Heat and Mass Transfer (2018) 54:3493–3508
https://doi.org/10.1007/s00231-018-2351-1

REVIEW

Thermophysical and tribological properties of nanolubricants: A review

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Received: 16 February 2017 / Accepted: 5 April 2018 / Published online: 12 May 2018

Abstract

Recent studies in heat transfer evident that the nanofluid shows better heat transfer results as compared to base fluid. This influences the research community for the dispersion of nanoparticles in lubricants to enhance its thermophysical and tribological properties and these suspensions are termed as Nanolubricants. This review focuses on the effect of nanoparticle additives on thermophysical and tribological properties of base lubricant. Initial section briefly summarizes the variation in thermophysical properties namely viscosity, thermal conductivity, density and specific heat of nanolubricants. In later section, the coefficient of friction and anti-wear properties of nanolubricants are summarized. This review along with the replenishment of current knowledge, also discusses the fundamental mechanisms that evolve with the dispersion of nanoparticles.

1 Introduction

Lubricants contribute in energy saving and life of a mechanical system. Basically, lubricants are used for cooling, sealing, and lubrication. It adheres to the moving surfaces and thus forms fluid films, which separates the surfaces of moving parts [1] and also removes heat and wear particles from the system. Commercially available lubricants are composed of wide variety of base oil and additives. Base oils are broadly classified as mineral, synthetic, and biological oil [2].

Additives are used to maintain overall performance of the lubricant such as film formation, clotting, viscosity stabilizer, anti-corrosion, anti-wear, anti-friction, etc. [1]. Chemical additives such as sulphur, chlorine, phosphorous, etc. are added to improve the lubrication performance by forming a sacrificial chemical layer; however these additives have hazardous effect on the environment [3]. Some recent studies reveal the potential of nanoparticle additives [2]. Nanoparticle additives are divided into seven types, based on the characteristic chemical element: metal, metal oxide, carbon, sulphide, rare earth compounds, nanocomposite and others [4]. Nanolubricant shows significantly modified thermophysical and tribological properties [5–8].

Heat transfer and flow behavior of nanolubricants depends upon its thermophysical properties. Viscosity of nanolubricants determines the shearing force between the adjacent fluid layers, which is responsible for viscous friction. Kole and Dey [5] reported an increment of nearly 3 times in viscosity with the dispersion of 2.5% volume fraction of CuO nanoparticles in gear oil (IBP Hauli-68). Jatti and Singh [9] used 1.5% weight fraction of CuO nanoparticles in engine oil and reported 18.2% increment in viscosity. Considering ethylene glycol (EG) as base fluid, Xie et al. [10] reported 29.2% increment in viscosity with 5% volume fraction of MgO nanoparticles, whereas Yu et al. [11] observed 138% increment with 9% volume fraction of AlN nanoparticles. Kotia and Ghosh [7] reported 10.5% increment in viscosity with 0.5% volume fraction of Al_2O_3 nanoparticle in gear oil (SAE EP90). Ettefaghi et al. [12] observed 1.74% increment in viscosity with 0.2% volume fraction of carbon nanoballs (CNB) in engine oil (SAE 20 W50). Increment in viscosity with the addition of nanoparticles is attributed to agglomeration of nanoparticles in nanolubricants, which prevents easy movement of adjacent oil layers. Ettefaghi et al. [13, 14] reported a slight decrease in viscosity at lower volume fraction due to the presence of nanoparticles between the oil layers leading to easy movement of adjacent layers.

Thermal conductivity of lubricant plays a dominating role in determining its cooling behavior, however, the low thermal conductivity of conventional lubricants limit their performance. Recent studies show the application of nanoparticles as thermal

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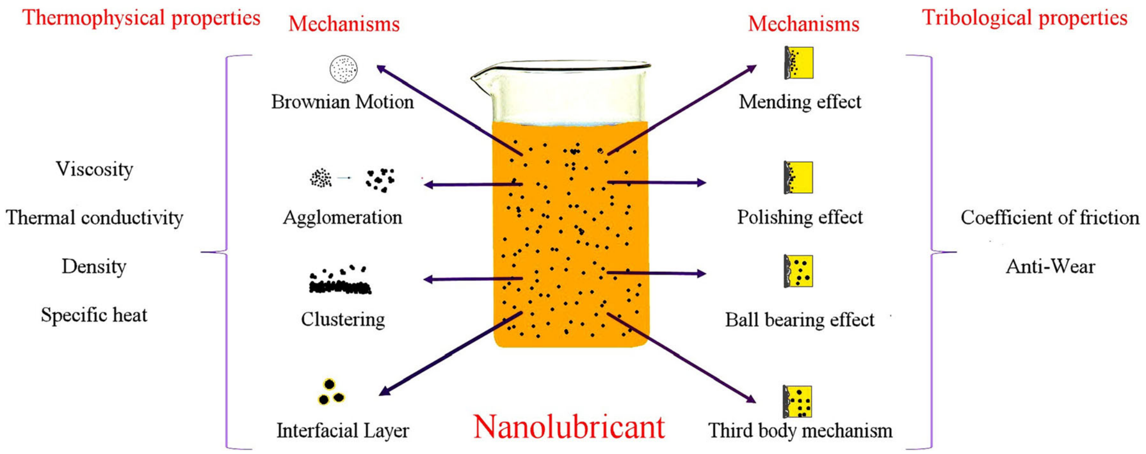

Fig. 1 Graphical representation of different mechanisms involved with nanolubricant

conductivity improver [15]. Paul et al. [16] reported 200% increment in thermal conductivity of EG with 7% volume fraction of ZrO_2 nanoparticles. Li et al. [17], with the same base fluid (EG) and volume fraction (7%), observed 9.13% enhancement in thermal conductivity using ZnO nanoparticles. This varying behavior with different nanoparticles in same base fluid motivates to summarize the results reported by various authors. Yu et al. [11] observed 38.71% increment in thermal conductivity of EG with 10% volume fraction of AlN nanoparticles. Authors reported the variation in thermal conductivity with volume fraction of nanoparticle is linear [11, 15, 17], which could be attributed to the lubricant layering [18]. However, some authors reported non-linear increment in thermal conductivity with nanoparticle volume fraction [10, 17].

Density of nanolubricants provides an account of nanoparticle additives it contains. Most of the authors have reported linear increment in density with nanoparticle volume fraction [7, 19, 20]. Mahbubul et al. [21] reported 0.54% increment in density of R141b refrigerant with 15% volume fraction of Al_2O_3 nanoparticles. Kedziersk [22] reported 10.9% increment in density of polyolestrol lubricant (RL68H) with 15% volume fraction of Al_2O_3 nanoparticles.

