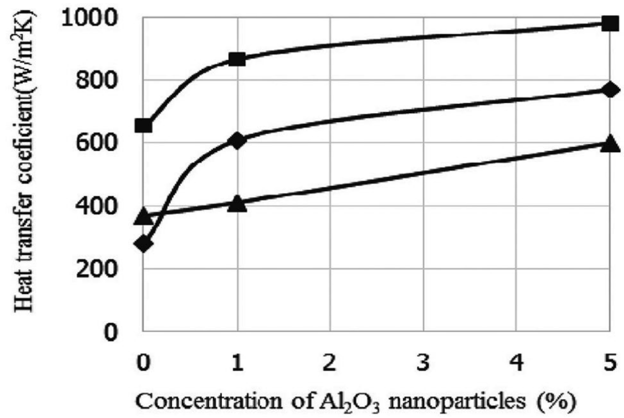


Fig. 11 Heat transfer coefficient of nanorefrigerant at 0.5 m/s velocities at inlet [121]

even for small volume concentrations. Thus, due to the high computational price, the Lagrangian–Eulerian method is not recommended. It concluded that all ofthe selected nanorefrigerants give improved HTC with a significant increase in nanoparticle volume fraction (Fig. 11). Sidik and Alawi [122] numerically investigated the thermal characteristics of selected nanorefrigerants (R141b/SiO_2, R141b/ZnO, R141b/CuO, and R141b/Al_2O_3) using ANSYS fluent. The study considered a computational domain consisting of an evaporator annulus. The author demonstrates the results on the average Nu number of selected various nanorefrigerants versus Re number (Fig. 12).

Kosmadakis and Neofytou [123] published a numerical report using various nanoparticles, including CuO, Cu, and Al_2O_3 with refrigerants R134a and R1234yf. The collected results explain that with distinct particle fractions (range

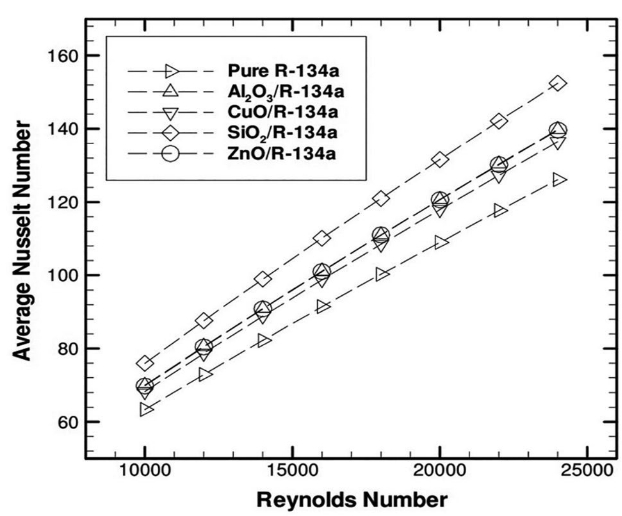


Fig. 12 Different nanorefrigerant effects on average Nu number [122]

