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Nanofluids Comprising Lyotropic Side-Chain Liquid Crystalline Poly(6-(4-Cyanobiphenyl-4’-Yloxy)Hexyl Acrylate) in Deep Eutectic Solvents for Enhanced Thermal Energy Storage

(Nanobendalir yang Terdiri daripada Poli(6-(4-Sianobifenil-4’-Iloksi)Heksil Akrilat) Kristal Cecair Rantai Sisi Liotropik dalam Pelarut Eutektik untuk Penyimpanan Tenaga Terma yang Dipertingkatkan)

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ABSTRACT

Nanofluids have attracted attention for thermal transfer and energy storage due to their superior thermophysical properties. Conventional fluids such as water, ethylene glycol, and mineral oil suffer from low thermal conductivity, high vapor pressure, corrosion, and limited thermal stability, highlighting the need for more efficient heat transfer fluids. This study reports a novel nanofluid composed of a side-chain liquid crystalline polymer (SCLCP), poly(6-(4-cyanobiphenyl-4’-yloxy) hexyl acrylate) (P6ACB), and choline chloride-based deep eutectic solvents (DESs) with urea, glycerol, or ethylene glycol as hydrogen bond donors (HBDs). P6ACB was dissolved in a DES/N-methyl-2-pyrrolidone (NMP) mixture (10:90) at 2 wt.% and 6 wt.%. Thermophysical properties, including viscosity, thermal conductivity, and specific heat capacity, were measured. Viscosity increased with polymer content but decreased with temperature, exhibiting Newtonian behaviour above 13 s^{-1}, even in the mesophase at 90 °C. Thermal conductivity increased with polymer fraction due to enhanced molecular alignment, which also improved heat capacity. NDES2- and NDES3-based nanofluids with NMP-DES mixture, incorporating glycerol and ethylene glycol respectively, showed high thermal conductivity and specific heat capacity, indicating potential for thermal energy storage (TES) applications. Maximum thermal conductivity enhancements of 17.35% (NDES2) and 16.07% (NDES3) were observed at 50 °C and 2 wt.% polymer. NDES2 exhibited higher specific heat at lower temperatures, while NDES3 showed greater increases at higher temperatures. The results demonstrated that the hybridization of molecularly organized liquid crystalline polymer with DESs offers promising potential as alternatives for TES systems.

Keywords: Deep eutectic solvent; nanofluid; side-chain liquid crystalline polymer; specific heat capacity; thermal conductivity

ABSTRAK

Nanobendalir telah menarik perhatian aplikasi pemindahan haba dan penyimpanan tenaga kerana sifat termofizikal yang unggul. Cecair konvensional seperti air, etilena glikol dan minyak mineral mempunyai kekonduksian haba yang rendah, tekanan wap yang tinggi, kakisan dan kestabilan haba yang terhad, yang meningkatkan keperluan untuk bendalir pemindahan haba yang lebih cekap. Kajian ini melaporkan nanobendalir baharu yang terdiri daripada polimer kristal cecair rantai sisi (SCLCP), poli(6-(4-sianobifenil-4’-iloksi) heksil akrilat) (P6ACB) dan cecair campuran eutektik (DES) berasaskan kolina klorida dengan urea, gliserol atau etilena glikol sebagai penderma ikatan hidrogen (HBD). P6ACB telah dilarutkan dalam campuran DES/N-metil-2-pirolidon (NMP) (10:90) pada 2bt.% dan 6bt.%. Sifat termofizik, termasuk kelikatan, kekonduksian haba dan muatan haba tentu, telah diukur. Kelikatan meningkat dengan kandungan polimer tetapi menurun dengan suhu, menunjukkan sifat Newtonian melebihi $13 s^{-1}$, walaupun dalam mesofasa pada 90 °C. Kekonduksian haba meningkat dengan peratusan polimer disebabkan oleh penjajaran molekul yang dipertingkatkan, yang turut meningkatkan kapasiti haba. Nanobendalir berasaskan NDES2 dan NDES3 dengan campuran NMP-DES, masing-masing menggabungkan gliserol dan etilena glikol, menunjukkan kekonduksian haba dan kapasiti haba tentu yang tinggi, menunjukkan potensi untuk aplikasi penyimpanan tenaga haba (TES). Peningkatan kekonduksian haba maksimum sebanyak 17.35% (NDES2) dan 16.07% (NDES3) diperhatikan pada suhu 50 °C dan peratusan berat 2bt.%. NDES2 menunjukkan kapasiti haba tentu yang lebih tinggi pada suhu yang lebih rendah, manakala NDES3 menunjukkan peningkatan yang lebih besar pada suhu yang lebih tinggi. Keputusan menunjukkan bahawa hibridisasi polimer kristal cecair yang tersusun secara molekul dengan DES berpotensi sebagai alternatif dalam sistem TES.

