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An overview of experimental studies on nanorefrigerants: Recent research, development and applications

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ABSTRACT

Emergence of nanotechnology opens up new avenues in diverse research frontiers. Nanorefrigerants are nanotechnology based refrigerants, which are stable mixture of nanoparticles of metal, oxide, carbon and its allotropes and refrigerants. Development of nanorefrigerants provides a new research frontier in the heat transfer perspective. The studies on nanorefrigerants are still in its budding stage. The intention of the present paper is to provide a comprehensive overview of experimental studies on thermophysical and rehological properties, boiling and condensation phenomena, pressure drop characteristics, aggregation behaviour, migration and degradation characteristics of different nanorefrigerants and application of nanorefrigerants in HVAC systems. Various outlooks of future scope associated with the studies of nanorefrigerants have also been suggested. It has been recognized that addition of nanoparticles in refrigerants contributes noteworthy augment in the thermal physical and heat transfer characteristics of refrigerants. Furthermore, application of nanorefrigerants in heating, ventilation, and air conditioning systems enhance the overall performance in terms of coefficients of performance (COP) and energy efficiency.

État des lieux des études expérimentales sur les nanofrigorigènes: Recherches récentes, développement et utilisations

Mots-clés: Nanofrigorigène; Propriétés thermophysiques; Coefficient de transfert de chaleur; Caractéristiques de migration; Coefficient de performance; Efficacité énergétique

Abbreviations

CFC	chlorofluorocarbon
CNT	carbon nanotubes
COP	coefficient of performance
CTAB	cetyltrimethyl ammonium bromide
EER	energy efficiency ratio
GNS	grapheme nano sheet
HCFC	hydro chlorofluorocarbon
HFC	hydro fluorocarbon
HTC	heat transfer coefficient
HVAC	heating ventilation and air-conditioning.
MO	mineral oil
MWCNT	multi walled carbon nanotube
PAG	plyalkylene glycol
POE	polyolester
SDBS	sodium dodecyl benzene supphonate
SDS	sodium dodecyl sulphate
SPM	scanning probe microscope
SWCNT	single walled carbon nanotube
TEM	transmission electron microscope
TPS	transient plane source
UV–vis	ultraviolet visible
VCRS	vapour compression refrigeration system

1. Introduction

A novel concept on heat transfer fluids by dispersing and stably suspending nanoparticles in base fluids, was presented by

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Nomenclature

d	nanoparticle diameter [nm]
h	heat transfer coefficient[$Wm^{-2}K^{-1}$]
k	thermal conductivity[$Wm^{-1}K^{-1}$]
q	heat flux[kWm^{-2}]
T	temperature [°C]
t	time[h]
x	vapour quality
Subscripts	
f	base fluid
nf	nanofluid
p	particle
PL	pure lubricant

Choi and Eastman (1995). These engineered colloids are called nanofluids. The primary motto behind this great invention was to augment the thermal transport phenomena in conventional heat transfer fluids. Compared to other fluidic heat transfer medium and micro-fluids, nanofluids have some exclusive features. Nanofluids exhibit superior thermal and heat transfer capabilities. Further, nanofluids found its own way into diverse fields of research. One of the primitive applications in the field of nanofluids is to cool crystal silicon mirrors used in high-intensity X-ray sources (Lee and Choi 1996). The major concerns in automotive engine performance are proper thermal management systems. The potentials of nanofluids as a smart coolant in automotive engines have been envisaged by Choi et al. (2008). Similarly the factors influencing the cutting tool life are frictional heat generation. Srikant et al. (2009) show that nanofluids have better prospects to overcome excessive heating problems. Studies show that the convective heat transfer capabilities of nanofluids go beyond several times than that of the base fluids (Elcock, 2007). Application in the renewable energy sector is one of the most hopeful outcomes of nanofluids. In order to attain optimal efficiency and to develop energy efficient and compact solar devices, the heat transfer performance must be enriched. Mahian et al. (2013) exploited the possibilities of nanofluids in solar thermal systems. Performance of solar collector and solar still have been enhanced with the use of EG-water based nanofluid (Mahian et al., 2014; Salavati Meibodi et al., 2015; Mahian et al., 2017). The heat transfer in micro channel has been enhanced with TiO_2/water nanofluids (Nitiapiruk et al., 2013). Nanoparticles, especially ferro- magnetic materials can also be used as drug delivery vehicles in cancer therapy (Sridhara et al., 2009).

The primary outcome of nanofluid research was the enhancement in effective thermal conductivity and convective heat transfer characteristics of heat transfer fluids. Wang et al. (1999) and Yoo et al. (2007) and recently this perception has been applied to refrigerants and give birth to the new concept of nanorefrigerants (Nair et al., 2016). Irrespective of the nanoparticle type, a similar trend is displayed by nanorefrigerants as well. For example, Jiang et al. (2009a) show that addition of Carbon Nano Tubes (CNT) to refrigerant trichlorotrifluoroethane manifested dramatic improvement in thermal conductivity by more than 100%. The nanorefrigerants are of two kinds, refrigerant based and lubricant based. In the first category, nanoparticles are directly dispersed into refrigerants, the second in which, lubricant appended with nanoparticles is ultimately circulated along with refrigerants (Nair et al., 2016).

The phase change heat transfer is a key area of research as far as refrigerants are concerned. The boiling heat transfer phenomena as such is complex in nature and boiling of refrigerants in the presence of nanoparticles appears to be more complex. Controversies are still subsist and scientific community have not arrived into an ample conclusion related to the existence and nature of mechanisms involved in nanofluids and nanorefrigerants, and their role in enhancing the heat transfer characteristics of colloidal suspensions. Contradictory results should not disparage researchers but increase the enthusiasm and encourage them towards the key research frontline.

A few reviews are available in literature based on thermophysical, heat transfer properties and application of nano-refrigerants in thermal systems (Celen et al., 2014; Alawi et al., 2015a; Azmi et al., 2016; Nair et al., 2016). However, significant studies on particle degradation in the refrigerant during phase change process of condensation and evaporation, aggregation characteristics and migration behavior of nanoparticles and applications in specific areas such as automotive air-conditioning systems, heat pumps, heat pipes etc. have not been addressed to provide ample insight.

The present emphasises on a comprehensive novel review of experimental studies on thermal, physical properties, phase change heat transfer characteristics, pressure drop characteristics, aggregation, and degradation and migration behavior of nanoparticles in refrigerants. Besides, it provides insights to the application of nanorefrigerants in refrigeration and air-conditioning systems, heat pipes and heat pumps. Future scopes and challenges pertaining to the novel research frontier have been recommended based on this review. It is expected that this article may handover an overview of the recent developments and applications of refrigerants appended with nanoparticles and the most influential parameters which are responsible for the exceptional thermal performance of it.

2. Thermophysical and rheological properties of nanorefrigerants

Effects of nanoparticles on the thermophysical properties of refrigerants are crucial factor that needs to be analyzed. Nanoparticles play crucial part in the augmentation of effective thermal conductivity and viscosity of base fluids. Thermal conductivity and viscosity are the properties of refrigerants which endure direct impact nano-additives (Jiang et al., 2009; Mahbubul et al., 2013a). The studies on viscosity have an impact on flow applications of nanorefrigerants. The increase in viscosity at higher particle concentration may go beyond the thermal conductivity enhancement (Bashirnezhad et al., 2016). This eventually results in pressure drop for the flow process and which in turn increases the pumping power requirement. Extensive experimentation is inevitable to arrive at an ample conclusion. The rheological behavior such as shear thinning and thixotropic behavior of base refrigerants with nano-additive are to be investigated along with surface tension, specific heat and latent heat. Table 1 shows the summary of studies on thermophysical properties of nanorefrigerants.

Jiang et al. (2009a) experimentally determined the thermal conductivity of R113/CNT nanorefrigerant. They also suggested a numerical model to forecast the thermal conductivity of CNT based nanorefrigerant. The thermal conductivity has been measured with Transient Plane Source (TPS) technique. Four kinds of CNTs having different aspect ratios 100,667.7, 18.8, and 125 were used. Studies show that the aspect ratio/ diameter of nano tubes have significant effect in the thermal conductivity enhancement. Increase in the aspect ratio results in thermal conductivity up surge. The proposed model predicts the thermal conductivity with a mean deviation of 5.5%. Rashidi, (2012) also developed a correlation to predict the thermal conductivity of R113/CNT nanorefrigerants after extensive experimentation. The model considered several parameters, including CNTs, diameter, length etc. Study shows that, the dimensions of nanoparticles have critical influence in the effective thermal conductivity of nanorefrigerant. The model predictions were in line with experimental data.

Table 1
Thermophysical and rheological properties of nanorefrigerants-A summary.

Researcher	Refrigerant	Nanoparticle	Evaluation
Jiang et al. (2009a)	R113	CNT	An increase in thermal conductivity by 50% - 104%.
Jiang et al. (2009b)	R113	Cu, Al, Ni, CuO, Al_2O_3	Nanoparticle volume fraction enhanced the thermal conductivity greatly.
Mahbubul et al. (2012)	R123	TiO_2	Diminution in viscosity with increase in temperature at all particle concentrations.
Rashidi et al. (2012)	R113	CNT	Model predictions are in line with experimental results.
Ozturk et al. (2013)	HFE-7500	CNT, Graphene nano sheet	An increase in thermal conductivity up15%was observed at 1% volume fraction.
Mahbubul et al. (2013a)	R141b	Al_2O_3	179 and 1.626 times increase viscosity and thermal conductivity were recorded respectively.
Mahbubul et al. (2014)	R141b	Al_2O_3	Exhibits non-Newtonian behaviour at lower shear rates and converted near to Newtonian at high shear rates.
Mahbubul et al. (2015)	R134a	Al_2O_3	28.58%, 13.68% and 11% augment in thermal conductivity; viscosity and density were obtained respectively.
Zhelezny et al. (2017)	R600a	Al_2O_3, TiO_2	Solubility and viscosity enhanced, however surface tension found to be decreased.

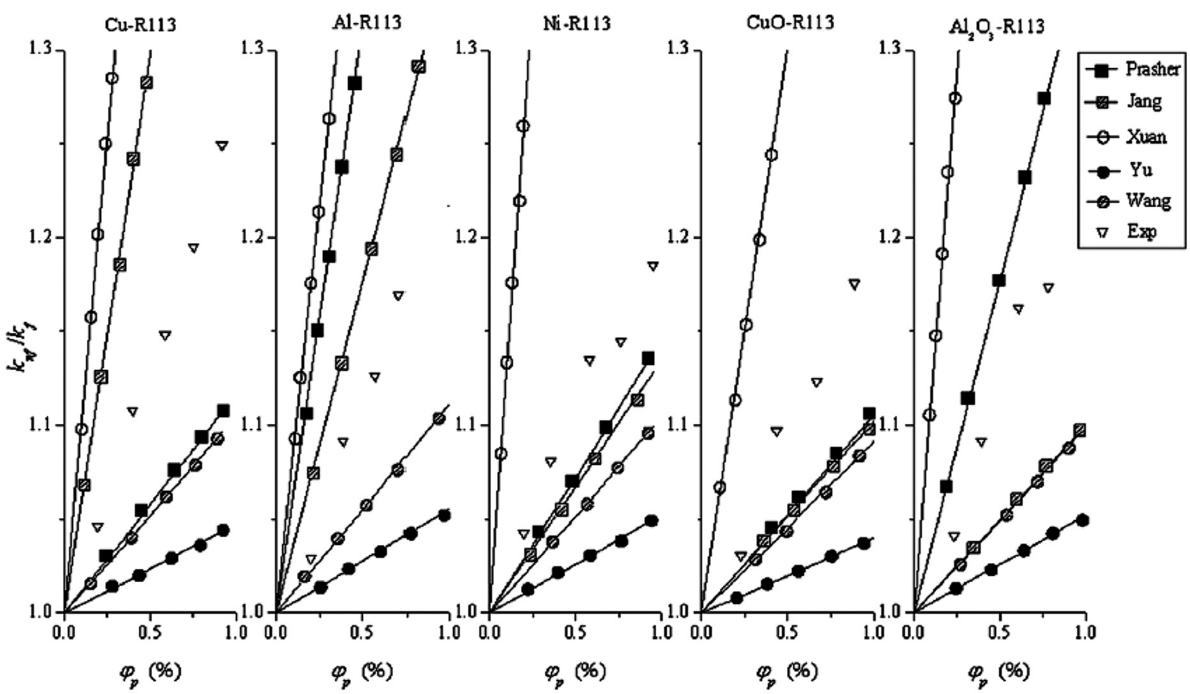


Fig. 1. Effective thermal conductivity comparison of nanorefrigerants (Jiang et al., 2009b).

Jiang et al. (2009b) investigated thermal conductivity and proposed a model to predict it in particularly for nanorefrigerants. R-113 was used as the host refrigerant. The nanoparticles include copper, aluminum, nickel, copper oxide, and aluminum oxide. The principle of measurement of thermal conductivity was transient plane source method. The nanoparticle loading ranges between 0.1% and 1.2%. Their study disclosed that, at a volume fraction of 1.0%, the thermal conductivity increased by 20%. Almost similar trend has been displayed by the entire nanorefrigerant considered, at same volume fractions. A comparative study has been performed with classical model predictions to evaluate the experimental results and is shown in Fig. 1. The model predictions deviate from the experimental results within 5%−10%. A new model has been developed based on particle aggregation theory and observed excellent agreement with experimental values.

Mahbubul et al. (2012) investigated the viscosity of R123/TiO_2 nanorefrigerant. The particle concentration ranges from 0.5% to 2%. Interestingly, the test section was a horizontal smooth tube. The temperature effect also considered for their studies. It was found that volume fraction has noteworthy role in the viscosity enhancement. Besides, intensification of temperature declines the viscosity of nanorefrigerant.

Ozturk et al. (2013) formulated graphene nanosheets (GNS) and MWCNT based nanorefrigerants. They considered only low particle loadings of 0.25 to 1 vol%, with an aim to increase the stability. The hydrofuoroether (HFE) refrigerant was used as the host fluid with fluorocarbon stabilizer Krytox 157 FSL mono functional carboxylic acid- termed as perfluoropolyether for their studies. Lower surfactant concentrations were deployed to reduce its effects on viscosity. Transient hot wire technique was the principle of measurement. Form the experimental studies, the authors inferred that graphene nano sheets have unique potential to improve the thermal conductivity similar to that of carbon nanotube suspensions, nonetheless unlike CNTs, viscosity of the colloid was marginally increased.

Mahbubul et al. (2013b) experimentally examined the impact of particle volume fraction (0.5 to 2 vol %) and temperature (5 °C −20 °C) on thermo physical properties of R141b refrigerant appended with alumina nanoparticles. The average particle size was 13 nm. The authors reported that the thermal conductivity of nanorefrigerant increased with the augmentation of particle

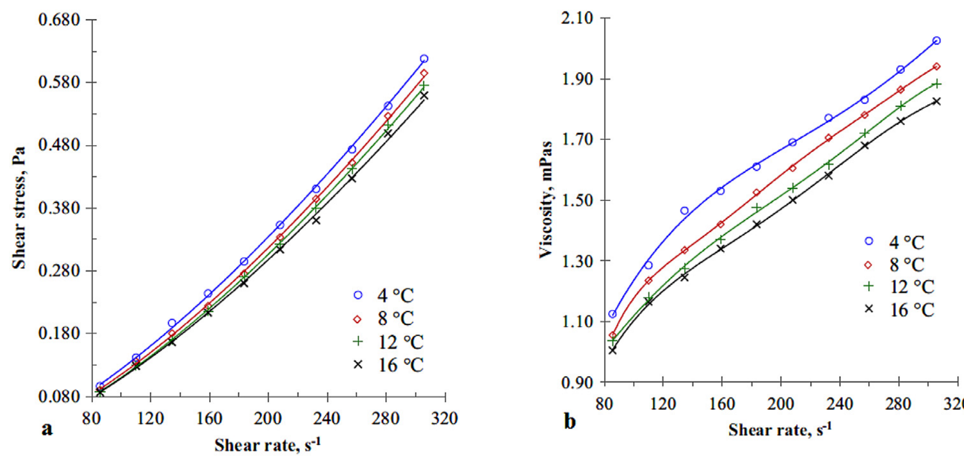


Fig. 2. Variation of (a) shear stress with shear rate (b) viscosity with shear rate (Al_2O_3/R141b nanorefrigerant at 0.1 vol. %, Mahbubul et al., 2014).

concentration and temperature. Viscosity of nanorefrigerant increased with increase in volume fraction and viscosity decreased accordingly with the increment of temperature. The experimental results were compared with classical model predictions. The classical models under predict the effective viscosity and thermal conductivity. At a temperature of 5 °C and volume fraction of 0.5%, the thermal conductivity was 1.214 times greater than that of base fluid. Highest thermal conductivity was observed at a temperature of 20 °C and 2vol% particle concentration and it was 1.626 times superior to that of host fluid.

Mahbubul et al. explained the underlying facts of this improvement in thermal conductivity in such a way that: “higher temperatures intensify the Brownian motion and eventually contribute to increased micro convection”. The viscosity of nanofluids generally shows a decreasing pattern with the increase of temperature, the same trend was exposed by nanorefrigerant also. The highest viscosity was observed as and 1.79 times higher than that of base fluid. Experimental results show that the augmentation in viscosity was at the higher side than thermal conductivity; in this view authors suggested further studies to optimize concentration of nanoparticles in refrigerants.

The rheological behavioral studies on the viscosity of nanorefrigerants cannot be shelved. The shear dependent viscosity variation and the mannerism of fluid, such as Newtonian or non-Newtonian also to be disclosed.

Kumar et al. (2016) summarized various studies on behaviour of nanofluids in their review. According to their study, it was realized that, as the particle dosing level was increased, Newtonian behaviour of nanofluids transformed into non-Newtonian. Studies on rheological properties of nanorefrigerants have great significance before practical implementation in various heat transfer systems. To predict the pressure drop and pumping power through various conduits experimental studies on the rheological properties of nanorefrigerants are essential.

