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Transformer oil-based nanofluid: The application of nanomaterials on thermal, electrical and physicochemical properties of liquid insulation-A review

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ABSTRACT

This century is undergoing a wave of knowledge and inventions making use of exceptional properties of nanofluids (NFs) in applications such as manufacturing and process heating, air conditioning and refrigeration systems, solar energy, heat pipes, electrical cooling systems and many others. Research investigations about NFs are on the increase due to growing attention and demand for NFs as heat transfer fluids. This can be observed from the number of articles published. To endorse the field further, the objective of this study is threefold. First, it presents the literature that specifies the preparation of NFs which are developed by the suspending of solid nanoparticles (NPs) in conventional working liquids. Secondly, it offers contemporary research on thermophysical features results of NFs. In this review, which primarily emphasizes research carried out in the last couple of decades, experimental inquiries from the latest developments of NFs applications and performance as a heat transfer system are summarized. Moreover, heat transfer mechanisms, challenges and impeding trends associated with NFs regarding heat transfer improvement are deliberated; which must motivate additional exploration.

This analysis also deliberates numerous dynamics affecting the thermophysical features; comprising of synthesis techniques, the stability of NFs, various base fluids, type, size, shape, surface modification and volume fraction of nanoparticles (NPs). Though, there are inconsistent findings have been observed in the literature on the effect of factors on the thermophysical traits of NFs. The study also discovers that appropriate characterization of NFs may result in superior heat transfer fluids compared to conventional base fluids. Nevertheless, more extreme exploration is required towards the suitable selection of NPs, their synthesis, characterization and long-term stability of NF is essential to exploit their full potential along with the application of these innovative fluids on commercial levels. The stability of NFs is likewise a fundamental feature of their sustainability and effectiveness. Both academia and professionals in the industry possibly will find this review valuable, as it summarizes significant outlines of research in the field.

1. Introduction

The expansion of the prospect high voltage (HV) grid has preeminent requirements on the performance and reliability of the transformer to cope with more vigorous and impulse operative conditions in the power system [1]. Transmission and distribution network is utmost imperative, severely overloaded and exclusive constituent of a power system. The transformer which converts the voltage and transfers energy is an absolute component of this network system which accounts for almost 60% cost of the total substation cost [2]. The collapse of this critical element might be

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catastrophic for the whole power system [3]. The rapid rise in electricity demand, better reliability and miniaturization of oil-immersed transformers have attracted growing consideration. One of the most significant elements of the transformer helping to provide a useful function, reliability and safety of transformers is transformer oil (TO), which is usually based on mineral oil (MO). It generally executes two common functions, i.e., cooling and insulation. It has been used to insulate transformer electrical components and to transmit heat produced in transformer windings for more than a century [4].

Thermal and insulating features of MO normally confine maximum power transfer and size reduction of transformer [5,6]. Nevertheless, MOs usually used in transformers have lower thermal conductivity and therefore present poor cooling performance [7]. Inadequate thermal conduct of the cooling system is the foremost aspect that confines further improvement of transformers, as high temperatures may lead to irrevocable impairment to insulation and condense the life expectancy of transformers radically [8–10]. It is well acknowledged that the leading motive of poor cooling outcomes is the trivial thermal conductivity of transformer oil.

Entirely conceivable transformer failure details endorse that lifespan of the transformer is exceedingly reliant on its insulation system and the life of items which were failed due to insulation concerns is 17.8 years, which is basically half of the projected life probability of 35 to 40 years [10–12]. The lifespan and operating reliability of transformers commonly be contingent on the condition and features of insulation material [13–15]. It is consequently exceedingly crucial to augment the features of insulation material. The main insulation tool applied in transformers is extremely refined MO. It is requisite to be unchanging at elevated temperature which is critical to mollify arcing, to function as insulation and coolant [16–18]. The oil applied as insulation between conductive elements also eliminates heat generated during the functioning of the transformer. Furthermore, size, weight and current density of transformer windings rely upon the volume of oil and rate of heat transfer [19].

MO utilized in the transformer endures numerous field stresses during functioning (thermal, electrical and chemical), thus deteriorating the insulating medium [20,21]. The quality, performance and physical traits of MO are directly associated with reliability, security and stability of transformers and hence the whole power system. Transformers are mostly consistent during their design life of 20–35 years and this lifespan is extendable to 60 years by appropriate maintenance practices of insulation system [22]. The insulation system (MO) always experiences elevated operating temperature; consequently, the temperature is the most essential influencer in the operation of the transformer. The studies have revealed that insulating traits of MO would not be influenced even if MO has been employed for multiple years but high temperature will cause obvious effects on its cooling features and hence create functional impediments for typical operations of transformers [23,24]. The conduct of an insulation system will deteriorate due to chemical, electrical and thermal stresses. For example, the degree of polymerization (DP) value will decline, when it is subjected to thermal pressure and hence originate partial discharge (PD) [25–27]. The discharge particles (ions, electrons) will initiate to depreciate the condition of the insulation system after PD. The cooling and insulating traits of insulation material would weaken gradually inside the transformer. The speed of degradation is influenced by temperature besides air and moisture [28].

With the rapid rise in transmission capacity and voltage levels which not only raises the volume and weight of the transformer constantly but also reduces its safety and reliability. This oil cooling system of transformers is prone to serious cohesive aging problems, specifically thermal aging issues as a result of intense thermal, mechanical and electrical stress [29,30]. Due to these stresses, MO has the inclination to ignite or oven explosion in transformers due to polycyclic aromatic hydrocarbons existed in it. MO is usually derived from petroleum yield which is no-sustainable and detrimental for the environment. Vegetable oils have attained attention as a potential alternate of MO but they were unable to provide required cooling and insulating features [31]. However, it is highly required to look for suitable potential liquid insulation of transformers with promising insulating, thermal and better heat transfer qualities [32–34].

The start of this century was loaded with constant development and energy demand, which urged the researchers to make uninterrupted efforts to look for advance technical resolutions in the energy management sector to supply a reliable and continuous supply of electricity. An encouraging idea to resolve this issue draws nanotechnology with novel material breeds, for instance, nanomaterials. One cluster of these types of materials is NPs-solid particulates with at least one dimension lesser than 100 nm. Potential applications of NPs were acknowledged in multiple fields such as biotechnology [35], biosensors, electrochemical sensors [36], environment protection [37–39], biology and medicine [40–42] and many more [43–45]. The range of nanotechnology applications is mounting in various sectors, for example, biomedicine, robotics, electronics, automobiles, and civil engineering industry (together with transportation) as a result of their superior conduct [46–52].

Potentials presented by materials in nanoscale within the framework of enhancing thermo-physical features of huge-scale systems were acknowledged by Choi et al. [7] in 1995. They determined the thermal traits of copper NPs scattered in water and concluded that the suspension of NPs might improve thermal conductivity by 350%. Furthermore, the word ‘‘nanofluid” was used by them to mention to a suspension of NPS for the first time. Now, NFs, a quite familiar term these days in the research community, has been a topic of enormous research over the past couple of decades. A fluid with homogenously dispersed nanosized particulates at just some weight percentage (wt%) is known as NF or nano liquid. Nevertheless, in HV liquid insulation inquiries, terms ‘‘nanofluid”and nanoliquid are used interchangeably to denote a blend of TO/NP for cooling and insulating concern.

Nanodielctrics attracted notable consideration due to current development in nanotechnology after its initial conceptual influx in the 1990 s [53]. The results have revealed that the suspension of nanomaterials efficiently expands the insulation lifespan of solid polymers. A similar technique was attempted to enhance the thermal and insulating features of liquid insulation. The nanomaterials were introduced into TO with the objective to enhance thermal and insulating traits. The experimental outcomes of NFs stated improved thermal [30–34] and insulating features [54–56]. Nevertheless, primarily traditional micron-sized particulates were used to enhance thermal conductivity [57]. The main drawback connected with these developed fluids was the consequent reduction in dielectric strength [58]. Another difficulty attached to micron-sized particles was that they tend to fall out of suspension.

2. Why nanofluids?

The understanding and knowledge of heat transfer are critical for the design and manufacturing of a variety of industrial, commercial and domestic processes, including energy production and conversion, chemical processing, refrigeration, air conditioning, refrigeration, oil and gas productions, and electrical cooling. The enhancement in thermal conduct of systems is designated as ‘heat transfer improvement’ in thermal engineering. Multiple techniques have been recommended to enhance heat transfer during the last decade. It has been noted that thermal conductivity of solids might be several orders of magnitude larger than thermal conductivities of traditional heat transfer liquids for instance oil, water or ethylene glycol, the suspension of particles into a liquid has potential to enhance the effective thermal conductivity of the fluid. With the progress of nanotechnology and its capability to raise the conduct of devices by developing it, an innovative fluid known NF has been devised. This is developed by mixing base fluid of smaller thermal conductivity with solid NPs of high thermal conductivity, and therefore a new fluid (nanofluids) has better transfer features compared with base liquids [56,57]. An NF is a fluid in which nanometer-sized particulates, homogeneously distributed in the base fluid, develop a colloidal solution of NPs in a base liquid. The NPs applied in NFs are usually prepared of metals (gold, copper, aluminum and iron), oxides (TiO_2, SiO_2, CuO, and Al_2O_3), nonmetals (carbon nanotubes, graphene, and graphite), nitrides of metals (SiN, AlN), carbides of metals (SiC), or carbon nanotubes, whereas base fluids include, oil, water, ethylene glycol (Fig. 1). NFs present novel features that assist them to be potentially suitable in numerous applications in heat transfer comprising of microelectronics, vehicle thermal management [52], heat exchanger, refrigerator chiller, in boiler flu gas for temperature decline.

Choi et al. [7] presented the term "nanofluid" to illustrate the suspension of NPs in base liquid. Their result revealed that the suspension of NPs into base liquid enhanced its thermal conductivity. The inclination toward NFs research emerged from increasing demand of engineers to design an advance insulation system that may offer necessary cooling and is capable to endure HV levels, for instance, for HV alternating current (HVAC) and HV direct current (HVDC) applications. Despite the fact, HVAC has been applied round the globe since the 1880 s whereas HVDC transmission system was developed in 1950 s due to their prospective to handle multiple issues (steady state and dynamic) related to interconnection with HVAC system for longer distances, consequently, numerous HVDC transmission systems are prevailing and are being deliberated as critical constituent of electric grid [58]. Both AC and DC voltage levels are projected to rise further to cope with the globally rising demand for electric power.

Unfortunately, the latest insulation system in practice has limited electrical and thermal performance, as a result, there is high demand to solve thermal, electrical, mechanical and economic concerns. For example, a thermally efficient insulation system may be developed by the suspension of micron-sized particles into traditional liquid insulation to achieve a blend of properties of both solid particulates and base liquid. The suspension of micronized particles, regardless of improving thermal properties (thermal conductivity), also causes more flaws into the general insulation system [58].

Contrary, the introduction of NPs into traditional liquid insulation is anticipated to enhance cooling and insulating features of the insulation system by considering economic and thermal fundamentals. This enhancement is thought to be related to the small size of NPs which consequently leads to a large interface area – an interaction precinct between NPs and oil. Due to this, NFs are projected to present distinctive dielectric traits that are vastly different from preceding conventional microfluidics. This exclusive enhancement in properties caused by NPs has led to an innovative class of fluids that may offer both electrical and thermal properties. In fact, multiple research projects were commenced to investigate the prospectus and potentials of NFs as next-generation liquid insulation for AC and DC power transmission systems.

During a recent couple of decades, NFs have attained a huge focus because of their exceptional and distinctive features. Even though few review articles on dielectric qualities of NFs are available, it would look like that no review presented their thermal features. This article not only offers insight into the understanding of thermal properties of TO-based NFs but also supplies inclusive details of related challenges and imminent opportunities. Moreover, it contributes a summary of the advantages, disadvantages and potential applications of these NFs. The advantages and disadvantages associated with NPs and NFs are given in Fig. 2.

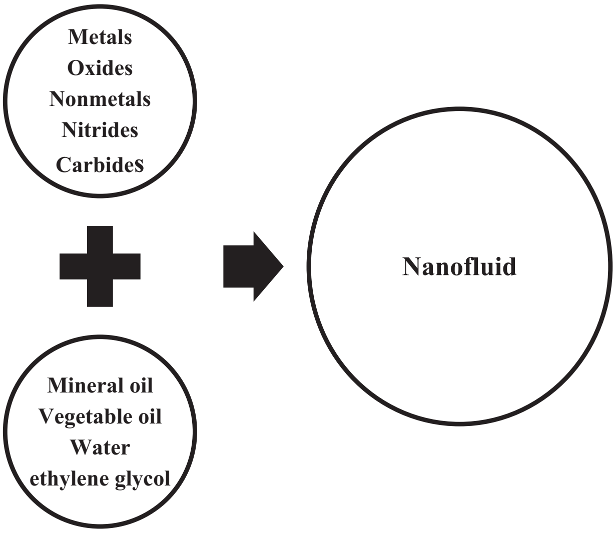


Fig. 1. Schematic diagram of NF development.