Kata kunci: Cecair campuran eutektik; kekonduksian haba; muatan haba tentu; nanobendalir; polimer kristal cecair rantai sisi

INTRODUCTION

Nanofluids, with dispersion of liquid at nanoscale in base fluids have attracted a lot of attention due to their high thermal conductivity and superior heat transfer capability (Peer et al. 2025; Utpol, Md. Shahriar Mohtasim & Das 2024). The increased surface area of nanostructured materials can enhance the heat transfer, and modify the flow properties, thus facilitate better convective heat transfer (Magendran et al. 2019). Today, nanofluids act as advanced heat transfer and storage media within thermal energy storage (TES) systems. TES technologies play a pivotal role in integrating renewable energy systems and shifting peak load energy demand to off-peak. By incorporating of energy storage systems, supply-demand can be met with the smooth supply of power (Hafiz et al. 2024). Traditionally, the effectiveness of TES systems is often constrained by the thermophysical properties of conventional heat transfer fluids (HTFs) such as ethylene glycol, and mineral oils, which possess relatively low thermal conductivity and low specific heat capacity (Mirahmad et al. 2025). These limitations hinder the overall efficiency of energy systems and thus necessitate the design of novel TES media with superior thermal and phase-change characteristics. Despite the advancements in nanofluids, they often face a number of challenges such as lack of stability, particle agglomeration and increased viscosity (Kaggwa & Carson 2019). Consequently, researchers today continue to explore optimal combinations of nanoscale materials and base fluids to achieve improved performance.

Among polymeric additives, a novel approach using phase change materials (PCMs) in the form of liquid crystals (LCs), which absorb or release energy during transitions between fluid phases, was proposed by Bayon and Rojas (Bayón & Rojas 2013; Rojas, Bayón & Zarza 2015). Initial studies by their research team have demonstrated promising results, highlighting the potential of LCs as effective thermal energy storage media (Bayón et al. 2016). Side-chain liquid crystalline polymers (SCLCPs) have attracted attention as a nanoscale material and for their unique molecular architecture. Compared to main-chain liquid crystalline polymers (MCLCPs), in which mesogens are integrated into the polymer backbone, SCLCPs have mesogens attached as side chains, retaining a degree of orientational freedom that depends on the coupling strength to the backbone. Moreover, due to this decoupling effect, SCLCPs with flexible spacer units tend to form lyotropic phases in organic solutions (Finkelmann, Portugal & Ringsdo 1978; Xue et al. 2004). The ordered molecular arrangements in the LC can improve heat dissipation in the polymer network by reducing phonon scattering (Trinh & Yeo 2024). Through the intermolecular interaction and molecular alignment, the mesogens achieved high orientation levels, thereby enabling superior thermal conductivity, which are beneficial for TES systems (Han et al. 2025; Trinh, Ku & Yeo 2025).

Parallel to the development of nanoscale SCLCP, deep eutectic solvents (DESs) have emerged as an alternative to ionic liquids (ILs). DESs are made up of at least one hydrogen bond donor (HBD) and one hydrogen bond acceptor (HBA), mixed in the right molar ratio to create a eutectic mixture that has a melting point significantly lower than either of the individual components (Boldrini et al. 2022). Low melting points, broad liquid ranges, high thermal stability, low volatility, and adjustable physical and chemical properties are among the advantages that DESs and ILs have in common. However, DESs are typically less expensive, less hazardous, and simpler to manufacture. These environmentally beneficial qualities have led to the widespread use of DESs in a variety of fields. DESs have also been successfully used as heat transfer fluids in concentrated solar power (CSP) plants as solar technologies have advanced (Kumar Das et al. 2022).

Shi, Chen and Wang (2024) recently used nanoparticles like SiO_2, TiO_2, and Al_2O_3 to study the density and viscosity of nanofluids based on choline chloride/ethylene glycol DES. Although density and viscosity were the focus of the study, it was also noted that these nanofluids had higher specific heat capacities and thermal conductivities than the base DES. Another study prepared nanofluids by dispersing TiO_2, FeO_3, CuO, SiC, and carbon nanoparticles in a glycerol/choline chloride DES. Effect of hydrogen bonding interactions between the DES and nanoparticles, specific heat capacity increased by 26.23% and thermal conductivity increased by up to 4.23% when compared to the base DES (Liu et al. 2022). The thermophysical characteristics and forced convection behavior of alumina/menthol DES nanofluids were also investigated by Dehury, Singh and Banerjee (2018). Thermal conductivity and heat capacity increased by 24% and 50%, respectively, at a 0.005 volume percent of nanoparticles. Fang et al. (2016) achieved a maximum improvement in thermal conductivity of 177% by introducing ammonium- and phosphonium-based DESs with dispersed functionalized graphene oxide nanoparticles (GNPs) without surfactants. Their findings showed that these nanofluids represent a new class of tailored fluids for heat transfer applications, reliant on temperature, DES type and composition, and GNP concentration.

Although DES have been widely studied as HTFs, the use of SCLCPs in TES applications remains unexplored. Incorporating SCLCP with DESs offers a new and sustainable approach to create high-performance nanofluids specifically for TES. The side mesogenic unit in SCLCP with polar functional group such as carbonitrile, hydroxyl or carboxyl are expected to form hydrogen bonding with the HBDs site like urea, glycerol and ethylene glycol (Abdul Samat et al. 2025). This hydrogen bonding interaction could potentially reduce interfacial thermal resistance which create heat phonons transfer more efficiently thus improve thermal conductivity and specific heat capacity of the nanofluids. Research on the coupling of SCLCPs and DESs is still lacking, despite this encouraging potential. The majority of earlier research has concentrated on either polymer-dispersed liquid crystals in conventional solvents (Agarwal et al. 2025) or DES-based nanofluids. The impact of SCLCP-DES interactions on phase behaviour, heat transport, and TES efficiency has not yet been thoroughly understood.

Thus, the aim of this work was to develop and characterize SCLCP-based nanofluids for TES applications employing deep eutectic solvents as base fluids. The design of next-generation TES materials, which combine molecularly organized nanoscale liquid crystalline polymer with environmentally friendly solvent media, is anticipated to advance as an outcome of this work.