Table 4 Summary of numerical studies on nanorefrigerants and nanolubricants

Authors	Nanorefrigerant/Nanolubricant	Type of study	Evaluation	Remarks
Helvaci and Khan [111]	Al_2O_3, CuO, SiO_2, and MgO + HFE7000	Entropy rate	The study resulted that the entropy inception ratio shows reduction with an increment in applied particles volume fraction	The entropy performance of the system using different shapes and sizes is not studied
Alawi et al. [112]	Al_2O_3, ZnO, CuO, SiO_2/R141b	Heat flow performance	Al_2O_3/R141b nanorefrigerant achieved the greatest improvement in heat flow rate compared to other particles	The heat transfer performance of selected nanorefrigerants could also have been studied for rectangular geometry
Mahbubul et al. [113]	Alumina/R134a	Heat transfer properties	Thermal conductivity and pressure drop of R134a refrigerant increases by the increases of particles volume fractions	The thermophysical properties are not studied at different mass flux and heat flux rate
Peng et al. [114]	–	Migration of nanoparticles in pool boiling of nanorefrigerant	The study concluded that nanoparticle fraction during liquid state changes for tenure, which leads to the compact bubble motion, and the movement of particles changes with respect to time	The study not conducted for nanoparticles shape
Turgut [115]	R134a/Al_2O_3	Shell and tube evaporator	The maximum overall HTC was increased by about 18%, and the total value of the heat exchanger device was reduced by about 5% using alumina particles in R134a	The HTC of R134a based shell and tube evaporator for multiple nanoparticles for comparison is not studied
Alawi et al. [116]	CuO + R134a	Heat transfer	It found that the thermal conductivity of nanorefrigerant improved by about 10% and 8.13% for 1 vol. % and 5 vol. %, respectively	Thermal conductivity of CuO/R134a nanofluid not studied at different particle shapes and size
Zohud et al. [117]	ZnO/R1270, CuO/R1270, Al_2O_3/R1270 and SiO_2/R1270	Heat flowpropertiesinside a roundpipe	The author observed an enhancement in convective heat exchange coefficient with the Re number and the nanoparticles fraction increment	The convective HTC not studied for various heat flux range
Ajayi et al. [118]	Cu/R134a and Cu/R600a	Flow-through capillary tube	Adding a 0.10% fraction of selected particles can improve the thermophysical behavior such as viscosity, thermal conductivity, specific heat, density, and of the pure fluid	The effect of geometry parameters and operating conditions such as capillary length, diameter, and coil diameter are not studied

Table 4 (continued)

Authors	Nanorefrigerant/Nanolubricant	Type of study	Evaluation	Remarks
Coumaressin and Palaniradja [119]	R134a/CuO	Thermal energy	The evaporating HTC improves with the increment in particles fraction up to 0.5% and then reduces, for all the values of heat velocity	The pressure drop throughout the pipe using nanorefrigerant is not studied
Hernandez et al. [120]	R113/CuO, R123/CuO and R134a/CuO	Refrigeration system	Thermal conductivity and HTC improved at higher volume fractions	The effect of CuO particles shape and size on the thermal conductivity is not studied
Akhbari et al. [121]	Al_2O_3/water	Heat transfer study	The heat transfer coefficient improved using Al_2O_3 in water	The HTC not studied at a different heat flux rate
Sidik and Alawi [122]	R141b/SiO_2, R141b/ZnO, R141b/CuO and R141b/Al_2O_3	Convective heat transfer	R141/SiO_2 has the highest Nu number compared to other blends	The contour plot for the flow of nanorefrigerant to understand the heat transfer profile was omitted
Kosmadakis and Neofytou [123]	CuO, Cu, and Al_2O_3 with refrigerants R134a and R1234yf	Heat transfer rate	HTC rose to 6%, specifically during condensation and boiling phases. Further, an increment in performance coefficient of about 6%, a drop in pump energy consumption, and 3.5% enrichment in pressure drop also significant results	The pressure drop at compressor suction and the discharge port is not studied

from 0 to 5 wt. %), the HTC raised to 6%, specifically during both condensation and boiling phase. Further, an increment in performance coefficient of about 6%, a drop in pump energy consumption, and 3.5% enrichment in pressure drop also significant results. Zarei et al. [149] published a research report which elaborates the pool boiling heat transfer coefficient of nanorefrigerant using ANN (artificial neural network) models available in the literature. The author studied various parameters such as heat flux, particles size, volume fractions of nanoparticles, thermal conductivity, and saturation pressure of flow boiling using nanorefrigerant. The study declared that the observed ANN having 19 hidden neurons could model a nanorefrigerant pool boiling heat transfer coefficient (Tables 4 and 5).