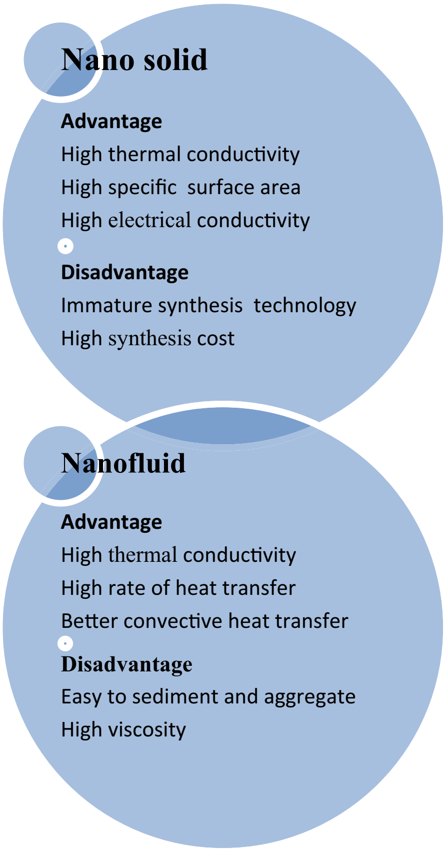


Fig. 2. Advantages and disadvantages associated with NPs and NFs.

3. Preparation of NFs

The development of NFs comes up merely applying novel techniques in particular single step and two step approach. Nevertheless, several additional methods are likewise exploited for producing NFs. Stability and quality NF are developed employing these schemes and NFs so formulated for intended heat transfer and experimental objectives.

3.1. Nps types and their synthesis techniques

NPs may be categorized into various types according to size, morphology, physical and chemical features. Several among them are carbon-based NPs, ceramic NPs, metal NPs, semiconductor NPs, polymer NPs and lipid-based NPs.

3.1.1. Carbon-based NPs

Carbon-based NPs comprise two major materials; carbon nanotubes (CNTs) and fullerene. CNTs might be categorized into single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs). CNTs are distinctive in a sense as they are thermally conductive along length and non-conductive across tube. Fullerene is allotropes of carbon possessing an arrangement of hollow cage of sixty or more carbon atoms. The configuration of C-60 resembles a hollow football. These have viable applications because of their electrical conductivity, arrangement, extraordinary strength and electron affinity.

3.1.2. Ceramic NPs

Ceramic NPs are inorganic solid developed from oxides, carbides, carbonates and phosphates. These NPs possess high heat resistance and chemical internes.

3.1.3. Metal NPs

Metal NPs are developed from metal precursors. These NPs may be prepared by chemical, electrochemical, or photochemical techniques.

3.1.4. Semiconductor NPs

Semiconductor NPs possess characteristics similar to metals and non-metal. These NPs possess wide bandgaps, which on tuning indicates dissimilar features. Some instances of semiconductor NPs include GaN, GaP, ZnO, ZnS, CdS, CdTe, silicon and germanium.

3.1.5. Polymer NPs

Polymer NPs are organic based NPs. They possess configuration shaped like nanocapsular or nanosphere depending upon the technique of synthesis. A nanosphere particle has matrix-like arrangement although the nanocapsuar particle has core–shell structure.

3.1.6. Lipid-based NPs

Lipid NPs are usually of spherical shape possessing diameter in the range of 10 to 100 nm. It comprises of a solid core developed of lipid and a matrix consisting of soluble lipophilic molecules. The outer core of these NPs is stabilized by the use of surfactants and emulsifiers.

Generally, NFs are fluids developed with various NPs mentioned above (particulates lesser than 100 nm) and base fluids. Multiple types of NPs for examples metals (Ag, Au, Ag), oxide ceramics (TiO_2, Al_2O_3, Fe_3O_4, CuO), carbon nanotubes, carbide ceramics (TiC, SiC) and several liquids e.g., mineral oil (MO) and vegetable oil (VO)**.** The assortment of NPs which are feasible for enhancement cooling and insulating performance of TO is extremely thought-provoking. In general, NPs are elected by observing their basic traits for instance permittivity and conductivity. Various kinds of NPs have been analyzed with the objective to augment thermal and dielectric traits of conventional liquid dielectric [59,60].

During previous decades, huge research has been conducted on the synthesis of NPs with various size and morphology. It is also evident from the research that physical and chemical attributes of NPs have a significant impact on thermal and dielectric characteristics of base fluid. Nevertheless, it is hard for a single NP to cope with mounting performance demands by the NFs developed with NPs as liquid insulation in HV equipment. These conventional NFs prepared by these single NPs type have tendency to high dielectric loss, which expedites the ageing of NFs and hence restricts their applications in HV equipment. During recent years, the core/shell structured NPs were developed and subsequently dispersed to develop NFs [61–66]. Core-shell structure NPs indicate huge prospective for formulating NFs, due to their exclusive features, for example extraordinary thermal conductivity, huge surface area and superior dielectric traits.

3.2. Different base fluids

For effective operation of base fluid in heat transferal applications, it is necessary to comprise of high thermal conductivity and lower viscosity. Heat transfer liquids are found in important applications such as electric transformers and in multiple other electric power equipment. During previous decades, the researchers have put huge efforts to enhance heat transfer features of base fluids by applying passive and active techniques [67,68] but these procedures have approached their bottleneck. Lately, investigators directed their efforts toward improving thermophysical traits of base liquids by suspending nano-sized particulates in these base liquids. The stability of NFs is also additional vital parameter which is accountable to acquire better heat transfer outcomes. Stability of NF is openly linked with its electro-kinetic traits and consequently pH control enhances the stability of a NF due to strong repulsive forces.

From a manufacturing perspective, NFs are lately passing through R & D stage. NFs are required to accomplish the mentioned functions with dynamic conduct in the aforementioned applications. Nevertheless, applications sectors are inadequate to a smaller amount of applications [69,70]. Multiple NPs types demonstrated to be good materials concerning their features which predominantly comprises of chemical stability, physically robust, and high thermal conductivity. All these qualities resulted in manufacturing of innovative NFs with various types of NPs with different type, shape, size, and concentration. Different NPs types, base fluids and surfactants applied to develop TO-based NFs are shown in Fig. 3.

3.3. Types of NFs

NFs, which is a word used to designate fluids comprising distributed elements of nanoscale, may be developed from NPs of single element (Cu, Ag and Fe), single element oxide (Cuo, Al_2O_3, TiO_2), alloys (Fe-Ni, Ag-Cu, Cu-Zn), multi-element oxides ($CuZnFe_4O_4$, $ZnFe_2O_4$), metal carbides (SiC, ZrC), metal nitrides (TiN, SiN, AlN), and carbon materials (graphite, carbon nanotubes, diamonds) suspended into base fluid (oil, ethanol etc.). They may also be categorized into major classifications: single-material and hybrid NFs.

3.3.1. Single material NFs

This type of NF was suggested by Choi in 1995 and is deliberated as traditional system of NFs, where a single category of NPs is applied to develop the suspension via various formulations techniques. It was stated by numerous investigators that NFs of this

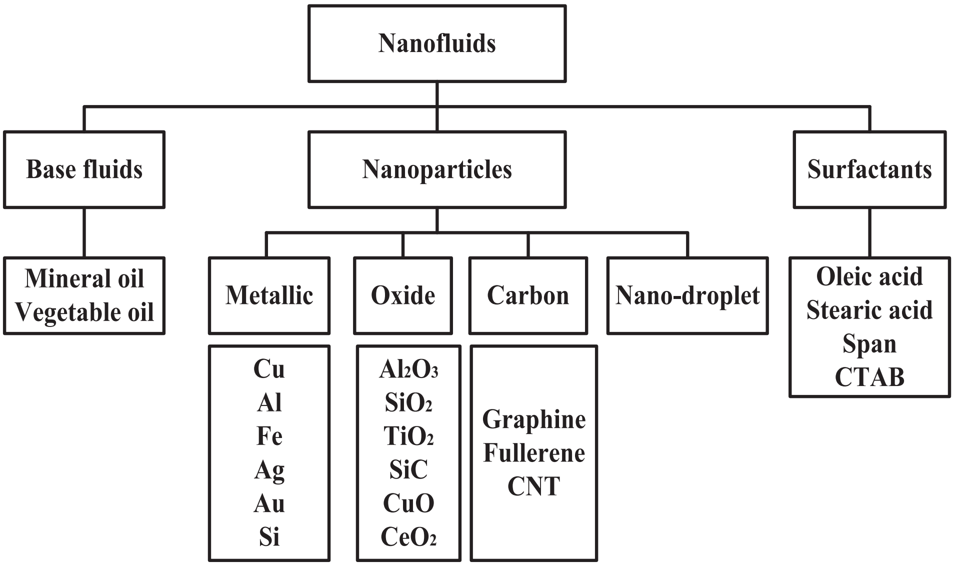


Fig. 3. NPs types, base liquids and surfactants used to develop TO-based NFs.

classification are superior conduct, because of much more suitable thermo physical features than their base fluid.

3.3.2. Hybrid NFs

Hybrid NFs are cutting-edge class of NFs which are developed by a mixture of more than one kind of NPs scattered in a base liquid. This class of NFs was initially investigated by Jana et al. in 2007 as a means to improve the thermal conductivity of a fluid beyond that of a customary single material category of NF.

3.4. Synthesis techniques of NFs

Generally, single step and double step schemes are utilized to formulate the NFs. In single-phase process comprised of simultaneously developing and scattering of particulates in fluid. In this process, operations of drying, storing, conveyance and dispersion of NPs are abstained, that is why the aggregation of NPs is curtailed and stability of fluids is augmented [71]. Eastman et al. [72] formulated single-step physical vapor condensation technique to develop NFs. There are numerous single-step methodologies for example physical vapor deposition (PVD) and liquid chemical technique. The fundamental single-phase scheme take account of one step direct evaporation technique proposed in Ref. [73]. The single phase systems can develop homogeneously distributed NPs and particles may be stably suspended in the base liquid. This process has the gains with regards to governing the size of NPs, diminishing the agglomeration of NPs and developing NFs including metallic NPs. This method cannot prepare NFs at huge scale, and cost is also large. Another major drawback associated with single-phase process is that it is quite challenging to develop NFs with higher volume loadings of NPs**.**

Two-phase process is commonly utilized for synthesis of NFs by stirring the NPs into base liquids. Typically, two phases are implicated in this technique. The NPs are accessible commercially and produced by applying physical, chemical and mechanical practices such as crushing, grinding, sol–gel etc. in first step. Subsequently, the developed dry NPs are scattered in base liquids by employing ultrasonication, magnetic mixing and high shear stirring in the second phase. During this step, some activities, for example, inclusion of dispersant or sonication, are usually implemented to improve the stability of derived NFs (Fig. 4**).**

Two-step technique is a cost-effective process to develop NFs on huge scale, because production of NPs methods has previously been extended to industrial fabrication scales. Due to great surface activity and surface area, NPs tend to aggregate. The surfactants may be applied to augment the stability of NPs in fluids. Nevertheless, the effectiveness of surfactants under huge temperature is similarly a giant challenge, specifically for elevated-temperature applications. The key shortcoming related with two-step system is that developed NFs are instable due to high surface energy of NPs [74]. Moreover, actions of desiccation, storage and conveyance of NPs were unavoidable in this approach. Nevertheless, the major gain associated with two-step scheme is its capacity to develop NFs on massive scale [75,76].

3.5. Dispersion techniques

It is extreme compulsory that NPs have been homogeneously scattered in base fluid to develop stable NFs. Different surfactants are applied for better dispersion of NPs. Surfactants supports in enhancing homogenous distribution of NPs into base liquid and hence the stability of NFs. Addition of dispersants or surfactants is an efficient and inexpensive technique to augment the stability of NFs. It has been noted huge sedimentation in NFs without surfactants. The existence of surfactants forms certain bond between NPs and base liquid. Surfactant molecules shield the NPs surface and eventually decrease the aggregation. In this way, surfactants execute stabilization of NFs [77]. Numerous techniques including ultrasonic bath, ultrasonic disrupter, stirrer and high pressure homogenizer are generally applied for improved distribution of NPs. In recent years, an adapted magnetron sputtering approach was applied in which sputtered NPs were intended to synthesis directly [78].

Furthermore, novel techniques comprise of synthesis of specific kind of NFs employing surface modification [79], and acid treatment [80]. These approaches were applied for enhanced compatibility of NPs with the base liquids.