EXPERIMENTAL DETAILS

BASE FLUID PREPARATION

The base fluid was prepared by diluting DES with *N*-methyl-2-pyrrolidone (NMP) solvent. First, DES were prepared by using choline chloride (>98%, Merck) as hydrogen bond acceptor (HBA) and different types of hydrogen bond donor (HBD), urea (>99%, Merck), glycerol (>99%, Merck), and ethylene glycol (>99%, Merck) at 1: 2 mole ratio. The reagents were used without further purification.

The mixture were mixed in an airtight sampling bottle and heated to 80 °C in an oil bath to produce a clear, uniform liquid (Chemat et al. 2016). Afterwards, the mixture was equilibrated at 40 °C in an oven for at least 24 h. DES with choline chloride/urea (ChCl/U), choline chloride/glycerol (ChCl/G) and choline chloride/ethylene glicol (ChCl/EG) were abbreviated as DES1, DES2, and DES3, respectively. Then, depending on the polymer's solubility in the mixture solvent and the polymer's capacity to display a liquid crystalline phase, the NMP to DES ratio was fixed at 90:10 (Abdul Samat et al. 2025). NMP/DES1, NMP/DES2, and NMP/DES3 are the three types of base fluid that were developed; these were subsequently shortened to NDES1, NDES2, and NDES3, respectively. The mixture of base fluids was prepared by heating in a closed container at 70 °C for 6 h. The resultant base fluids were kept at room temperature for later usage.

NANOFLUID PREPARATION

The nanofluids were prepared using a two-step method. Poly(6-(4-cyanobiphenyl-4'-yloxy) hexyl acrylate), abbreviated as P6ACB, which was successfully synthesized via solution polymerization by previous work (Abdul Samat et al. 2025), was used as the SCLCP. The chemical structure of the polymer is shown in Figure 1. The polymer was then dissolved into NDES1, NDES2, and NDES3, respectively, with 2 wt% and 6 wt% of P6ACB. These two mass fractions were selected based on the solubility of P6ACB in the base solvent and the ability to form lyotropic phase (Abdul Samat et al. 2025). The sample with 2 wt% P6ACB was prepared by dissolving P6ACB (0.2 g) into a solvent system (9.8 g) with a Sartorius TE 2145 model micromass balance (standard deviation = 0.01 mg). Elmasonic P ultrasonic immersion was used to dissolve the polymer into the solvent at a frequency of 36 kHz and power of 80% for five to ten minutes at a temperature of 70 °C until a colorless solution was formed. The samples were equilibrated for 3 days at room temperature to ensure that the system reach a thermodynamically stable and homogeneous state before the next experiment was conducted (Fang et al. 2019).

CHARACTERIZATIONS

The viscosity of the nanofluids was measured using a Rheometer MCR 301 (Anton-Paar) equipped with a cone-plate geometry of 25 mm diameter, 2° cone angle, and 0.05 mm gap. Measurements were conducted at room temperature and 90 °C under an air atmosphere over a shear rate range of 0.1-200 s^{-1}. These two temperatures were selected based on the lyotropic behaviour observed previously through Polarized Optical Microscopy (POM) and Differential Scanning Calorimetry (DSC) analysis.

Thermal conductivity was measured at temperatures ranging from 30 to 50 °C using a KD2 Pro instrument,

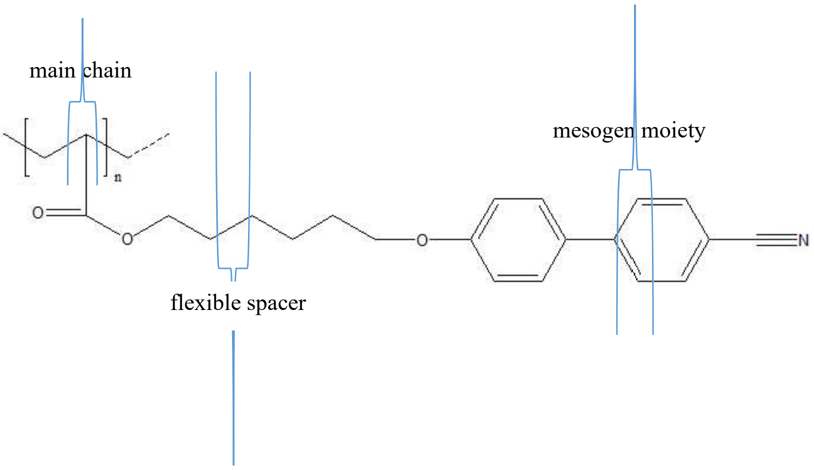

FIGURE 1. Chemical structure of P6ACB

which operates based on the transient hot-wire method. The KD2 Pro analyzer was calibrated by using deionized water prior to use. Thermal data were recorded every second over a 90-s cycle, with an accuracy of ±5%. Each sample was tested in triplicate, and the average value was reported. A water bath maintained a stable temperature, while a thermometer with an accuracy of 0.1 °C was used for precise temperature monitoring.