6 Effect of nanorefrigerant on power consumption

The dispersion of nanoparticles in pure refrigerants and lubricants significantly enhances the heat transfer rate and tribology characteristics, which delivers better system stability, which assists in power consumption saving [124]. Table 6 shows the power consumption of pure refrigerant R134a and R134a/TiO_2 nanorefrigerant.

The use of nanolubricant inside a compressor crank has reduced the wearing, enhanced thermal dissipation, and better lubrication characteristics, ultimately lowering the compressor energy use [125]. Shengshan and Lin [126] fabricated a vapor compression refrigeration cycle and studied R134a/TiO_2 mixture at varying TiO_2 concentrations. The results showed that selected nanorefrigerant at 10 mg/L fractions normally and energetically work inside the cycle with low energy consumption compared to the pure refrigerant. In another theoretical study, Aktas et al. [127] mixed Al_2O_3 nanoparticles with varying pure refrigerants, namely R12, R134a, R430a, R600a, and R436a, and received the highest increment on performance coefficient and reductions in power consumption when applied R600a/Al_2O_3 nanorefrigerant. Kumar et al. [128] used ZnO particles at varying concentrations inside the R290/R600a based vapor compression unit and received a significant saving on the power consumption of about 7.48%. In another report by Kumar et al. [129], the ZnO particles at distinct fractions mixed in LPG refrigerant, and the results reported 10% reductions in compressor power consumption. Jwo et al. [130] experimentally investigate the performance coefficient and power consumption of the refrigeration cycle using 0.05 wt%, 0.10 wt%, and 0.20 wt% Al_2O_3 nanoparticles with R134a fluid. The results showed 2.4% reductions in pumping power consumptions and a 4.4% increment in performance coefficient. Kumar et al. [130] experimented on a domestic vapor compression-based refrigeration unit

Table 5 Summary of numerical methods used in previous numerical studies

Authors	Numerical method	Numerical models		
		Thermal Conductivity	Viscosity	Other
Helvaci and Khan [111]	The second-order upwind, SIMPLE algorithm	Hamilton and Crosser	Einstein	NA
Alawi et al. [112]	FEM	Maxwell–Garnetts (MG)	Brinkman	NA
Mahbubul et al. [113]	NA	Sitprasert et al. [150]	Brinkman	NA
Peng et al. [114]	NA	NA	Brinkman	Cole and Rosenhow [151] used to calculate the departure diameter of the bubble
Turgut [115]	NA	NA	NA	Shell HTC calculated through model given by Kern [152]
Alawi et al. [116]	NA	Koo and Kleinstreuer	Tiwari and Das	NA
Zohud et al. [117]	SIMPLE algorithm	Vajjha and Das	Brinkman	NA
Ajayi et al. [118]	NA	NA	Brinkman	NA
Coumaressin and Palaniradja [119]	NA	Maxwell – Eucken	Einstein	NA
Hernandez et al. [120]	NA	NA	NA	k – epsilon (turbulent model)
Akhbari et al. [121]	VOF model	NA	Chon et al. [153]	NA
Sidik and Alawi [122]	NA	NA	NA	NA