4. Thermal, electrical and physicochemical properties

It is highly essential to know the facts about dielectric and thermophysical features of a thermal system working with NFs to gauge its conduct. These properties are extremely associated with

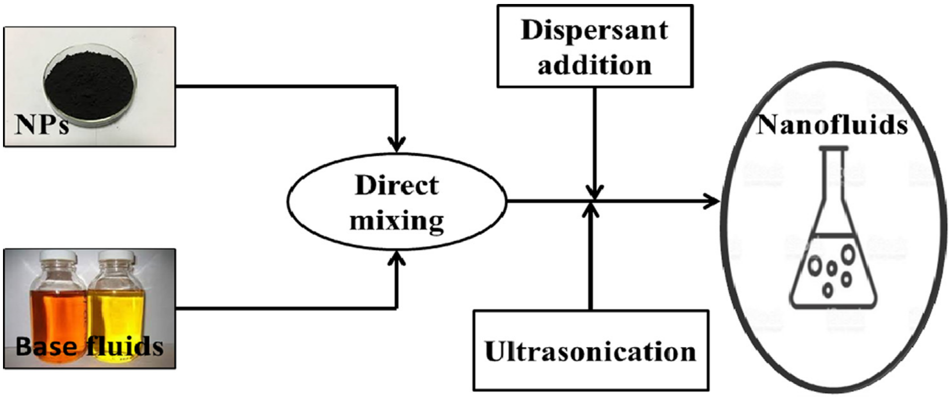


Fig. 4. Two-step method for preparation of NFs.

the amount of NPs scattered into base liquid. Overlooking thermophysical features of NFs either systematically or experimentally, it is supposed that NPs were homogeneously suspended into base liquids. Choi [81] prepared NFs for heat exchange in early 1990 s, which subsequently indicated perfect substitute of traditional TO with remarkable thermal conductivity qualities.

There are numerous features of these NFs mainly take account of thermal conductivity, density, specific heat and viscosity. Nevertheless, pressure drop and heat transfer coefficient are likewise additional significant traits to be deliberated. Thermal features generally be governed by several physical features such as size, shape, concentration and surfactant of NPs. Thermal conductivity of a liquid is directly associated with heat transfer capacity of liquid however viscosity relates to pressure drop, flowing affluence and pumping power that implicates during conveyance of NPs in fluid medium [82]. Thermal conductivity of NFs varies with physical parameters of NPs (type, size, shape, concentration). Viscosity of NFs depends on physical constraints of NPs but is also affected by ionic strength of base liquid, pH value of solution, Vander Walls and repulsive forces of NPs [83]. Addition of surfactants in NFs must be organized as its excess could cause adverse influence on its viscosity, stability and thermal features. However, NPs may tend to agglomerate in the fluid and result in growth in diameter of NPs, which increases total viscosity of NFs overall [84]. Various factors such as base liquid, working temperature etc., are required to be taken into account while analyzing thermophysical features of NFs. The Graphic illustrations of general outline of thermophysical and electrical features of NFs are given in Fig. 5.

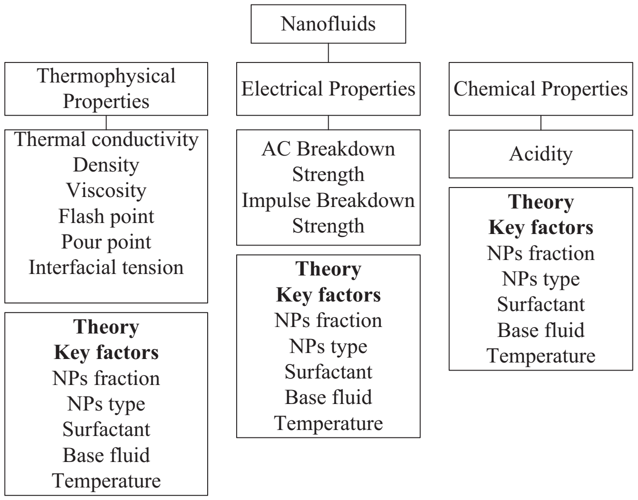


Fig. 5. Graphic illustrations of general outline of thermophysical and electrical features of NFs.

Physical and thermal traits of liquid insulation are very significant as it performs binary of its tasks of insulation and cooling effectively. The subsequent portion will provide general description of physical and thermal of transformer liquid insulation.

4.1. Viscosity

The viscosity of oil is a degree of resistance to shear rate if the oil. It is also recognized as resistance of flow or continuous flow circulation. Meanwhile the cooling of transformer is associated with viscosity of insulating fluid, the assessment of viscosity is critical to evaluate nature of liquid insulation. As a result of oxidation in fluid insulation, the degradation course initiates causing an increase in viscosity.

Viscosity is also identified as resistance to flow. A larger viscosity designates great resistance to flow, however a small viscosity indicates a little resistance to flow. Viscosity of liquid insulation impacts capacity to transference heat by conduction. The primary heat exclusion phenomenon in HV equipment is cooling by conduction and larger viscosity would lead to greater hot spot temperature inside the HV apparatus. The investigational findings have revealed that viscosity of NFs developed with Cu NPs drops by enhancing temperature and surges with rise in concentration of NPs but it is always greater than the base liquid [85].

4.1.1. Factors influencing viscosity of NFs

The analysis findings have revealed that viscosity of NFs be influenced by multiple constraints for instance temperature, shear rate, loading of NPs, synthesis method, shape and size of NPs. The experimental investigation of various parameters affecting viscosity is concisely presented.

4.1.1.1. Concentrations of NPs. The viscosity of NF varies with the changes of NPs concentration. The investigations [86,87] have revealed that NP rise in concentration leads to growth in viscosity of NFs. Fontes et al. [88] developed NFs with MWCNT NPs suspended in TO with various concentrations. The outcomes indicate that viscosity of NFs rises extensively with increase in NPs loading. The prepared NF presented a 25% rise in its viscosity at optimal concentration as compared to base oil. Jin et al. [89] developed NFs with various loadings of Silica NPs and concluded that viscosity of developed NFs was almost same as for base MO.

Ilyas et al. [83] revealed an enhancement in dynamic viscosity with an increase in NPs concentration, but the effect was concluded to be negligible at high shear rates. It was discovered that with enhanced concentration of NPs improved dynamic viscosity up to 18% at 25 °C. Taha-Tijerina et al. [84] studied the effect of boron nitride (h-BN) NPs concentration on viscosity of NFs. It was witnessed that there was insignificant effect on viscosity up to concentration of 0.05 wt%, however the affect was noticed at higher NPs filling of 0.35 wt% (<30%). In the same way, Qing et al. [85] found an enhancement in viscosity of hybrid NFs with NPs loading (0.01 to 0.04 wt%) but reduced at higher concentrations due to self-lubricating features.

4.1.1.2. Influence of temperature. The viscosity of NFs is affected by variations in temperature. The investigational findings by various investigators have determined that viscosity strongly influenced by temperature and it generally reduces with rise in temperature [86–88]. Taha-Tijerina et al [84] witnessed a decline in viscosity of developed NFs with rise in temperature from room temperature to 100 °C. Ilyas et al. [83] found a reduction in dynamic viscosity of MO-based NFs developed with Alumina NPs with a rise in temperature because of abating of intermolecular forces of attraction among molecules. They stated that variation in viscosity at various shear rates for a temperature range from 20 °C to 90 °C is insignificant. Amiri et al. [90] studied the viscosity of pure TO and NF as function of temperature is shown in Fig. 6.

4.1.1.3. Effect of type, size and shape of NPs. The viscosity of NFs is affected by the physical traits (type, size, shape) of scattered NPs. The experimental findings presented by investigators [89,91] have reported that viscosity enhances by decreasing the size of NPs. The shapes of NPs also influence the viscosity of NFs as shown in Fig. 7.

4.1.1.4. Surface modification of NPs. The viscosity of NFs is affected by surface modification of NPs. The excess amount of surfactant has an adverse influence on viscosity, thermal features and chemical stability and therefore it is advised to carefully monitor amount of surfactant applied on NPs [93].

4.1.1.5. Dispersion techniques of NPs. The viscosity of NFs is also influenced by dispersion techniques of NPs. Different dispersion procedures have diverse effect on viscosity of NFs [94]. In addition, multiple supplementary dynamics for instance sonication time might also affect the viscosity of NFs.

The suspension of NPs in TO might augment viscosity but reduces with increasing temperature. The viscosity of NFs enhances with NPs concentration due to development of clusters that are bonded by attractive forces, hindering the flow of NFs [95]. It implies extra energy to resolve the intrinsic resistance of NF. Nevertheless, high temperature decreases the viscosity of NF owing to rise in average velocity of Brownian motion of NPs [96]. Additional energy is required to weaken the bonds of molecules, reducing internal resistance of NF. Smaller viscosity of NFs is suitable since it allows easy flow of fluid. The schematic illustration for the key mechanisms on the viscosity of NFs is given in Fig. 8.

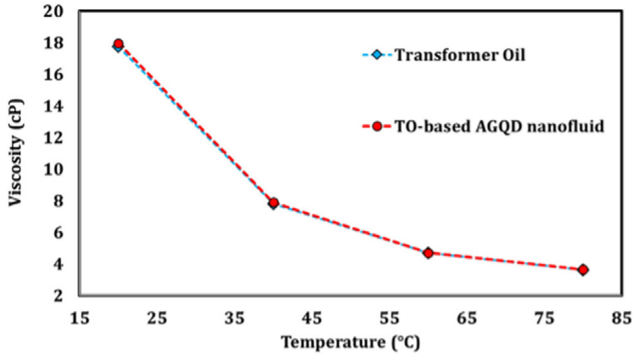


Fig. 6. Impact of temperature on viscosity of TO and NF [90].

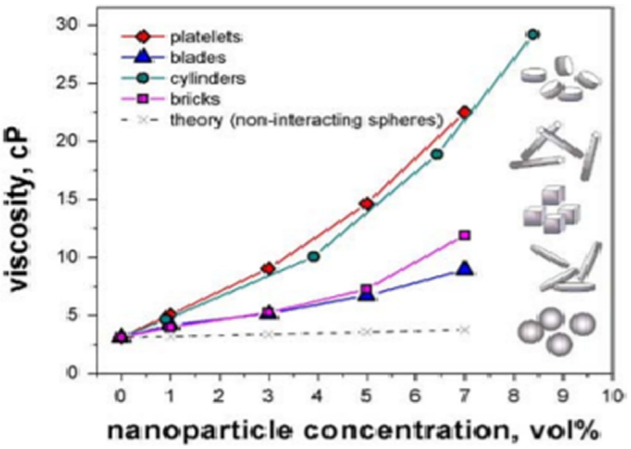


Fig. 7. Viscosity of alumina NFs as a function of concentration and shapes of NPs [92].

4.2. Density

Density is one of the most significant factors that changes with temperature. Only a few investigations have been stated regarding the density of fluid with respect to NPs concentration and temperature. For example, Ilyas et al. [83] projected the density of TO-based NFs added with alumina NPs by applying a theoretical model suggested by Pak and Cho [97]. The findings were found adjacent to experimental outcomes at smaller NPs concentrations. It was noticed that density showed an enhancement with suspension of NPs and reduced with temperature rise. Amiri et al. [90] concluded that the density of TO-based NFs prepared with amine-based grapheme quantum dots (AGQD) declines as temperature rises due to thermal expansion of oil as shown in Fig. 9. More research work is needed to evaluate the influence of size, type and concentration of NPs on density of NFs.

The density of NFs is influenced by NPs concentration and temperature. Density rises with enhancing NPs concentration and reduces with elevated temperature. The increase in temperature

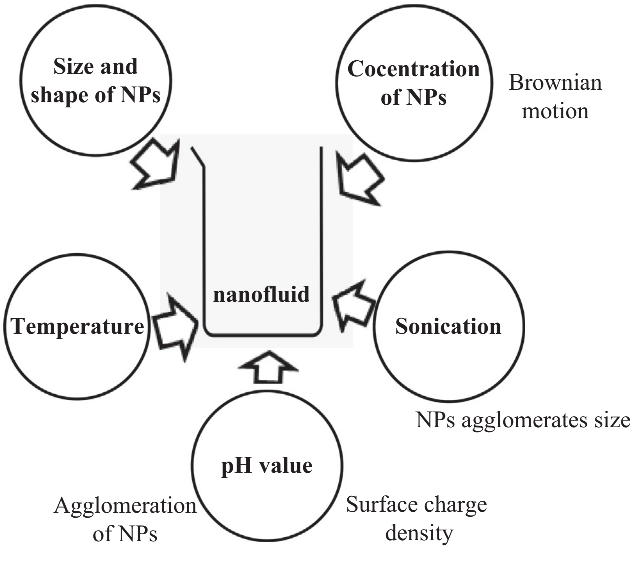


Fig. 8. Schematic illustrations for the key mechanisms on the viscosity of NFs.