Specific heat capacity (C_p) of the nanofluids was determined using a Netzsch 214 Differential Scanning Calorimeter (DSC), following the ASTM-E1269 standard method with sapphire as the reference. The DSC heating procedure ranged from 30 to 100 °C at a heating rate of 1 °C/min. This slow rate of 1 °C/min was selected due to the very small value of the transition heat energy when the LC changes from an ordered phase to a disordered phase or vice versa (Sautina & Galyametdinov 2019). Measurements were performed for an empty pan, a pan with the reference, and a pan with the sample. About 40-60 mg samples was added into a crucible in each test. The specific heat capacity of the sample was obtained directly from the DSC software by comparing the thermal curves of the sample pan with the reference pan.

RESULTS AND DISCUSSION

THE VISCOSITY OF NANOFLUIDS

To illustrate a solvent's fluidity and flow resistance, viscosity study is essential (Ijardar 2020). The dynamic viscosity of the nanofluids was investigated at two concentrations, 2 wt.% and 6 wt.%, and at two temperatures, 25 °C and 90 °C. No LC phase was observed below 2 wt.%, while P6ACB was insoluble in the solvent above 6 wt.%. Figure 2 shows the viscosity of nanofluids with different base solvents at room temperature. As illustrated in Figure 2, viscosity increases with the mass fraction of P6ACB in all systems (a–c) compared to the respective base solvents, NDES1, NDES2, and NDES3. This trend is consistent with observations reported for most nanofluids containing various nanoparticles and base solvents (Isaza-Ruiz et al. 2021; Vaka et al. 2021, 2020). The addition of P6ACB increases internal friction, resulting in higher resistance to flow and, consequently, increased viscosity. As a result, more energy is required for the nanofluid to flow. The viscosity enhancement is also attributed to the formation of anisotropic phases, which create more ordered microstructures (Yu et al. 2021). The microstructural arrangement of lyotropic liquid crystals (LLCs) further increases fluid consistency, making the flow more viscous (Chavda et al. 2022). Similar behaviour has been observed in other lyotropic systems, where viscosity rises with the formation of lyotropic phases and the aggregation of structures with various textures (Chandrasekar, Ren Lu & Dierking 2023; Rodríguez-Fabià et al. 2019).

At a low shear rate of 13 s^{-1}, shear-thinning or shear-thickening behaviour, indicative of non-Newtonian flow, was observed, particularly in the NDES1- and NDES2-based systems. This may be attributed to measurement instability of the equipment at low torque (Jo & Banerjee 2014). Beyond a shear rate of 13 s^{-1}, the viscosity of all systems became independent of shear rate, indicating Newtonian behaviour. In general, the transition between non-Newtonian and Newtonian behaviour in such systems is governed by particle agglomeration and the arrangement of interacting particles in solution. In non-Newtonian fluids, particles form agglomerates at low shear rates. When the shear rate exceeds a critical value, these agglomerates break down into individual particles, and the fluid exhibits Newtonian behaviour (Isaza-Ruiz et al. 2021). In these LLC systems, the P6ACB molecules dissolved in the solvent formed a dilute system with relatively weak polymer–solvent interactions, resulting in flow behaviour that is closer to Newtonian (Chavda et al. 2022).

The viscosity of the nanofluids is also strongly influenced by temperature. Figure 3 illustrates the effect of high temperature (90 °C, isotropic phase) on the viscosity

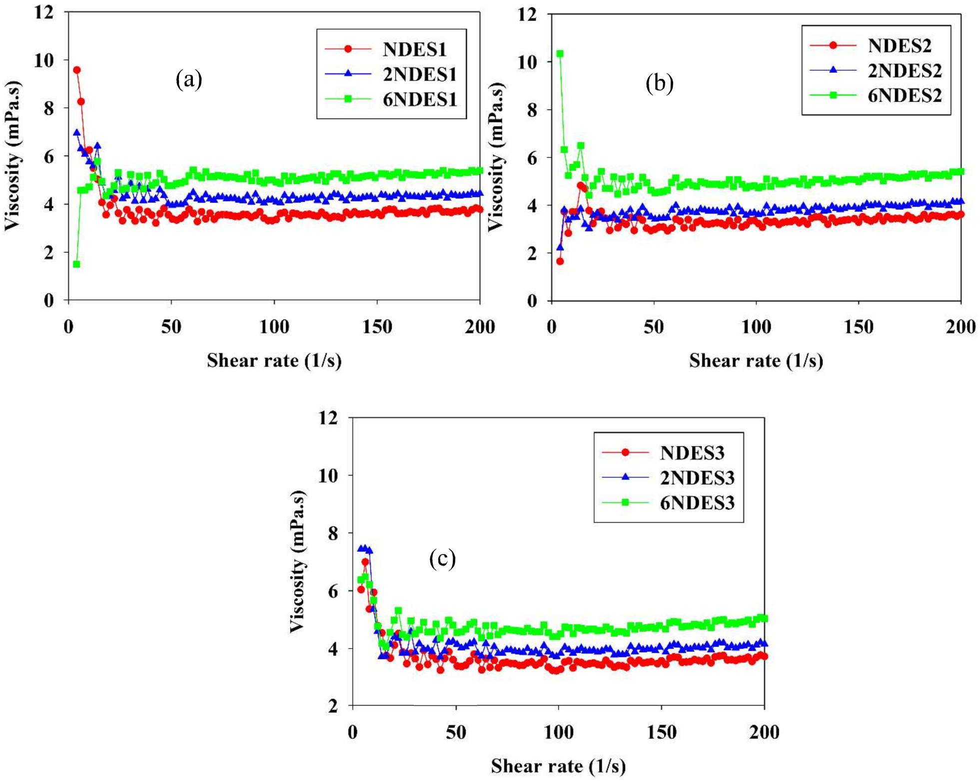

FIGURE 2. Viscosity of nanofluids with different base solvents (a) NDES1 (b) NDES1 and (c) NDES3 at room temperature