Specific heat contributes in heat transfer performance of nanolubricants [23]. Shin and Banerjee [24] reported 14.5% increment in specific heat of eutectic salt mixture lubricant with 1% volume fraction of SiO_2 nanoparticles. The formation of chain like nanostructure is the probable reason for such enhancement. Ghazvini et al. [25] observed 30% increment in the specific heat of engine oil (SAE 20W40) with 1% weight fraction of nano-diamond. However, Elias et al. [23] reported 14% decrement in specific heat of EG with 1% volume fraction of Al_2O_3 nanoparticles. Authors reported that the

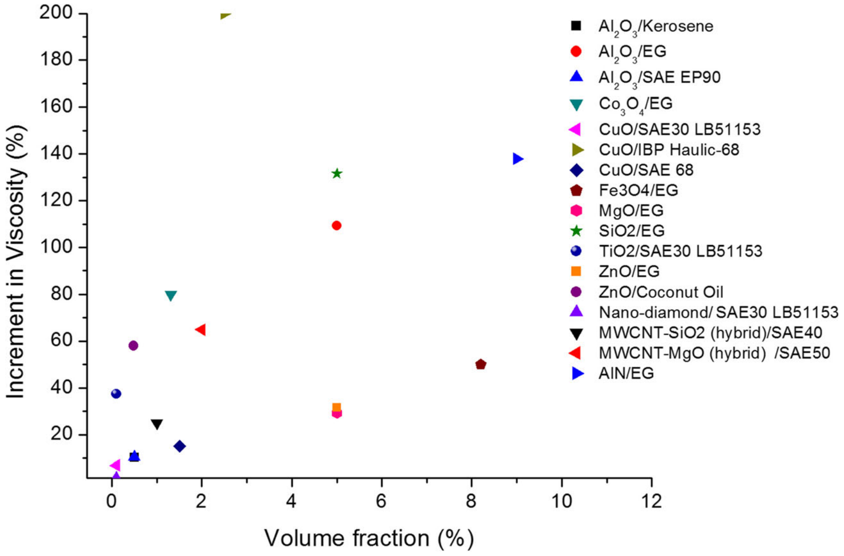

Fig. 2 Viscosity results for nanolubricants [5, 7, 10, 11, 37, 38, 40–44]

Table 1 Summary of viscosity of nanolubricants

S. No.	Nanoparticles	Base lubricants	Size (nm)	Concentration	Viscosity enhancement (%)	References
1.	Al_2O_3	Kerosene	13 50	0.5vol. %	10.3 8.2	Agarwal et al. [41]
2.		RL68H	10	25 wt.%	88.2* (KV)	Kedzierski [22]
3.		EG	26	5vol. %	109.3*	Xie et al. [10]
4.		SAE EP90	40	0.5 vol%	10.5*	Kotia and Ghosh [7]
5.	Al_2O_3/TiO_2 (hybrid)	SAE 5 W30	75	0.05 wt.%	4.5* (Decrease)	Ali et al. [39]
6.	Co_3O_4	EG	<50	5.7vol. %	40*	Mariano et al. [20]
7.	CuO		10	1.31vol. %	80*	Shima et al. [42]
8.		Mineral oil	40	1.5 wt.%	18.26	Jatti and Singh [9]
9.		SAE30 LB51153	5	0.1vol. %	6.9*	Wu et al. [43]
10.		SAE 20 W50	–	0.5 wt.%	5.7	Ettefaghi et al. [13]
11.		IBP Haulic-68	40	2.5vol. %	200	Kole and Dey [5]
12.		SAE 68	40	1.5vol. %	15*	Kotia et al. [38]
13.	Fe_3O_4	EG	8.7	8.2vol. %	50*	Shima et al. [42]
14.	MgO		20	5vol. %	29.2*	Xie et al. [10]
15.	SiO_2		–	5vol. %	131.6*	Xie et al. [10]
16.	TiO_2	SAE30 LB51153	80	0.1vol. %	37.5	Wu et al. [43]
17.		EG	–	5vol. %	31.6*	Xie et al. [10]
18.	ZnO		18	5vol. %	859.3*	Xie et al. [10]
19.		Coconut-oil	26	0.48vol. %	58	Rashin and Hemalatha [44]
20.	CNB	SAE 20 W50	70	0.2 wt.%	1.7* (KV)	Ettefaghi et al. [12]
21.	Fullerene		10	0.2 wt.%	0.3* (KV)	Ettefaghi et al. [12]
22.	MWCNT	Mineral oil	–	0.05 wt.%	115.43	Lijesh et al. [45]
23.		SAE 20 W50	10–20	0.2 wt.%	0.3* (KV)	Ettefaghi et al. [14]
24.	Nano-diamond	SAE30 LB51153	10	0.1vol. %	1.5*	Wu et al. [43]
25.	$MWCNT/SiO_2$ (hybrid)	SAE40	MWCNT(Inside dia.: 3–5; Outside dia.: 5–15); SiO_2 (20–30)	1vol. %	25*	Esfe et al. [37]
26.	MWCNT/MgO (hybrid)	SAE50	30	2vol. %	65*	Asadia et al. [40]
27.	AlN	EG	50	9vol. %	138*	Yu et al. [11]

*Exact value is not available; Kinematic viscosity: KV; Engine oil: SAE5W30, SAE20W50, CD 15 W/40, SAE30LB51153; Gear oil: SAE EP90; Commercial polyolester lubricant: RL68H; Motor oil: SAE 30 LB51153; Mineral oil: SN 650, SAE10, SAE40, SAE50; Hydraulic oil: SAE 68

nature of variation in specific heat of nanolubricants depends on the specific heat of nanoparticles [23, 25].

The main application of lubricants is to reduce the wear and maintain the surface quality [2]. The dispersed nanoparticles improve the tribological properties of base lubricants by various mechanisms like ball bearing effect [8, 26], mending effect [27], tribofilm formation [28], polishing effect [8, 29] etc. Tao et al. [8] reported that the diamond nanoparticles dispersed in paraffin oil, penetrates into the rubbing surfaces, which convert sliding motion into rolling motion by acting as ball bearing. Liu et al. [27] observed the deposition of Cu nanoparticles onto the wear scar using scanning tunneling microscopy, which is termed as mending effect. Zhou et al. [28] observed that the nanoparticle of Cu interact with the friction pair surfaces to form a tribofilm, which principally enhance the antiwear ability of the friction surfaces. Tang et al. [29] observed the decrease in surface roughness due to the surface polishing effect, which produces micro-plateaus with extremely smooth surfaces and almost uniform height. Lee et al. [30] reported 24% decrease in frictional coefficient for mineral oil using 0.5% volume fraction of graphite nanoparticles. Chang et al. [31] reported 60% reduction in frictional coefficient for lithium grease using 2% volume fraction of graphite nanoparticles. Kimura et al. [32] reported 75% reduction in wear for paraffinic mineral oils with 8% volume fraction of boron nitride (BN) nanoparticles. BN adheres to the surfaces and slightly increase the friction but significantly decreases the wear. Ma et al. [33] observed the negative wear with ZrO_2 nanoparticles in machine oil, due to high deposition rate as compared to wear rate. Thottackkad et al. [34] reported that CeO_2 nanoparticles display highest reduction (17%) in wear for coconut oil as compared to paraffin oil and engine oil. Authors have observed that the specific wear rate decreases at first then comes to a minimum level and then increases with the increase in volume fraction of nanoparticles.