Mahbubul et al. (2014) conducted systematic experimental investigations to explore the rheological behavior of Al_2O_3/R141b nanorefrigerant. The volume nanoparticle dosing level varied from 0.05 to 0.15% in the temperature range of 40C to 16 °C. The shear rate was up to 305.75 s^{-1}. In their experiments, a mechanical shaker (orbital incubator type) was used to homogenize the nanoparticles in the refrigerant. In this study, a Brookfield type rheometer was used to characterize the rheological behavior. For each sample, the temperature of nanorefrigerant was varied at an interval of 4 °C to analyze the temperature effect. The variation of shear stress with shear rate for 0.10 vol% concentration of Al_2O_3/R141b with four different temperatures was shown in Fig. 2(a) and (b).

According to Mahbubul et al., “viscosity increases with increase of shear rates. At low shear rates, these increasing trends were found to be non-Newtonian behavior up to the yield stress point. Beyond the yield stress, the rheograms showed almost Newtonian trend”. This is an important observation as the shear thickening behavior exhibited by the nanorefrigerant is disappeared with the increase of shear rate. The sedimentation formed because of the particle agglomeration easily broken to form a dispersed suspension with the increase of shear rate, which exhibits near Newtonian behavior. It could be a favorable benefit for practical application of nanorefrigerants in refrigeration cycles with compressors, as with the force provided by the compressor de-agglomerates to form a dispersed solution. Intensification of temperature lowers viscosity. Moreover, this decreasing trend was more significant for higher particle concentrations and shear rates. The experimental viscosity found to be higher than the value predicted by Brinkman model. After exhaustive experimentation the authors established that the “volume fraction and temperature have significant effects over the viscosity of nanorefrigerants” .

Mahbubul et al. (2015) put their efforts in the measurement of thermo physical properties of Al_2O_3 /R134a nanorefrigerant. They analyzed the, density and specific heat in addition to thermal conductivity, viscosity. Analyses have been carried out for a constant mass flux in a smooth horizontal tube. Studies were conducted with pure refrigerant and nanorefrigerants at various temperatures to find the temperature dependent thermal conductivity variation. Results revealed that the thermal conductivity of nanorefrigerant increases with increase in temperature whereas that of pure refrigerant decreases with temperature increment. According to Mahbubul et al., “When temperature of fluid increases, the inter particle and intermolecular adhesion forces were decreased and which resulted in a decrease in viscosity also”. The density pure and nanorefrigerant was found to be decreased moderately with rise in temperature. The presence of nanoparticle contributes to further increase in density as well. The specific heat of both pure and nanorefrigerant increases linear in manner with in the temperature limit (10 °C–35 °C) and establishes a strong temperature dependency.

Zhelezny et al. (2017) conducted complex investigations and presented experimental data for viscosity, density, capillary constant, surface tension and solubility of natural refrigerant isobutene R600a/ mineral compressor oil based nanorefrigerant. The nanoparticles used in their experiments were Al_2O_3 and

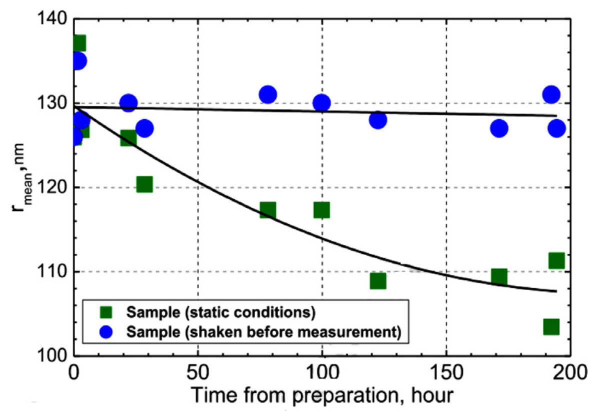


Fig. 3. Variation of the mean size of Al_2O_3 (0.5 mass %) nanoparticles with time (Zheleznу et al., 2017).

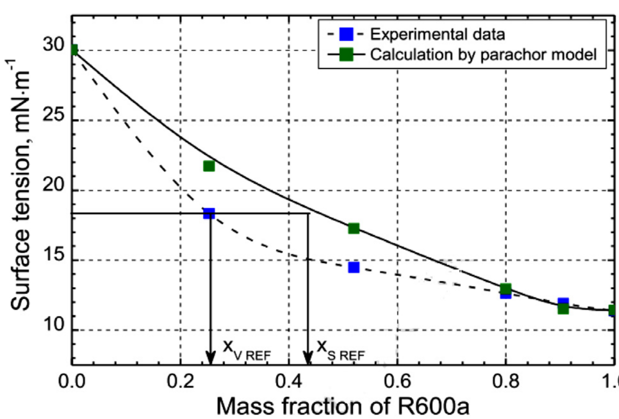


Fig. 4. Variation of surface tension with volume fraction (Zheleznу et al., 2017).

TiO_2. The refrigerant nano-oil solutions (RONS) were prepared by two step method. Experiments to investigate the stability of the nano-oil have been performed.

The time elapsed stability studies were carried out by measuring the mean radius of nanoparticles at static and dynamic conditions by dynamic light scattering technique.

The deviations of mean diameter of Al_2O_3 nanoparticle at 0.5% mass fraction with time is shown in Fig. 3. There was an obvious reduction in mean size. The size varied from 130 nm to 110 nm after 12 days at static conditions. This is a hint of fractional sedimentation of the nanoparticles. After agitation, almost constant particle size was noted.

The viscosity studies revealed the similar trend as that obtained by other researchers (Mahbubul et al., (2014); Ozturk et al., (2013)). Zheleznу et al. (2017) attempted to explore the effect of alumina nanoparticles on the surface tension with modified differential method of capillary rise. According to them; "the essence of this method was measurement of difference in the height of liquid's meniscus in few capillary pair and followed by the calculation of weighted average value of capillary constant".

Fig. 4 shows the variation of surface tension with respect to volume fraction.

Following conclusions were derived out from their investigations. Presence of nanoparticles consequences decrease in surface tension of pure refrigerant, however, it boosts the solubility.

3. Boiling heat transfer phenomena in nanorefrigerants

Researches regarding boiling, both pool boiling and two-phase flow boiling phenomena in nanorefrigerants are still remains ambiguous. The flow boiling phenomena involves in diverse of applications such as energy conversion systems, heat exchangers, chemical thermal processes, nuclear reactors etc. The most prominent one among them is refrigeration and air-conditioning systems. Pool boiling and flow boiling are the critical types of boiling regime. Addition of nao-sized particles into the phase change fluids is one of the state of the art methods to enhance the boiling heat transfer performance. Recently researchers focus on the studies regarding the boiling heat transfer performance of nanorefrigerants and disclose the crucial role of nanoparticles on it (Kedzierski, 2009; Peng et al., 2011a; Yang et al., 2015). Few studies on pool and flow boiling heat transfer of nanorefrigerants are reviewed here.

3.1. Pool boiling heat transfer in nanorefrigerants

The nanofluid research community published limited experimental studies concern to boiling phenomena in nanorefrigerants and is conflicting in many ways. Interestingly, both enhancement and detriment in heat transfer with the addition of nanoparticles are reported. This scenario unwrap more opportunity to researchers Table 2 represents a summary of major studies on nucleate pool boiling of nanorefrigerants with and without addition of lubricants.

Park and Jung (2007a) studied the influence of CNTs in nucleate pool boiling heat transfer of R_{22} refrigerant with particle concentration of 1.0vol%. In this study multi walled CNTs were mixed with working fluid. The average size of nanoparticle was 20 nm in diameter and 1 μm in length. The test apparatus consists of test vessel, boiling tube, circular channel for refrigerant etc. The boiling process is observed with a sight glass incorporated with the test rig. The heat flux was varied from 80kWm^{-2} to 10kWm^{-2} in the decreasing order. The pool temperature was set at 7 °C. Test results show an improvement in nucleate boiling HTC of the refrigerant. There maximum increase in heat transfer coefficient recorded was 24.7% and which was obtained low heat flux. The authors established the relation between heat flux and HTC such a way that: " as the heat flux increases, the heat transfer performance with CNTs decreases" .

Liu and Yang (2007) examined the effect of Au nano-additive on the boiling characteristics of R-141b. Tests were conducted in horizontal plain tubes. The heat flux varied from 3.5 to 100 kWm^{-2}. Three particle volume concentrations, (0.09%, 0.4 and 1.0%) were considered for their study. Chemical reduction method was employed for the preparation of nanoparticles. The copper test tube has 100 mm length, 18 mm outer diameter. The heat is supplied with a cartridge heater. The test tube is submerged in refrigerant bath. The results revealed the pool boiling heat transfer improving potential of Au particles. However, significant changes in surface roughness of the conduit and particle size were reported. These factors cause degradation of the boiling heat transfer performance eventually. The deterioration is shown in Fig. 5(a) and (b).

The reason for the decline is clearly explained after conducting scanning probe analysis by Liu and Yang (2007): "Deterioration of boiling performance was due to the trapped particles on surface and reduced number of active nucleation sites".

Park and Jung (2007b) examined the effect of CNTs as an additive to R123 and R134a refrigerants. A test vessel and refrigerant circulation loop are the major components of test apparatus. As observed in previous studies, here also enhancement in nucleate boiling HTCs is reported. Specifically, up to 36.6% increment in heat transfer was manifested at low heat flux, however the heat transfer enhancement at higher heat fluxes are comparatively at lower side.

They derived the underlying facts as following (Park and Jung, 2007a): "At low heat fluxes, the bubble generation was not vigorous and CNTs with higher thermal conductivity can penetrate into the bubble zone near the surface and touch the surface

Table 2
Pool boiling heat transfer in nanorefrigerants- A summary.

Researcher	Refrigerant	Nanoparticle	surfactant	Lubricant	Test section	Evaluation
Park and Jung (2007b)	R123	CNTs	–	–	Horizontal circular tube	Increase in nucleate boiling HTC up to 36.6%
Park and Jung (2007b)	R22	CNTs	–		Horizontal tube	Nucleate boiling HTC was increased up to 24.7%.
Ki-Jung Park & Jung (2007a)	R123, R134a	CNT	–	–	Plain tube	HTC decreased with increase in heat flux.
Liu & Yang (2007)	R141b	Au	–	–	Horizontal plain tube	At particle concentration of 1.0%, the heat transfer coefficient was more than twice
Wong wises et al. (2009)	R141 b	TiO_2	–	–	Horizontal cylindrical heater	Deteriorates the nucleate boiling HTC.
Peng et al. (2009)	R113	CuO	–	–	Horizontal smooth tube	Mass fraction significantly boost the frictional pressure drop
Kedzierski (2009)	R134a	CuO		POE	Straight surface	Boiling heat transfer enhancement between 50% and 275%.
Trisaksri et al. (2009)	R141b	TiO_2	–		Boiling tube	Addition of nanoparticle deteriorates the boiling heat transfer.
Peng et al. (2010)	R113	Diamond	–	VG68	Horizontal flat surface	Nucleate pool boiling HTC was maximum of 63.4%.
Peng et al. (2010a)	R113	CNTs	–	VG68	Boiling vessel	The nucleate pool HTC increased up to 61%.
Yang and Liu (2010)	R141b	Au	–	–	Plain copper tube	At 1%particle concentration, the pool boiling HTC was twice than that of pure refrigerant.
Peng et al. (2011)	R113	Cu	SDS, CTAB, Span-80	–	Boiling vessel	Surfactants enrich the nucleate pool boiling heat transfer.
Peng et al (2011)	R113	Cu	–	VG68 ester oil	Boiling vessel	Up to 49% pool boiling HTC observed.
Kedzierski (2011)	R134a	Al_2O_3	–	POE	Horizontal flat surface	Increased boiling heat transfer.
Hu et al. (2013)	R113	Cu	–	VG 68	Boiling surface	Surfactants show the potential to augment boiling heat transfer.
Tang et al. (2014)	R141b	Al_2O_3	SDBS	–	Boiling vessel	R141b/ D-Al_2O_3 with SDBS enhanced the pool boiling HTC.
Kedzierski (2014)	R134a	Al_2O_3		POE	Turbo-BII-HP boiling surface	At lower mass fraction, average enhancement in heat transfer over the entire heat flux range was approximately 10%.
Diao et al. (2015)	R141b	Cu	SDBS	–	Boiling vessel	Cu nanoparticles improves the boiling heat transfer performance of R141b.
Yang et al. (2015)	R141b	MWCNT	Span-80	–	Corrugated tube	Optimal heat transfer enhancement was at 0.3 wt%,

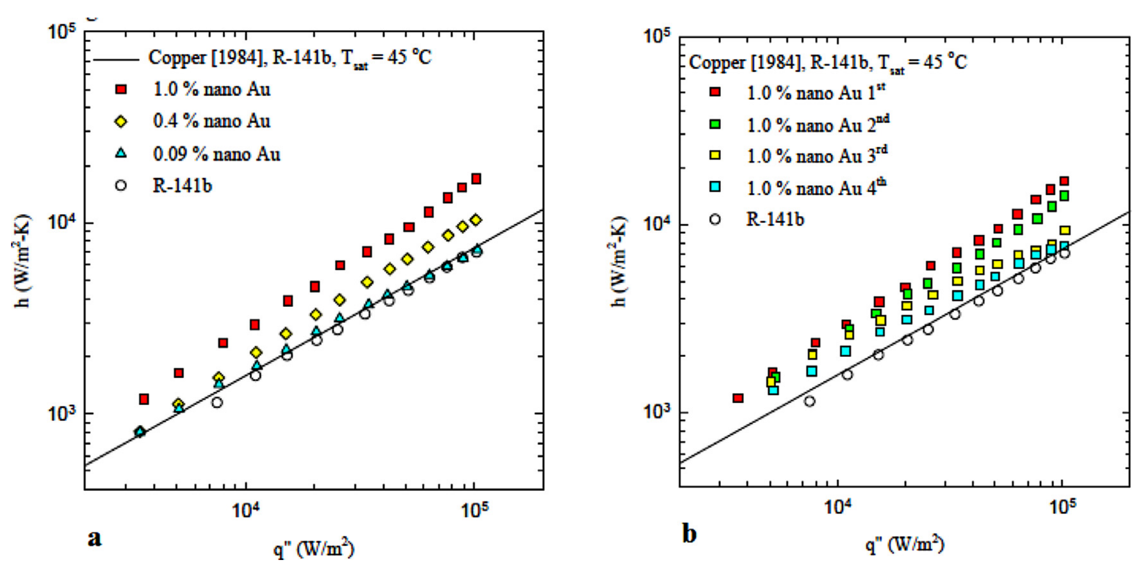


Fig. 5. Heat transfer coefficient versus heat flux at different particle concentrations (a) for different particle concentration and (b) test after each five days (Liu & Yang (2007).

(thermal boundary layer)". The boiling heat transfer variation with heat flux for R113 and R134a based nanorefrigerants are shown in Figs. 6 and 7.

Kedzierski and Gong (2009) first time conducted experiments in modified surfaces. The role of copper oxide nano-additive in the boiling characteristics of R134a/POE combination have been tested on a roughed, horizontal, flat surface. Boiling heat flux ranges between 10 kWm^{-2} and 120 kWm^{-2}. For 0.5% to 1% mass fraction, an enhancement in heat transfer of 50% to 275% relative to pure R134a/POE of was observed. An average deterioration in heat transfer by 12% was noted at mass fraction of 2%.

Trisaksri and Wongwises (2009) conducted experiments on the nucleate pool boiling heat transfer of R141b based nanorefrigerant at various particle concentrations and operating pressures.TiO_2

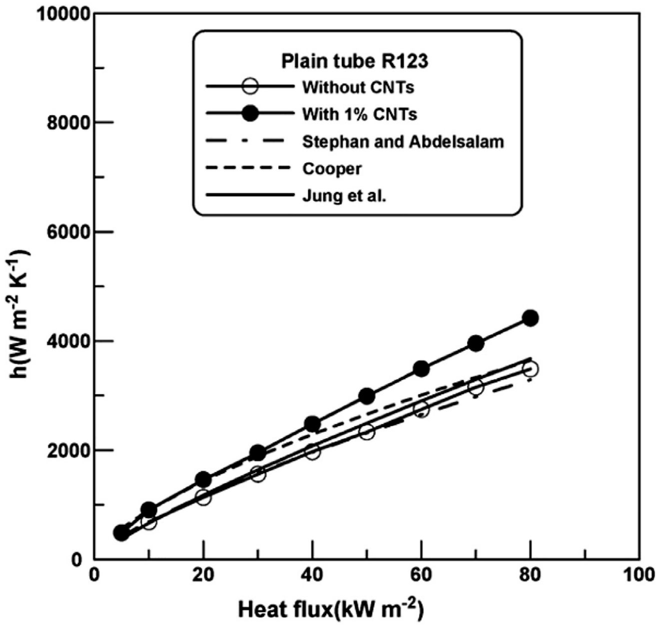


Fig. 6. Heat transfer coefficient vs heat flux (R123 + 1.0 vol. % CNT) (Park and Jung, 2007a).

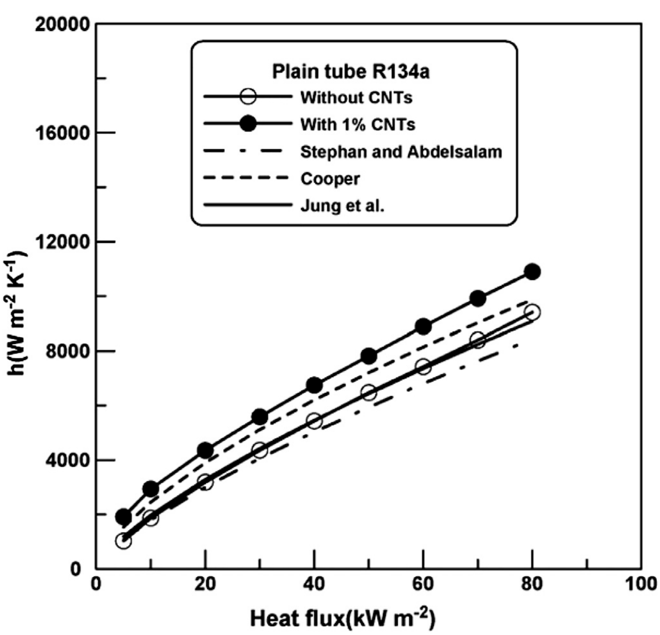


Fig. 7. Heat transfer coefficient vs heat flux (R134a + 1.0 vol. % CNT) (Park and Jung, 2007a).

nanoparticles were stably suspended with refrigerant HFC 141b at 0.01, 0.03 and 0.05 vol%. Experimental apparatus consists of a horizontal cylindrical heater, pressure vessel, condenser etc. Experiments were performed at four pressure conditions of (200–500 kPa). The concentration plays a vital part in the heat transfer characteristics. Both enhancement and deterioration were displayed.