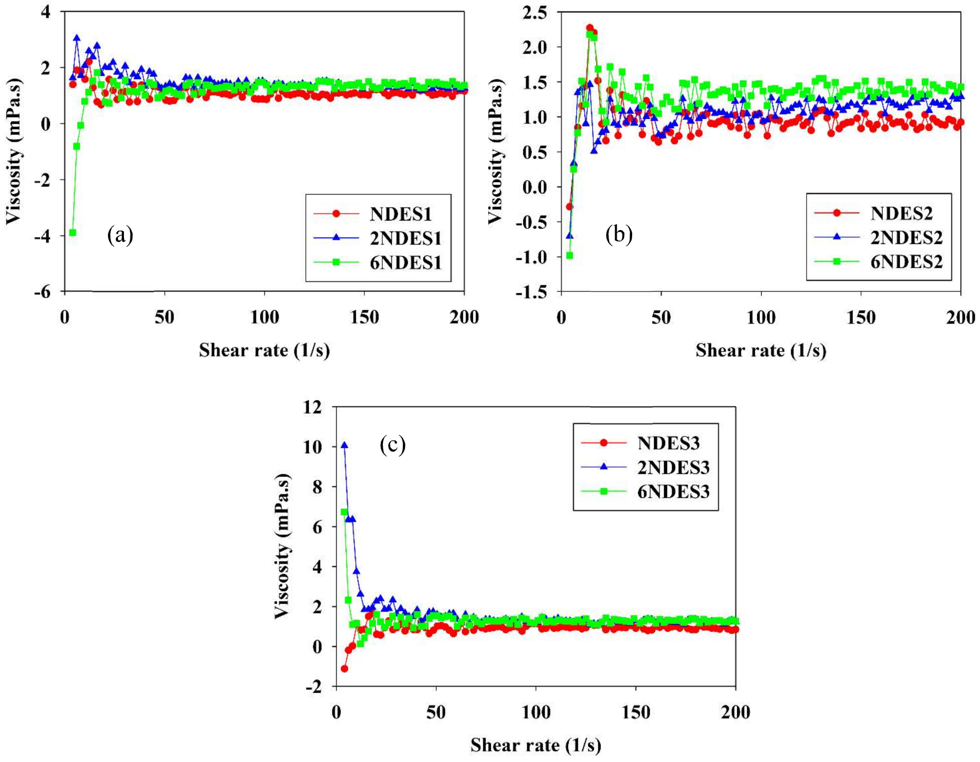

FIGURE 3. Viscosity of nanofluids with different base solvents (a) NDES1 (b) NDES2 and (c) NDES3 at 90 °C

of the systems. It is observed that viscosity decreases at elevated temperatures for all systems while maintaining Newtonian behaviour. This reduction in viscosity is generally attributed to enhanced Brownian motion, which increases the average distance between particles and the base fluid. Additionally, as temperature rises, the molecules in the base fluid gain kinetic energy, increasing their average velocity and overcoming intermolecular adhesion forces (Asadi, Alarifi & Foong 2020; Ho et al. 2021; Kazemi, Sefid & Afrand 2020). The decrease in viscosity is further supported by the transition of the system from the ordered liquid crystalline phase to the less ordered isotropic phase (Sampaio et al. 2001).

Compared to non-Newtonian fluids, which exhibit complex rheological behaviour, Newtonian fluids are easier to handle and pump. This predictable and consistent behaviour is particularly advantageous for TES applications, as it facilitates efficient heat transfer and storage. The stable viscosity with respect to shear rate simplifies modelling, design, and operation of TES systems (Guerrero & Shaw 2023; Shaw & Guerrero 2023).

THERMAL CONDUCTIVITY OF NANOFLUIDS

In this analysis, the thermal conductivity of NMP-based nanofluids was investigated to evaluate the effect of incorporating DES as the base fluid. At room temperature, the thermal conductivity of nanofluids increased with NMP/DES base fluid, as shown in Figure 4. A significant enhancement was observed for NDES2 with 6 wt.% P6ACB, which increased by 9.52%, followed by NDES3 at the same polymer concentration, which increased by 3.44%.

As the nanofluid temperature was raised up to 50 °C, the thermal conductivity of all nanofluid systems increased for both 2 wt.% and 6 wt.% P6ACB, as illustrated in Figures 5 and 6. At 40 °C, the NDES2-based nanofluid exhibited the highest thermal conductivity, with increases of 17.11% and 13.13% for 2 wt.% and 6 wt.%, respectively, followed by the NDES3-based nanofluid, which increased by 7.61% and 4.54% for the same mass fractions. At 50 °C, the trend persisted, with the NDES2-based nanofluid showing higher thermal conductivity than NDES3 for both mass percentages. Specifically, NDES2 increased by 17.35% and 16.39%, while NDES3 increased by 16.07% and 12.88% at 2 wt.% and 6 wt.%, respectively.

For the NDES1-based nanofluid, thermal conductivity also increased with temperature, but the enhancement was less pronounced compared to NDES2 and NDES3. Similarly, the NMP-based reference nanofluid showed a moderate increase in thermal conductivity with temperature for both P6ACB mass percentages; however, the improvement was lower than that observed in nanofluids containing the NMP/DES mixtures.