Fig. 1 represents the various mechanisms involved in augmentation in thermophysical and tribological properties of nanolubricants. Thermophysical properties of nanolubricants are influenced by Brownian motion [35], particle agglomeration [5], clustering [6], interfacial layer [36] etc. Dispersed nanoparticles are contributed in mending, polishing, ball bearing and third body mechanism [2], which contributes in tribological property enhancement.

The effect of nanoparticles additives on thermophysical and tribological properties of nanolubricants have been summarized in the present review. Various mechanism involved with the dispersion of nanoparticles is discussed in details. Nanolubricants are categorized on basis of nanoparticles type (metal, metal oxide, carbon, sulphide, rare earth compounds, nanocomposite and others) and base fluid (mineral, synthetic, and biological oil). This arrangement enables us to easily understand the properties enhancement mechanism involved with different nanoparticle additives.

2 Thermophysical properties

The thermophysical properties of nanolubricants are important factors for heat transfer performance of machines. These properties include viscosity, density, thermal conductivity and specific heat capacity. In the subsequent section, the variation of thermophysical properties with the dispersion of nanoparticles has been discussed.

2.1 Viscosity

Viscosity of a nanolubricant determines its load carrying capacity and viscous friction. Esfe et al. [37] dispersed 1% volume fraction of MWCNTs/SiO_2 (hybrid) nanoparticles in engine oil (SAE 40) and observed 25% increment in viscosity. Kotia et al. [38] used 1.5% volume fraction of CuO nanoparticles in hydraulic oil (SAE 68) and reported 15% increment in viscosity. Ali et al. [39] observed 4.5% decrease in viscosity of engine oil (SAE 5 W30) with the dispersion of 0.05% weight fraction of Al_2O_3/TiO_2 (hybrid) nanoparticles, which is beneficial for enhancement of automotive engine efficiency. Asadia et al. [40] dispersed 2% volume fraction of MWCNT/SiO_2 (hybrid) nanoparticles in engine oil (SAE 50) and observed 25% increment in viscosity. Mariano et al. [20] used 5.7% volume fraction of Co_3O_4 nanoparticles in EG and observed 40% increment in viscosity. Fig. 2 [5,

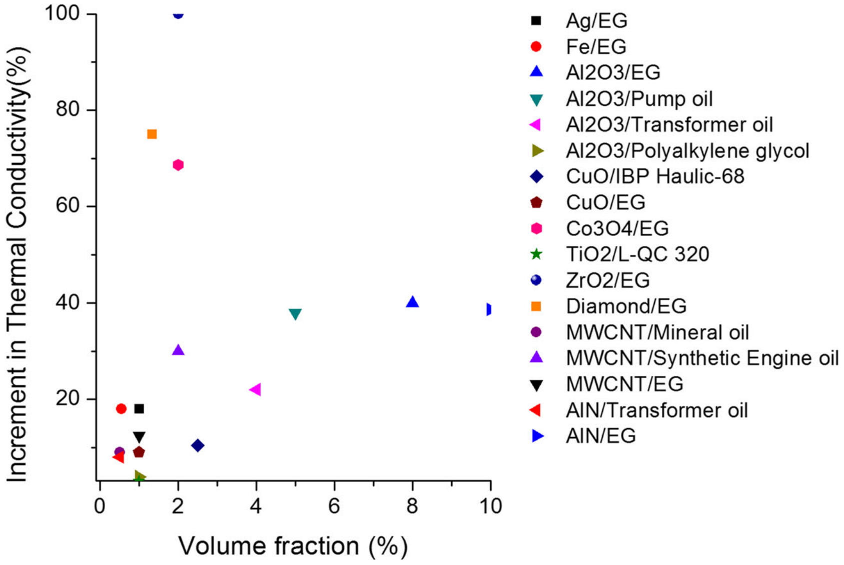

Fig. 3 Thermal conductivity results for nanolubricants [6, 11, 16, 46, 47, 49–56]

Table 2 Summary of thermal conductivity of nanolubricants

S. No.	Nanoparticles	Base lubricants	Size (nm)	Concentration	Thermal conductivity enhancement (%)	References
1.	Ag	Heat transfer oil	20	0.72 wt.%	18.5*	Aberoumand et al. [48]
2.		EG	100	1 vol.%	18	Sharma et al. [46]
3.	Fe		10	0.55vol. %	18*	Hong et al. [50]
4.	Al_2O_3		20	8vol. %	40	Wang et al. [51]
5.			38.4	5vol. %	18*	Lee et al. [57]
6.			–	5vol. %	29*	Xie et al. [52]
7.		Pump oil	–	5vol. %	38	Xie et al. [52]
8.		Transformer oil	13	4vol. %	22	Choi et al. [53]
9.		Polyalkylene glycol	13	1vol. %	4	Sharif et al. [49]
10.	CuO	SAE 20 W50	–	0.1 wt.%	3	Ettefaghi et al. [13]
11.		IBP Haulic-68	40	2.5vol. %	10.4	Kole and Dey [6]
12.		500SN	50	2 wt.%	6.2	Saeedinia et al. [58]
13.		EG	35.4	1vol. %	9*	Hwang et al. [54]
14.	Co_3O_4		<50	5.7 wt.%	24.7*	Mariano et al. [20]
15.	TiO_2		–	2vol. %	68.7*	Paul et al. [16]
16.		L-QC 320	10	1vol. %	3.1*	Wei et al. [47]
17.	ZnO	EG	30	10.5 wt.%	14*	Li et al. [17]
18.	ZrO_2		–	2vol. %	100	Paul et al. [16]
19.	CNB	SAE 20 W50	70	0.1 wt.%	18*	Ettefaghi et al. [12]
20.	Diamond	EG	30–50	1.33vol. %	75*	Kang et al. [55]
21.	Fullerene	SAE 20 W50	10	0.1 wt.%	2.1*	Ettefaghi et al. [12]
22.	Graphene	SAE 20 W50	–	0.1 wt.%	9*	Ettefaghi et al. [12]
24.	MWCNT	Mineral oil	10–30	0.5vol. %	9*	Hwang et al. [54]
25.		SAE 20 W50	10–20	0.1 wt.%	13.2	Ettefaghi et al. [14]
26.		Synthetic Engine oil	20–30	2vol. %	30	Liu et al. [56]
27.		EG	20–30	1vol. %	12.4	Liu et al. [56]
28.	AlN	Transformer oil	50	0.5vol. %	8	Choi et al. [53]
29.		EG	50	10vol. %	38.71	Yu et al. [11]

Diathermic oil: L-QC 320; Base oil: 500SN

7, 10, 11, 37, 38, 40–44] shows the viscosity of different types of nanolubricants. It has been observed that viscosity of nanolubricants increase with the dispersion of nanoparticles. A summary of viscosity of nanolubricants is shown in Table 1.