For pure refrigerant and nanorefrigerant, the HTC enhanced with heat flux.

At lower concentration of 0.01vol%, boiling HTC found to be the same as that of pure R141b, evidently indicating the fact that, addition of exceedingly low amount of nanoparticles produces no effect the boiling heat transfer, whereas addition of TiO_2 nanoparticles at 0.03vol% and 0.05vol% concentrations reduce the HTC.

Peng et al. (2010b) determined the nucleate pool boiling of R113refrigerant/ VG68 oil mixture with diamond nanoparticles with an average diameter 10 nm. The experimental conditions were heat fluxes from 10to 80kWm^{-2}, mass fraction of oil is from 0–5 wt%. Three different nanoparticle weight fractions (5wt%, 10wt% and 15 wt %) were prepared and tested.

It was evident from their studies that, the presence of oil reduces the nucleate pool boiling heat transfer of pure R113. As the lubricant mass fraction increases boiling performance also diminishes. That is, the presence of lubricating oil deteriorates nucleate pool boiling heat transfer in refrigerants. The pool boiling heat transfer of R113/oil mixture with 3wt% and 5wt% lubricating oil concentrations were 14.4% and 19.8% smaller than that of pure R113. According to them, presence of diamond nanoparticles along with oil displays dramatic improvements in heat transfer characteristic of refrigerant. The maximum enhancement of nucleate pool boiling heat transfer reached up to 63.4%, 57.1% and 53.04% when the mass fractions of lubricating oil at 1, 3, and 5wt%, respectively.

It would be interesting to see the effect of diameter and length of CNT particles on the boiling heat transfer performance of refrigerants.

Peng et al. (2010a) made an attempt to evaluate the effect of particle size on boiling process of R113 /oil mixture. Carbon nano tubes with outside diameter from 15 nm to 80 nm and length from 1.5 μm to 10 μm were used for their studies. The mass fractions ranges from 0 to 5wt%. Test facility consists of a boiling apparatus and a condensation loop. The results show that, R113-oil-CNT mixture exhibits higher nucleate pool boiling heat transfer coefficient. The enhancement reached up to 61% and the enhancement factor was in the range of 1.23 to 1.61 and was increased with decrease of CNTs outside diameter and increase of length.

Peng et al. (2011a) experimentally investigated the effect of surfactant additives on nucleate pool boiling heat transfer of R113 refrigerant suspended with Cu nanoparticles. The surfactants including SDS, CTAB and Span-80, which are anionic, cationic and nonionic, respectively, were used.

The surfactant concentration were 200,500, 1000, 2000 and 5000 ppm by weight and nanoparticle concentrations were 0.1, 0.5, and1.0 wt%.

The experimental set up includes a copper block test section, a boiling and condensation loop etc. Experimental conditions were, varying heat flux from 10 kWm^{-2} ^{to} 80 kWm^{-2} and saturation pressure of 101.3Kpa. It was reported that maximum enhancement of 55.4% in the nucleate pool boiling heat transfer coefficient occurred at 1.0wt%. Presence of surfactants enhances the nucleate pool boiling heat transfer of pure R113.

In view of the experimental studies, they arrived in an ample conclusion, i.e. Surfactant concentrations and types have noteworthy effects on nucleate pool boiling heat transfer coefficient of nanorefrigerants.

Peng et al. (2011d) determined the influence of particle size on nucleate pool boiling HTC of refrigerant R113/oil mixture. Cu nanoparticles with average diameters of 20, 50 and 80 nm were used as the nano-additive. Wide range of heat fluxes were investigated at particle concentrations between 0 and 5 wt%. Up to 49% increase in pool boiling HTC displayed by the nanorefrigerant at lowest particle size. The heat transfer coefficient appears to be diminished with increase in particle size and the authors establishes the strong particle size dependent heat transfer performance.

Kedzierski (2011) quantified the pool boiling performance of R134a/ Al_2O_3/polyolester mixtures on a geometrically modified flat surface at various heat fluxes. In general, their studies show that Al_2O_3 nanoparticles caused a heat transfer enhancement compared to pure R134a/POE oil mixture for all the lubricant mass fractions. The average heat transfer improvement for the heat fluxes less than 40kWm^{-2} was approximately 105%, 49% and 155% with mass fractions 0.5%, 1% and 2%, respectively. They also proposed a correlation to predict the heat transfer.

The mechanism of increase in heat transfer is explained by the authors in the following way: "transfer of momentum from the nanoparticles to the bubbles is responsible for the boiling heat transfer enhancement" . The model predictions show better agreement with experimental results. The similar studies were conducted by Hu et al. (2013) with refrigerant R113 and revealed the surfactant effects as well. They introduced a term as surfactant impact factor (SIF), (the ratio of heat transfer coefficient of refrigerant/nanolubricant mixture with surfactants to that without surfactant). The value of SIF increases with the increase of surfactant concentrations and then decreases. And SIF increases with the decrease of surfactant molecular weight, nanolubricant concentration and heat flux.

Tang et al. (2014) investigated experimentally the nucleate pool boiling heat transfer characteristics of Al_2O_3-R141b nanorefrigerant on a flat square copper surface at 10–200kWm^{-2} heat flux under atmospheric pressure. The particle concentrations have been varied from 0.01 to 0.1 vol% without and with the addition of surfactant (SDBS). The boiling surface roughness was controlled. Experimental results show that the suspended nanoparticles enhanced the pool boiling heat transfer characteristics of R141b at all concentrations with the surfactant, however at 0.1vol% without surfactant, the heat transfer coefficient deteriorated.

Kedzierski (2014) quantified pool boiling performance of R134a based nanorefrigerant on a Turbo-B-II-HP boiling surface. Polyester lubricant appended with Aumina particles (10 nm size) were used as nanolubricant. Boiling experiments with four combinations of refrigerant nanolubricant mixtures were conducted. The mass fraction of nanolubricant and corresponding particle concentrations were 5.6%, 8.2%, and 16.7% and 1.6%, 2.3%, and 5.1%, respectively.

Fig. 8 shows the test apparatus. The major components of the equipment were test chamber, condenser, and the purger. In principle, the test apparatus was used for the measurement of saturation temperature of the liquid, boiling heat flux, and the test surface temperature. Quartz windows were included with the apparatus to visualize the test section. A brine cooled shell and tube condenser is used to condense the vapours.

The ratio between the heat fluxes of nanorefrigerant and pure refrigerant (q"Al/q"PL) versus the heat flux of pure refrigerant (q"PL) at the same wall superheat and lubricant mass fraction was plotted to depicts the influence of Al_2O_3 nanoparticles on the boiling heat transfer of nanorefrigerant (Fig. 9).

The principal observations are the following. The R134a/ Al_2O_3 nanolubricant with volume fractions 1.6 vol% and 2.3vol% were exhibited an average improvement of approximately 13%, 10%, respectively. Interestingly, nanolubricant with 5.1 vol% exhibits an average heat transfer degradation by 14% The authors reported the possible reason for this decay as agglomeration of nanoparticles.

Diao et al. (2015) performed experimental investigations on the critical heat flux and boiling characteristics of Cu-R141b nanorefrigerant at different particle concentrations (0.008, 0.015 and 0.05 vol%) under atmospheric pressure on a flat surface. The boiling surface was polished before each test. The average size of Cu particles was 30 nm and two-step preparation method was employed. SDBS was used as the surfactant. The boiling heat transfer coefficient of nanorefrigerant was larger than that of pure R141b, according to their experiments. The impact of nanoparticle concentration on enhancement ratio has been explored and shows that there is an increase with nanoparticle concentration.

They put forward some possible factors which lead to the enhancement. Presence of surfactants alters the surface tension of nanorefrigerant, this consequences decrease in bubble departure diameter and increase in bubble nucleation sites. This eventually increases the departure frequency of bubbles. Similarly, the interaction between nanoparticle and particle enriched surface increases the active nucleation sites. The combined effect results in enhanced the boiling heat transfer performance.

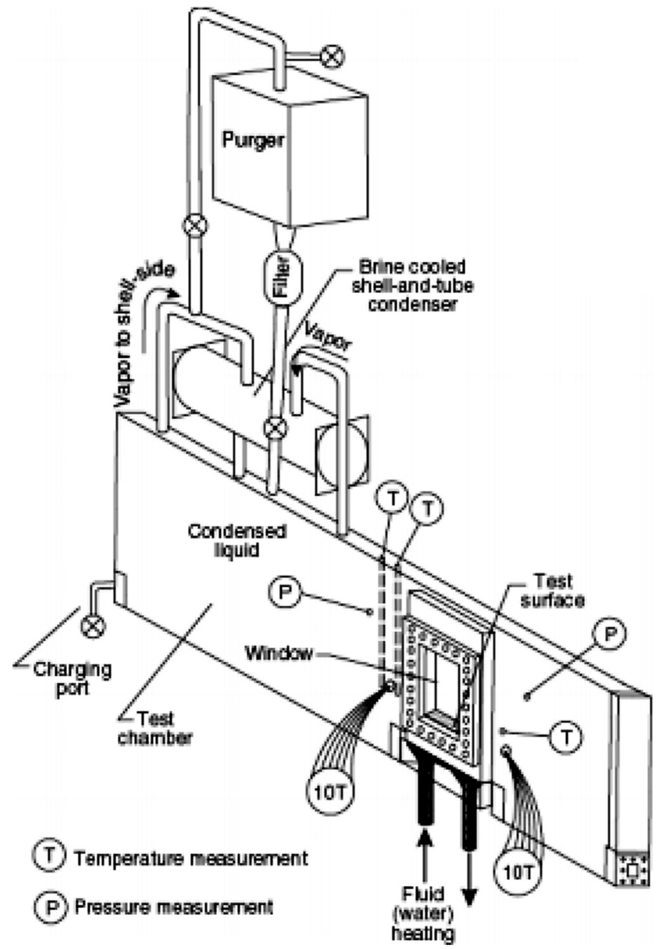


Fig. 8. Schematic of test apparatus (Kedzierski, 2014).

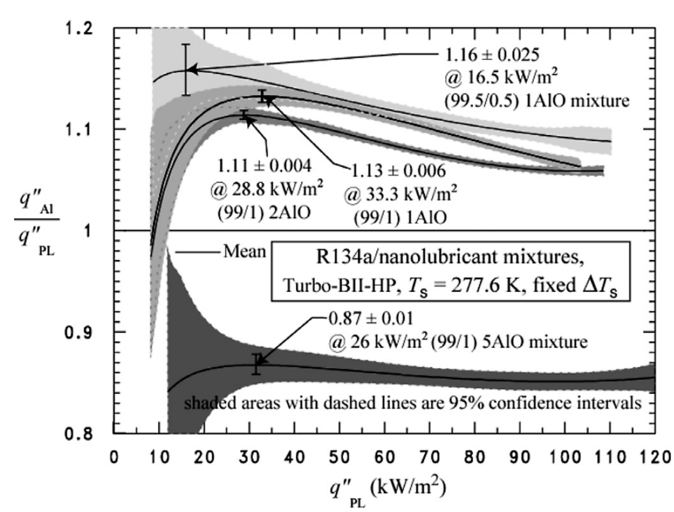


Fig. 9. Boiling heat flux of R134a/nanolubricant mixture vs of R134a/pure lubricant (Kedzierski,2014).

Table 3
Flow boiling heat transfer in nanorefrigerants - A summary .

Researcher	Refrigerant	Nanoparticle	surfactant	Lubricant	Test section	Evaluation
Bartelt et al. (2008)	R-134a	CuO	–	POE	Horizontal smooth tubes	An enhancement up to 42% in the flow boiling HTC was manifested.
Peng et al. (2009)	R113	CuO	–	–	Horizontal smooth tube	Max. heat transfer enhancement obtained was 29.7%
Henderson et al. (2010)	R-134a	CuO	–	Polyolester	Horizontal smooth tubes	Up to 101% increase in flow boiling HTC was noticed.
Henderson et al. (2010)	R-134a	SiO_2	–	–	Horizontal smooth tubes	Convective boiling heat transfer coefficient decreased.
Henderson et al. (2010)	R134a	SiO_2	–	POE(RL68H)	Horizontal tube	Increase in particle concentrations reduces the HTC
Sun et al. (2013a)	141b,	Cu,Al, Al_2O_3,CuO	Span-80		Horizontal tube	The maximum flow boiling HTC was up to 49% at a mass fraction of 0.3wt% and quality 0.5.
Sun and Yang (2013b)	R141b	CuO	–	–	Horizontal pipe	The HTC increased about1.14 times.
Sun et al. (2013d)	R141b.	Cu, Al, Al_2O_3,CuO	Span-80	–	Internal threaded copper tube	The HTC of the nanorefrigerant increased by 17.25%.
Akhavan et al. (2014)	R600	CuO	–	POE	Smooth horizontal tube.	The forced convection boiling heat transfer enhancement was up to 42.2% at 1.5wt%. At 5% mass fraction HTC deteriorated.
Mahbubul et al. (2015)	R134a	Al_2O_3	–	–	Horizontal smooth tubes	Significant increment in HTC resulted.
Yang et al. (2015)	R141b	MWCNT	Span-80	–	Corrugated tube	Optimal heat transfer enhancement at 0.3 wt% compared with pure refrigerant.
	R600	CuO	–	POE	Smooth horizontal tube.	Up to 63% improvement in flow boiling HTC noticed.

3.2. Flow boiling heat transfer in nanorefrigerants

We cannot generalize the boiling phenomena in nanorefrigerants with pool boiling studies alone. The boiling phenomenon normally happens in HVAC and other thermal systems are forced convective/ flow boiling. So investigations are to be focused on that aspect as well. The boiling behavioral study of refrigerants appended with nanoparticles is of great importance. Besides, the influence of nanoparticles on the flow regime formation and boundary layer formation need to be critically examined. Limited studies are available in literature concerning to flow boiling of nanorefrigerants. Unfortunately no studies are existing in literature which addressing the boundary layer effect of nanorefrigerants. There are a few correlations available in literature to envisage the heat transfer coefficient of pure refrigerant flow boiling inside the horizontal tubes. Nevertheless, correlations to predict the flow boiling heat transfer coefficient of nanorefrigerants are scarce. Furthermore, the experimental studies show contradictory results and many aspects should be better illuminated. An overall review of the most representative studies is presented below. Table 3 presents a summary of studies on flow boiling heat transfer in nanorefrigerants.

Bartelt et al. (2008) experimentally explored the impact of CuO nanoparticles on flow boiling characteristics of R134a/polyolester mixture in a horizontal tube. Nanolubricant was prepared with synthetic ester and 30 nm sized CuO particles. Observations portray that, for 0.5% nanolubricant mass fraction, there was no noticeable effect on two-phase boiling heat transfer coefficient. Conversely, for a nanolubricant mass fraction of 1%, an enhancement in the heat transfer coefficient between 42% and 82% were manifested at mass fluxes of 100 and 400 $kgm^{-2}s^{-1}$, respectively. Further increase up to 2% produces better increment in HTC and that goes beyond 100%. Besides, presence of nanoparticles shows insignificant effect on the system pressure drop. Finally, it was also realized that, the presence of surfactants improves the dispersion property.

Peng et al. (2009a) presented the influence of CuO nanoparticles in flow boiling of R113 refrigerant through a horizontal smooth tube. They also proposed a model to predict the HTC. Experimental results show that, heat transfer coefficient of refrigerant mixed with nanoparticles was higher than that of pure refrigerant. The predictions of proposed correlation agree 93% of the experimental data with a deviation of ±20%. Local heat transfer coefficients versus vapour qualities at three different mass fluxes were depicted in Fig. 10(a), (b), and (c). The enhanced heat transfer was evident according to the figures. Heat transfer increases with increase of inlet vapour quality at a given mass fraction. Peng et al. (2009a) reported the underlying facts behind the heat transfer enhancement as: (i) The effect of nanoparticles on the boundary layer formation, i.e. reduction in boundary layer height due to the disturbance of nanoparticles (ii) The formation of molecular adsorption layer on the surface of nanoparticles and (iii) with the increase of vapour quality the flow regime transformed towards annular flow and which eventually augmented the convective heat transfer. The maximum enhancement in HTC perceived was 29.7%.

Henderson et al. (2010) quantified the influence SiO_2 nanoparticles on flow boiling of R134a and R134a/polyolester mixture at different vapour qualities in mass flux range of 100 $kgm^{-2}s^{-1}$ –400 $kgm^{-2}s^{-1}$. Direct dispersion of SiO_2 nanoparticles in R134a resulted in decrease of heat transfer coefficient compared to pure refrigerant. Degradation in heat transfer coefficient was due to difficulties in obtaining stable dispersions. But excellent dispersion was achieved for a mixture of R134a/POE/CuO particles. For the case of R134a/POE/CuO mixture at 0.02% nanoparticle concentration, there was no apparent effect on heat transfer coefficient. However, an enhancement in heat transfer coefficient of 42% and 101% was observed at volume fractions 0.04% and 0.08%, respectively. Authors concluded that, moderate dosing level of particles may boost the heat transfer performance.