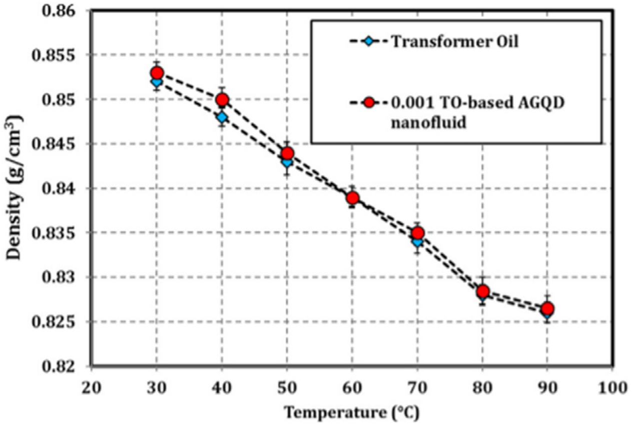


Fig. 9. Density of TO-based AGQD NF and pure oil [90].

leads to expansion of liquid volume and hence causes its density to diminish. It must be noted that suspension of NPs into TO affects heat transfer traits. Nevertheless, this benefit might be due to rise in density since it is reliant on buoyancy driven natural convection. More research studies are required to examine the influence of NPs suspension on density of NFs.

4.3. Thermal conductivity

Thermal conductivity is the quality of a material to conduct heat. It is a critical constraint to evaluate the heat transfer conduct of a liquid insulation. A large value of thermal conductivity of liquid insulation is considered as good cooling liquid for high voltage equipment. Liquid insulation with higher thermal conductivity absorbs further heat within HV equipment, which reduces the heat loss and enhances the performance of system.

In power transformers, dielectric liquid insulation performs the function of not only insulation but also in heat dispersal. The intrinsic heat origin of oil-filled transformer is generally produced by core and winding losses and these losses are turned into heat leading to rise in temperature of the oil [98]. The temperature rise in the intrinsic portion of transformer expedites the aging process of insulating materials and curtailed the functional lifetime of transformer. The enhanced insulation and heat transfer conduct are favorable for downsizing of HV transformers.

Thermal conductivity is one of the significant factors in enhancing heat transfer of base liquid. It is thus recommended for a fluid to have higher thermal conductivity. Thermal conductivity and more particularly heat transfer traits of materials are believed fundamental factors in determining liquid insulation of transformer. Various methods are utilized to enhance thermal conductivity and heat transfer conduct of this liquid insulation. One such novel method to augment thermal conductivity of oil insulation is suspension of NPs into oil with the aim to improve heat transfer conduct in transformer. Numerous investigators presented research analysis on thermal conductivity of NFs. A good heat transfer liquid is desired to possess great thermal conductivity and low viscosity. Thermal conductivity of typical MO is small; hence there are high probabilities of thermally motivated downfall of transformer from momentary overloading. It is therefore, imperative to search for means to improve the thermal conductivity of MO to accomplish prolongation lifespan of transformer, enhancement in cooling and loading proficiency. An ideal TO must hold high thermal conductivity to disperse heat, smaller viscosity to expedite flow continually and exceptional insulating traits. Evidently, the correct choice is to scatter NPs into oil to remove heat away by raising its thermal conductivity. The improved thermal conductivity of NFs provides multiple advantages for instance greater cooling rates, reduced pumping power, reduced size cooling system, and enhanced wear resistance. Similar substantial advantages of NFs have motivated investigators globally to focus on heat transfer traits of aforementioned fluids for pragmatic applications. Thermal conductivity of NFs increases by enhancing mass fraction of NPs [99]. Thermal conductivity was also improved by addition of silica NPs [100] and alumina NPs [101].

4.3.1. Factors influencing thermal conductivity

The experimental analysis has revealed that thermal conductivity of NFs be determined by multiple dynamics for example NPs type, NPs loadings, NPs size, NPs shape, base liquid and temperature. The nature and quantity of additive is also found to be significant in enhancing thermal conductivity. In the subsequent portion, experimental findings related with thermal conductivity of TO-based NFs are presented.

4.3.1.1. Volume/mass fraction of NPs. The effect of NPs concentration on thermal conductivity of base oil has been reported in various analyses in literature. Li et al. [102] studied thermal conductivity of Kerosene based NFs with various mass fraction of Cu NPs. The results revealed an improvement in thermal conductivity of NFs with rise in mass fraction of NPs.

Singh et al. [99] examined thermal conductivity mineral oil (Transol) based NFs suspended with Al_2O_3 NPs. NFs were prepared with 20 nm diameter NPs with various volume concentrations. The maximum improvement in thermal conductivity was noted 4%. Fontes et al. [81] determined thermal conductivity of NFs prepared with diamond NPs and multi-walled carbon nanotubes (MWCNT) suspended into TO. The NFs were prepared with various NPs concentrations by using two-step process. The maximum improvement was 27% for MWCNT and 23% for diamond NPs. This enhancement was greater than the estimates delivered by effective medium model employing equation suggested by Maxwell [103].

Zeng et al. [104] concluded that NFs have higher thermal conductivity and this increase is not only with rise in mass fraction of NPs, but also with temperature rise. Jin et al. [89] examined thermal conductivity of TO-based NFs prepared with silica and fullerene NPs. The diameter of SiO_2 NPs was 10–20 nm and for fullerene was 1 nm. The volume concentration was 0.01 and 0.1% and temperature range was 10∘C~80∘C. With this concentration range, an insignificant influence was noted. Likely description of these findings is that NPs concentration was too trivial to cause any impact on oil. Hwang et al. [105] studied thermal conductivity improvements of NFs developed with MWCNT and fullerene NPs as a function of NPs concentration. Shukla et al. [106] investigated thermal conductivity of NFs developed by AlN and nanodiamond NPs with different concentrations of NPs. Ilyas et al. [91] examined thermal conductivity of NFs with rise in temperature and NPs concentrations. They found maximum enhancement in thermal conductivity of 16% at 3 wt NPs concentration. Alicia et al. [107] observed thermal conductivity rise of 29% with graphene loading range from 0.01 to 0.1 wt% at 60 °C. It is more likely that with higher NPs concentration, thermal conductivity will also enhance as there will be more probabilities of particles collisions enhances. Nevertheless, NPs loadings must be monitored as it could undermine other traits, particularly stability and dielectric features. Choi et al. [99] studied the impact of volume fraction of NPs on thermal conductivity of various developed NF is shown in Fig. 10**.**

4.3.1.2. Nps type. The type of NPs is also a significant factor that might impact the thermal conductivity of base fluid. Because every NP possesses different thermal conductivity so their influence on thermal conductivity of NFs will be different with various kinds of NPs. Although research suggests that NPs type might cause

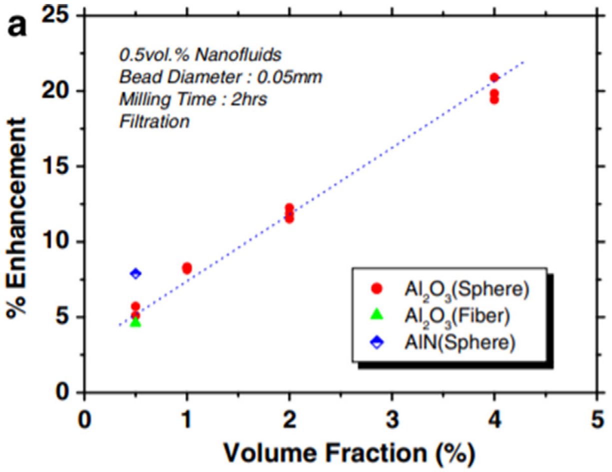


Fig. 10. Thermal conductivity as a function of volume fraction for NP-oil suspensions [99].

change in thermal conductivity of NFs by further means. Chen et al. [92] explored thermal conductivity of oil-based NFs loaded with MWCNT NPs. The findings manifested an improvement of 160%. The author revealed that this huge increase is caused by attributes of NPs. Chiesa et al. [10] described thermodynamics of various types of NPs in TO by evaluating thermal conductivity and medium effective model as shown in Fig. 11. Du et al. [108] and Du and Li [109] expounded the substantial augmentation in thermal features of TO with a suspension of BN and Fe_3O_4 NPs as a result of ballistic phonon transport and slight effect of Brownian motion with BN being excellent in thermal traits. Yao et al. [110] concluded thermal conductivity of developed vegetable oil-based NFs was improved by 14% with small volume concentration. The existence of electric field was beneficial for heat transfer nano-oil-based h-BN fillers. Such enhancements in thermal and insulating properties are advantageous for miniaturization of HV transformers.

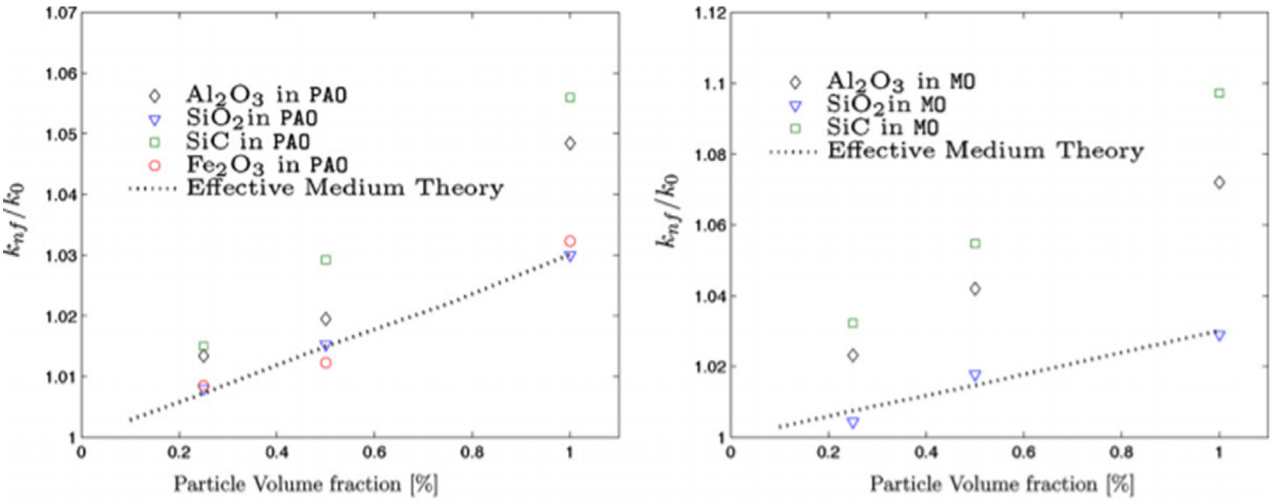
4.3.1.3. Mass of surfactant. The type and amount of surfactant for NPs is also a significant factor that might affect the thermal conductivity of base fluid. Because the amount and type of surfactant holds different features so their influence on thermal conductivity of NFs will also be dissimilar. Choi et al. [99] examined thermal conductivity of NFs prepared with different shaped NPs (Al_2O_3, AlN). They stated an enhancement in thermal conductivity together with additional thermal traits and its degradation with abundance of surfactant.

4.3.1.4. Base fluid. The viscosity of base liquids impacts Brownian motion of NPs and in turn affects thermal conductivity of NFs [98]. In addition, Gobin et al. [111] examined influence of electric double layer developed in the vicinity of NPs on thermal conductivity of NF and determined that thermal conductivity and electric double layer rely on base liquid. Accordingly, influence of vegetable oil (VO) on thermal conductivity as base liquid might be distinct than the MO as base liquid. It is difficult to identify the influence numerically; hence additional research is imperative that may examine the influence of base liquid on thermal conductivity of NF. Alicia et al. [107] studied thermal conductivity of NFs developed with graphene NPs. A decline in thermal conductivity was seen at 40 °C because of traits of naphthenic TO [112].

Amiri et al. [104] concluded that the density of TO-based NFs prepared with amine-based grapheme quantum dots (AGQD) declines as temperature rises due to thermal expansion of oil.

4.3.1.5. Temperature. Generally, thermal conductivity of NFs is additional temperature in relation to base liquid. Consequently, thermal conductivity enhancement of NFs is also temperature reliant. Amiri et al. [104] studied the impact of temperature on thermal conductivity as shown in Fig. 12. Patel et al. [113] explored thermal conductivity of NFs with different types of NPs (Al, Cu, Cuo, Al_2O_3) and sizes. Thermal conductivity was investigated at temperature range 20–50 °C. Thermal conductivity improvement for Al_2O_3 NFs was 3–17% and Al, Cu and CuO NFs was 3.5–24%, 5–38% and 5–26% respectively.

Xuan et al. [114] explored thermal conductivity oil-based NFs developed with Cu NPs. The temperature range was 20 to 60 °C. An improvement of 45% in thermal conductivity was noted for prepared NFs. Taha-Tijerina et al. [92] prepared oil-based NFs with h-BN and examined improved thermal conductivity as temperature rises from 20 °C to 50 °C. A maximum enhancement of thermal conductivity of almost 77% was noted at loading of 0.1 wt%. Bhunia et al. [115] studied thermal conductivity of NFs with boron nitride nanosheets with temperature. A 45% increment of thermal



(a) PAO based nanofluids (b) Mineral Oil based nanofluids

Fig. 11. Thermal conductivity improvements as a function particle volume concentration [10].