2.2 Thermal conductivity

Thermal conductivity of nanolubricants significantly contributes to its heat transfer behavior. Sharma et al. [46] reported 18% enhancement in thermal conductivity of EG with 1% volume fraction of silver nanoparticles. Wei et al. [47] observed 3.1% increment in thermal conductivity of diathermic oil (L-QC 320) with the dispersion of 1% volume fraction of TiO_2 nanoparticles. The increment in thermal conductivity follows a linear trend with nanoparticle volume fraction. Li et al. [17] reported 14% increment in thermal conductivity of EG with 10.5% weight fraction of ZnO nanoparticles and also reported that this increment in thermal conductivity with concentration of nanoparticles is nonlinear. Aberoumand et al. [48] observed 18.5% enhancement in thermal conductivity with 0.72% weight fraction of Ag nanoparticles in heat transfer oil, which is further increased with the rise in temperature due to Brownian motion of nanoparticles. Sharif et al. [49] reported 4% increment in thermal conductivity of polyalkylene glycol with the dispersion of 1% volume fraction of Al_2O_3 nanoparticles, however it decreases with rise in temperature. Such ambiguous variation in behavior of nanolubricants, demands for a comprehensive study on them. Fig. 3 [6, 11, 16, 46, 47, 49–56] shows the thermal conductivity of different nanolubricant.

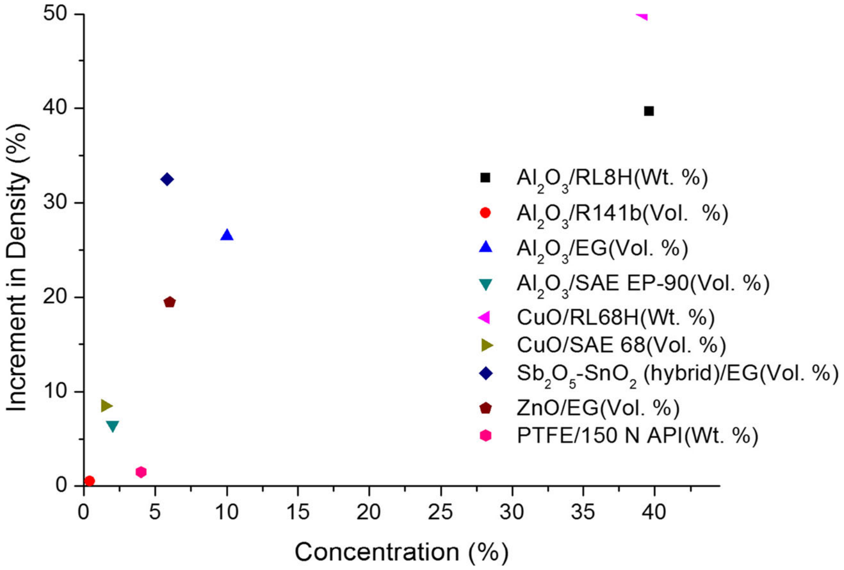

Fig. 4 Variation in density of nanolubricants [7, 21, 22, 38, 60–62]

Table 3 Summary of density of nanolubricants

S. No.	Nanoparticles	Base lubricants	Size (nm)	Concentration	Density enhancement (%)	References
1.	Al_2O_3	RL68H	60	39.6 wt.%	39.7*	Kedziersk [22]
2.		R141b	13	0.4vol. %	0.54*	Mahbubul et al. [21]
3.		EG	44	10vol. %	26.5*	Vajjha et al. [60]
4.		SAE EP-90	40	2vol. %	6.5*	Kotia and Ghosh [7]
5.	CuO	RL68H	30	39.2 wt.%	50*	Kedzierski [61]
6.		SAE 68	40	1.5vol. %	8.5*	Kotia et al. [38]
7.	Sb_2O_5/SnO_2 (hybrid)	EG	44	5.8vol. %	32.5*	Vajjha et al. [60]
8.	ZnO		70	6vol. %	19.5*	Vajjha et al. [60]
9.	PTFE	150 N API	30–50	4 wt.%	1.5	Dubey et al. [62]

Note: Nano refrigerant: R141b; Group II base oil: 150 N API

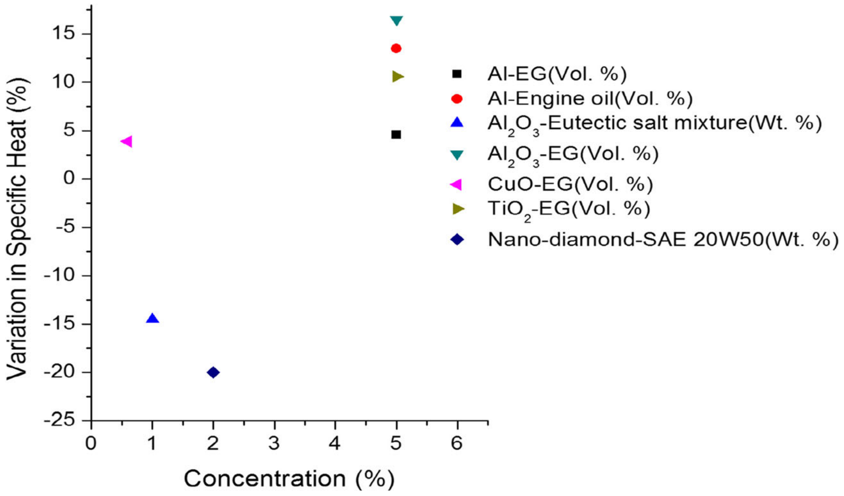

Fig. 5 Variation in specific heat of nanolubricants [24, 25, 63]

Table 4 Summary of specific heats of nanolubricants

S. No.	Nanoparticles	Base lubricants	Size (nm)	Concentration	Specific heat decrement (%)	References
1.	Al	EG	80	5vol. %	4.6*	Murshed [63]
2.		Engine oil	80	5vol. %	13.5*	Murshed [63]
3.	Al_2O_3	Eutectic salt mixture	20–30	1 wt.%	14.5 (Increase)	Shin and Banerjee [24]
4.		EG	13	1vol. %	11.7*	Elias et al. [23]
5.			80	5vol. %	16.5*	Murshed [63]
6.			45	2.5vol. %	5.1*	Barbes et al. [64]
7.			10	5vol. %	1.2*	Popa et al. [65]
8.	CuO		25–50	0.6vol. %	3.9*	Zhou et al. [96] (2010)
9.	TiO_2		15	5vol. %	10.6*	Murshed [63]
10.	Nano-diamond	SAE 20 W50	–	2 wt.%	20 (Increase)	Ghazvini et al. [25]

It has been noted that thermal conductivity of nanolubricant enhanced with the dispersion of nanoparticle. A summary of thermal conductivity of nanolubricants is shown in Table 2.