Sun and Yang (2013a) experimentally studied the flow boiling characteristics of four types nanorefrigerants flow boiling inside a horizontal tube. Experiments were conducted with different mass fractions, qualities and mass velocities. Nanorefrigerants were Cu/R141b, Al-R141b, Al_2O_3/R141b and CuO/R1414b. Mass fractions varied from 0.1 to 0.3wt%. The vapour quality ranged within 0.3–0.8 and mass velocities between 120 $kgm^{-2}s^{-1}$ and 330 $kgm^{-2}s^{-1}$. A copper tube having inner diameter 10 mm and wall thickness 1 mm was considered as the flow channel. The lengths of pre heating section and test section were 500 mm and 1400 mm respectively. Nanorefrigerants were prepared by two step method. Span-8o surfactant was used to improve the dispersion quality. Light transmittance technique was employed to examine

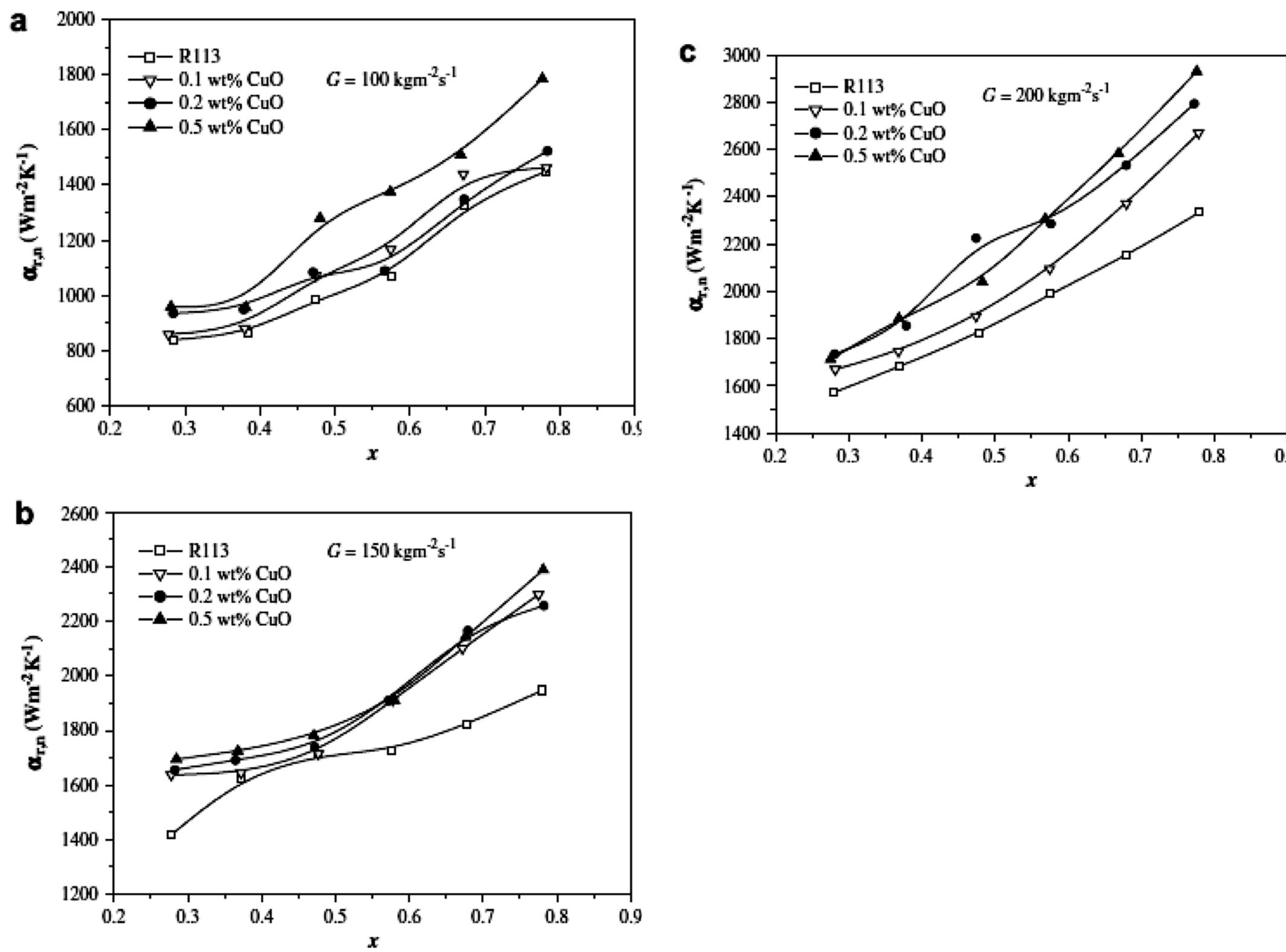


Fig. 10. Heat transfer coefficient of CuO/R113 nanorefrigerant vs local vapour quality at different mass fluxes (a) G = 100 kg $m^{-2}s^{-1}$; (b) G = 150 kg $m^{-2}s^{-1}$ (c) G = 200 kg $m^{-2}s^{-1}$ (Peng et al., 2009).

the stability of nanorefrigerants. Results show that flow boiling heat transfer was enhanced due to the presence of nanoparticles. The parameters responsible for the increase in HTC were increased mass fraction, quality and mass velocities. They reported that, at constant mass fluxes, the critical parameter which influences the HTC was the nanoparticle concentration. A larger concentration resulted in a higher HTC. Different nanoparticles display different effects on the HTC of nanorefrigerant.The maximum heat transfer coefficient was obtained for Cu/R141b combination and it was up to 49% at a mass fraction of 0.3% and vapour quality 0.5.

Studies on heat transfer performances of nanorefrigerants flow boiling through modified channels are of great importance and quite interesting to observe.

Sun and Yang (2013b) experimentally studied flow boiling heat transfer characteristics of four kinds of nanorefrigerants in an “internal threaded copper tube” . The performance of nanorefrigerants (Cu –R141b, Al-R141b, Al_2O_3-R141b and CuO-R141b with mass fractions 0.1wt%, 0.2wt%, 0.3wt%) at different inlet vapour quality and mass fluxes were investigated. The quality varied from 0.3 to 0.8 and mass fluxes were 120, 210, 330 kgm^{-2} s^{-1} . The flow is visualised with a high speed camera. The internal threaded copper tube test section has 1400 mm lngth, 9.52 mm outer diameter and 8.22 mm inner diameter. To improve the stability, Span −80 was used as the dispersant.

Experimental results show that, there is a substantial increase of HTC with respect to mass fraction at constant mass flow rate and this was almost in linear manner as well. Cu-R141b nanorefrigerant exhibits largest average HTC by 25% at 0.3wt%.

Yang et al. (2015) conducted experiments in a corrugated tube to portray the boiling performance of MWCNT-R141b nanorefrigerant. Mass fractions of 0.1, 0.2, and 0.3% have been examined.

Constant heat flux boundary condition to the test section was accomplished with electric heating tape with temperature controller.

Optimal heat transfer enhancement compared with pure refrigerants was displayed by 0.3 wt% MWCNT/R141b nanorefrigerant.

The maximum increase in Nusselt number was obtained as 41%. The specific pressure drop of nanorefrigerant increased with increase in Reynolds number. The maximum value of Nu_{nf}/Nu_f increased with increased mass flow rate.

The mass fraction was the key factor for the heat transfer enhancement. They also studied the effect of surfactants on heat transfer enhancement in nanorefrigerants. At 1wt% mass fraction of span −80 surfactant, the highest heat transfer coefficient was observed, in which the enhancement effect was found to be 1.21 times. Under the same vapour quality, the pure refrigerant has the lowest pressure drop. Largest pressure drop was observed at 0.3wt% MWCNT/R141b.The responsible factor for this phenomenon

Table 4
of studies Flow condensation heat transfer in nanorefrigerants - A summary.

Researcher	Refrigerant	Nanoparticle	Lubricant	Test section	Evaluation
Pamitran et al. (2007)	R410A	Ni	Ze-GLES68	Condenser tubes.	Larger fluid sub cooling degree with nanorefrigerant was attained.
Akhavan et al. (2015)	R600a	CuO	POE	Horizontal smooth tube.	Flow condensation HTC of nanorefrigerant is significantly higher than that of pure refrigerant.
Peng et al. (2018)	R141b	CuO	–	Vertical circular tube	The condensation heat transfer coefficient increased by 39.68% at mass fraction of 1%.
Darzi et al. (2018)	R 600a	CuO	POE	Horizontal tube	The frictional penalty factor during condensation was independent at higher vapour qualities.

was the enhanced viscosity of nanorefrigerant. The Nusselt number increases first and then decreases under the three mass fluxes. One of the critical parameter that influences the HTC is vapour quality. Increase in vapour quality deteriorate the HTC, this is due to the reduced content of liquid refrigerant.

Forced convective boiling heat transfer of R600a-oil-CuOnanoparticle mixture in a smooth horizontal tube was experimentally investigated by Baqeri et al. (2014). The nanoparticle concentrations were 0.5, 1.0, 1.5, 2.0 and 5.0 wt %. The mass velocities varied from 50 to 700 kgm^{-2}. The lubricant oil used was polyolester RL68H. The other experimental conditions were heat flux 3–6 kWm^{-2} and inlet vapour quality less than 0.25.

Increase in mass flux resulted in an increase in average HTC for all cases considered. Baqeri et al. (2014) explained it in such way that:

> “Increasing the mass flux and consequently increase in Reynolds number leads to decreased thickness of boundary layer. This causes increment of the temperature gradient near the wall and results in heat transfer enhancement”.

Maximum enhancement in heat transfer was by 46.5% and it was observed at a particle volume fraction of 2.0%. The enhancement of heat transfer coefficient was reported as 4.56, 18.25 and 32.5% at 0.5, 1.0 and 1.5% mass fractions, respectively. Conversely, at a mass fraction of 5%, the heat transfer coefficient decreased by 7.94% .

Akhavan-Behabadi et al. (2014) researched the influence of CuO nanoparticles on flow boiling of R600a/nanolubricant mixture flowing through smooth horizontal tube.

The experimental conditions were mass velocities from 50 to 400 $kgm^{-2}s^{-1}$, inlet vapour qualities from 0 to 0.9, heat flux from 3 to 8 kWm^{-2} and mass fractions of nanoparticles from 0 to 1.5wt%. The experimental setup consists of a pump, flow meter, pre-heater, test evaporator and condenser. Three different nanoparticle mass fractions were considered for their experimental studies (0.5wt%, 1wt%, and 1.5wt%). The heat transfer coefficient of pure R600a was compared with predictions by Gungor-Winterton correlation. The following conclusions were derived out after the experimentation. CuO nanoparticles show an excellent heat transfer improving potential with R600a refrigerant. The most average heat transfer enhancement occurred at 1.5 vol% was up to 42.2%, 37%, 30% and 28% for mass velocities 77,154,232, and 348 kgm^{-2} respectively.

4. Flow condensation heat transfer phenomena in nanorefrigerants

The studies regarding flow condensation heat transfer in nanorefrigerant are scarce. Analogous to pool and flow boiling research, systematic experimental investigations are necessary to explore the condensation behavior of nanorefrigerants. Formation of flow regimes in nanorefrigerant should also be perceived. The research on this specific area divulges best hope for application of nanorefrigerants in HVAC systems. Researches are underway and the available experimental studies are summarized in Table 4.

Pamitran et al. (2007) systematically investigated the effect of nanoparticles in condensation process of refrigerant R410a. The Ni nanoparticles having mass fraction 1% was mixed with Ze-GLES68 lubrication oil. The condensation heat transfer in an air-conditioner was studied. It has been found that fluid sub-cooling with nanoparticles was larger than that without nanoparticles by 1.8 °C. Authors arrived at the following conclusions. The behavior of nanoparticles with in the lubricant oil and refrigerant has significant role on heat transfer enhancement and the development of flow regimes in forced convection condensation.

Akhavan-Behabadi et al. (2015) practically explored the flow condensation heat transfer characteristics of R600/POE/CuO nanorefrigerant inside a smooth horizontal tube. Experiments were conducted with three different types of working fluids including pure R600a, R600a/POE Oil and R600/POE oil/CuO mixture. Nanorefrigerant with particle concentrations 0.5%, 1% and 1.5l% were prepared. Schematic diagram of the experimental setup is shown in Fig. 11.

The experiment covered a wide range of variables including, mass fraction from 154.8 to 265.4 $kgm^{-2}s^{-1}$, vapour qualities between 0.1 and 0.8, heat flux from 17 to 20kwm^{-2} and condensation pressure from 5.1 to 6.2 bar. The experimental findings revealed significant heat transfer enhancement with nanorefrigerant. From Figs. 12 and 13 it is clear that for all cases, the heat transfer increased with nanoparticle concentration and the maximum heat transfer augmentation was observed for nanorefrigerants with 1.5% mass fraction, and it was 83% higher compared to pure refrigerant under the same experimental conditions. The possible underlying mechanisms of this augmented heat transfer have been explained by Akhavan-Behabadi et al. (2015) as follows:

> “Nanoparticle disturbance leads to the decrease in boundary layer thickness, which in eventually reduces the thermal resistance and enhances heat transfer, liquid molecules were absorbed by nanoparticles which in turn upsurges the heat transfer rate, the surface tension of the mixture was increased in comparison with pure refrigerant and this consequences an increase in the wettability and hence the heat transfer improves”.

Darzi et al., 2018, conducted experiments with a primary objective to determine the condensation pressure drop of nanorefrigerant flows through horizontal tube. The working fluid was isobutene-CuO-POE nanorefrigerant. The particle concentrations varied from 0.5% to 1.5%. Effect of mass flux, vapour quality and concentration on the condensation pressure drop has been elucidated. They introduced a parameter called “Frictional penalty factor” which is the ratio between the frictional pressure drop exhibited by nanorefrigerant to that obtained from pure refrigerant at same vapour quality and mass flux. Results disclosed that at lower vapour qualities, significant hike in frictional penalty factor has been manifested by the nanorefrigerant.

Peng et al., 2018 observed the effect of CuO nanoparticles on the flow condensation heat transfer of R141b refrigerant at

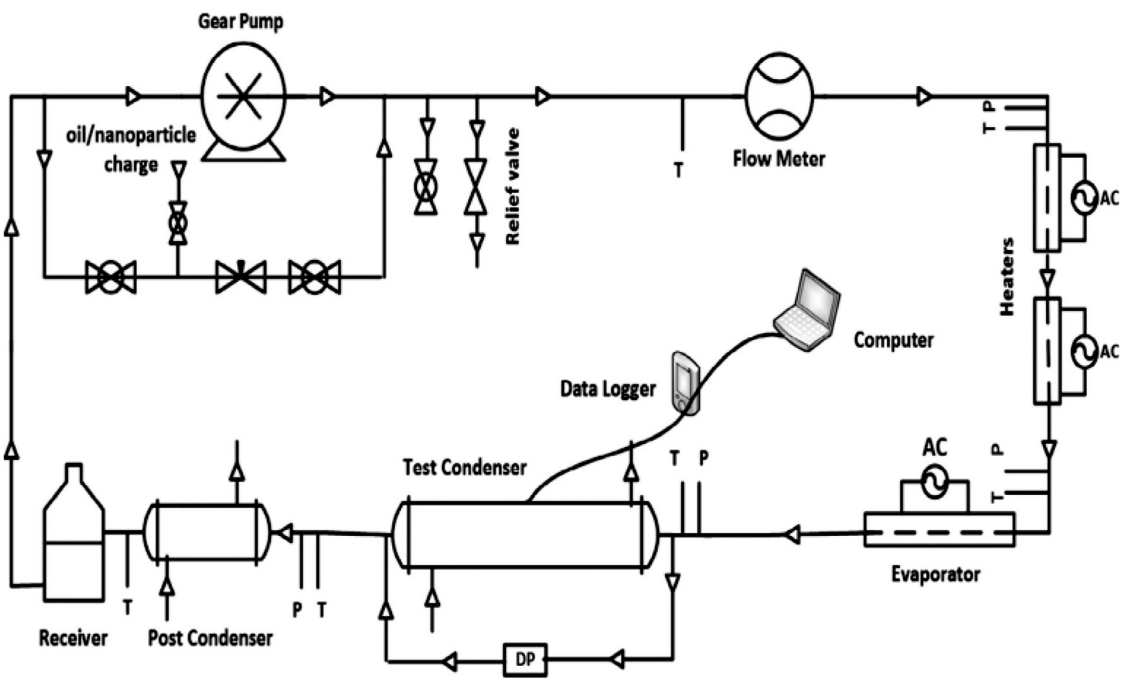


Fig. 11. Schematic of experimental setup (Akhavan et al., 2015).

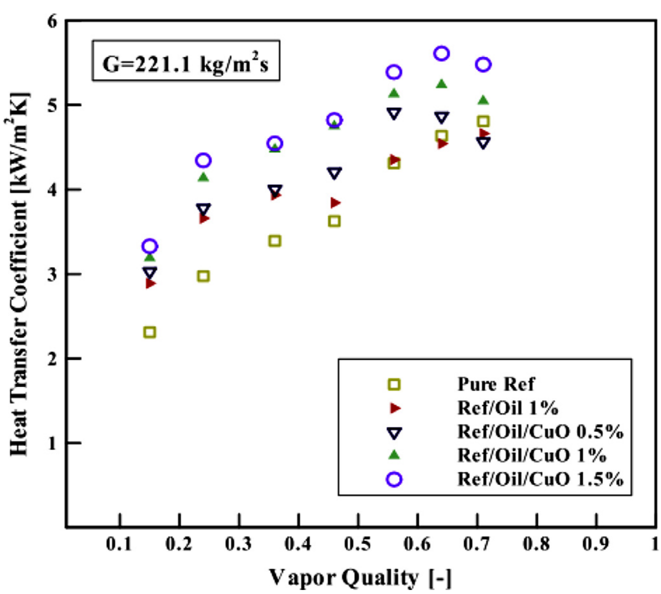


Fig. 12. Condensing HTC vs vapour quality (Akhavan et al., 2015).