to study Al_2O_3 particles using varying refrigerants, namely, R12, R22, R600, R600a, and R134a. The author evaluated that the power consumption of about 11.5% was reduced using a 0.06% mass fraction of Al_2O_3 with base refrigerants. Kumar and Elansezhian [131] studied ZnO nanoparticles inside an R152a based vapor compression cooling unit. The author mixed varying ZnO fractions (0.1, 0.3 and 0.5 Vol. %) with R152a. The results showed that the applications of ZnO nanoparticles reduced the pumping power consumption by about 21%. Subramani et al. [132] investigated the effect of TiO_2 nanoparticles on R134a dependent vapor compression cooling rig and reported 15.4% less energy consumption using 0.3 g/L TiO_2 fractions. In a similar report of Kumar et al. [133], about 7% reductions in compressor energy were observed using CuO nanoparticles in LPG-based domestic refrigerating unit. Senthil et al. [134] mixed hybrid nanoparticles CuO/Al_2O_3 in R600a refrigerant and studied various parameters of refrigerating test rig. The study reported 24% reductions in compressor power utilization using proposed nanorefrigerant compared to base refrigerant R600a. Joshi et al. [135] studied the effect of alumina oxide nanoparticles inside a refrigerating machine using R134a and R600a refrigerants with mineral oil and polyester oil lubricant. The highest reduction in compressor power, about 31.85%, was reported at 0.1 wt. % fraction of Al_2O_3 particles used with 200 g of R600a/mineral oil blend. Nair et al. [136] tested Al_2O_3 nanoparticles inside an R134a refrigerating unit. They reported maximum savings of about 6.1% on compressor energy utilization at saturation temperature of 307.15 K. Sabareesh et al. [137] studied varying fractions of TiO_2 nanoparticles in an R134a refrigeration system and reported 11% reductions in compressor work using 0.01 vol. % fraction of TiO_2 with mineral oil as a lubricant.

7 Effect of nanorefrigerant on cooling capacity

Based on earlier reports, the nanorefrigerant enhanced the cooling capacity (time required to reach the desired temperature) of the compression refrigeration system. Ahmed et al. [97] used Al_2O_3 nanoparticles in a domestic vapor compression-based air conditioner unit and reported a significant enhancement in the cooling capacity of the air conditioner unit. The elapsed time required to cool the

Table 6 Power consumption of pure R134a and R134a/TiO_2 nanorefrigerant [124]

TiO_2 mass fraction (%)	0 (Pure R134a)	0.06 TiO_2	0.1 TiO_2	0.1 (50 days later)
Power consumption (kWh/day)	1.077	0.849	0.796	0.8
Power saving (%)	---	21.2	26.1	25.7

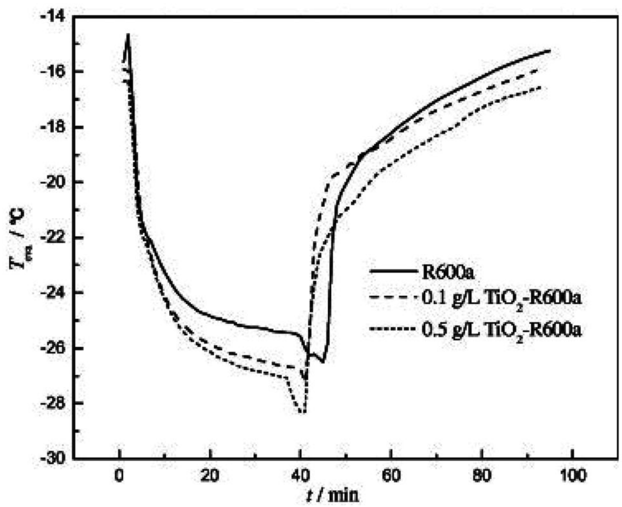


Fig. 13 Evaporation temperatures of R600a and R600a/TiO_2 [91]

air was reduced using alumina nanorefrigerant compared to pure fluid. The experimental results reveal that nanorefrigerant, due to its improved heat transfer coefficient, enhances the cooling rate of the refrigerating unit. Bi et al. [91] reported evaporation temperature performance of the R600a/TiO_2 refrigeration system. The evaporation temperature is enhanced using nanorefrigerant, leading to a lower compartment temperature than the pure refrigerant. Figures 13 and 14 shows the graphical trend of evaporation and evaporator compartment temperatures, respectively.