2.3 Density

Density of base lubricant significantly varies with the dispersion of particles, however its data in literature are still scarce [59]. Vajjha et al. [60] performed a bench mark study on measurement of the density of different nanolubricants. They reported 26.5%, 32.5% and 19.5% increment in density of EG with the dispersion of 10%, 5.8% and 6% volume fraction Al_2O_3, Sb_2O_5/SnO_2 and ZnO nanoparticles respectively. Kedzierski [61] observed 50% increment in density of commercial polyolester (RL68H) with the dispersion of 39.2% weight fraction of CuO nanoparticles. Further, author reported 39.7% increment in density of same base lubricant with 39.6% weight fraction of Al_2O_3 nanoparticles [22]. Kotia and Ghosh [7] reported 6.5% increment in density of gear oil (SAE EP90) with the dispersion of 2% volume fraction of Al_2O_3 nanoparticles. Further, author reported 8.5% increment in density of hydraulic oil (SAE 68) with 1.5% volume fraction

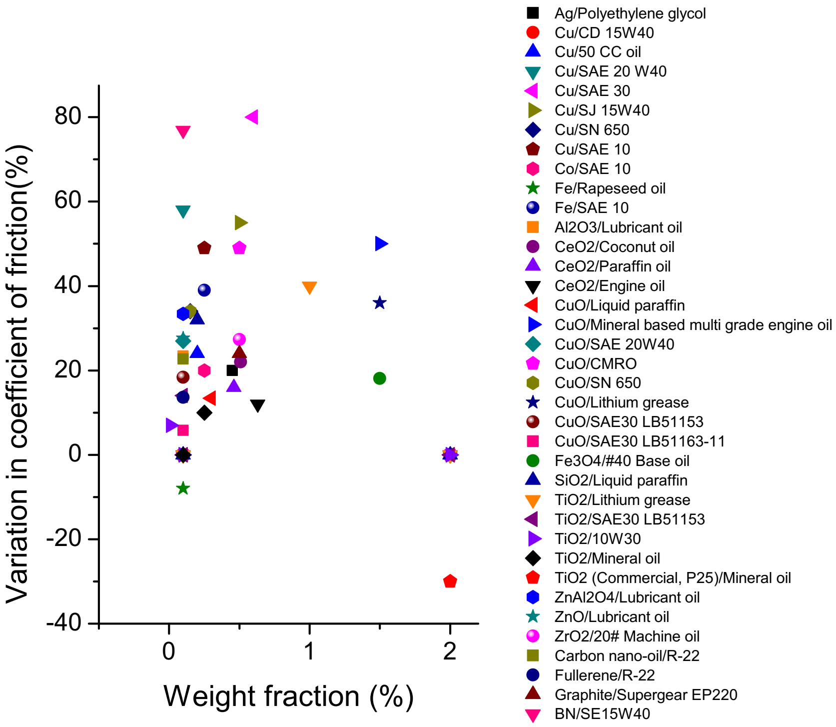

Fig. 6 Variation in coefficient of friction for nanolubricant [9, 30, 31, 33, 34, 43, 66–84]

Table 5 Variation of frictional coefficient with the dispersion of nanoparticles

S. No.	Nanoparticles	Base lubricants	Size (nm)	Concentration	Approx. variation (%)	References
1.	Ag	Polyethylene glycol	7	0.45 wt.%	20 (Decrease)	Neuffer et al. [69]
2.	Boric acid	SAE 15 W40	< 50	1:10 vol. proportion	8*(Decrease)	Vadiraj et al. [85]
3.		SAE 90	< 50	3:10 vol. proportion	13*(Decrease)	Vadiraj et al. [85]
4.	Cu	CD 15 W40	50	7.5 wt.%	35 (Decrease)	Zhang et al. [70]
5.		50 CC oil	20	0.2 wt.%	24 (Decrease)	Long et al. [71]
6.		SAE 20 W40	40	0.1 wt.%	58 (Decrease in frictional force)	Kaviyarasu and Vasanthan [72]
7.		SAE 30	–	0.6 wt.%	80* (Decrease)	Tarasov et al. [73]
8.		SJ 15 W40	3*	0.5 wt.%	55 (Decrease)	Zhang et al. [74]
9.		SAE 15 W40	< 20	1:10 vol. proportion	6*(Decrease)	Vadiraj et al. [85]
10.		SAE 90	< 20	3:10 vol. proportion	33*(Decrease)	Vadiraj et al. [85]
11.		SN 650	–	0.15 wt.%	34 (Decrease)	Wang et al. [67]
12.		SAE 10	50–80	0.25 wt.%	49(Decrease)	Padgurskas et al. [68]
13.	Co	SAE 10	50–80	0.25 wt.%	20*(Decrease)	Padgurskas et al. [68]
14.	Fe	Rapeseed oil	50–140	0.1 wt.%	8* (Increase)	Maliar et al. [75]
15.		SAE 10			15*(Increase)	
16.			50–80	0.25 wt.%	39 (Decrease)	Padgurskas et al. [68]
17.	Al_2O_3	Lubricating oil	78	0.1 wt.%	17.61 (Decrease for four-ball test) 23.92(Decrease for thrust-ring test)	Luo et al. [86]
18.		Lubricant oil	95	0.1 wt.%	23.4* (Decrease)	Song et al. [76]
19.	CeO_2	Coconut oil	30–150	0.51 wt.%	22(Decrease)	Thottackkad et al. [34]
20.		Paraffin oil		0.46 wt.%	16(Decrease)	
21.		Engine oil		0.63 wt.%	12(Decrease)	
22.	CuO	Liquid paraffin	5.5	0.3 wt.%	13.4* (Decrease)	Liu et al. [77]
23.		Mineral based multi grade engine oil	40	1.5 wt.%	50 (Decrease)	Jatti & Singh [9]
24.		Poly-alphaolefin (PAO)	5	–	20* (Decrease)	Alves et al. [87]
25.		SAE 20 W40	40	0.1 wt.%	27 (Decrease in frictional force)	Kaviyarasu & Vasanthan [72]
26.		CMRO	40	0.5 wt.%	49 (Lesser than CMRO) 18 (Lesser than SAE20W40)	Baskar & Sriram [78]
27.		SN 650	<30	0.15 wt.%	34 (Decrease)	Wang et al. [67]
28.		Lithium grease	90–110	1.5 wt.%	36* (Decrease)	Chang et al. [31]
29.		SAE30 LB51153	5	0.1 wt.%	18.4 (Decrease)	Wu et al. [43]
30.		SAE30 LB51163–11	5	0.1 wt.%	5.8 (Decrease)	Wu et al. [43]
31.	Fe_3O_4	#40 Base oil	–	1.5 wt.%	18.06 (Decrease)	Xiang et al. [79]
32.	SiO_2	Liquid paraffin	58	0.2 wt.%	32* (Decrease)	Peng et al. [80]
33.	TiO_2	Lithium grease	40–60	1 wt.%	40 (Decrease)	Chang et al. [31]
34.		SAE30 LB51153	80	0.1 wt.%	14* (Decrease)	Wu et al. [43]
35.		10 W30	25	0.01 wt.%	7 (Decrease)	Chang et al. [81]
36.		Mineral oil	20–25	0.25 wt.%	10* (Decrease)	Ingole et al. [82]
37.	TiO_2 (Commercial, P25)	Mineral oil	20–25	2 wt.%	30* (Increase)	Ingole et al. [82]
38.	$ZnAl_2O_4$	Lubricant oil	95	0.1 wt.%	33.37 (Decrease)	Song et al. [76]
39.	ZnO	Lubricant oil	95	0.1 wt.%	27.6* (Decrease)	Song et al. [76]
40.	ZrO_2	20# Machine oil	< 100; < 50 (surface modified)	0.5 wt.%	5.36 (Decrease from the four-ball test)	Ma et al. [33]
41.					27.34 (Decrease from the thrust-ring test)	Ma et al. [33]
42.	Carbon nano-oil	R-22	–	0.1 wt.%	22.7* (Decrease)	Lee et al. [83]