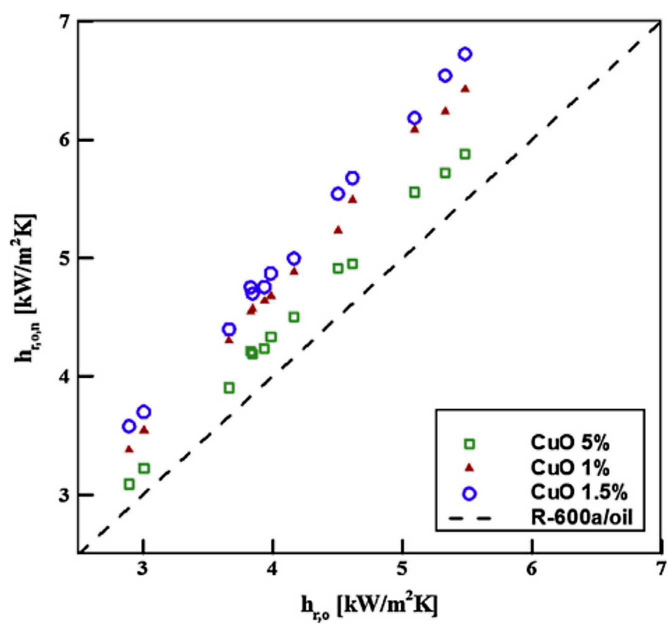


Fig. 13. Comparison of condensing HTC for R-600a/oil/CuO with R-600a/oil (Akhavan et al., 2015).

various mass fractions. Mass fluxes and inlet vapour qualities were altered accordingly to evaluate its impact as well. The study unveiled that augment of nanoparticle mass fraction promotes the heat transfer coefficient and this enhancement was prominent at lower mass fluxes. The maximum observed heat transfer enhancement was 39.68%.

5. Pressure drop characteristics of nanorefrigerants

Numerous studies have been reported concerning to the single-phase pressure drop phenomena of different nanofluids, nonetheless studies on the phase-change pressure drop characteristics of refrigerants appended with nanoparticles are still in its infancy. Increased pumping power requirement is one of the probable consequences of large drop in pressure. A definite conclusion on the effects nanoparticles in the pressure drop characteristics of nanorefrigerants has not been evolved so far. To design and optimize refrigeration systems with nanorefrigerants, extensive experimentations on pressure drop characteristics are also quite important. Some investigations on pressure drop characteristics in nanorefrigerant are enumerated here in Table 5.

Peng et al. (2009b) investigated the frictional pressure drop characteristics of CuO/R113 nanorefrigerant inside a smooth horizontal tube. They also proposed a numerical correlation to predict the pressure drop. The experimental conditions involved were mass fluxes 100–200 $kgm^{-2}s^{-1}$, heat flux from 3.08 to

Table 5
Pressure drop characteristics in nanorefrigerants – A summary.

Researcher	Refrigerant	Nanoparticle	Test section	Evaluation
Peng et al. (2009b)	R113	CuO	Horizontal smooth tube	frictional pressure drop increased with increased nanoparticle mass fraction
Mahbubul et al. (2013b)	R141b	Al_2O_3	Horizontal tube.	pressure drop enhancement was up to 181%
Alawi et al. (2015a)	R123	TiO_2	Horizontal tube.	The pressure drop enhancement was 42.5% at 0.5 vol.%

6.16 kWm^{-2}, vapor qualities from 0.2 to 0.7 and mass fraction of nanoparticles from 0 – 0.5wt%. Studies exposed that; addition of nanoparticle to refrigerant slightly increases the frictional pressure drop. It was also found that, the frictional pressure drop increased with increased nanoparticle dosing level. The frictional pressure drop increases to 20.8% at a mass flux of 100 kgm^{-2} and at a mass fraction of 0.5 wt%. Besides, as the vapor quality increases, flow regime transforms to annular flow and consequences an increase in the pressure drop.

Peng et al. introduced a term, nanoparticle impact factor ($F_{PD)}$ to represent the effect of nanoparticles on the frictional pressure drop quantitatively. This impact factor changes with change in vapor quality and nanoparticle mass fluxes. The proposed correlation provides good agreement with experimental data within the deviation of ±15%.

Mahbubul et al. (2013c) performed an investigation on the drop in pressure of R141b refrigerant. Alumina nanoparticles at different volume fraction were tested. Effect of mass flux and vapor qualities were also examined. No surfactants were used to improve the dispersion stability. After extensive experimental study, the authors arrived at the following conclusions. Even small amount of nanoparticles could intensify the pressure drop of nanorefrigerant. According to their study, when the volume fraction goes beyond 3%, irrespective of vapor qualities, drastic increase in the pressure drop was observed. Increased collision between molecules and subsequent wall interaction were the reason for this anomaly.

Alawi et al. (2015b) conducted experimental measurements and proposed a correlation to forecast frictional pressure drop of TiO_2/R123 nanorefrigerants. Extensive experimentations were carried out at temperature from 27 to 52 °C, nanoparticle concentrations from 0.5% to 2%, mass fluxes from 150 to 200 kg m^{-2} s^{-1} and inlet vapor qualities from 0.2 to 0.7. From the studies the following conclusions were derived. The inference of their studies is in line with previous researches, i.e. particle volume concentration has key role in the pressure drop.

6. Studies on particle aggregation behavior in nanorefrigerants

The nanoparticles in any base fluids are likely be agglomerated due to strong Brownian motion, Van der Walls force and high surface free energy. This will eventually results in coagulation and sedimentation which in turn affect the suspension steadiness, which will impede the performance during continuous operation. Researches to disclose particle aggregation behavior within the base fluid is inevitable for the development of sustainable nanorefrigerants. The effect of surfactants on the aggregation behavior has also been elucidated. Azizian et al. 2014, Ismay et al. 2013, Jiang et al. 2009, Li et al. 2007, and Pang et al. 2014 reported the particle aggregation behavior of nanofluids based on water, ethylene glycol, silicon oil, gear oil etc. The studies regarding the aggregation behavior of nanoparticles in refrigerants are very few. The major investigations are summarized here in Table 6.

Bi et al. (2008) systematically investigated the stability and sedimentation of TiO_2 nanoparticles in R113, R123 and R141b refrigerants, experimentally. Determination of light transmission ratio index and distribution particle size was adopted for their studies. It was revealed that the stability of TiO_2 nanoparticles in refrigerant was better than that of some other nanofluids. The polarity and dielectric constant of the refrigerants were the crucial factors concerned to the stability improvement. They reported the significance of temperature on the stability.

Peng et al. (2015) investigated the influence of primary particle size and surfactant on the aggregation characteristics of TiO_2-R141bnanorefrigerant. TiO_2 nanoparticles of size 20, 40, 60 and 100 nm were dispersed in to R141b refrigerant by two-step method. The concentration ranged between 25–500 mg L^{-1}. Anionic, cationic and nonionic surfactants were considered. Using DLS technique, the time evolution of particle size was measured. Experimental results show that particles can attain steady state with elapse of time and the hydrodynamic diameter depends on primary particle size. An increase by 127.6% was obtained. The effect of surfactant concentration was also established. However, effect of addition of lubricating oil on aggregation behavior has not been addressed by the researchers.

The effect of lubricating oil on particle aggregation is a key factor to be considered as far as refrigerants-lubricant mixtures are concerned.

Lin et al. (2016) carried out experimental studies to divulge the effect lubricant on particle aggregation behavior. Moreover, they observed the influence of primary particle size, particle concentration and temperature on particle aggregation behavior. The nanoparticles, refrigerant and lubricating oil considered were, TiO_2, R141b, ATMOS and NM56 respectively. The time evolution of hydraulic diameter was quantitatively evaluated to divulge the particle aggregation behavior. DLS technique has been used for the evaluation. The diagram of apparatus is shown in Fig. 14.

As shown in Fig. 15, the time averaged hydrodynamic diameter of aggregates in refrigerant-nanolubricant mixtures was smaller than that of oil-free nanorefrigerants. This is clear indication of inhibition of particle aggregation and the inhibition enhanced with the increase of lubricant concentration. The reason behind this phenomenon was explained as; "addition of oil increases the viscosity of nanorefrigerant and consequently the collision frequency between particles reduces". The authors summarized the following findings. The particle size, concentration and temperature considerably influenced the aggregation of nanoparticles in refrigerant-nanolubricant mixture.

7. Migration and degradation characteristics of nanoparticles in nanorefrigerants

In the application perspective of nanorefrigerants in diverse thermal systems, the knowledge pertaining to the migration and degradation characteristics is essential. The migration of nanoparticles during the phase change process results in the deterioration of particle concentration, which should be evaluated scientifically. The influence of particle size, type, concentration, and surfactant effects on migration characteristics need to be addressed. Similarly, the degradation, as explained by Lin et al. (2017) "the continuous diminution of the mass fraction of the nanoparticles during alternation process of condensation and evaporation" is a critical factor needs to be focused. Since the thermal conductivity of nanolubricant–refrigerant mixture is generally positively associated with the suspended nanoparticle mass fraction (Jiang et al., Mahbubul et al.) the degradation of nanolubricant–refrigerant mixture will reduce the thermal conductivity and thus the heat

Table 6
Studies on particle aggregation behavior in nanorefrigerants – A ssummary.

Researcher	Refrigerant	Nanoparticle	Lubricant	Surfactant	Evaluation
Bi et al. (2008)	R113, R123, R141b	TiO_2	–	Span 80	Better stability of TiO_2 nanoparticles.
Peng et al. (2015)	R141b	MWCNT	–	Anionic, cationic, non- ionic	The presence of surfactants prevents the aggregation of nanoparticles in nanorefrigerant.
Lin et al. (2016)	R141b	TiO_2	ATMOS, NM56	–	Presence of lubricating oil inhibits the aggregation behaviour.

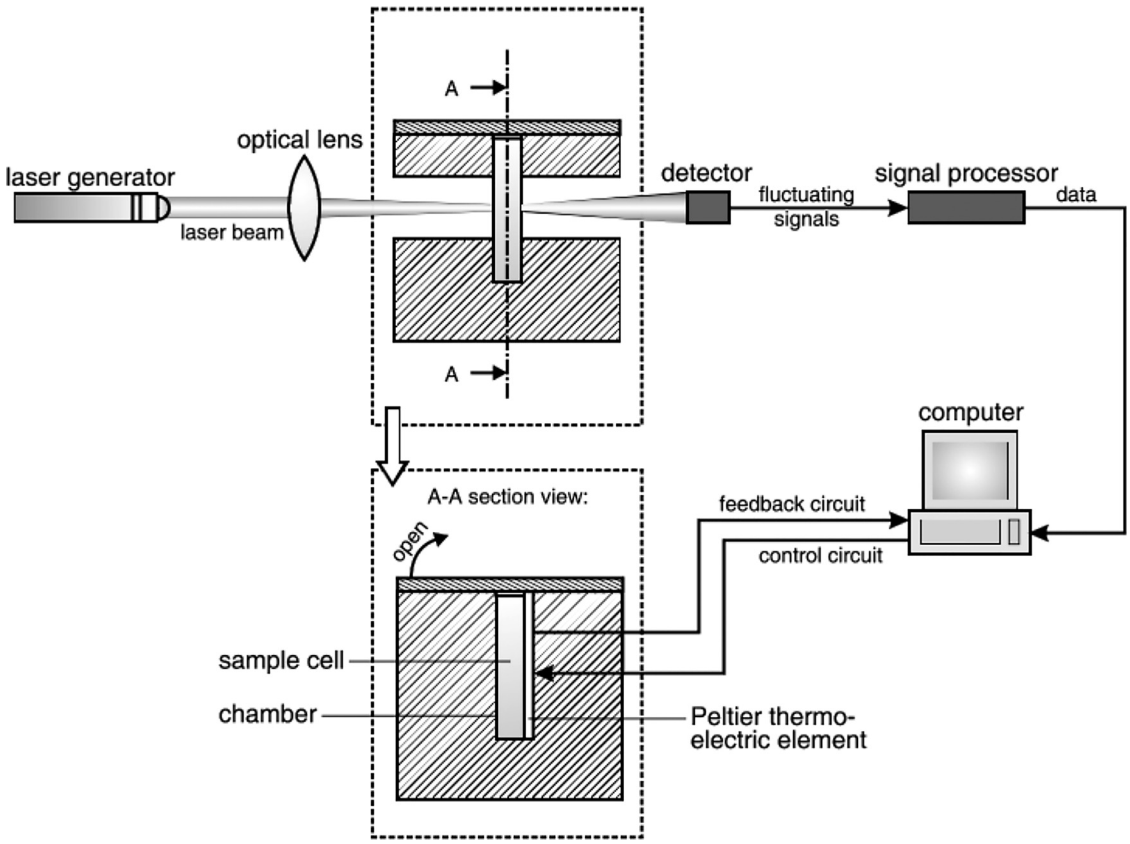


Fig. 14. Schematic diagram of experimental apparatus (Lin et al., 2016).

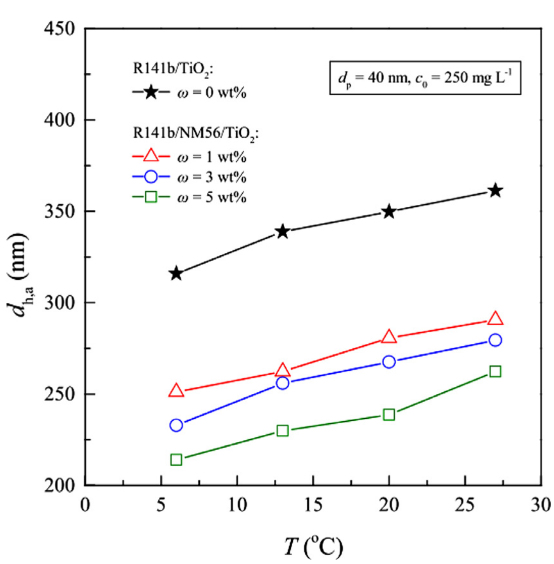


Fig. 15. Variation of hydrodynamic diameter ($d_{h,\ a}$) with temperature (T) at different concentrations (ω), (Lin et al., 2016).

transfer performance under continuous phase transformation. The effects of lubricant mass fraction, nanoparticle mass fraction, heating condition, and cooling condition on degradation should be considered. Until now, there are very few studies on the migration characteristics and a single experimental study related to degradation of nanoparticles in the phase change process of refrigerant are reported. The available literatures are included in Table 7.

Ding et al. (2009) examined experimentally the effect of mass of nanoparticles and the mass of refrigerant on the migration characteristics of nanorefrigerant–oil mixture and proposed a numerical model to forecast it.

CuO nanoparticles with an average diameter of 40 nm was suspended and dispersed in refrigerant R113. Lubricating oil used was RB68EP which was well soluble with R113.

A cylindrical glass container was the test vessel. A radiation heater was utilized to boil off the refrigerant.

The boiling of pure nanorefrigerant and nanorefrigerant–oil mixture in the container was activated by the radiation heater. High precision electronic balance was used to weigh the migrated mass. The difference in weight after complete vaporization of refrigerant with nanoparticle was the measure of migrated mass. The conclusion was the migrated mass of nanoparticles increases with increase in initial mass of particle as well as refrigerant. The

Table 7
Particle migration/degradation characteristics in nanorefrigerants - A summary .

Researcher	Refrigerant	Nanoparticle	Lubricant	Test section	Evaluation
Ding et al. (2009)	R113	CuO	RB68EP	Boiling vessel	As the mass of nanoparticle increases, migrated mass also increases.
Peng et al. (2011b)	R113, R141b, n-pentane	Cu, Al,Al_2O_3, CuO	RB68EP	Boiling vessel	As the teat flux increases, Migration ratio also increases.
Peng et al. (2011c)	R113, R141b and n-pentane	CNT	RB68EP	Boiling vessel	Physical properties of CNT, oil concentration and liquid level influenced the migration characteristics.
Mahbubul et al. (2013a)	R141b	TiO_2	Mineral oil	Boiling vessel	The initial mass and heat flux have crucial impact on migrated mass.
Kamyar et al., (2014)	R141b	Al_2O_3,TiO_2	–	Boiling vessel	Migrated mass increases with particle size and decreases with density.
Lin et al. (2017)	R141b	TiO_2	NM56	Boiling & condensing vessel	The observed degradation ratio ranges between 28%–73%.

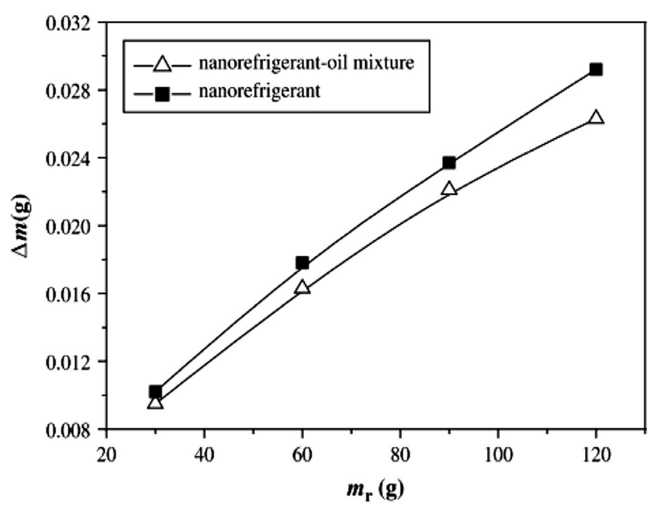


Fig. 16. Migrated mass of nanoparticle vs mass of refrigerant (Ding et al., 2009).