Newtonian fluids efficiently transfer heat through conduction and convection, making them particularly suitable for thermal energy storage (TES) systems (Guerrero & Shaw 2023; Shaw & Guerrero 2023). As observed in the viscosity analysis, all systems exhibit Newtonian behaviour at higher shear rates, indicating uniform dispersion of P6ACB in the base solvents, which helps minimize phonon scattering. Phonons quantized lattice vibrations are the primary carriers of thermal energy in condensed phases, significantly influencing both heat capacity and thermal conductivity (Shuguang et al. 2023). Efficient phonon transfer enhances interfacial adhesion (Jiao et al. 2023) through non-covalent interactions such as ionic bonds, hydrogen bonds, Van der Waals forces, or π-π stacking between the base solvent and nanoparticles (Kim & Choi 2021). Strong interfacial adhesion is critical for reducing resistance that can impede heat transfer, while also maintaining uniform nanoparticle dispersion to prevent phonon scattering that could lower thermal conductivity (Yang et al. 2021).

Beyond uniform dispersion, the degree of molecular alignment in SCLCPs plays a key role in thermal conductivity. Highly oriented polymers exhibit greater thermal conductivities along the alignment direction of LC molecules compared to the transverse direction (Luo et al. 2022). Increased crystallinity and molecular interactions within the polymer further enhance thermal transport (Yang et al. 2024). These effects were evident in the present results: the addition of P6ACB with mesogenic moieties to the base solvent enhanced the thermal conductivity of the nanofluids. The NDES2-based nanofluid showed the highest increase at 2 wt.%, with thermal conductivity rising by 17.35% at 50 °C, followed by the NDES3-based nanofluid, which increased by 16.07%. The alignment of LC molecules and overall crystallinity were further facilitated by the presence of DES in the base solvent, compared to NMP alone. Many studies have been reported previously that use DES to replace conventional fluids as heat transfer and heat storage fluids (Dehury, Mahanta & Banerjee 2020; Dehury, Upadhyay & Banerjee 2019; Liu et al. 2019).

Similar to ionic liquids, the thermal conductivity of DES-based nanofluids is strongly influenced by the molecular structure of the DES components. Different hydrogen bond donors (HBDs) result in varying solvophilic interactions between the polymer and the base solvent, which in turn affect the alignment of LC molecules (Ibrahim et al. 2020). The molecular structure of urea allows it to function as both HBD and HBA due to its N-H linkages (amine) and C-O bonds (carbonyl), respectively (Rezus & Bakker 2006). In comparison to glycerol and ethylene glycol, urea and chlorine chloride produce more extensive hydrogen bonding networks, resulting in increased DES viscosity (Zhang et al. 2020), which affect NDES1-based nanofluid. This consequently reduce the formation of LC which decrease the thermal conductivity as phonon scattering in the nanofluids limits the thermal transport. Glycerol and ethylene glycol are also alcohols that can form hydrogen bonding networks, with three and two

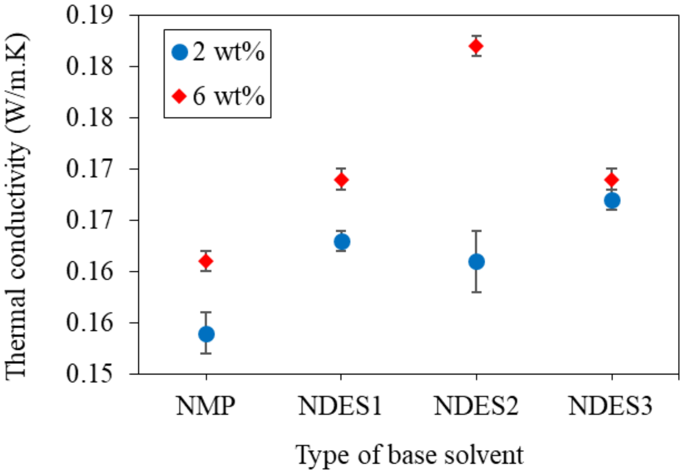

FIGURE 4. Thermal conductivity of nanofluids with 2 wt.% and 6 wt.% P6ACB at room temperature

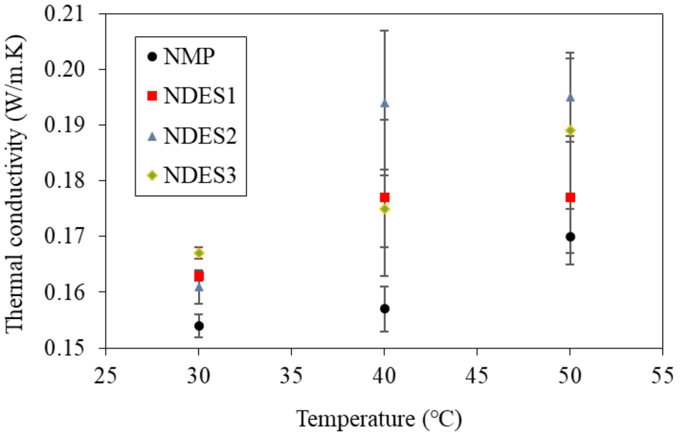

FIGURE 5. Thermal conductivity of nanofluids with 2 wt.% P6ACB at various temperatures