Table 5 (continued)

S. No.	Nanoparticles	Base lubricants	Size (nm)	Concentration	Approx. variation (%)	References
43.	Fullerene	R-22	–	0.1 wt.%	13.6* (Decrease)	Lee et al. [84]
44.	Graphite	Supergear EP220	55	0.5 wt.%	24 (Decrease)	Lee et al. [30]
45.	Nano-diamond	R68	4.37 ± 0.45	2 vol.%	50* (Decrease)	Chu et al. [88]
46.		Turbo oil	–	2-3 wt.%	*(Decrease)	Khuzani et al. [89]
47.		SAE30LB51153	10	<0.1 wt.%	5* (Decrease)	Wu et al. [43]
48.		SAE30 LB51163–11	10	<0.1 wt.%	20* (Increase)	Wu et al. [43]
49.	BN	SE15W40	120	0.1 wt.%	76.9 (Decrease)	Wan et al. [66]
50.	CeF_3	500SN	25	0.5vol. %	26.5 (Decrease)	Sunqing et al. [90]

Engine oil: SE15W40, SAE20W40, 10W30, Turbo oil; Mineral oil: Supergear EP220, SAE10, SN 650; Refrigerant oil: R-22; Commercial oil: R68

of CuO nanoparticles [38]. Dubey et al. [62] reported 1.5% increment in density of 150 N API Group II base oil with dispersion of 4% volume fraction of polytetrafluoroethylene (PTFE) polymer nanoparticles. Further they reported that the decrease in size of PTFE nanoparticles leads to rise in density, which is due to the increase Van der Waal's interaction between particles and base fluid. Fig. 4 [7, 21, 22, 38, 60–62] shows the density of various nanolubricants. It has been noted that density of nanolubricants increases with the dispersion of nanoparticles. Table 3 summarizes the density of nanolubricants.

2.4 Specific heat

Specific heat is the key parameter for analyzing the heat transfer performance of nanolubricants. Murshed [63] dispersed 5% volume fraction, each of Al, Al_2O_3 and TiO_2 nanoparticles in EG and observed 4.6%, 16.5% and 10.5% reduction in specific heat respectively. Also, 5% volume fraction of Al produces 13.5% reduction in specific heat of engine oil. Author mentioned that the low specific heat of nanoparticles as compared to base lubricant is responsible for the linear decrement in nanolubricant's specific heat with nanoparticle volume fraction. Barbes et al. [64] observed 5.1% reduction in specific heat of EG with dispersion of 2.5% volume fraction of Al_2O_3 nanoparticles. Popa et al. [65] reported a minor decrement of 1.2% in specific heat with 5% volume fraction of Al_2O_3 nanoparticles in EG. Fig. 5 [24, 25, 63] shows the specific heat of various nanolubricants. Table 4 summarizes the specific heat of nanolubricants.

Diathermic oil: L-QC 320; Base oil: 500SN.

3 Coefficient of friction and anti-wear properties of nanolubricants

Dispersion of nanoparticles produces significant modification in coefficient of friction and anti-wear properties of base lubricants. The lubrication mechanism with nanoparticles as aforementioned includes rolling, triobofilm formation, mending, patching and surface polishing effect ([8, 26–29, 66]). In the subsequent section, the modification in coefficient of friction and anti-wear properties of base lubricant with the dispersion of nanoparticles has been discussed.

3.1 Coefficient of friction

Coefficient of friction is a crucial parameter for the performance of the lubricants. Lee et al. [30] observed 24% reduction in coefficient of friction with 0.5% volume fraction of graphite nanoparticles dispersed in gear oil (supergear oil EP220). The graphite nanoparticles act as ball bearing spacers between friction surfaces, which reduced contact between them. Chang et al. [31] reported 40% decrease in coefficient of friction with 1% weight fraction of TiO_2 nanoparticles dispersed in lithium grease. This is attributed to rolling action by spherical nanoparticles, which is similar to micro bearing action. Wang et al. [67] observed 34% reduction in coefficient of friction with 0.15% weight fraction of Cu nanoparticles dispersed in mineral oil (SN650). The possible reason for this reduction may be due to the formation of self repairing film in lubricating oil, which separates the friction surfaces. Padgurskas et al. [68] reported 49% reduction in coefficient of friction with Cu nanoparticles (0.5 g) dispersed in SAE 10 mineral oil (100 ml), which is due to formation of metallic nanoparticle layer. Wu et al. [43] reported 18.4% reduction in coefficient of friction with 0.1% volume fraction of CuO nanoparticles dispersed in engine oil (SAE30 LB51153), which is attributed to rolling effect by spherical nanoparticles. Fig. 6 [9, 30, 31, 33, 34, 43, 66–84] shows the variation in friction coefficient for different nanolubricants. It has been observed that wide varieties of nanolubricants were tested for coefficient of frication property. It has been noted that that coefficient of friction improved in most of the cases. Table 5 shows the summary of variation in frictional coefficient with dispersion of nanoparticles.