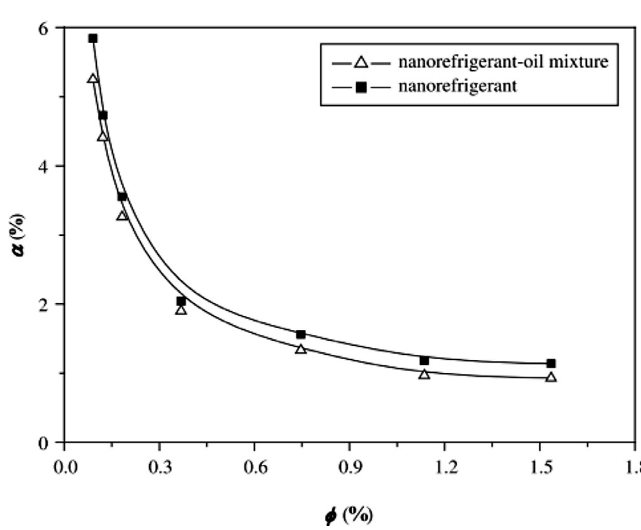


Fig. 17. Migration ratio vs. volume fraction (Ding et al., 2009).

migration ratio (ratio between migrated mass and original mass) was observed as 5.84% and 1.14% at 0.0912 and1.536% particle concentration. For the case of nanorefrigerant-oil mixture it was found as 5.25% and 0.93%. That is, particle volume fraction and presence of lubricating oil in refrigerants have significant effect in migrated mass as shown in Figs. 16 and 17. The proposed numerical model well predicts the migrated mass.

Peng et al. (2011b) experimentally determined the role of refrigerant composition and heating condition on the migration of nanoparticles during boiling phenomena. Different nanoparticles having different diameters and different refrigerant compositions were used for the experimentation. The particles considered were Cu (average diameters 20, 50, and 80 nm), Al (average diameter 20 nm), Al_2O_3 (average diameter 20 nm) and CuO (average diameter 40 nm). The refrigerants were R113, R141b and n-pentane. Lubricating oil used with these compositions was RB68EP (0 to 10 wt%). Experiments were conducted at varying heat fluxes. The experimental set up consists of pool boiling apparatus, a boiling vessel in cylindrical glass container, electric heating membrane, and a capture cover. The experimental results revealed that, nanoparticle size, dynamic viscosity of refrigerant, mass fraction of lubricating oil are the most influencing parameters. Their studies confirmed that, the particle size effect on migration behavior prevails than others. The migration ratio of Cu particles having 20 nm diameters was found to be 315.6% higher than that of 50 nm diameter and 448% than that of 80 nm diameter.

In another study, Peng et al. (2011c) focused to identify the influence of physical dimension of CNTs, type of refrigerant, oil concentration, heat flux and initial liquid-level height on migration behavior of R113 and R141b nanorefrigerant during boiling. CNTs with various aspect ratios were utilized for the study.

According to Peng et al. (2011c),

> "The migration of CNTs from liquid phase to vapor phase involves the following physical processes; (i) the departure of bubble from the heating surface, (ii) movement of bubble and CNTs in the liquid phase, (iii) the capture of CNTs by bubble, and (iv)the escape of CNTs from the liquid-vapor interface".

Results show that migration ratio increases with increase in diameter and length of CNT. Moreover, increase in initial liquid level results an increase in migration ratio. The maximum migrated ratio was displayed by R141 based nanorefrigerant than R113, thus establishes the influence of refrigerant type on migration ratio.

Mahbubul et al. (2013a) conducted studies to observe the effect of vessel size and insulation on the migration characteristics of nanoparticles during pool boiling of TiO_2/R141b nanorefrigerant under atmospheric pressure. Boiling vessels with two different dimensions were utilized to study the effect of boiling vessel size on the migration characteristics. To examine the effect of insulation on migration phenomenon, teat vessel was exposed to heating with and without being insulated. Migration studies were performed with and without lubricants. The test procedure was same as that reported by Ding et al. (2009).

The investigators reported the effect of various factors on migrated mass of nanoparticles as follows:

Migration of nanoparticles intensified when the boiling vessel was smaller in size. This is due to the increase in characteristic size of the heater surface.

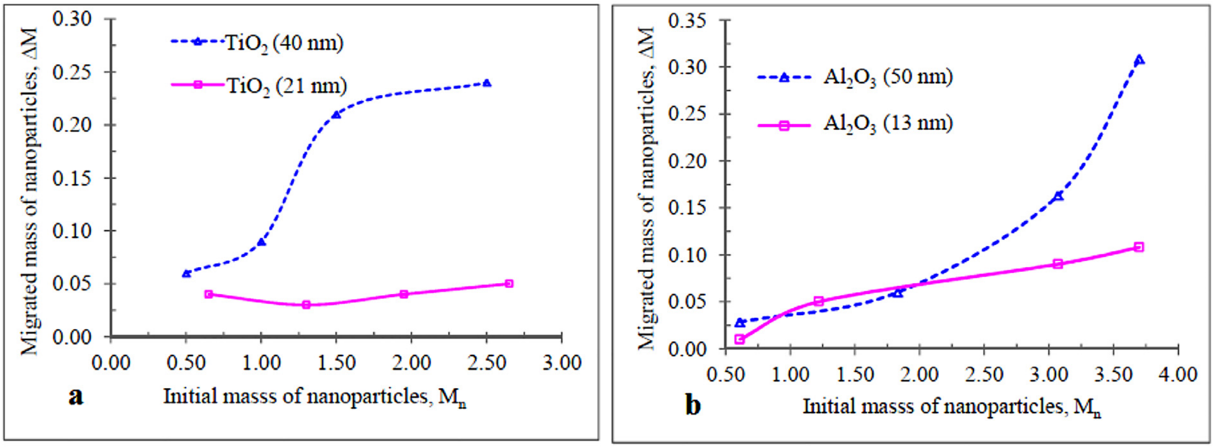


Fig. 18. Influence of particle size on migrated mass (a) TiO_2 nanoparticles (b) Al_2O_3 nanoparticles (Kamyar et al., 2009).

Migration mass of nanoparticles increased when the boiling vessel was insulated and is due to the reduced heat loss and this eventually enhances the wall super heat and which in turn develops more active nucleation sites.

Other critically influencing factors in the migration process are explained as, at higher heat fluxes and nanoparticle mass fraction, bubble formation and bubble departure frequency increases in larger volumes. This phenomenon leads to attach more particles to the bubbles, and consequently; more migration occurs, at same mass fraction, lower liquid level helps to evaporate the refrigerant at a faster rate. Therefore the particles would not get enough time to become agglomerated. Nanorefrigerant without lubricant exhibits less migration rate.

Despite, few studies on particle migration during boiling of nanorefrigerants, the influence of nanoparticle weight, type of nanoparticle etc. was uncertain.

Kamyar et al. (2014) considered the aforesaid parameters also for their studies. TiO2 and Al2O3 nanoparticles with two different particle sizes 21 nm, 40 nm and 13 nm, 50 nm, respectively were tested in an apparatus similar to that in the studies of Mahbubul et al. (2013a). Therefrigerant was R141b. As shown in Fig. 18(a) and (b), enhancement in particle migration was observed with larger nanoparticles.

Kamyar et al. derived out the following corollaries in view of their experiments:

> "The mechanism of migration greatly depends on the bubble dynamics during boiling and which related to the Brownian diffusion, and gravity and inertia effects. Vigorous bubble generation may lead to attach more particles with the bubbles and which will results in increased migration rate".

The difference in density plays vital role in particle migration behaviour. Al_2O_3 and TiO_2 nanoparticles have densities of 4000 kgm^{-3} and 4260 kgm^{-3}, respectively. Higher the value of density, the faster will be the sedimentation process.

Lin et al. (2017) quantitatively evaluated the degradation of nanolubricant–refrigerant mixture by the "suspending ratio", which is defined as the mass ratio of particles remains suspended in liquid to the total nanoparticles during continuous phase changing processes of condensation and evaporation, and investigate the effects of lubricant mass fraction, nanoparticle mass fraction, heating condition, and cooling condition on degradation. TiO_2/NM56/R141b combination has been chosen as the nanolubricant–refrigerant mixture for the experiments. The experimental parameters cover lubricant mass fraction of 5–20%, nanoparticle mass fraction of 0.2–1.0%, heating temperature of 50–80 °C, and cooling temperature of 5–15 °C. The experimental setup used for the investigation consists of three parts, i.e., phase-change system, cooling system, and heating system, as shown in Fig. 19.

Two interconnected identical vessel as shown in fig. is used to simulate the phase change process. Initially, the vessels A and B are charged with measured volume of nanolubricant and pure refrigerant liquid respectively. The boiling and condensation processes were achieved through heater and refrigerated circulator respectively. The vapor evolved in the vessel B is condensed in vessel A. The vessels switch each other after entire evaporation and condensation process. During the boiling process of nanorefrigerant, the migration process initiates. The same process is repeated the predetermined times to measure the degradation characteristics. Light absorbance method was utilized to determine the mass fraction.

The following conclusions were derived out of the experiments. During continuous phase change process, gradual degradation of nanorefrigerant was noticed. The degradation ratio varied between 28% and 73% after 20 alternations. Progressive decrease in suspending ratio was observed at elevated temperatures. The degradation process can be reduced by increasing the lubricant mass fraction, lowering the particle concentration and lowering the heating or cooling temperature. Fig. 20(a)–(d) shows the variations.

8. Experimental studies on refrigeration and air-conditioning systems with nanorefrigerants

The current energy scenario portrays an exponential increase in power consumption; increase in number of HVAC systems in both commercial as well as domestic sectors worldwide accelerates the per capita energy consumption. Energy saving, how small it will be an added advantage in conserving our natural resources. The available studies in literature depict that nanorefrigerants have the immense potentials to be an alternative to conventional refrigerants and are energy efficient also (Azmi et al., 2016). This novel research frontier offers numerous prospects to explore, however there are great encounters as well. The experimental studies related to applications of nanorefrigerants in refrigeration and air-conditioning systems are presented in the section. Table 8 summarizes the available studies.

Bi et al. (2008) experimentally conducted performance evaluation and reliability of a domestic refrigerator with nanolubricant/refrigerant mixture as the working fluid.

POE Oil appended with TiO_2 and Al_2O_3 nano particles were used as the lubricant as a substitute of pure oil in the refrigerant compressor. The refrigerant used was HFC 134a. The compatibility of the system with HFC 134a and nanolubricant mixtures was

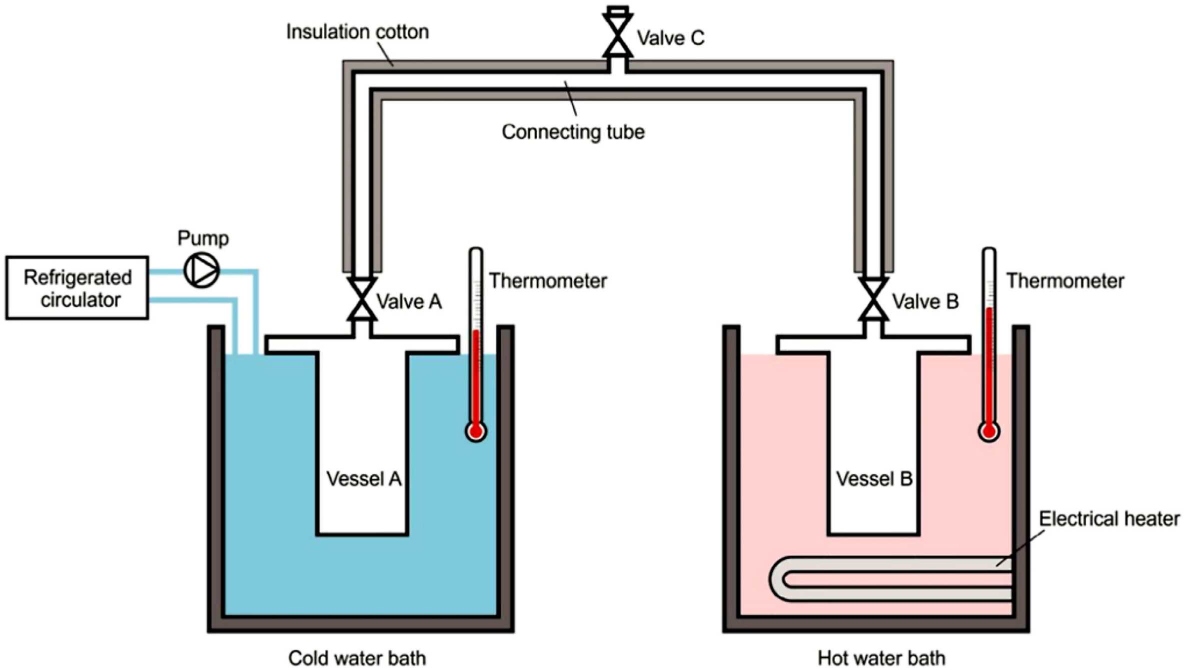


Fig. 19. Schematic diagram of condensation –evaporation alternation setup (Lin et al., 2017).

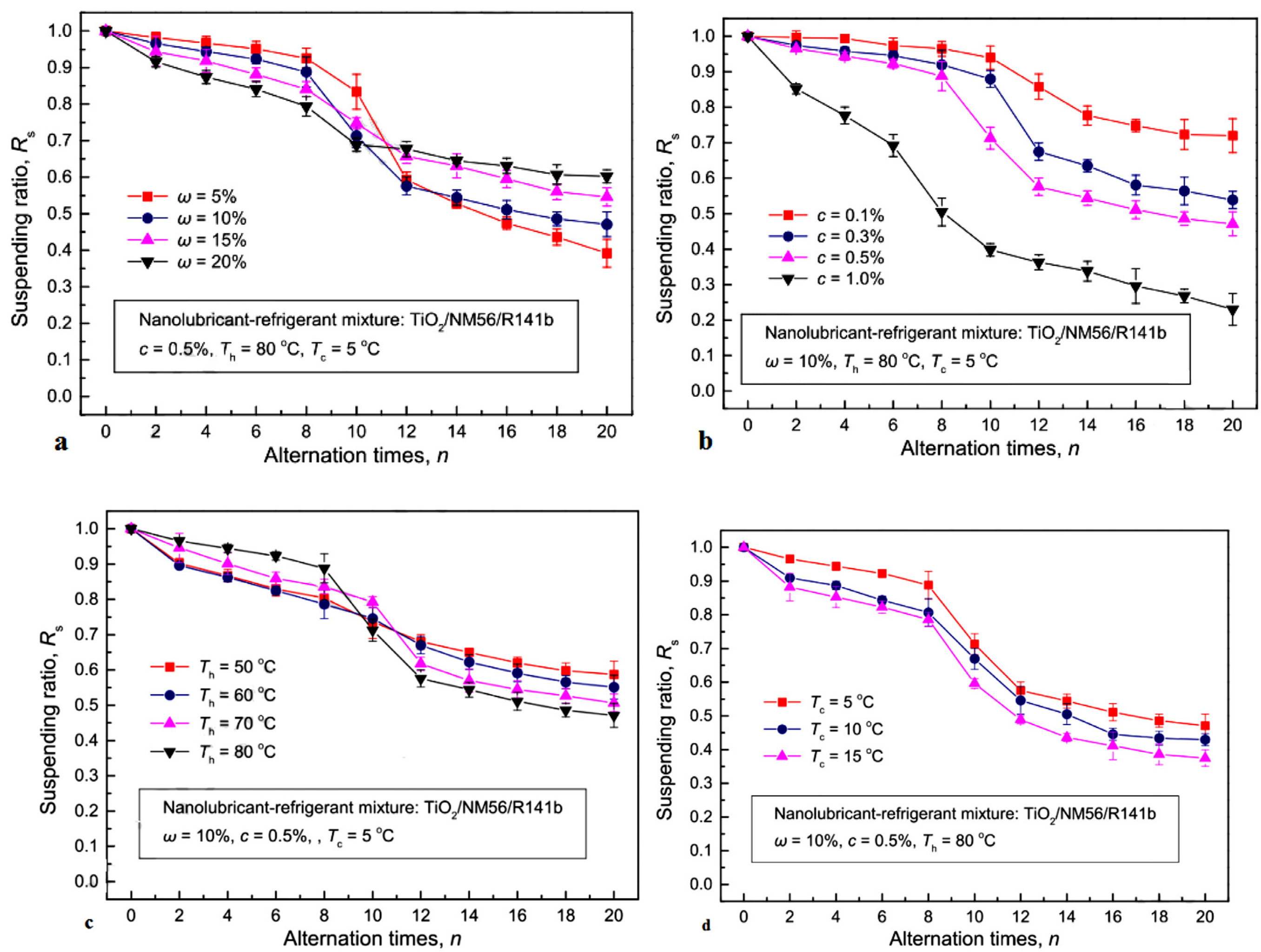


Fig. 20. Variation of suspending ratio with alternation times at (a) varying lubricant mass fraction, (b) varying particle mass fraction, (c) different heating temperatures, (d) different cooling temperatures (Lin et al., 2017).

Table 8
Refrigeration systems with nanorefrigerants – A summary .