Senthil et al. [134] mixed hybrid nanoparticles CuO/Al_2O_3 in R600a refrigerant and studied various parameters of refrigerating test rig. The study reported the highest increased cooling capacity of 200 watts using 0.4 g/L

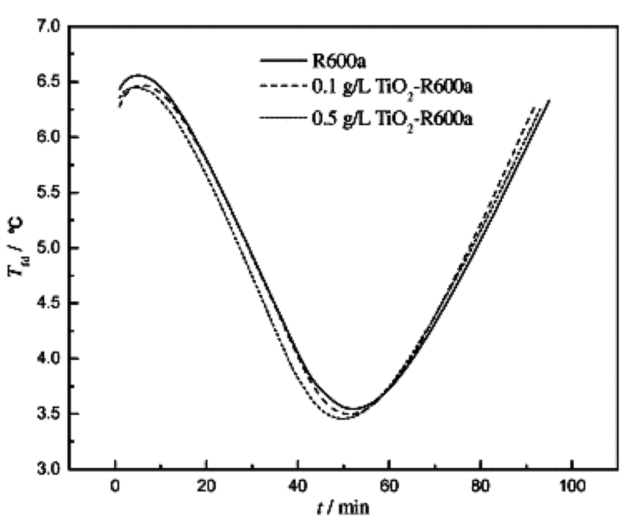


Fig. 14 Evaporator cabin temperatures of R600a and R600a/TiO_2 [91]

nanorefrigerant blends, which is improved from 160 to 200 watts. Joshi et al. [135] studied the effect of alumina oxide nanoparticles inside a refrigerating machine using R134a and R600a refrigerants with mineral oil and polyester oil lubricant. The reductions in the pull-down time about 23% using 0.1 wt. % fraction of Al_2O_3 particles in 200 g mass of R600a/mineral oil blend was reported. Soliman et al. [138] mixed varying fractions of Al_2O_3 nanoparticles with R143a refrigerant and studied various parameters such as performance coefficient and freezing capacity to compare the performance of nanorefrigerant and refrigerant. The results showed that the time was reduced using a 0.1% fraction of nanorefrigerant and this reduction in time increases the cooling capacity of the unit. Kundan and Singh [139] studied Al_2O_3 nanoparticles in the R134a cooling cycle and reported that the cooling capacity of the refrigerating unit had been improved at an atmospheric temperature of 21 °C. Pico et al. [140] mixed diamond nanoparticles at 0.1 and 0.5 Vol. % fractions in R410a refrigerant to study the performance characteristics of the refrigerating machine. The author reported that the cooling capacity of the cooling unit was improved using diamond nanolubricant. The highest cooling capacity, about 7%, was enhanced using a 0.5% mass fraction of diamond nanoparticles.

8 Conclusions

The present paper targeted research reports available in the literature on experimental and numerical studies related to nanorefrigerants and nanolubricants. The experimental studies in nanorefrigerants and nanolubricants are available in a wide range, but the numerical investigation in this area shows a significant gap in the literature. Although, the numerical studies available related to nanorefrigerants performance in refrigeration and HVAC systems are well discussed and help to understand the physics behind the communication of nanoparticles with conventional fluid.

Most of the experimental studies focused on the performance enhancement of domestic refrigerators and air conditioners and pool boiling heat transfer rate of nanorefrigerants. The author noted that few studies had investigated the flow condensation heat transfer characteristics of nanorefrigerants. The conclusions derived through the available research reports have mentioned as below:

1) Applying various nanoparticles in conventional refrigerants and lubricating oil enhanced the coefficient of performance (COP), freezing rate, and cooling capacity. As a result, it reduced the energy consumption of domestic vapor compression refrigerators. Furthermore, the tribology properties such as friction coefficient and wear rate of refrigerator compressor were also enhanced

using nanolubricants. Therefore, nanolubricants are a suitable method to minimize the electricity crisis in the HVAC and cooling industries.