3.2 Anti-wear

Anti-wear properties of nanolubricants are responsible for durability of equipment. Sia et al. [91] reported significant reduction in wear with 0.5% weight fraction of SiO_2 nanoparticles in mineral oil (Ecocut HSG 905), which is attributed to the deposition of nanoparticles in surface grooves. However at 0.8% weight fraction of SiO_2 nanoparticles, degradation in behavior is observed due to collision of nanoparticles, which leads to less deposition of nanoparticles. Chang et al. [31] observed 60% decrease in wear with 2% weight fraction of CuO nanoparticles dispersed in lithium grease. CuO nanoparticles penetrate into asperities of the rubbing surfaces and form a protective tribofilm. Zhang et al. [74] reported 90% reduction in wear with 0.5% weight fraction of Cu nanoparticles dispersed in engine oil (SJ 15 W/40). It was observed that initially the Cu nanoparticles tribolayer between the rubbing surfaces is desorbed due to rubbing process. But, due to the enough energy on the fresh wear surface, Cu gets attached on the shearing surface easily by melting and welding. The formation of *in-situ* protective layer, compensate the wear loss of tribo-pairs. Wang et al. [67] observed formation of self repairing film, which lead to 32% reduction in width of worn trace with 0.15% weight fraction of Cu nanoparticles dispersed in mineral oil (SN650). Padgurskas et al. [68] used Fe, Cu and Co nanoparticles (0.5 g) and their combinations in SAE 10 mineral oil (100 ml). It was observed that a maximum reduction of 47% in wear with Cu nanoparticles, where as 23% and 11% reductions are observed with Fe and Co nanoparticle respectively. Wu et al. [43] observed 78.8% reduction in worn scar depth with 0.1% volume fraction of CuO nanoparticles dispersed in base oil (SAE30 LB51163–11), which is attributed to deposition of CuO nanoparticles on the worn surface. Fig. 7 [9, 31–34, 39, 43, 66–68,

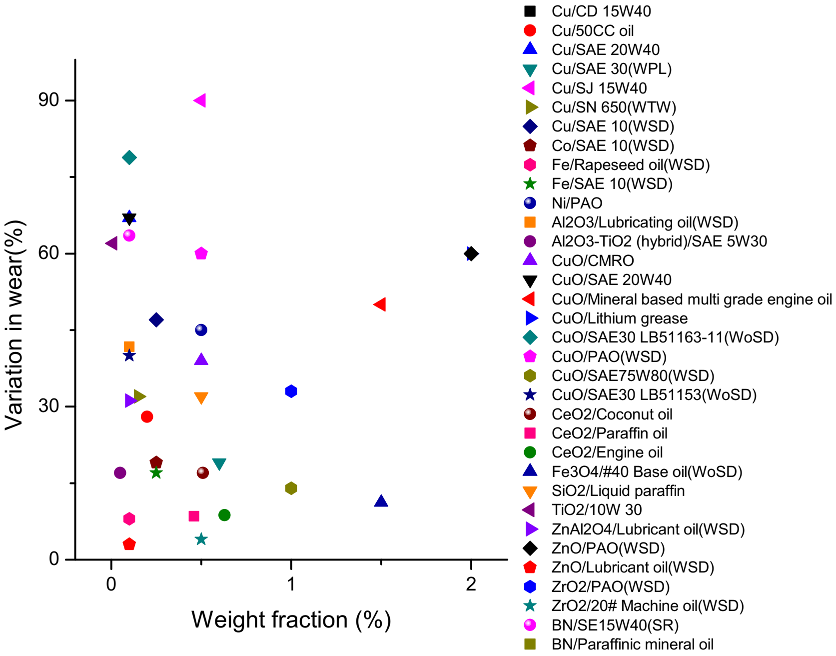

Fig. 7 Variation in wear for different nanolubricants [9, 31–34, 39, 43, 66–68, 70–76, 78–81, 86, 92–94]. where WPL-wear path length, WTW-wear trace width, WSD-wear scar dia, WoSD-worn scar depth and SR-Surface roughness

Table 6 Summary of wear with the dispersion of nanoparticles

S. No.	Nanoparticles	Base lubricants	Size (nm)	Concentration	Approx. variation (%)	References
1.	Ag	Polyethylene glycol	7	0.45 wt.%	*(Decrease)	Neuffer et al. [69]
2.	Cu	CD 15 W40	50	7.5 wt.%	35 (Decrease)	Zhang et al. [70]
3.		50CC oil	20	0.2 wt.%	28 (Decrease)	Long et al. [71]
4.		SAE 20 W40	40	0.1 wt.%	67 (Decrease)	Kaviyarasu and Vasanthan [72]
5.		SAE 30	–	0.6 wt.%	19* (wear path length decrease)	Tarasov et al. [73]
6.		SJ 15 W40	–	0.5 wt.%	90(Decrease)	Zhang et al. [74]
7.		SN 650	3*	0.15 wt.%	32(Decrease in wear trace width)	Wang et al. [67]
8.		SAE 10	50–80	0.25 wt.%	47 (Decrease in wear scar dia)	Padgurskas et al. [68]
9.	Co	SAE 10	50–80	0.25 wt.%	19*(Decrease in wear scar dia)	Padgurskas et al. [68]
10.	Fe	Rapeseed oil SAE 10	50–140	0.1 wt.%	8* (Decrease in wear scar diameter) 6* (Increase in wear scar diameter)	Maliar et al. [75]
11.		SAE 10	50–80	0.25 wt.%	17*(Decrease in wear scar dia)	Padgurskas et al. [68]
12.	Ni	PAO	20	0.5 wt.%	45(Decrease)	Chou et al. [92]
13.	Al_2O_3	Lubricating oil	78	0.1 wt.%	41.75 (Decrease for four ball-test)	Luo et al. [86]
14.		Lubricant oil	95	0.1 wt.%	7* (Decrease in wear scar dia)	Song et al. [76]
15.	Al_2O_3/TiO_2 (hybrid)	SAE 5 W30	75	0.05 wt.%	17 (Decrease)	Ali et al. [39]
16.	CuO	CMRO	40	0.5 wt.%	39 (lesser than CMRO) 5 (lesser than SAE20W40)	Baskar & Sriram [78]
17.		SAE 20 W40	40	0.1 wt.%	67 (Decrease)	Kaviyarasu & Vasanthan [72]
18.		Mineral based multi grade engine oil	40	1.5 wt.%	50 (Decrease)	Jatti & Singh [9]
19.		Lithium grease	90–11	2 wt.%	60 (Decrease)	Chang et al. [31]
20.		SAE30 LB51153	5	0.1 wt.%	16.7 (Decrease in worn scar depth)	Wu et al. [43]
21.		SAE30 LB51163–11	5	0.1 wt.%	78.8 (Decrease in worn scar depth)	Wu et al. [43]
22.		PAO	30–50	0.5 wt.%	60 (Decrease)	Battez et al. [93]
23.		SAE75W80	<50	1 wt.%	14 (Decrease in wear scar dia)	Peña-Parás et al. [94]
24.		PAO	<50	2 wt.%	14 (Decrease in wear scar dia)	Peña-Parás et al. [94]
25.		SAE30 LB51153	80	0.1 wt.%	40* (Decrease in worn scar depth)	Wu et al. [43]
26.		Lithium grease	40–60	1 wt.%	54* (Decrease)	Chang et al. [31]
27.	CeO_2	Coconut oil	30–150	0.51 wt.%	17 (Decrease)	Thottackkad et al. [34]
28.		Paraffin oil		0.46 wt.%	8.5(Decrease)	
29.		Engine oil		0.63 wt.%	8.7(Decrease)	