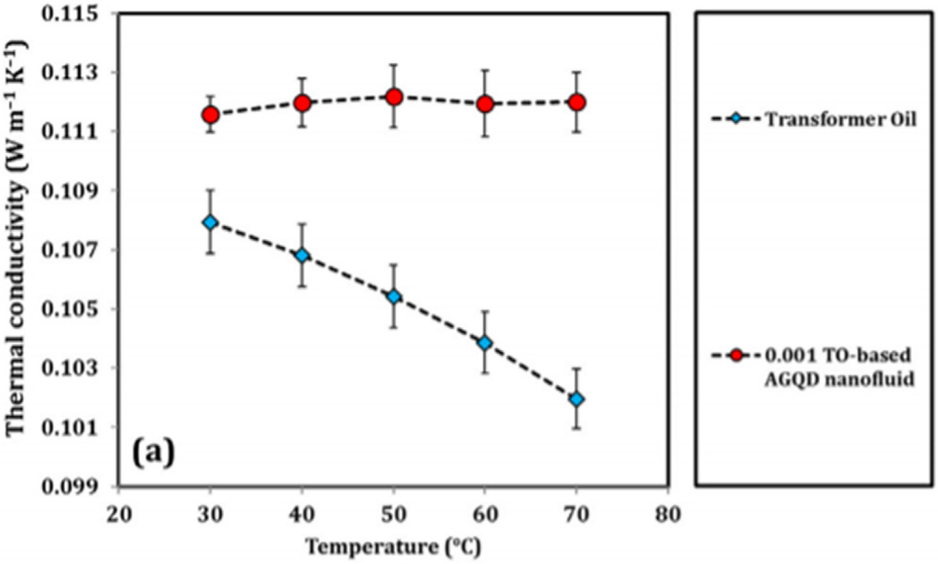


Fig. 12. Thermal conductivity of pure TO and TO-based NF [104].

conductivity was stated at 0.05 wt% concentration of nanosheets. Jafrimoghaddam [116] studied thermal conductivity of TO-based-NFs developed with Ag-WO_3 NPs with temperature rise. They noted an improvement of 41% in thermal conductivity of NFs with 4 wt% WO_3 NPs at 100 °C temperature. Beheshti et al. [113] studied thermal conductivities of TO and NFs at different temperatures. Decline of thermal conductivity associated with TO is evident and this might be seen in Fig. 13.

Researchers noticed a rise in thermal conductivity with elevation in temperature as a result of increase of Brownian motion. With temperature rise, NPs take up more kinetic energy triggering more particulates collisions. Particle collisions degree rise with temperature elevation because of Brownian motion.

4.3.1.6. Shape and size of NPs. NPs size is a vital parameter which impact thermal conductivity of NFs. Thermal conductivity augment by reducing size of NPs. This type of conduct is influenced by (i) liquid layer development around NP and (ii) Brownian motion of NPs. With larger size of NPs, Brownian motion of NPs decreases as a result of which heat transfer rate between NP and base liquid diminishes which successively decreases thermal conductivity. Various investigators [117,118] examined the influence of size on thermal conductivity. Various shapes of NPs have diverse contact area with base liquid; they will possess distinct liquid layer development and therefore diverse thermal conductivity. Cylindrical shape NP revealed a rise in thermal conductivity as compared to sphere NP as aspect ratio of cylindrical NP is bigger and consequently there is extra contact area between NP and base liquid. Improvement in thermal conductivity for cylindrical NPs is resulted by a mesh developed by extended particle that directs heat across the liquid [119]. The impact of shape of NPs on thermal conductivity of NFs is shown **in** Fig. 14. The fundamental mechanisms for the impact different elements on thermal conductivity of NFs are indicated in Fig. 15**.**

4.4. Pour point

The pour point is specified as temperature of fluid at which it transformed into semi-solid and absolves its flow features. This implies that it is the lowermost temperature at which fluid remain

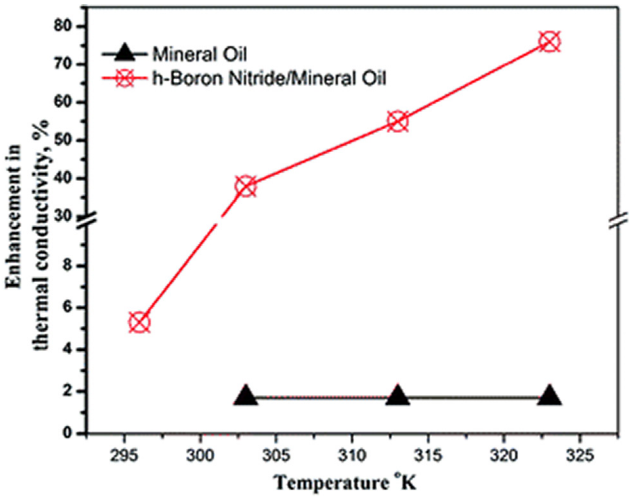


Fig. 13. The impact of temperature on thermal conductivity of NFs [113].

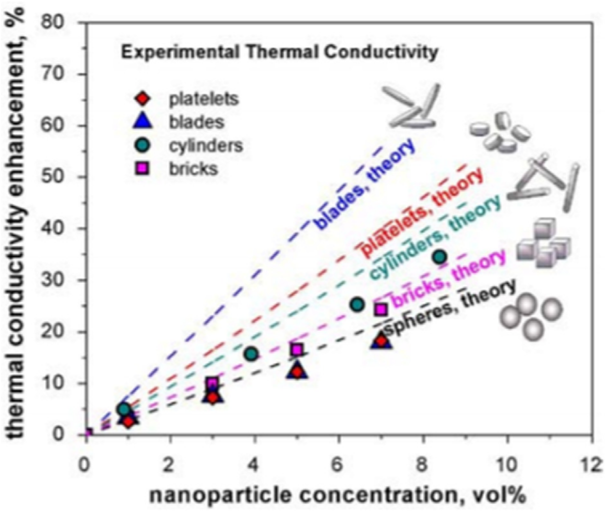


Fig. 14. Thermal conductivity of alumina NFs with various shapes of NPs [98].

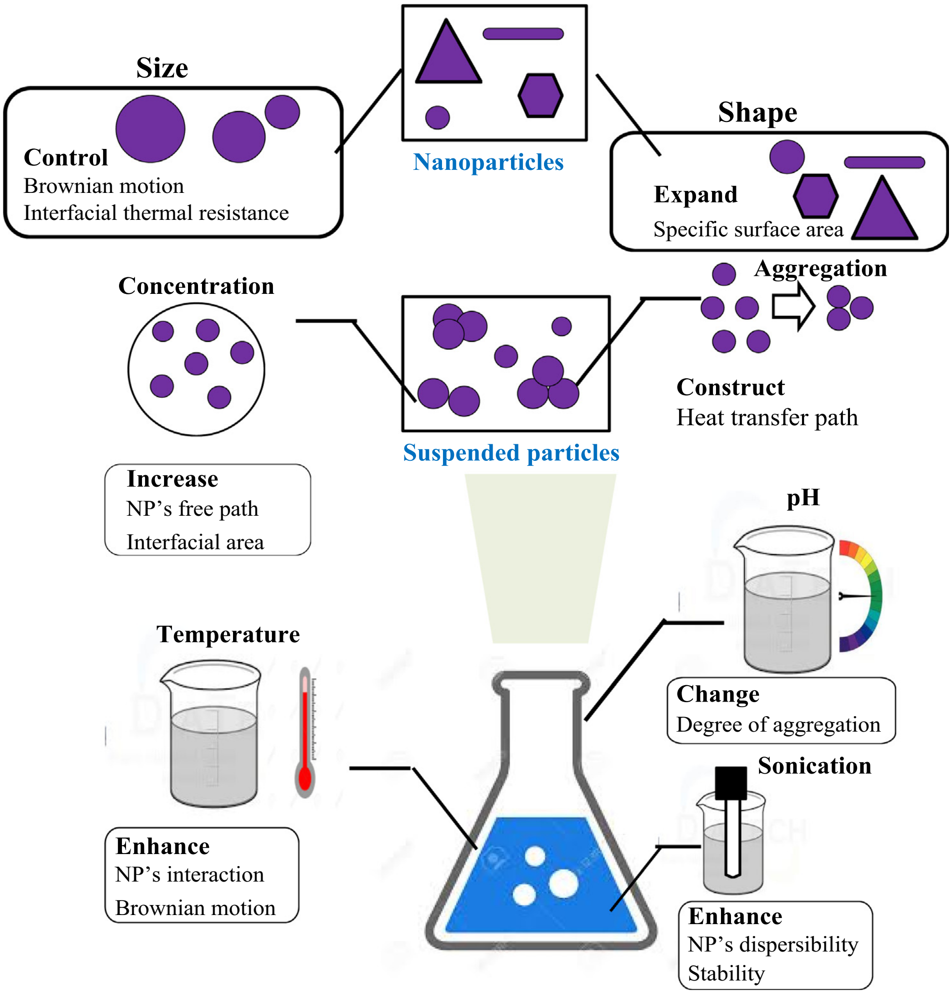


Fig. 15. The fundamental mechanisms for the impact different elements on thermal conductivity of NFs.

flow able (meaning it performs as fluid). It is also primary parameter to characterize liquid insulation for HV equipment. Beheshti et al. [120] classified several samples with pour point smaller than −45 °C.

4.5. Flash point and flame point

The flammability of fluid is a severe safety-related issue in recent years. Numerous events have been reported regarding transformer explosion which is difficult to quench and which might lead to nearby environment due to oil leakages. Flash point is smallest temperature at which liquid surface discharge adequate vapors to develop a flammable mixture in the atmosphere. A minimum flash point is prescribed to obstruct hazard of fire that may be outcome of contingent burst. The flash point might be generally higher than 140 °C. The flashpoint of NFs is usually determined using ASTM D93 [121]. Sumathi et al. [122] developed NF with various NPs (TiO_2, Al_2O_3, MoS_2) and measured flash point and concluded that flashpoint of prepared NFs was higher as compared to base TO.

The fire/flame point is temperature at which vapors constantly blaze post ignition. It is the smallest temperature at which, on further heating above flash point, the sample would maintain a fire for five seconds. Consequently, as the fluid is adequately heated, it initiates to ignite. Flash point is regarded as one of the quality signs to identify the probabilities of fire risks. Beheshti et al. [120] evaluated the flash point with reference to loading of NPs. The flash point of NF manifested an improvement of 4.6% at NP loading (0.001 mass fraction %), although flash point declines with additional rise in NPs loadings as shown in Fig. 16.

Sumathi et al. [122] determined fire point of developed samples and found that fire point of developed NFs was higher as compared to base oil. Karthic et al. [14] evaluated vital factors of developed NFs. The changes in concentration of NPs in TO indicated

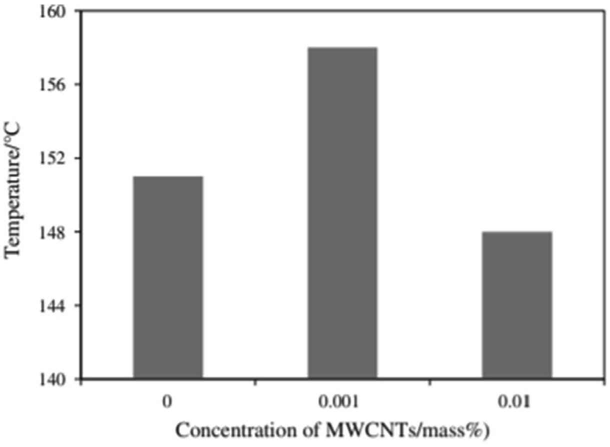


Fig. 16. Flash points of pure oil and NFs [119].

enhancement in viscosity, fire point and flash point. The key elements of TO can be enhanced by selecting optimal size and loading of NPs. Amiri et al. [104] studied the flash points of pure TO and TO-based AGQD NF are shown in Fig. 17.

4.6. Interfacial tension (IFT)

IFT is vale of molecular attractive force among oil and water molecules at their interfacial level. It is likely to evaluate the soluble polar impurities existing in oil that decreases the molecular attraction force between oil and water. The value of IFT indicates the quality of oil. A high value of IFT manifests lesser polar contaminants in oil and therefore certifies enhanced quality and conduct of oil. The lower value of IFT leads to decline in integrity of TO, which originates development of oxides and peroxides in insulating oil during service. The pure TO should have a minimum value 18 dyn/cm and maximum 40 dyn/cm. The IFT of TO is generally evaluated by ASTM D971 standard [77]. It can be measured by equipment named tensiometer. IFT is found by the difference of the interactions among the molecules of one liquid with molecules of another liquid. So, well scattered NPs improves IFT as compared to TO, as the capillary forces between particles oppose any deformation on interface [123] The experimental findings of Ref. [122] indicated that TO-based NFs developed with TiO_2 and Al_2O_3 NPs have higher IFT as compared to base TO whereas TO-based NF prepared with MoS_2 NPs presented lower IFT as compared to base TO. Maharana [124] observed the ageing process and performed the experiment in the existence of oxygen. The IFT of TO-based NFs prepared with exfoliated hexagonal boron nitride (Eh-BN) and TiO_2 NPs was far higher to the base TO. A continuing rise in oxidative ageing period causes a decline in IFT for both base TO and NFs, however in all cases, NFs offered superior IFT in comparison with TO (Fig. 18). Niharika Baruah et al. [125] determined the IFT of NFs with Eh-BN NPs using different base oils. They concluded that IFT of Vegetable oil (VO) based NFs was lower as compared to mineral oil (MO) based NFs. This is due to molecular structure of VO that constitutes of unsaturated fatty acid chains and moisture content in oil.