2) The behavior of nanoparticles boosts the HTC of pool boiling and flow condensation of refrigerants. The size and shape of particles have a crucial role in the enhanced heat transfer rate of nanorefrigerants. Some studies recommended the usage of small size particles as they showed large improvements in the heat transfer coefficient of refrigerants. It also observed that the various variables such as mass velocity, heat flux, and vapor quality are highly responsible for influencing the heat transfer rate of pool boiling and flow condensation phenomena.
3) In general, the addition of nanoparticles in lubricating oil enhanced the tribology characteristics of the refrigeration compressor, which further reduced its energy consumption. However, a few researchers reported increased compressor work due to a rise in fluid pressure drop if the volume fraction of nanoparticles in refrigerant were more than an optimum amount. Hence, to maximize the efficiency of the compressor and overall COP of the refrigeration unit, there is a further need to work on the optimum volume fraction of nanoparticles.
4) Nanorefrigerant reduced the time required to reach the desired cooling temperature of the compression refrigeration system. Nanorefrigerant is a superior heat transfer capability candidate that augments the flow condensation and boiling heat transfer coefficient in the refrigerating cycle. As a result, the freezing or cooling capacity of the VCR system gets enhanced.
5) In terms of numerical reports, most of the studies are available under the single-phase simulation method. Under this approach, the synthesized nanorefrigerant assumed a special and similar fluid. As a result, the pool boiling and convective heat transfer coefficients increase rapidly at higher nanoparticle volume concentrations in most studies.
6) The mass of nanoparticles in the liquid state decrease with time following pool boiling of nanorefrigerants, resulting in altering bubble movements and nanoparticle transport characteristics.
7) Lastly, it concluded that applying nanorefrigerants and nanolubricants inside heating and cooling systems improves performance. Therefore, nanorefrigerant had proved as a suitable candidate for improved efficiency of refrigeration and air conditioning systems.

9 Challenges and future prospective

Nanorefrigerant proved as a suitable candidate in the sector of refrigeration and air conditioning components due to its better heat transfer properties. However, the detailed literature available on the application of nanorefrigerant and nanolubricant in domestic and industrial refrigeration appliances still demands more numerical and experimental investigations. The below mentioned are some challenges and future demands to expand the study of nanorefrigerant in cooling and heating units:

1) The blending of low boiling point refrigerants like R134a, R600a, R32, etc., with nanoparticles on atmospheric conditions, is a challenging concern. Therefore, more research needs to synthesize a low boiling point refrigerant-based nanorefrigerant without using any lubricant or oil.
2) Nowadays, industries are using natural refrigerants like NH_3 and CO_2 to decline environmental concerns. However, no literature study is available on natural refrigerant-based nanorefrigerant. Moreover, the investigation related to the usage of metal and metal oxide particles with natural refrigeration fluids such as ammonia (NH_3) is a challenging issue due to the toxic nature of ammonia fluid, and accordingly, further research is needed.
3) Most investigations on pool boiling heat transfer using nanoparticles have been performed on industrial refrigerants such as R113 and R141b. However, more experimental studies on boiling heat transfer coefficient of refrigerants having low GWP and ODP values such as R600a, R290, R1234yf, R1234ze using nanoparticles are required.
4) Research is needed to explore some crucial characteristics, such as the dielectric aspect and surface tension of nanorefrigerants. Also, a new series hybrid nanofluid needs to use inside the cooling units to understand the effect of composite nanoparticles on heat transfer rate.
5) The use of high thermal conductivity nanoparticles such as graphite, gold, and diamond particles with pure refrigerants and lubricants shows a lack of study. It needs broad research to understand the physics behind the heat transfer efficiency of nanorefrigerants.
6) The studies related to flow condensation of nanorefrigerants inside the heat exchangers are not much available and demand additional investigations to recognize the heat transfer characteristics of nanorefrigerants on the condensation of cooling appliances. The flow regimes of nanorefrigerant during condensation inside the tube need to investigate, which is not observed by any researcher yet.
7) The researchers need to explore more analytical and numerical studies in nano refrigeration to understand the physics behind the improved heat transfer coefficient.

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Declarations

Conflict of interest The authors declare no conflict of interest for the present work.

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