Table 6 (continued)

S. No.	Nanoparticles	Base lubricants	Size (nm)	Concentration	Approx. variation (%)	References
30.	Fe_3O_4	#40 Base oil		1.5 wt.%	11.2 (Decrease in worn scar dia.)	Xiang et al. [79]
31.	SiO_2	Liquid paraffin	58	0.5 wt.%	32* (Decrease)	Peng et al. [80]
32.		Ecocut HSG 905	55	0.8 wt.%	(Increases when the mixing ratio increases from 0.55 to 0.8 wt.%)	Sia et al. [91]
33.	TiO_2	10 W30	25	0.01 wt.%	62* (decrease)	Chang et al. [81]
34.		Mineral oil	20–25	0.25 wt.%	*(Decreases with increase in wt.%)	Ingole et al. [82]
35.	Commercial TiO_2 (P25)	Mineral oil	20–25	2 wt.%	*(Increases with increase in wt.%)	Ingole et al. [82]
36.	$ZnAl_2O_4$	Lubricant oil	95	0.1 wt.%	31.15 (Decrease in wear scar dia)	Song et al. [76]
37.	ZnO	PAO	20	2 wt.%	60* (Decrease in worn scar dia.)	Battez et al. [93]
38.		Lubricant oil	95	0.1 wt.%	3* (Decrease in wear scar dia.)	Song et al. [76]
39.	ZrO_2	PAO	20–30	1 wt.%	33* (Decrease in worn scar dia.)	Battez et al. [93]
40.		20# Machine oil	< 100; < 50 (surface modified)	0.5 wt.%	3.98 (Decrease in wear scar dia from the four-ball test)	Ma et al. [33]
41.					−0.0163 g (weight loss from the thrust-ring test)	Ma et al. [33]
42.	Nano diamond	Turbo oil	–	–	68 (Decrease for cylinders, gaskets, drive shaft, gears, camshaft, and valve mechanism); 64 (Decrease for rings, the bearings, gaskets and exhaust valve)	Khuzani et al. [89]
43.		SAE30 LB51153	10	<0.1 wt.%	43.3 (Decrease in worn scar depth)	Wu et al. [43]
44.		SAE30 LB51163–11	10	<0.1 wt.%	62.1 (Decrease in worn scar depth)	Wu et al. [43]
45.	BN	SE15W40	120	0.1 wt.%	63.5(Decrease in surface roughness)	Wan et al. [66]
46.		Paraffinic mineral oil	2.85 μm	8 wt.%	75 (Decrease)	Kimura et al. [32]
47.	CeF_3	500SN	25	0.5vol. %	6.5 (Decrease in wear scar dia)	Sunqing et al. [90]
48.	CuS	Liquid paraffin	–	2 wt.%	(Decrease)	Chen et al. [95]

70–76, 78–81, 86, 92–94] shows the anti-wear properties of different nanolubricants. Table 6 shows the summary of variation in wear with dispersion of nanoparticles.

Engine oil: SE15W40, SAE20W40, 10 W30, Turbo oil; Mineral oil: Supergear EP220, SAE10, SN 650; Refrigerant oil: R-22; Commercial oil: R68.

Figure 8 represents the fraction of research data available in open literature for different properties of nanolubricants. It has been observed that friction coefficient and anti-wear properties of nanolubricants are widely investigated, which also indicates the positive attitude of research community towards potential nanoparticle additives. It has also been noted that there are only few experimental results are reported for density and specific heat of nanolubricants, however well established mathematical models are widely used for prediction in variation of these with varying nanoparticle volume fraction.

4 Concluding remarks

This review article summarizes the effect of nanoparticle additives on thermophysical and tribological properties of base lubricants. Various mechanisms evolve with the dispersion of nanoparticles, which contributes to enhancement of thermophysical and tribological properties, are also discussed. This review provides a platform for the comparative study for properties of different nanoparticle and base lubricant combinations.

Most of the research groups have reported increment in viscosity with nanoparticles volume fraction, however a slight decrement is also reported at lower volume fraction. Dispersion of nanoparticles improves the thermal conductivity of lubricant, which is attributed to nanoparticles size, shape and volume fraction. Density of nanolubricant is varied with the addition of nanoparticles. Smaller size and higher volume fraction of nanoparticles leads to increment in density. Nanoparticles having higher specific heat, contributes in increment in specific heat of nanolubricants. However, most of the nanoparticles (metal and metal oxide) produce decrement in specific heat, which is due to their lower specific heat. Coefficient of friction and anti-wear properties of nanolubricant are significantly enhanced as compared to base lubricant due to various mechanisms such as ball bearing, mending, tribofilm formation and surface polishing effects. Metal and metal oxide nanoparticles are most widely used as additives to produce enhancement in the properties of lubricants.

Thus, the prospect of using nanolubricants as an alternative to conventional lubricants appears to be very promising.

Compliance with ethical standards

Conflicts of interest We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

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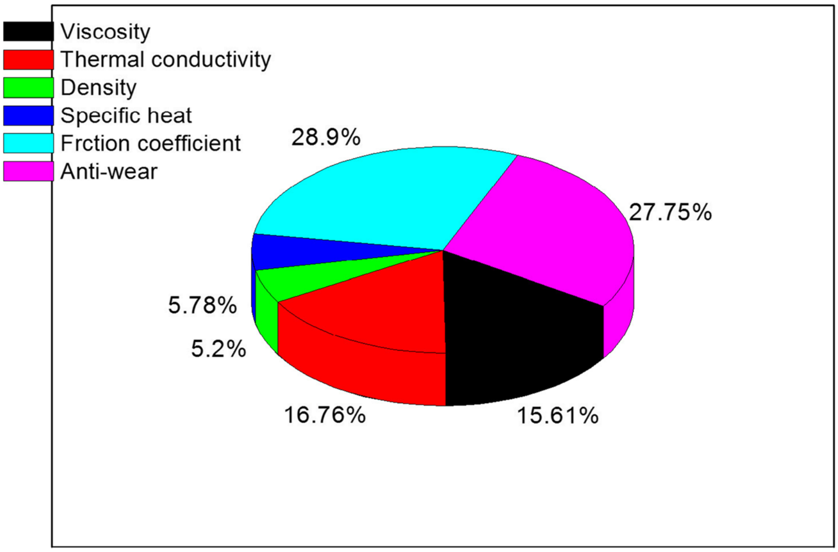

Fig. 8 Fractions of results available for different properties of nanolubricant

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