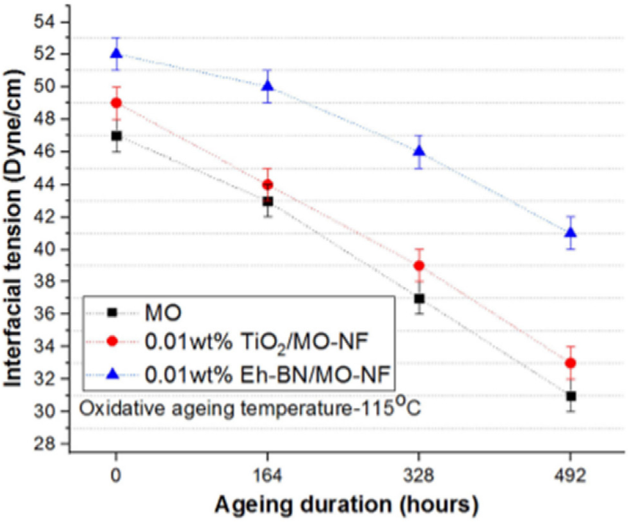


Fig. 18. Interfacial tension versus ageing duration [124].

4.7. Acid number

Acidity is a degree of organic and inorganic acids existed in oil and is quantified in terms of milligrams of potassium hydroxide (KOH) needed to counteract the total free acids in 1 g of oil. The acidity of TO is generally determined by utilizing ASTM D974 standard [126]. Acids in the TO emanates from oil decay/ oxidation derivatives. These acids can also proceed from outer sources in particular from atmospheric pollutants. These organic acids deteriorate the insulation structure and can generate corrosion within transformer in the presence of moisture. Ideally in pure TO, there must be no acid content. Nevertheless, practically in most circumstances, there would be certain acid content. S. Sumathi et al. [122] compared the acidity between developed NFs and base TO. The prepared NFs with Al_2O_3, TiO_2 and MoS_2 NPs has smaller acid content as compared to base TO, hence there will be less hazard of erosion taking place in transformer. Acidity is higher with the rise in ageing time. M. Maharana et al. [124] measured acid number for developed NFs and compared with TO for duration of 492 h. The prepared NFs with Eh-BN and TiO_2 NPs were lower than the base TO for all ageing period (Fig. 19).

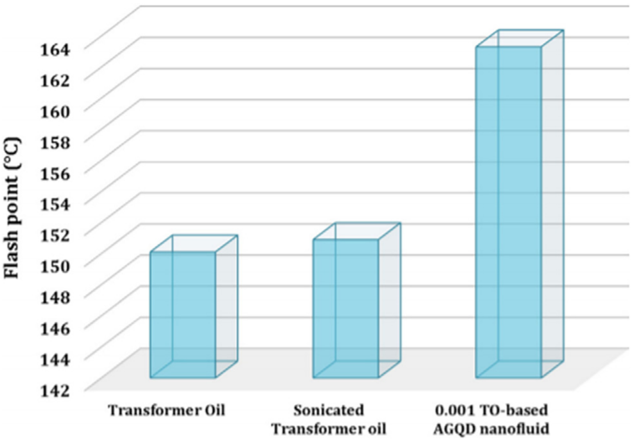


Fig. 17. Flash points of TO-based AGDQ NF and pure transformer oil [104].

4.8. Dielectric strength (DS)/Breakdown voltage (BDV)

The dielectric strength is one of the most important parameters that specifies the insulation oil conduct in transformer and is a degree of its capability to endure electrical stress without collapse, pressure, temperature, humidity and electrode configuration. HV equipment such as transformers copes with high voltage and current. The TO not only required to disperse heat however to endure or insulate electric field to secure safe operations. The TO with high DS will not only ensure secure operation, but also reduce weight

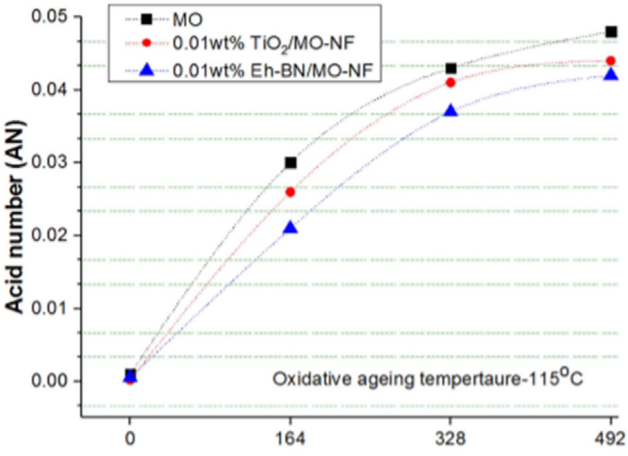


Fig. 19. Acid number versus ageing duration [124].

and vlume of the equipment. The DS of TO is desired to be high. Contamination, moisture, bubbles, particulates and acidity are significant elements which influence the DS of oil.

For every liquid insulation, it is essential to be capable to endure power frequency AC voltage in addition to undesirable lightning and switching stresses arise during function of power system. Recently prepared nano based liquid insulation indicates remarkable improved DS as compared to base TO. The degree of improvement evaluated with numerous voltage magnitude and waveform (e.g. AC, DC or impulse) as well as NPs.

AC BDS is the most vital precondition for implementation of liquid insulation in transformers. It might be identified as the value of AC voltage at which disruptive discharge appears in liquid insulation. AC BDS is influenced by contaminations, for example small particulates, humidity, and gas or air bubbles. As a result, assessed AC BDV is typically designates quality of liquid instead of its attributes itself. The LI BDV is stimulating lightning strokes that generally have 1.2 μs upsurge for a wave to approach 90% of amplitude and decline to 50% amplitude after 50 μs. The LI BDV generally examined by IEC 60897. LI BDS is affected by several factors of NPs for instance type, shape and concentration of NPs. The enhancement in AC and LI BDS of firstly prepared NFs was investigated [54,55]. Some other studies also investigated AC, DC and LI BDS [121,122]. Sartoratto et al. [127] demonstrated AC BDS of TO-based NFs with magnetic NPs with different surfactants. Hwang et al. [57,58] and O'Sullivan [68] described the enhanced conduct of TO-based NFs by modeling a correlation among streamer propagation and relaxation time of NPs. Herchl et al. [128] explained the BD distribution function by employing mathematical approaches over magnetic NFs. Das and Chiesa [10] used NPs with smaller relation time and found improvement in BDS of developed NPs. Kudelcik et al. [129] examined DC BDS of prepared magnetic NFs with various concentrations of NPs. The semiconductive (TiO_2) based NFs presented superior AC and LI BDS results as compared to TO [130,131].

A comparative investigation indicates that surface modified TiO_2 NPs addition in TO can endure higher voltage even in the presence of moisture as compared to untreated TiO_2 based TO [132,133]. The suspension of NPs into vegetable oil enhanced AC and LI BDS as compared to base oil [134]. The vegetable oil-based NFs prepared with Fe_2O_3 NPs enhance BDS of 20% higher in comparison to base liquid [135] whereas the ester based NFs prepared with TiO_2 NPs enhance to 30% [136]. Du et al. [137] used shallow trap model to designate the improvement in BDS of TO-based NFs prepared with semiconductive NPs. Rafiq et al. [138–156] also explored AC and LI BDS of developed NFs with various NPs. The authors used different types, shapes, surface modifications and concentrations of NPs to investigate their impact on BDS of TO.

Given et al. [157] presented a comparative investigation to observe the impact of magnetic NPs on BDS of various base oils. Another study [158] explored the influence of TiO_2 NPs on BDS. The results indicated an improvement in AC, LI BDS of developed NFs as compared to base TO. Lv et al. [159] investigated the impact of loading of NPs (Al_2O_3, SiO_2) on BDS of TO. The author concluded that declination in BDS at higher concentration is attributed to agglomeration of NPs. Mansour et al. [160] explained the adverse influence of surfactant of NPs on BDS of TO.

Lee et al. [161] concluded the enhancement in BDV at optimum quantity of surfactant and manifested a decline in BDV beyond this optimum value. In another study, Lee et al. [162] found BDS of developed NFs double as in comparison to base TO. Li et al. [163] examined AC and LI BDV of manufactured NFs. Hanai et al. [164] studied AC BDS enhancement of prepared NFs with TiO_2 and ZnO NPs. Dehkordi et al. [165] explored the BDS of NFs with bas TO under different temperature [166].

Atiya et al. [167] indicated 27% improvement in BDS of TO with the suspension of TiO_2 NPs. Du et al. [109] found an improvement in BDV with BN NPs whereas a less improvement with the suspension of magnetic NPs in TO. Cavallini et al. [168] investigated AC and DC BDS of NFs developed with magnetic, silica, and graphene oxide under uniform and divergent field and concluded superior BDS as compared to TO. The DS of TO tend to decrease with the suspension of MWCNT and nano-diamond in oil [88], whereas in Ref. [106], a minor enhancement in BDS of oil with addition of nano-diamond has also been noticed. Sima et al. [169] and Wang et al. [138] demonstrated the LI BDS of TO with suspension of conductive, dielectric and semiconductive NPs. Li et al. [170] found the improvement BDV of vegetable oil with various sizes and surfactant thickness of Fe_3O_4 NPs.

Researchers witnessed that suspension of NPs have tendency to improve BDV of TO. The NPs behaved as scattering obstacles and trap sites in the way of charge carriers, hindering the electrons mobility. Size of NPs plays a vital role in improving the BDV of TO [171]. Smaller size of NPs certifies a higher density of NPs in NFs than NPs with larger size for similar concentration. This leads to rise in NPs population to apprehend free electrons from streamers at greater rate, causing a higher BDS [172]. In addition, type of NPs affects BDV of NFs. for example, NFs prepared with Fe_3O_4 NPs manifests higher BDV because of smaller time relaxation [22]. Nevertheless, raising the volume concentration would diminish the BDV due to agglomeration [173]. The outline of electrical traits findings accessible in field of TO- based NFs are indicated in Table 1**.**

5. Challenges related with NFs

Numerous stimulating features of NFs have previously reported in multiple studies. In prior analysis, thermal conductivity has attracted huge consideration, and recently multiple studies have also diverted their emphasis on other heat transfer traits of NFs. The use of NFs has shown huge potential in several applications however the expansion of the field is slowed down by multiple factors such as i) poor stability of suspensions ii) deficiency of agreement of findings acquired by various investigators iii) lack of hypothetical understanding of improvement mechanisms of characteristics. Consequently, this analysis attempted to conclude various significant subjects which must be resolved through appropriate attention in future. Numerous issues, for example thermal conductivity, particulate movement, Brownian motion of particles and thermo-physical feature modification with temperature, should be cautiously measured with convective heat transfer in NFs. However, most of the convective investigations have been accomplished with oxide NPs, which enhanced the viscosity and pumping power of fluid, it will be exciting to investigate NFs scattered with metallic NPs, since thermal conductivity of pure metallic NPs is approximately 100 times higher as compared to oxide NPs. Forthcoming convective investigations must be focused on metallic NPs with various shapes and loadings to deliberate heat transfer improvement. The application of NFs has manifested improvement in heat transfer conduct but some of latest explorations also showed aggregation of particles. More research work is needed in these fields to recognize the details of these mentioned issues. The applied investigation in the field of NFs which will outline their prospect as heat transfer fluids is projected to develop at a rapid pace in forthcoming [179].

5.1. Stability issue of NFs

Development of NFs with uniform suspension is the prevalent challenge since NPs generally develop aggregate because of Van

Table 1
Outline of findings (AC, DC, LI BDS measurement) by several investigators in field of transformer oil-based NFs for liquid insulation of transformer.