Researcher	Refrigerant	Nanoparticle	Lubricant	Test section	Evaluation
Sheng et al. (2008)	134a	TiO_2, Al_2O_3	POE	Refrigeration system	Power consumption reduced by 26.1% at 0.1% mass fraction for T_iO_2.
Jwo et al. (2009)	R134a	Al_2O_3	–	Refrigerator	An increase in COP by 4.4% and decrease in energy consumption by 2.4% were observed. The refrigerant charge was reduced by 40%.
Bi et al. (2011)	R600a	TiO_2	–	Refrigeration system	Reduction in energy consumption of 5.94% and 9.60% at a volume concentration of 0.1% and 0.5% respectively.
Subramani and Prakash (2011)	R134a	Al_2O_3	POE	Refrigeration system	The freezing capacity and COP were increased and power saving was 25%.
Abdel-Hadi et al. (2011)	R134a	CuO	–	Vapor compression system	Optimum nanoparticles size and concentration was determined as 25 nm and 0.55% respectively.
Krishna Sabareesh et al. (2012)	R12	TiO_2	Mineral oil	Refrigeration system	Reduced the average compressor work by 11% and an increased COP by17%.
Kumar and Elansezhian (2012)	R134a	Al_2O_3	PAG oil	Refrigeration system	10.32% less energy consumption at 0.2% vol concentration.
Muhammad Abbas (2013)	R134a	CNT		Refrigeration System	At a concentration of 0.1wt%, enhancement in COP was 4.2%.
Kumar and Elansezhian (2014)	R152a	ZnO	PAG oil	Refrigeration system.	Reduction in power consumption was 21%.
Aktas et al. (2014)	R12, R134a, R430a, R436a, and R600a	Al_2O_3	–	Refrigeration system	Maximum COP was obtained for R600a/Al_2O_3 mixture.
Coumeressin and Palaniraja (2014)	R134a	CuO	Mineral Oil	Refrigeration system	Increase in overall performance of the system.
Jia et al. (2014)	R134a, R600a	MoFe2O-4eNiFe2O4, MoFe2O4eNiFe2O4-Fullerene	KFR32	Domestic refrigerator	The COP was increased by 5.33%
Lou et al. (2015)	R600a	Graphite	Mineral Oil	Domestic refrigerator	Reduction in pull-down time and power consumption by 15.22% and 4.55%, respectively.
Sozen et al. (2014)	Ammonia /water	Al_2O_3	–	Diffusion Absorption refrigeration system	51% improvement in the performance.
Singh et al. (2015)	R134a	Al_2O_3	–	Refrigeration system	The COP enhancement was 8.5%
Manoj babu et al. (2015)	R134a	TiO_2, Al_2O_3	POE, mineral oil	Refrigeration system	HFC-134a nanorefrigerant performed efficiently.
Kamaraj and Manoj Babu (2016)	R134a	Carbon black	POE, mineral oil.	Refrigeration system	Improvement in COP up to 16.67%.
Kumar & Singh (2016)	R290/R600a (50/50)	ZnO	Mineral oil	Refrigeration system	Addition of (0.2–1.0) wt% nanoparticles lowered the energy consumption by 7.48%, and boosted COP by 45%.
Adelekan et al. (2017)	LPG	TiO_2	Mineral oil	Domestic Refrigerator	Reduction in power consumption and increase in cooling capacity has been observed.
Air-conditioning systems with nanorefrigerants – A summary					
Wang et al. (2010)	R410a	$NiFe_2O_4$	VG32	Air conditioning system	The EER of the system increased about 6%.
Sharif et al. (2017)	R1342	SiO2	PAG	Automotive Air-conditioner	The maximum increase and average COP enhancements were 24% and 10.5%, respectively.

studied before conducting performance tests. Results showed that mixture of HFC134a and TiO_2 nanolubricant works normally and safely. Refrigerator exhibits better performance than that with pure refrigerant-oil system. The TiO2 nanoparticles perform well with the experimental system. The energy consumption was reduced by 26.1% at 0.1% mass fraction. An increase in freezing capacity also manifested by nanolubricants.

Jwo et al. (2009) performed experiments to replace R134a/POE lubricant with a HC refrigerant and modified lubricant. Al_2O_3 nanoparticles at concentrations of 0.05, 0.1 and 0.2Wt% and HC-12 refrigerant were used to prepare nanorefrigerant. Performance tests were conducted with pure refrigerant and compared with the results obtained from nanorefrigerant. A refrigerator with 440 L capacity was used as the test facility. Experimental results show that performance of the refrigeration system was better when it was charged with 90 g of hydrocarbon refrigerant instead of 150 g R134a. Besides, the author suggested the optimum combination as 60% R134a and 0.1wt% Al_2O_3 nanoparticles. Under the suggested optimum conditions, the energy consumption reduction was by 2.4%, and enhancement in COP was by 4.4%. The refrigerant charge was reduced by 40% as well.

Subramani and Prakash (2011) experimentally determined the overall performance of a VCR system using nanolubricant in the refrigerant compressor. Al_2O_3 nanoparticles were used with mineral oil in a refrigeration system charged with R134a refrigerant. The volume fraction of the particle was 0.06%. It was observed that the system works normally and the heat transfer performance at the evaporator side has been increased. An increase in freezing capacity, COP of the system and reduction in power consumption were the major findings. They reported an increase of 33% in COP and a descent of 25% in power consumption. In another study, they were conducted some more experiments with three different nanoparticles as additives in SUNISO 3GS compressor oil to determine the performance of a VCR system charged with R134a. Nanoparticles were TiO_2, CuO. Experimental results show that, the freezing capacity and COP were at higher side than that of pure lubricant .The enhancement in COP was by 20%, 16% for TiO_2, Al_2O_3 nanorefrigerants, respectively. The corresponding energy enhancement factor was 1.5353 and 1.5338 respectively. Notable reduction in power consumption of 15.4% has been attained for the case of TiO_2 based nanorefrigerant.

Bi et al. (2011) presented a study on TiO_2-R600a nanorefrigerant with different particle concentrations in a domestic refrigerator with no design modification. Results indicate that TiO_2-R600a works efficiently and safely in the domestic refrigerator. The reduction in energy consumption by 5.94% and 9.60% were observed at a volume concentration of 0.1% and 0.5%, respectively. The nanorefrigerant displays enhanced freezing velocity as shown in Fig. 21. According to their report, nanorefrigerants have great potentials to be an alternative to conventional refrigerants.

Abdel-hadi and Taher, (2011), Krishna Sabareesh et al., (2012) and Coumaressin and Palaniradja, (2014) conducted performance evaluation of vapor compression refrigeration systems with different refrigerant/nanolubricant combinations. As expected these studies also revealed the upper hand of nanorefrigerants in the overall performance improvement.

There are limited studies in literature regarding the application of nanorefrigerants in refrigeration system other than VCRS.

The performance an absorption refrigeration system was first time evaluated by Sozen et al. (2014) examined experimentally. A diffusion absorption refrigeration system (DARS) using water couple with Al_2O_3 nanoparticles was considered. The working fluid was ammonia-water mixture with 20% ammonia 80% water and 2wt% of Al_2O_3 particle concentration. Tests were conducted with and without nanoparticles under same experimental conditions. Heat supplied from a boiler is utilized to evaporate ammonia

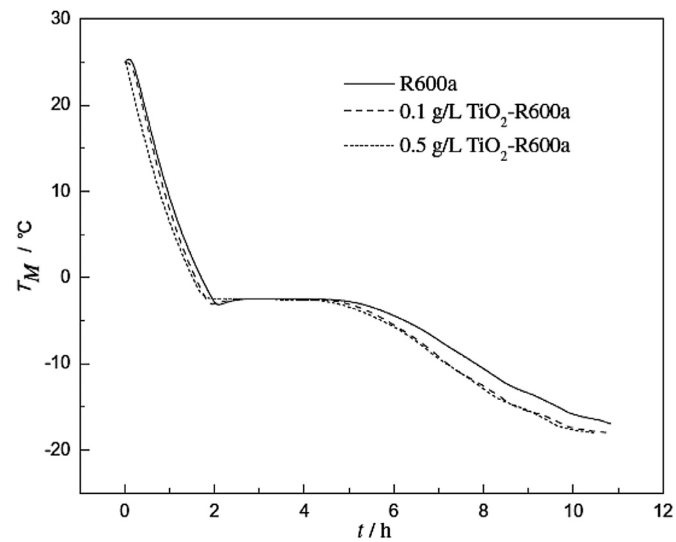


Fig. 21. Freezing capacity of R600a/TiO_2 nanorefrigerant (Bi et al., 2011).

in the mixture. Interestingly, the solution with nanoparticles enhances the temperature of the working fluid by 20 °C. The responsible factor for this phenomenon is the increased heat absorption capacity of metal oxide nanoparticles suspended in the working fluid. In addition the DRAS with nanoparticles exhibits about 5% augment in COP than the other.

Ozone depletion and global warming are the two major threats associated with conventional refrigerants. So the studies on nanorefrigerant with eco-friendly refrigerants are of great significance.

Kumar and Elansezhian (2014) conducted investigation on a vapour compression refrigeration system with zero ODP and very less GWP environmental friendly green refrigerant R152a. ZnO with volume fraction from 0.1% to 0.3% were the nano-additive.

Various performance parameters such as suction and discharge pressure of compressor, evaporator pressure, evaporator temperature etc., have been measured. After extensive experimentation the author arrived in to the conclusion that, the Zno/R152a nanorefrigerant shows excellent performance in the system with reduced power consumption by 21%, decreased suction pressure by 10.5% and decrease in evaporator temperature by 6%.

Jia et al. (2014), selected two types of nanolubricants (naphthenic mineral oil with $MoFe_2O_4$–$NiFe_2O_4$ compound and MoFe2O4-$NiFe_2O_4$-Fullerene) in a domestic refrigerant compressor for their studies. Before conducting experiments, the tribological characterization of the nanolubricant with varying particle concentrations was conducted to arrive in an optimum concentration. The tribological studies reveal that, the nanolubricant with 0.8075vol% substantially reduces the friction coefficient and which has been considered for further investigation in the refrigeration test rig with R134a and R600a refrigerants.

Two compressors were selected to compare the performance of R600a and R134a nanorefrigerant. The major conclusions arrived by the researchers were: The MoFe2O4-NiFe2O4 /KFR32 nano oil showed better tribological performance. Significant improvement in COP was observed with R600a based nanorefrigerant as the working fluid whereas, with R134a based nanorefrigerant, there was no noticeable positive outcome with any of the nanolubricant. The experimental studies suggested that, selection of optimum combinations of refrigerant and nanolubricant is an important factor to be considered while design the system with nanorefrigerants.

Singh et al. (2015) made an investigation to evaluate the performance of nanorefrigerant in a refrigeration system. In this study 20 nm diameter alumina nanoparticles were dispersed in refrigerant R134a in an attempt to improve the performance. A 165 l domestic refrigerator has been utilized as the experimental set up. Volume flow rate of refrigerant and power consumption was measured by means of glass tube rotameter and energy meter, respectively. Experiments were conducted using nanorefrigerants of particle volume fractions 0.5wt% and 1.0wt% at different heat fluxes. Result demonstrated that, at ambient temperature of 21 °C and at constant heat flux, the COP was found as 0.98 for pure R134a. On the other hand with the use of nanorefrigerant at a particle concentration of 0.5%, COP was found be increased as 1.07. At higher concentration, marginal decline in COP was noted. The similar experiments were repeated at different ambient temperatures and the authors concluded that, COP of the domestic refrigerator decreases with an increase in ambient temperature from 21 to 28 °C.

Manoj Babu et al. (2015) investigated the performance of a refrigeration system with POE based nanolubricant along with HFC134a refrigerant. TiO_2 and Al_2O_3 were the nano additives. Studies were conducted to see the reliability of mineral oil based nanolubricant at concentrations of 0.1 and 0.2 g L^{-1}. According to the study, author stated that, the nanorefrigerant performed smoothly and efficiently in refrigeration system. It was also realized that, TiO_2 based nanolubricant provides superior performance than the other. Author concluded that, the mineral oil appended with nanoparticles can contribute positive effects to the energy saving and refrigeration effect.

Most of the studies in refrigeration systems were with spherical metallic oxide nanoparticles. Very few researchers have used nanoparticles other than metallic oxide in refrigeration systems. The available researches with allotropes of carbon as nano additives are presented here.

Abbas et al. (2013) conducted a performance test in a refrigeration system with CNT based nanolubricant with R134a refrigerant. Polyolester oil with particle volume fractions of 0.01%, 0.05% and 0.1wt% were used for the preparation of nanolubricant. Experimental results show that CNT nanoparticles into POE lubricant produced enhancement in COP of the system. Significant reduction in power consumption has also been noted. COP of the system increased with increase in CNT wt% and a maximum COP was obtained at a concentration of 0.1wt%. Sendil kumar and Elansezlian (2012) conducted similar experiments with Al_2O_3-PAG oil based nanorefrigerant and reported reduction in energy consumption by10.30%.

Lou et al. (2015) analyzed the applicability of graphite based nanolubricant in a domestic refrigerator with isobutene (R600a) refrigerant. The primary objectives were: determination of pull-down time, power consumption, and freezing speed etc. Tests were conducted with nanorefrigerants after base line tests with pure refrigerant of to verify the efficiency and reliability. Nanolubricant with surface modified graphite was prepared by two step method. The test apparatus consists of a environment chamber, temperature and humidity control systems, domestic refrigerator, and data acquisition system. Fig. 22. shows the schematic of experimental setup.

Isobutene charge was 44 g, and the volume charge of the lubricant in the hermetically sealed reciprocating compressor was 150 ml. Pull-down time is the time is the measure of freezing speed. To attain steady state condition, the test setup was kept in a controlled atmosphere for more than 24 hrs. After exhaustive experimentation, authors reported reduction in pull-down time. The time require to reach the predetermined temperature was reduced by 11.96%, 15.22%, 14.67%, and 10.87% for mass fractions 0.05%, 0.1%,0.2%, and 0.5%, respectively. According to them, the possible factor for the anomalous enhancement was improved boiling heat transfer coefficient of nanorefrigerant. The maximum reduction in power consumption was by 4.55%. The pattern of power consumption is shown in Fig. 23.

Significance drop in pressure was also reported by the authors and which may be due to the higher viscosity of nanorefrigerant. As a conclusion, authors stated that, presence of nanoparticles in lubricant enhances the tribological as well as heat transfer properties of refrigerant-lubricant mixture.

Kamaraj (2016) conducted experiments on a vapor compression refrigeration system with R134a/POE oil/carbon black and R134a/Mineral oil/carbon black combinations as the working fluids. They reported that, the R-134a with carbon nanolubricants were performed smoothly, safely and efficiently and the coefficient of performance of the system has been improved in both the cases of nanolubricant compared to pure lubricant- refrigerant combination. The COP was enhanced by 16.67%. The freezing capacity of the system with nanorefrigerant has also been improved significantly.

To evaluate the effect of ZnO particles on the performance of VCR system, Kumar and Singh (2016) conducted experimental studies. ZnO nanoparticles with particle size 20 nm were used as the lubricant additive along with blended hydrocarbon refrigerant (R290/ R600a). No surfactants were avoided, since it may adversely affect on the thermo physical properties of the colloid. Major finding were decrease in suction and discharge pressure by 17% and 21%, respectively, drop in condenser temperature by 21%.

From the performance view point, it has been reported that the compressor energy expenditure was reduced by 7.48% and the COP was increased by 45%.

Experimental investigations with liquefied petroleum gas (LPG) of varying mass charge supplemented with TiO_2-mineral oil based lubricant as the refrigerant in a domestic refrigerator was first presented by Adelekan et al. (2017). A domestic refrigerator having 50 liter capacity has been used for their experimentation. The refrigerator was originally designed for R134a refrigerant, however all the experiments with LPG were conducted without any design modification. The mass charge of refrigerant was varied from 40 g to 70 g and TiO_2 nanoparticle concentrations were varied as 0.2 gL^{-1}, 0.4 gL^{-1} and 0.6 gL^{-1}. The presence of nanolubricant on the pull down time, power input, cooling capacity, and COP has been analyzed. The authors reported that, the pull down time has been reduced for all the cases of nanorefrigerants. The lowest compressor power input was obtained with 70 g of LPG with of 0.2 gL^{-1} particle concentration. The highest cooling capacity index of 65 W was obtained at 70 g of LPG using 0.6 gL^{-1} concentration, whereas the highest COP was found as 2.08 with 40 g LPG charge with 0.4 gL^{-1} concentration of nanolubricant.

After extensive experimentation, Sanukrishna et al. (2017) confirmed that, addition of CuO nanoparticles to refrigerant compressor oil enhances the performance of a R134a refrigeration system. The authors performed thermo physical and tribological studies of CuO-PAG nanolubricant and concluded that, the nanoparticles play a central role in improving the heat transfer and tribological characterestics of refrigerant .

In view of the researches presented here, it is obvious that nanorefrigerants have enormous capabilities to enhance the overall performance and reliability of refrigeration systems, especially in lowering the energy consumption. Nonetheless, limited studies are reported in literature regarding the application of nanorefrigerants in air-conditioning systems. No controversies what so ever, as expected, the same results as in the case of refrigeration systems are reported for the case of air-conditioners also. Few studies available are described here.

Wang et al. (2010) explored the potentials of $NiFe_2O_4$ nanoparticles in an air-conditioning system with R410a refrigerant- nanolubricant mixture as the working fluid. Naphthene based mineral oil blended with $NiFe_2O_4$ was the lubricant. The performance

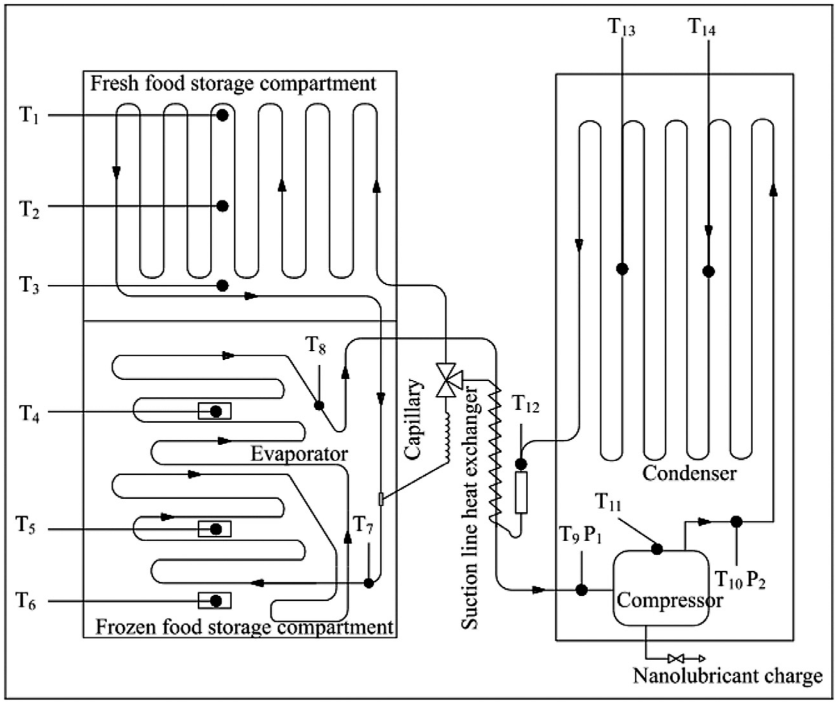


Fig. 22. Domestic refrigerator experimental setup-schematic diagram (Lou et al., 2015).