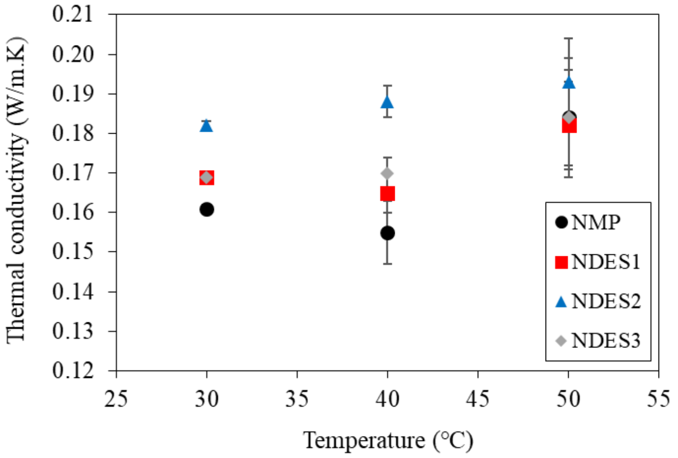

FIGURE 6. Thermal conductivity of nanofluids with 6 wt.% P6ACB at various temperatures

hydroxyl groups, respectively, as in NDES2- and NDES3-based nanofluids (Pandey et al. 2017). Nevertheless, the addition of NMP facilitated the dissolution of P6ACB into the base solvents. While at 6 wt.% polymer concentration, both NDES2 and NDES3 also showed a decrease in thermal conductivity, likely due to weaker polymer–solvent interactions that reduce the degree of molecular alignment. These findings were in line with the previous work in which high mass percentage of 6 wt.% polymer resulted in low level of LC molecules (Abdul Samat et al. 2025).

SPECIFIC HEAT CAPACITY OF NANOFLUIDS

The specific heat capacities (C_p) of all nanofluid systems, including their respective base fluids, were measured over a temperature range of 35 °C to 95 °C. As shown in Figure 7(a), NMP-based nanofluids with 2 wt.% P6ACB exhibited lower C_p values compared to NMP/DES-based nanofluids across the studied temperature range, indicating that the incorporation of DES as a base fluid enhances the specific heat capacity of nanofluids (Boldrini et al. 2022). At 35 °C, the percentage increase in C_p was 55.32%, 39.36%, and 25.53% for NDES2, NDES1, and NDES3, respectively. However, at higher temperatures starting from 55 °C, NDES3-based nanofluids showed a greater increase in C_p than NDES2 and NDES1, reaching a maximum percentage increase of 64.48% at 95 °C.

For nanofluids with 6 wt.% P6ACB, the trend differed (Figure 7(b)). Overall, C_p increased for all three DES-based nanofluids at temperatures from 65 °C to 95 °C. At lower temperatures (≤55 °C), the increase was observed primarily in NDES1 and NDES2 systems. The largest percentage increase at this polymer concentration occurred for NDES3 at 85 °C, reaching 97.93%. These trends correlate with the thermal conductivity results, where both C_p and thermal conductivity generally increased with polymer mass fraction and temperature. Similar observations have been reported in previous studies, which showed that nanofluid C_p increases with nanoparticle mass fraction (Dehury, Singh & Banerjee 2018; Liu & Yang 2017; Martín et al. 2019).

The thermal properties of the nanofluids are influenced by molecular alignment, solvent type, and polymer concentration. The ordered arrangement of mesogens in P6ACB facilitates phonon transfer, which plays a crucial role in heat capacity (Shuguang et al. 2023). LLCPs forming liquid crystal phases in the presence of solvent allow heat transfer along the polymer chains (Tanaka et al. 2018). The presence of solvent also enhances C_p compared to the pure solid polymer, as solvent molecules contribute to the overall heat absorption capacity (Chew, Daik & Hamid 2015). Additionally, the C_p of DES itself depends on the composition of the hydrogen bond acceptor (HBA) and donor (HBD) (Taherzadeh et al. 2020). For example, NDES2, with glycerol as HBD, exhibited the highest base fluid C_p (1.68-2.69 J/g·°C), whereas NDES3 showed the lowest (0.22-0.91 J/g·°C), due to differences in molecular mass among the HBDs (Leron & Li 2012).

After the addition of P6ACB, NDES3-based nanofluids demonstrated the highest C_p increase at higher temperatures (60-95 °C), while NDES2-based nanofluids showed greater C_p enhancement at lower temperatures (35-55 °C) for both mass fractions. The high C_p of NDES3 at elevated temperatures is likely due to stronger solvophilic interactions between P6ACB and NDES3, promoting a more ordered molecular arrangement of the liquid crystal, which increases the total heat absorbed. In contrast, the weaker interactions in NDES1 hinder ordered LC formation, resulting in lower energy storage. These observations are consistent with thermal conductivity results in which the molecular structure of the HBD play important role. In PACB–DES nanofluids, variations in thermal conductivity and heat capacity arise from the coupling between the intrinsic hydrogen-bond network of the DES and the anisotropic ordered domains introduced by the P6ACB. Strong interfacial hydrogen bonding between SCLCP chains and DES components enhances thermal coupling and reduces interfacial resistance, promoting heat transfer particularly in the nanofluid systems (Perri et al. 2025). Simultaneously, the presence of mesogenic side chains and polymer–DES interfacial regions increases configurational and orientational degrees of freedom, leading to pronounced heat capacity enhancement, especially in NDES2- and NDES3- based nanofluids (Boldrini et al. 2022). The resulting thermal behavior reflects a balance between enhanced energy transport through ordered polymer domains and increased energy storage within microstructured polymer-DES networks (Sadeghi & Vaali 2026).