NPs Type	Ref.	Base oil	Particle size	Surfactant	Comments
TiO_2	[174]	TO	20	–	The amplification in BDS was designated by shallow trap model.
	[175]	MO	<20	–	AC, DC, LI BDS and PD traits were explored of prepared NFs.
	[130]	TO	<20	OA	The influence of aging on AC and LI BDS was studied.
	[167]	MO	<100	CTAB	The surface modification of NPs was studied.
	[176]	MO	100	–	Relative permittivity and dielectric constant of NFs was witnessed.
Fe_3O_4	[55]	MO	10	–	AC, DC, LI BDS, PD, Resistivity traits are explored.
	[129]	TO	10.6	OA	DC BDS under the influence of magnetic field is explored.
	[157]	MO, Synthetic ester oil, THESO	10	OA	LI and DC BDS explored.
	[177]	MO	10	OA	BDS enhancement explained with electron scavenger theory.
	[133]	MO	10.2	OA	BDS was inspected with electric & magnetic field orientation.
	[127]	MO	7.4	OA, dodecanoic, decanoic acids	BDS with suspension of NPs described.
	[177]	VO	30	OA	The influence of surface modifications on BDS was studied.
	[135]	Natural ester oil	30	OA	The influence of kind of NPs on BDS was inspected.
	[10]	MO, PAO	<100	span	Influence of several NPs on BDS was explored.
	[128]	MO	8.5	OA	BDS, PD and Dielectric loss & features was investigated.
	[108]	TO	20	–	BDS and thermal properties of NFs were studied.
	[169]	TO	10	OA	BDS of NFs with conductive NPs with charge accumulation postulate was explored.
	[57]	VO	13.4	OA	The influence of surface modification on BDS was discovered.
Al_2O_3	[137]	MO	<50	–	Positive and negative LI BDS traits are explored.
	[10]	MO	<80	span	BDS of various NPs was investigated.
	[173]	TO	23, 80, 100	OA	AC BDS was determined with numerous moisture levels.
SiO_2	[18,78,89]	MO	15	Silane coupling agent (z6011)	AC BDS of NFs was found with different moisture levels.
	[98]	Synthetic oil	15	Benzalkolium chloride	Dielectric features of NFs
ZnO	[173]	TO	40, 80	OA	The effect of loadings, size and shape on BDS was explored.
SiC	[10]	MO, PAO	<80	span	Relative investigation of several NPs on BDS was studied.
AlN	[178]	MO	40	OA	The influence of loadings of NPs on BDS and PD were explored.

der Waal forces. Several physical and chemical techniques have been applied for example adding of surfactant and use different surface modification for NPs.

For practical application of NFs, one of the primary necessities is usually long-term stability of NPs dispersion. Thermal conductivity of NFs has direct correlation with its stability as a stable NF presents improvement in thermal conductivity [180,181]. Choi et al. [99] examined that extreme amount of surfactant has adverse influence on stability, thermal features and viscosity therefore it is highly suggested to administer the count of surfactant. They also concluded that surfactant may possibly initiate chemical/physical instability issues.

5.2. Pressure drop and pumping power

For an effective NFs application, the pressure drop originated through the flow of fluid is also one of the significant factors. Pumping power and pressure drop are narrowly related with each other. Some of the features which might affect the NFs as coolant pressure drop include its viscosity and density. It is anticipated that NF with greater viscosity and density experience greater pressure drop. This has added to the shortcomings of NFs use as coolant fluids.

5.3. Thermal performance of NFs

In addition to thermal conductivity, convective heat transfer conduct of NFs has also attained huge focus from various investigators. In most of the studies, the application of NFs has significantly enhanced this feature of NFs. However, turbulent flow has been noticed as issue that must be looked into prudently to attain better thermal conduct of NFs during their application. Presently, discrepancy in findings has been stated by various scientists.

5.4. Higher development price of NFs

Greater development price of NPs is one of reasons that may impede their practical and commercial applications. NFs are generally developed by either single-phase or two-phase techniques. Nevertheless, both these methodologies involve cutting-edge, expensive, and sophisticated apparatus to prepare NFs.

5.5. New research subject

NFs are of huge academic attention because these latest thermal transport phenomenon outclass the fundamental constraints of traditional macroscopically concepts of suspensions. As a consequence, the NFs have evolved as a new subject of research and novel applications.

5.6. Awareness of capabilities

NFs have been endorsed as an encouraging choice for several engineering applications, because of stated improvement of thermophysical features and enhancement in affectivity of thermal phenomenon. Numerous studies have been observed in recent years, in order to evaluate thermo-fluidic conduct of NFs. However, still more research is needed to create awareness of NFs capabilities among researchers in academia and industry.

5.7. Growing market

NFs are anticipated to be future-generation of heat transfer liquids due to their extraordinary thermal features and improved heat transfer levels as compared to customary cooling liquids. Now days, research for a fluid with improved thermal and insulating features is essential for optimization of components and apparatus design with enhanced efficiency in the NF market. There is huge interest in NFs activity investigation and potential market for NFs heat transfer applications which is in billions dollars/year globally, with projections of additional evolution in coming years.

5.8. Enhanced heat transfer

NFs are being deliberated as impending heat transfer fluids in multiple heat transfer applications. They are expected to provide superior thermal performance as compared to traditional fluids due to existence of scattered NPs which possess extraordinary thermal conductivity. The developments in heat transfer levels are novel opportunity marked by advancements in nanoscience.

5.9. Future industrial trials

Nowadays, it has become evolving development to test the prepared NFs in real-time applications to see their impact of working environment on the performance and efficiency of NFs. In light of improved performance of NF, long-term advantages are required to be endorsed, and impact of NPs on remaining system elements to be prudently assessed for practical applications.

5.10. Environmentally friendly working fluids

There is a developing trend for development of NFs employing nontoxic, eco-friendly and reliable procedures to multiply their applications. Recently, there is huge concern to develop NPs which are environmentally friendly, have greater heat transfer possibilities, low cost and mass fabrication.

5.11. Other related problems in the manufacturing process

Conventionally, NFs were developed by either a single-step process in which NPs are produced and scattered simultaneously into base liquid, or a two-step technique that includes forming NPs and consequently suspending them into host liquid. During both these techniques, NPs are intrinsically developed from methods that implicate decline reactions or ion exchange. Moreover, base liquids comprise of other ions and reaction products which are challenging to detach from liquids. Additional issue related to the development of NFs is the inclination of NPs to agglomerate and transform into bigger particulates, which confines the advantages of high surface area NPs. Several dispersion additives are usually included into base liquid with NPs. However, this approach might alter the surface of NPs and developed NFs possibly will comprise of undesirable levels of contaminations. Majority of investigations up to now are generally restricted to a sample size of not more than a few hundred millimeters of NFs. This is also issue because huge samples are required to test multiple features related to NFs and, especially to evaluate their prospective usage in practical applications [181]. Up till now, the information that NFs have more arguments in favor of them than against, for application as a cooling liquid, has developed as an undoubted outlook. This demands more resolute research on NFs. Contrary to the conventional unilateral methodology, this requires to analyze thoroughly a multiplicity of concerns, for example preparation, characterization, thermophysical traits, heat and mass transport, modeling along with commercial applications. Hence, a multidisciplinary methodology including investigators such as chemists, thermal engineers, material expert, and physicists required to be initiated. Simply such a method might pledge a “coolant future” with NFs [182]. The revealed challenges of To-based NFs are summarized in Fig. 20.

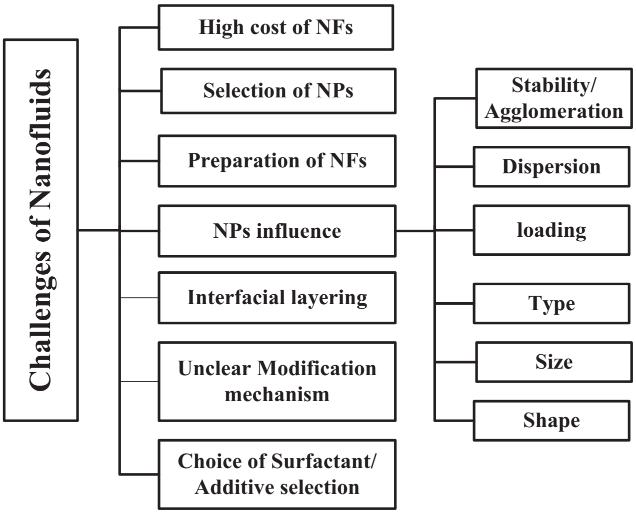


Fig. 20. General challenges of NFs development.

6. Threats associated with NFs

6.1. Health and safety concerns

The safety concerns of NPs are not widely known however their potential for hazard is obvious because of large surface area to volume ratio, which turn them very catalyst or reactive. Moreover, they have the ability to penetrate through skin and might interact with biological organisms. Health and safety risks of NPs incorporate possible toxicity of several varieties of nanomaterials together with flame and dust outbreak threats. Since nanotechnology is a latest trend, the health and safety impacts of exposures to NPs and what degrees of expositions might be permissible, are matters of existing research [183].

6.2. High price

The ready to use NFs are expensive as compared to conventional heat transfer liquids. Higher cost of NFs is one of the causes that might obstruct the industrial applications of NFs. NFs are generally developed by single-step or two-step process. Nevertheless, both these approaches need sophisticated and innovative apparatus. High cost of NFs is amongst the significant hindrance of NFs applications [184,185].

6.3. Toxicity

One of the critical threats that must be considered in hereafter, prior the enormous formation of NPs, is their toxicity to human and implications on surroundings. There is huge discussion concerning novel features of NPs might result in detrimental ecological impacts, with likelihood to induce toxicity [186].

6.4. Large scale production

NFs are generally developed by dispersing NPs into base fluid. High surface to volume ratio of NPs offers high surface energy. To mitigate this energy the NPs start to agglomerate. This agglomeration affects the thermal performance of NFs. Therefore, NFs are potentially impractical for large scale production [187].

6.5. Recognize real and practical application

Most of the NFs research is still in experimental phase so it is highly required to look for real and practical application fields for

NFs. The real applicability can only be checked by applying the NFs in the real-time environment and with actual working parameters. In the light of encouraging results of NFs, the long-term advantages on thermal conduct required to be endorsed, and the influence of NPs on actual system constituents requires to be wisely assessed prior their practical implementation.

7. Strengths of NFs

7.1. Higher heat transfer coefficients

The TO-based NFs manifested greater heat transfer coefficients in comparison to base fluid. The findings indicate that thermal conductivity of NPs plays a vital role in heat transfer improvement of heat exchangers as NPs generally higher thermal conductivity which helps to augment the thermal conductivity of base liquids [188,189].

7.2. High heat transfer rate / high thermal conductivity

Customary heat transfer liquids, for instance mineral oil and vegetable oil, present inadequate heat transfer capabilities. Therefore, multiple investigators tried to improve the heat transfer convection of these liquids through enhancing their thermal conductivity [31,190].

7.3. Wide area of applications

The primary driving force for NFs research lies in a large variety of applications. NFs are basically used to due to superior thermal traits as coolant in heat transfer apparatus such as heat exchangers, radiators and electronic cooling system.

7.4. Expected impact in industry of NFs

NFs may be believed as prospective heat transfer liquids in several heat transfer applications. They are intended to provide superior thermal conduct than customary fluids due to existence of suspended NPs which possess larger thermal conductivity. NFs will have enormous impact on contemporary industry where nanomaterials are used in countless applications and consequently the efficiency of any equipment to utmost opportunities [191].

7.5. Ability to reduce size and price of the equipment

The insulation and thermal features enhancement results in efficient operation of the equipment with fewer amounts of fluid requirements consequently facilitating decline size, weight and price of the equipment. Along with the breakdown strength, enhancement in thermal conductivity is useful for obtaining high ratings at educed size due to enhanced heat dispersal [99].

8. Weakness related with NFs

8.1. Low stability

One of the biggest issues related to NFs is their stability and it still remains a huge challenge to ensure required stability of NFs. Stability of NFs is largely significant in order to preserve their thermophysical traits after manufacturing for long certain amount of time. Accordingly, improving stability of NFs and insight understanding performance of NF are part of the succession required to commercialize such kind of innovative fluids.

8.2. Environmental concern not clear

The use of nanotechnology offers a serious vulnerability to environment as well. The NPs and their products could be emitted into the atmosphere and water in the course of their development or transportation. These NPs would accumulate in environs for instance plants, soil and water and might influence human health and environment through the different stages of their life progression. This impact is essential to be examined for imminent evolution by means of Life Cycle Assessment [192]. The likely hazard to the environments by NPs might be lessened by applying efficient means of development and shipping.

8.3. Safety and health issues

The use of NPs have been observed as one of the central Occupational Health and Safety risk (OHS) and authentic concerns have been publicized concerning their application in various global protocols [193]. The difficulty linked with NPs is still uncertain and research society is uninformed and lately their concentration is simply on their encouraging applications. The NPs are commonly more hazardous as compared to bulk materials because of their high reactivity of their surface region [194]. The contact of even little mass of NPs could source stern threats to health. For example, iron oxide possibly will originate anguish to human lungs [195,196]. The zinc, copper and chromium NPs might instigate lug dysfunction and even tumor. There are excessive likelihoods that some NPs can go into to the fundamental nervous organism and produce serious health problems [190]. Research findings indicate that ZnO NPs are enormously poisonous, alumina NPs are rationally lethal, and magnetites NPs are fairly deadly [197]. TiO_2 NPs are lethal and could travel to brain through fragrant neurons through inhale in [198,199].

The NPs might furthermore have the ability to intrude through the skin and go into blood tributary and concentrate in liver [200–202]. It is necessary for scholars to search for NPs which are less harmful to human health and also protection procedures must be guaranteed for workforces, investigators and experts during synthesis of NFs to obviate aforesaid adversities.