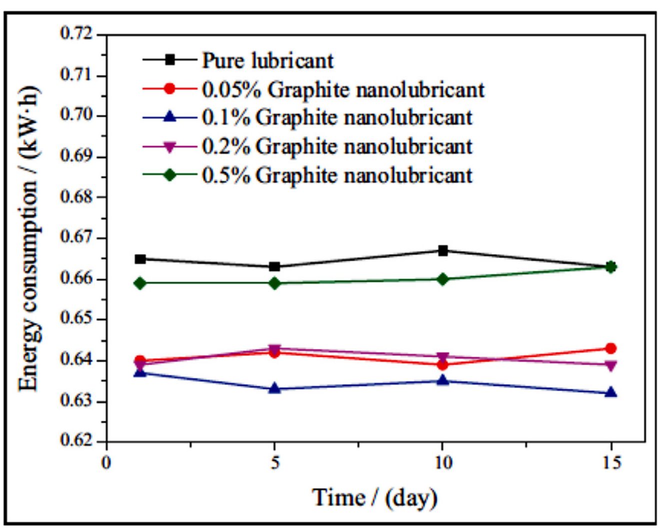


Fig. 23. Power saving of the refrigerator (Lou et al., 2015).

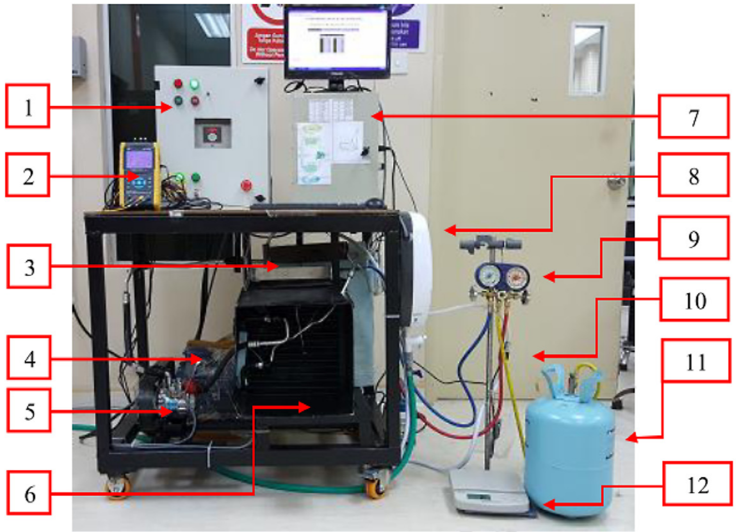
parameters of the AC system viz. cooling and heating capacities, power input and EER were evaluated. The studies show any anomalies in working with mixture of R410a/nanolubricant. The energy efficiency ratio (EER) of the air-conditioning system increased about 6% by replacing the mineral oil with modifed nano-oil.

Plenty of efforts on design modifications have been devoted to improve the performance of automotive air-conditioning systems. The potentials of nanoparticles as a lubricant additive in automotive air-conditioning systems have not been widely exploited by researchers till now.

Sharif et al. (2017) conducted performance evaluation of automotive air conditioner (AAC) by the determination of heat absorb, compressor work and COP with R134a/SiO_2/PAG nanorefrigerant. Experiments were carried out with SiO2/PAG nanolubricant up to 1% volume concentration. An AAC test rig was developed from the original components of an automotive air conditioning system. No surfactants were introduced in to the nanolubricant. The AAC system was properly instrumented with temperature indicators, pressure gauges and digital power analyzer etc. The test rig of the AAC system is shown in Fig. 24.

The following key findings were reported by the authors, the heat absorb was amplified with the raise of volume concentrations and decreased with the compressor speeds. A peak value of heat absorb attained at a volume concentration of 0.05% for low to medium compressor speeds. At volume concentrations of less than 0.1%, sudden decrease in heat absorb was noticed. The compressor work decreases at 0.05% volume fraction contrast to the pure PAG lubricant. As the further increased up to 0.1% there is an insignificant increase in compressor work was reported. But further increase in nanolubricant volume concentrations, the compressor work constantly increased. This behaviour was applicable for all compressor speeds. It should be noted that, even though the compressor work increased with volume concentrations, the compressor work for nanolubricants was still lower than that with pure PAG lubricant. The SiO_2/PAG nanolubricants were manifested reduced the compressor work of automotive air conditioning system and it was found to be minimum at 0.05% volume concentration. The COP of SiO_2/PAG nanolubricant was observed to be maximum at 0.05% volume concentrations irrespective of compressor speeds. The maximum COP enhancement for SiO_2 nanolubricant was 24% at 2100 RPM and the average enhancement was 10.5%. Based on the experiments, authors concluded that, the optimum volume concentration of SiO_2/PAG nanolubricants for applications in automotive air conditioning system was 0.05%.

After experimentation, the surface morphology studies on the evaporator tubes have been carried out. From the critical observation, it was found that no sedimentation occurred in the micro channels of AAC evaporator. Further investigation inside the micro channel wall also confirmed no evidence of erosion



1.Frequency converter controller 2. Power analyser 3. Evaporator 4. Induction motor 5.Compressor 6.Condenser 7.Data logger 8.Water heater 9.Pressure gauge 10.Flow transducer. 11.R134a refrigerant gas 12.Weight scale.

Fig. 24. Experimental setup of automotive air conditioning (AAC) system (Sharif et al., al.,2017).

Table 9
Heat pumps with nanorefrigerant- A ssummary .

Researcher	Refrigerant	Nanoparticle	Lubricant	Test section	Evaluation
Fedele et al. (2014)	R134a	TiO_2, SWCNH	POE	Heat pump	No obvious improvement in COP
Li et al. (2015)	R22	TiO_2	–	Heat pump	80% increase in COP of heating cycle was recorded

during the experimental work. Hence, it can be concluded that the use of SiO_2/PAG nanolubricant produces any harm to the AAC components.

9. Experimental studies on heat pumps with nanorefrigerants

Most of the experimental studies of nanorefrigerants are confined on refrigeration systems. Heat pumps are widely used for heating and cooling process in many industrial applications. They have the potential to reduce the cost of energy. Refrigerants are used in heat pumps as a transitional fluid, which absorbs heat energy. The application of nanorefrigerants in heat pumps is of great significance. Least numbers in published data make it clear that, little effort is spent by the nanofluid research community towards this prospective research area, and the results generated form the studies are somewhat contradictory as well. The limited experimental studies available in literature are summarised here (Table 9).

The effectiveness of a heat pump has been evaluated by Fedele et al. (2014). Number of combinations of refrigerant /nanolubticant was considered for their experimental study. The nanoparticles were TiO2, MWCNT and the base fluids were polyolester and mineral oil. Many parameters viz. mass fraction, sonication period, power of sonication, agitation temperature were considered to optimise and to develop a stable nanorefrigerant with R134a. Extensive experimentation have been performed and in contrast with the result obtained from refrigeration systems, all the performed tests with nanolubricants have not shown any improvements in terms of compressor efficiency and heat transferred in the heat exchangers. From the research findings, authors inferred that, the type of compressor used was not suitable for nanolubricants. Most of the studies reported in literature are usually carried out with reciprocating compressors instead of rotary models and suggested that to repeat the same tests, in the same working conditions, using a reciprocating compressor for any possible optimistic effect on the performance.

Li et al. (2015) critically analyses the heating and cooling cycles of a heat pump with R22/TiO2 nanorefrigerant (0.5 wt %). Base line test were performed with pure R22 for the comparison of performance. A scroll compressor, water cooed condensed and evaporator were the principal components of the experimental set up. The flow rate of cooling water is controlled so as to obtain various cooling loads. The cooling capacity is calculated based on the flow rate, power input and temperature data acquired throughout the experiments.

The conclusions extracted from their experimental results are the following. The presence of nano-additive into the refrigerant couldn't produce any substantial improvement in the cooling performance of the heat pump, however, for the heating cycle; dramatic progress in COP, up to 80% was recorded. Moreover, the power consumption of the compressor was slightly increased.

Figs. 25 and 26 show the huge discrepancy in cooling and heating cycle performance of the heat pump, which should be further investigated to arrive at an ample conclusion.

10. Experimental study on heat pipe with nanorefrigerant

Miniaturization is the major outcome of nanotechnology. Heat dissipation is one of the persisting hurdles with the modern electronic devices. Now a heat pipes are extensively used with variety of electronic devices due to its remarkable heat transfer capability, especially in electronic devices operating at high speed and requires high rate of heat dissipation. The reliability and durability of these devices primarily relies on the heat transfer capability of working medium used in it. Inherently poor thermal transport properties of conventional heat transfer fluids limit the

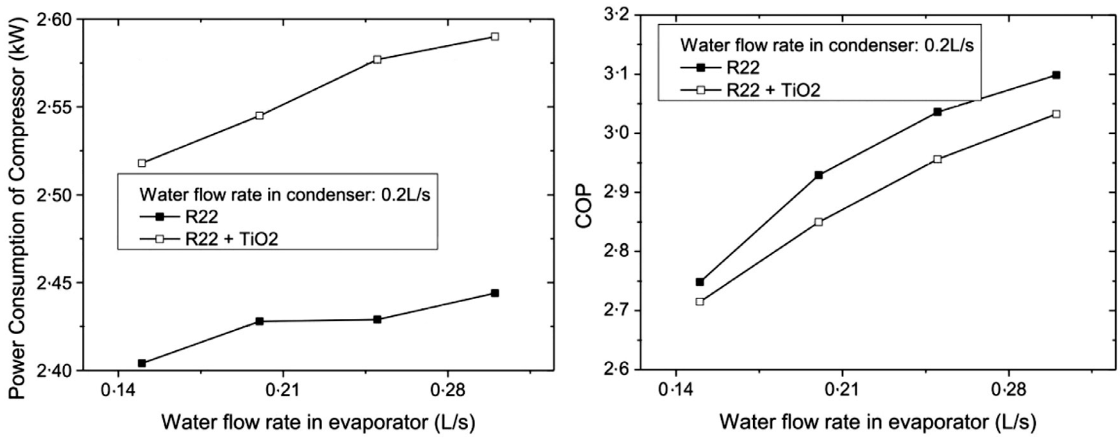


Fig. 25. Input power and COP of the cooling cycle (Li et al., 2015).

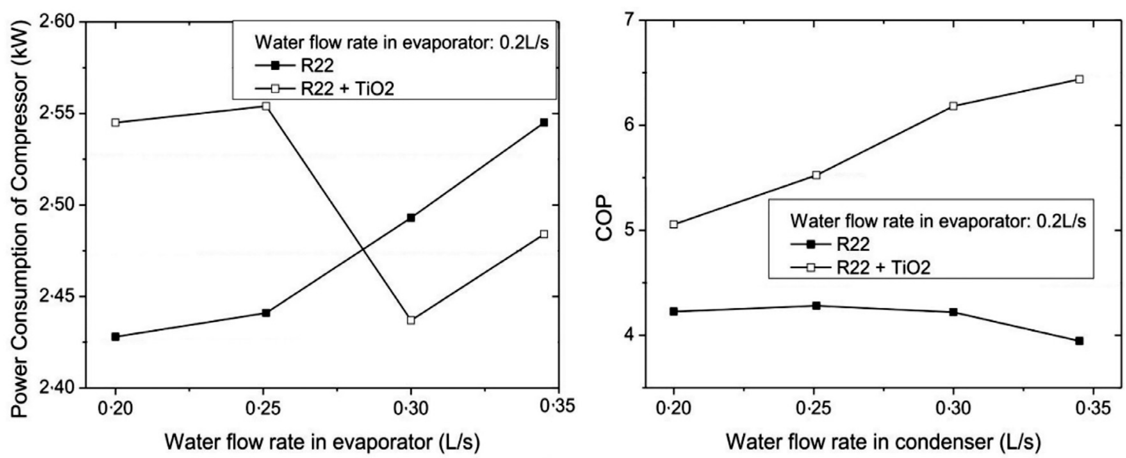


Fig. 26. Input power and COP of the heating cycle (Li et al., 2015).

Table 10
Heat pipe with nanorefrigerant – A summary.

Researcher	Refrigerant	Nanoparticle	Lubricant	Test section	Evaluation
Naphon et al. (2009)	R11	Ti	–	Heat pipe	At 0.1% nanoparticle concentration, efficiency increased up to 1.4 times

performance of heat pipes. Studies show that, nano-additives to the working fluids dramatically improves the heat transfer capability and flow features of heat pipes (Kumar et al., 2013). Nevertheless, the studies related to the heat transfer performance of the heat pipe with nanorefrigerants have seldom been reported to the best of author's faith. The only published work is given in Table 10.

To evaluate the effectiveness of a heat pipe with nanorefrigerant, Naphon et al. (2009) conducted experimental studies. R11 and titanium nanoparticles with 21 nm average diameter were used to prepare the working fluid. The major components are test section, refrigerant loop and cold water loop. Experiments condition were heat pipe tilt angles varying from 0° to 90°, particle concentration from 0.01 to 1.0% volume and varying heat fluxes. In their experiments, angle of tilt was gradually changed in small increments with constant heat flux in the evaporator, so as to arrive in an optimum tilt angle. The optimum tilt angle has been observed as 60°.Further investigations were conducted at the optimum tilt angle and portrayed the efficiency with respect to heat flux as shown Fig. 27.

Form figure it is evident that, the efficiency of heat pipe increases with increase in heat flux. This is a clear indication of increased heat transfer rate at condenser and evaporator sides (Naphon et al., 2009). Form the experimental results it was observed that the efficiency of the heat pump has been increased with the use of nanorefrigerant as the working fluid. The maximum efficiency obtained at an optimum tilt angle of 60° was 83%.

11. Concluding remarks and future directions

Nanorefrigerants have better prospects as an energy efficient substitute for conventional refrigerants, in spite of many controversial findings. Obviously there are many challenges also in the new research frontlines that must be addressed before these refrigerants could be used in diverse applications. This review attempts to cover most of the experimental studies on nanorefrigerants, i.e. from thermo physical and heat transfer capabilities to its real application in HVAC systems.

The conclusions derived out from the present review are the following:

1. Nanoparticles display significant influence on the thermal, physical and heat transfer characteristics of refrigerants. The thermal conductivity and viscosity increases with particle dosing level.

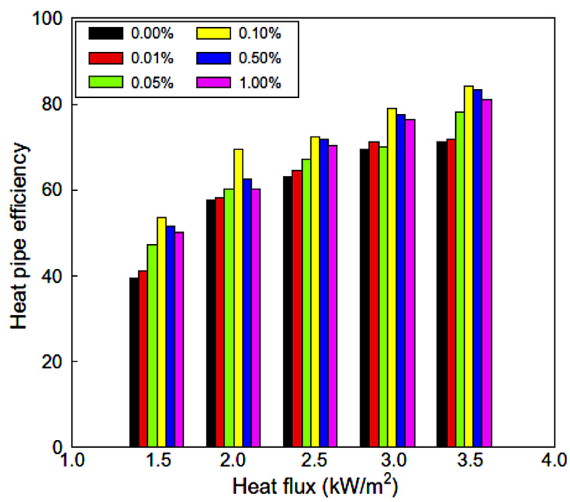


Fig. 27. Heat pipe efficiency vs heat flux at different nanoparticle concentrations (Naphon et al., 2009).

2. The heat transfer rate increases with increased nanoparticle concentration and with decreased nanoparticle dimension.
3. The most important factors that influence the flow boiling and condensation heat transfer in nanorefrigerants are vapour quality, heat flux, mass flux and particle concentration.
4. Power consumption can be reduced by using nanorefrigerants in refrigeration systems; moreover the freezing speed and COP of HVAC devices can be increased significantly.
5. The overall performance of heat pumps and heat pipes augments by the application of nanorefrigerants as the working fluid.
6. The surfactant type and presence of lubricant impedes the aggregation characteristics of nanoparticles in refrigerants and hence diminishes the agglomeration problems concerning their long-term usage.
7. The migration and degradation characteristics of nanoparticles have crucial impact on the heat transfer performance of nanorefrigerants.
8. Metal oxide nanoparticles (Al_2O_3, TiO_2, and CuO) and allotropes of carbon (CNTs) can be considered as promising nano-additives to enhance thermal performance of refrigerants/lubricants.

The following suggestions are put forth as future research scope.

Even though the prospective of nanorefrigerants in heat transfer applications are optimistic, a detailed understanding of underlying mechanisms of the thermal transport enhancement remains elusive at an atomic level. More experimental and quantum molecular dynamic studies are necessary to identify the chemical interactions between molecules and to generate theoretical models to approximate it. Experimental work involving the surface chemistry of nanoparticles is required to understand the particle-particle interaction in nanofluids.

Furthermore,

1 Ozone depletion and global warming are the potential threat across the globe. Most of the researches on nanorefrigerant are focused on CFCs, HCFCs and HFCs, which are phase out refrigerants according to Montreal Protocol. More experimental investigations are required with natural refrigerants in HVAC systems. The studies with natural refrigerants such as CO_2 and NH3 appended with nanoparticles are nil.
2 Scientific community have not been arrived at an ample conclusion regarding the boiling and condensation heat transfer characteristics of nanorefrigerants and the effect of nanoparticles in two phase flow regime and boundary layer formation. Studies on flow through modified surfaces and geometries are also need to be conducted.
3 Extensive parametric studies are inevitable to examine the reliability of different kinds of nanoparticles with critical components used with HVAC systems.
4 There are conflicts between the thermo physical property data obtained from the experimental results and proposed correlations for nanorefrigerants. Future works are needed to clarify this and studies should be extended to develop more models to predict the thermo physical properties of nanorefrigerants by considering all the underlying mechanisms of nano-level heat transfer.
5 Studies regarding the agglomeration and sedimentation of nanoparticles with in their host fluid are still insufficient and not convincing. Detailed studies are required to evaluate the stability and sustainability of various nanoparticles –refrigerant combinations for prolonged use.
6 The wettability of refrigerant-nanoparticle-oil mixture on surfaces is a key property to be analyzed for its application in phase change heat transfer phenomena.

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