From a thermodynamic perspective, the liquid crystal component of P6ACB acts as an alternative phase change material (PCM), offering two main advantages. First, energy exchange occurs primarily through convection, which is more efficient than conduction. Second, during both charging and discharging, the power output remains consistent over time. Additionally, if the mesophase range is sufficiently large, sensible heat can also be stored. Consequently, LCs provide the dual benefit of transferring and storing heat while maintaining flow, making them suitable for both heat transfer and thermal energy storage (Bayón & Rojas 2015).

Based on these properties studied, the thermal conductivity and specific heat capacity are found to be moderate to competitive to those existing TES nanofluids. This study represents an early investigation, and further research is needed to fully elucidate the role of SCLCPs in enhancing heat storage capacity.

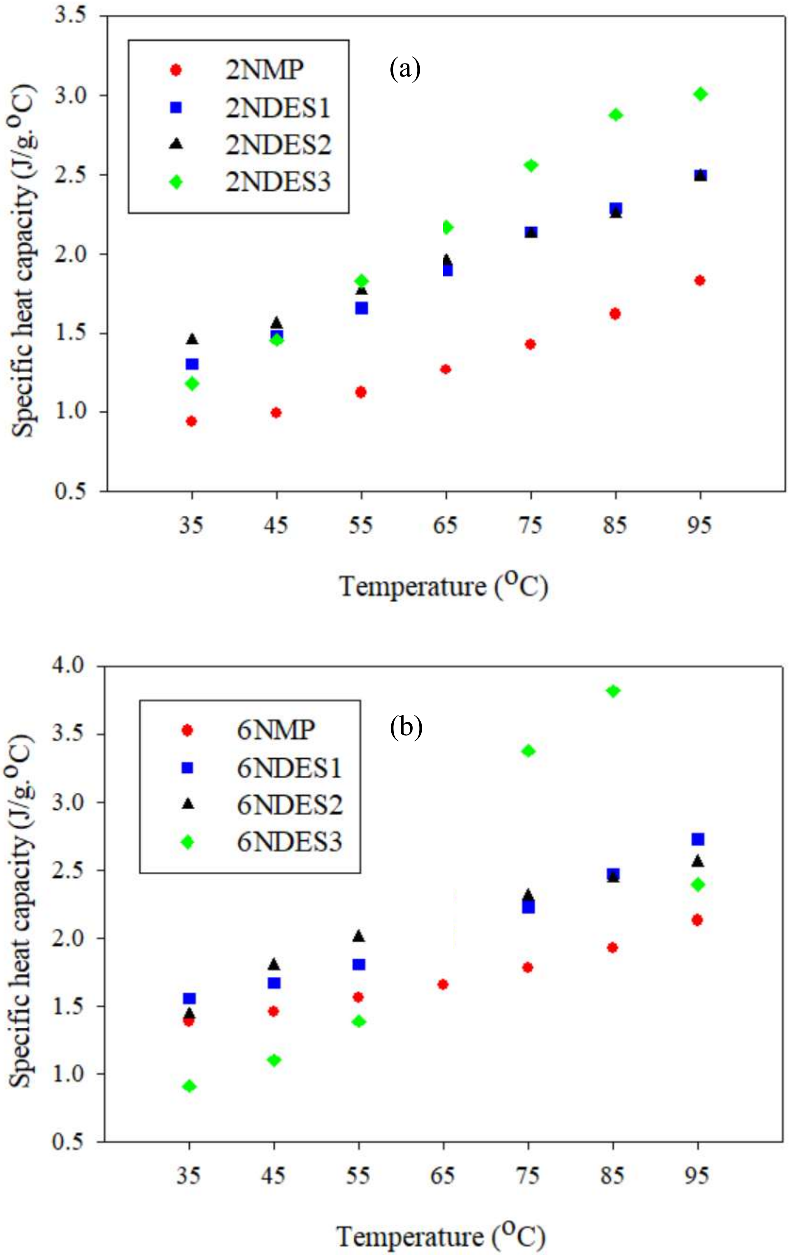

FIGURE 7. Specific heat capacity of nanofluids with (a) 2 wt.% P6ACB, and (b) 6 wt.% P6ACB at various temperatures

CONCLUSION

This paper aims to characterize a novel liquid crystal polymer nanofluid that exhibits a lyotropic phase, as observed in previous POM analysis. In this study, the nanofluid was prepared by dissolving poly(6-(4-cyanobiphenyl-4’-yloxy) hexyl acrylate) (P6ACB), a side-chain liquid crystalline polymer, into a mixture of DES and NMP at a 10:90 ratio. The thermophysical properties of the nanofluids including viscosity, thermal conductivity, and specific heat capacity were measured at polymer mass fractions of 2 wt.% and 6 wt.%. Viscosity was found to increase with polymer concentration and decrease with temperature. Beyond a shear rate of 13 s^{-1}, the viscosity of all systems became independent of shear rate at room temperature, indicating Newtonian behaviour, which was retained at 90 °C (mesophase). This Newtonian behaviour contributed to enhanced thermal conductivity by minimizing phonon scattering. Increasing the mass fraction of P6ACB also improved thermal conductivity due to the higher degree of molecular alignment, which similarly played a key role in heat capacity. Based on the experimental results, NDES2- and NDES3-based liquid crystal polymer nanofluids demonstrated promising potential as alternatives for TES systems, owing to their high thermal conductivity, elevated specific heat capacity, and Newtonian flow characteristics.

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