8.4. To improve the concept of “nanofluid” in the research community

The enhanced features brought about by NPs have resulted in suggestion that it’s could be an innovative category of fluids that research community has been searching for, as it would be a unique future potential liquid. It is a huge need of the time to enhance the concept of NFs in research community so they can put more efforts to enhance the properties of NFs.

8.5. Data inconsistent or unreliable

There are huge discrepancies in described data stated by various investigators regarding NFs. The exact mechanisms of improvement of NFs features are still unclear as presented by various researchers. Results presented by NFs are still inappropriate with the required data for practical applications.

8.6. Lack of “coordinated” capabilities

The research on NFs requires coordinated efforts to analyze numerous subjects for instance synthesis, characterization, properties, modeling in conjunction with marketable applications. Therefore, a coordinated approach including various researchers from various academic fields and background is critical to take full advantages of the potentials offered by NFs.

8.7. Stability at rest and under flow

The stability of NFs ate rest as are in experiments will be definitely different and challenging under flow in practical applications due to different working conditions. Therefore, more research work is needed to approximate this stability dissimilarity.

9. Merits of NFs

NFs may be deliberated as prospect of heat transfer liquids in multiple heat transfer applications. They are projected to supply superior thermal conduct as compared to traditional liquids due to existence of scattered NPs which possess higher thermal conductivity. Recently, there have been several studies which have shown the improvement of thermal conductivity and superior heat transfer degree of NFs. Substantial improvement in heat transfer level with the application of different NFs in several applications compared to customary fluids have been stated by numerous researchers. Knowledge the characteristics of NFs, for example thermal conductivity, viscosity and specific heat, are very vital for the use of NFs in different applications. Moreover, investigation of basics for heat transfer and friction dynamics in the case of NFs is deliberated to be very imperative in order to extend the applications of NFs [202–205]. The merits of TO-based NFs as compared to TO are outlined as follows:

(i) The NFs have presented superior insulating and cooling performance as compared to customary based liquid insulations.
(ii) The NFs have higher thermal conductivity as compared to base MO and it is useful to provide enhanced cooling performance of HV equipment.
(iii) The NPs have high surface area and consequently additional heat transfer surface between NPs and fluids.
(iv) NFs possess better dispersion stability with principal Brownian motion of particles.
(v) NFs manifest decreased pumping power as compared to base fluid to attain equivalent heat transfer intensification.
(vi) NFs presents particle clogging in comparison with customary slurries, hence stimulates system downsizing.
(vii) NFs offer adaptable behaviors, including thermal conductivity and surface wet ability, by altering NPs loadings to serve various applications.

During recent years, solvent free synthesis of organic composites has acquired enormous prominence. Many significant compounds may be synthesized in an effective and environmentally friendly mode. Solvent free synthesis possesses multiple benefits over conventional synthesis techniques. Few key advantages includes, such as nontoxic reactions, reduction of perilous derivatives and energy resource requirement, convenient extraction and higher yields of biodegradable final product with a lesser sever reaction circumstances. As a result of these gains of solvent free reactions, innovative solvent-free methodologies are being revealed for eco-friendly of various compounds.

10. Shortcoming associated with NFs

The applications of NFs as substitute for liquid insulation for HV equipment deliver superior cooling and dielectric performance as compared to conventional base fluid however still there are few dynamics which are restraining their pragmatic applications. The implementation of NFs in industrialized applications call for lower cost, long-term stability, and consideration of the impact of nanomaterial on health and surroundings. Few of the shortcomings associated with the NFs are presented as follows:

(i) One of the prevalent shortcomings associated with the practical application of NFs is their poor stability. The agglomeration and sedimentation in NFs is mainly caused by gravity and the fact the density of NPs is greater than base fluids.
(ii) The larger processing cost of NFs is also one of the major causes that hinder their commercial and practical applications. The processing methods require expensive, contemporary equipment for development of NFs which transform them expensive substitute of customary fluids.
(iii) The application of surfactant to enhance stability of NFs lead to dropping of conductivity owing to development a thermal boundary layer around particles.
(iv) NPs are acknowledged as one of the leading occupational and safety risks (OHS) and thoughtful distresses are presented about them in several guidelines. The hazardousness level of NPs is still uncertain. Generally, NPs are considered hazardous because of their higher reactivity of surface area.
(v) The nanotechnology raises severe danger to environment. The NPs and their derivatives might be liberated into atmosphere during development, manufacturing and conveyance. These developed NFs might accumulate in soil, watercourse and plants and intrude into the lifecycle of humans and other inhabitants. The merits and shortcomings associated with NFs are outlined in the below Fig. 21**.**

11. Application of TO-based NFs

High voltage equipment requires fluids with outstanding cooling and insulating features. NFs are proposing superior insulation and cooling traits as compared to conventional fluid and these NFs are being recognized as prospect substitute cooling an insulation liquid for HV equipment. Furthermore, by applying NFs, the issue of size and weight of HV equipment might be condensed due to their exceptional dielectric and cooling abilities [206]. The transmission voltage capabilities might also be augmented by using NF as fluid insulation. The functioning reliability and lifespan of pre-existing equipment may be improved also collapses caused by insulation issue might be dwindled by using NFs as liquid insulation as an alternative conventional liquid insulation [8,9,207,208]. The suspension of conductive NPs in TO might decreases top-oil and hot spot temperature in TO by approximately 5 °C relative to base TO [209].

Choi et al. [99] utilized a prototype transformer to trial cooling influence of Al_2O_3/AlN-oil based NFs on heating component and the oil itself. The authors concluded that extra amount of surfactant has adverse influence on thermal conductivity, stability and viscosity. The use of oil-based NFs is on rise and this inclination is expected to remain in impending years due to huge research gap and less R & D efforts on this subject field. The dielectric and cooling features enhancement is the primary factor to enforce this technology in HV equipment particularly in transformers. Nevertheless, this technology may also be applied in various other applications with appropriate nano modifications. The stability of NFs for extended period still remains a topical issue for applying them in specified applications. Long term influence of NPs in base oil also requires to be further investigated.

12. Research gap and prospectus for future research

It is clear from the accessible literature that most of investigators approve on the causes of enhancement of thermal and dielectric performance of NFs, i.e. on the workings of the mechanisms

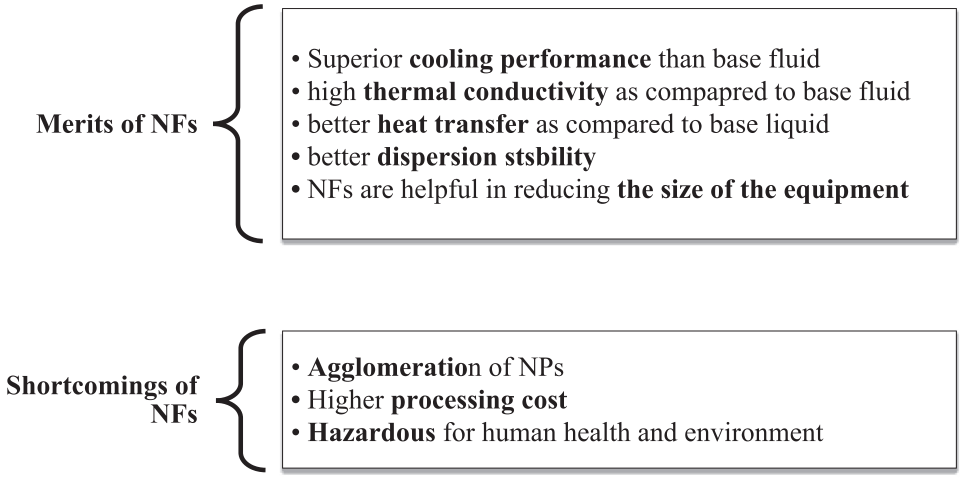


Fig. 21. Merits and shortcomings associated with NFs.

which renders NFs superior to their corresponding base fluids. From the literature analysis, it is obvious that concentration of NPs into base fluids depends on nature of base fluid itself, on the kind of NPs, on the surfactants and on the treatment, i.e. the process of synthesis of NFs. The outline of gains achieved by the application of NFs as an alternative of TO is given in Fig. 22.

Experimental outcomes appear to be very profound to all aforementioned constraints. Subsequently, further research need to be conducted in materials field with the purpose of understanding the performance of NFs and their impact on thermal and dielectric properties, predominantly in the light of certain inconsistent findings. The impact of NPs agglomerations requires more research studies. The function of surfactants has to be systematically investigated [135]. The long term stability of NFs also requires an urgent attention [210]. The previously stated enhancements of NFs-regarding their thermal and insulating conduct-mechanisms of improvement of NPs requires to be further explored in long run and observe whether experimental outcomes are repetitive.

An additional feature of NFs that need to be further examined is the compatibility of certain fluids with solid insulation. Moreover, NFs must be developed with vegetable derived fluids or synthetic esters, which are thought to present a “green performance”. One more aspect of NFs that requires attention is to observe the performance of NFs at higher temperature. Finally, and this is effective for all nanomaterials, research society has to understand how statistics and experiments may be transformed into greater samples of industrialized levels [191,211].

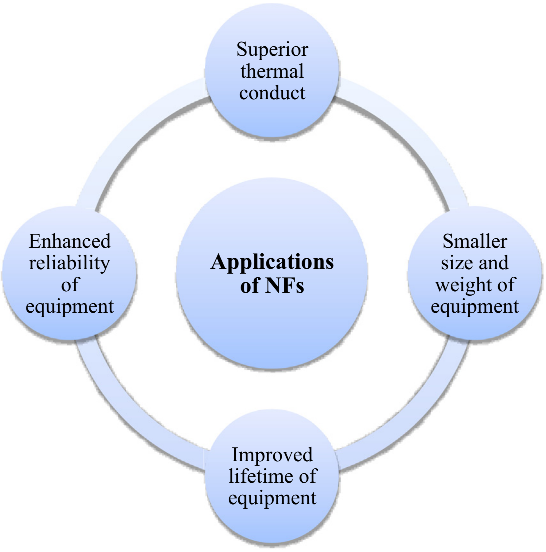


Fig. 22. Advantages of NFs applications as liquid insulation of HV equipment.

13. Conclusion

Nanotechnology as a succeeding generation medium makes it possible to deliver acute solution to acquire innovative insulation system possessing outstanding improved dielectric strength and heat transfer characteristics. The paper reviews the studies accessible in literature emphasizing on thermal characteristics improvement in TO among others with adequate NPs suspension. The statistics from several sources are evaluated and matched in order to recognize the influence of NPs on various parameters such as thermal conductivity, viscosity and density. A comprehensive tubular inventory of majority of the literatures on the field is conducted to benefit the readers.

The surfactant as an additive performs effective role on thermal conductivity improvement of NFs. Majority of researchers applied surfactant to develop stable NFs but the impact of surfactant concentration in improving thermal conductivity in many cases is not investigated. In this paper, it has been indicated that some research has been conducted on viscosity of oil-based NFs. Various investigators stated viscosity of various oil-based NFs with various types, sizes and concentration of NPs. With reference to heat transfer studies, the investigators applied various NPs in several base liquids with different sizes and concentrations of NPs. From the stated findings, it is evidently witnessed that NFs have enormous prospective for heat transfer improvement and are largely applicable for applications in pragmatic heat transfer proceedings. This suggests a prospect for investigators to prepare compact and efficient heat transfer apparatus. More research work in this subject is hence needed to recognize the complicated heat transfer properties of oil-based NFs.

The BDV and dielectric strength of NFs is not so far consistently reviewed. The factors like size, shape, concentration, surface modification of NPs, moisture content, electrode gap etc., require comprehensive investigation with suspension of NPs in various base oils. Nevertheless, the preparation of oil-based NFs is still obstructed by multiple parameters for instance scarcity of agreement amongst outcomes and poor characterization of suspensions. A comprehensive and in-depth research is needed in this field with the view of miniaturization of system applying NFs theory for heat transfer. Based on literatures, it has been concluded that enhanced thermal conductivities of NFs are one of motivating dynamics for enhanced conduct in various applications.

- It has been regarded that NFs might be deliberated as prospective applicant for numerous applications. It was also found through some literature the enhanced thermal, rheological and heat transfer conduct without relating these performances with particular applications.
- The heat transfer might be improved by usage of NFs, heat exchange devices can be manufactured more energy efficient and compact.
- It was also concluded that there are discrepancies in the conveyed findings published by several investigators. Some scholars stated the contradictions between model and experimental findings of thermal conductivity of NFs.
- Precise mechanism of improved heat transfer for NFs remains ambiguous as described by various investigators. Nevertheless, it must be observed that multiple challenges are required to be acknowledged and resolved for various applications.
- The stability and price of NFs are primary concerns that obstruct the commercial applications of NFs. After unraveling these issues, it is anticipated that NFs can mark considerable effect as coolant in hat exchange apparatus.

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