TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 66, Issue Specail II, October, 2023

OVERVIEW OF NANOPARTICLE ENHANCED THERMAL OILS FOR HEAT TRANSFER APPLICATIONS

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Abstract: *The aim of this paper is to explore recent advances in the nanofluids applications by using different nanoparticles added in thermal oil. In the last years nanofluids have been recognized as a new heat transfer fluid, particularly in heat exchange applications. Lately, ionanofluids are demarcated as a new class of nanofluids that may overcome the drawbacks of simple nanofluids. Briefly, this paper start point was the use different type of nanoparticles enhanced with thermal oil previously studied in terms of their stability in service and thermophysical properties. Concluding, in this paper all the results from literature was discussed in term of thermophysical properties of the nanofluids based thermal oil if compares to conventional heat transfer fluids.*

Key words: *thermal oil, nanoparticles, thermophysical properties, nanofluids, heat transfer*

1. INTRODUCTION

In recent years, there is a great need to improve thermal processes, especially in terms of the search for new solutions that favor the miniaturization of the components of most thermal devices. Another pressing need is to achieve higher heat transfer rates with higher energy conversion levels. In terms of properties, a suitable heat transfer fluid should consider: low viscosity, to maintain a pumping power as low as possible when flowing through pipes; "friendly" with the environment; long-term stability, because their lack of stability over time could cause blockage of pipes; non-flammability and non-volatility in the environment and high thermal conductivity - property indicating the ability of a fluid to conduct heat. The lifetime of a heat transfer fluid is an important thing that must be taken into account, it is recommended that under normal working conditions, the lifetime of a fluid should be 35000 - 40000 hours [1-5]. From the studies and the characteristics described, there is no heat transfer fluid that meets all the highlighted conditions, but the most important thing when choosing a heat transfer fluid is the maximum operating temperature. In addition, apart from viscosity, operating temperature, thermal conductivity, the total energy consumption must also be taken into account. Figure 1 shows the advantages and disadvantages of the most common heat transfer fluids. As is already known, water and ethylene glycol are used at low and medium temperatures and oils are used at high temperatures. Research in the field led to the creation of new fluids by adding solid nanoparticles (with high thermal conductivity), fluids that were called "nanofluids" in the specialized literature [6,7]. The dispersion of nanometer-sized particles in the base fluid produces changes in the thermophysical properties of the fluid, which ultimately leads to improved heat transfer. However, nanometer-sized particles cause some problems, such as low stability and can lead to blockage of flow channels (especially in microtubes) [8-10]. A better option may be thermal oils, which are heat transfer fluids with acceptable thermophysical properties, and with this in mind, the following sections will present extensive discussions on nanofluids based on thermal oils, with an emphasis on heat transfer properties [8-12].

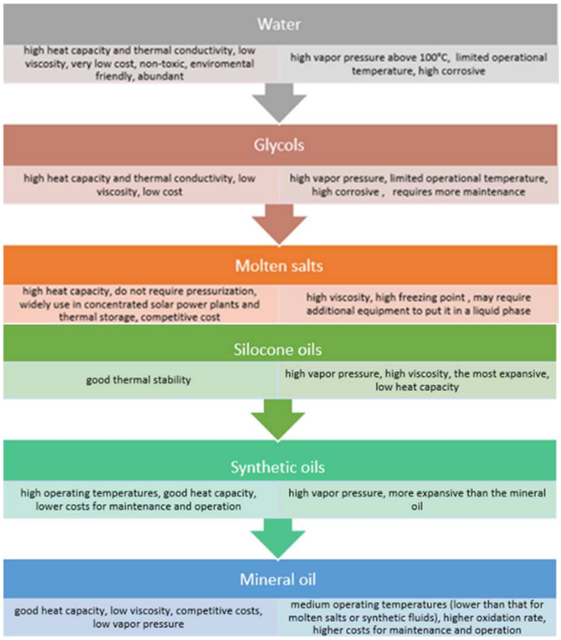

Fig.1. Advantages and disadvantages of the most common heat transfer fluids

Theoretical and experimental studies are incomplete and scattered, being insufficient to clearly understand the mechanisms underlying the thermal transfer of nanofluids. The dynamics of research in this field can be seen in the graphs in Figures 2 and 3. The graphs can be interpreted from several perspectives. At a first glance, the graph shows the number of publications published from 2015 to the present, using the keyword "Nanofluids". From another point of view, the analysis of research dynamics in the field of nanofluids was carried out using different databases, namely: Scopus, Science Direct, Web of Science. From these histograms it can be seen that there is a special attention given to this new type of heat transfer fluid, by different research groups (such as: Portugal, France, USA, India). This can be explained not only by the interesting properties and behavior of these nanosystems, but also by the large number of potential applications in industry, triggered by the research of nanofluids, but also as a result of the extraordinary opportunities offered by the use of thermal oils (considered as liquids that can work at high temperatures) [13 – 20]. The trend observed in these histograms is normal, given the increase in the number of publications appearing each year, and this suggests that there are still many reasons to study these complex systems.

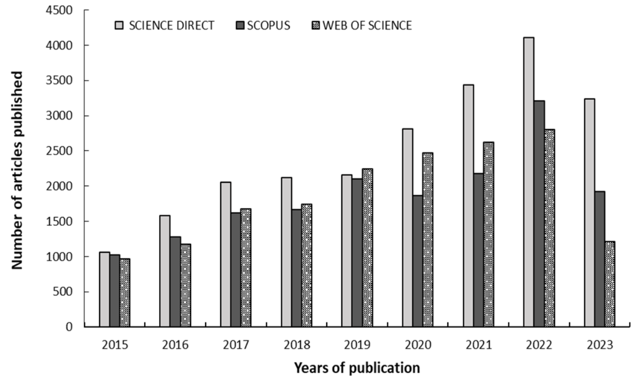

Fig.2. Number of articles published in different databases (keyword: Nanofluids)

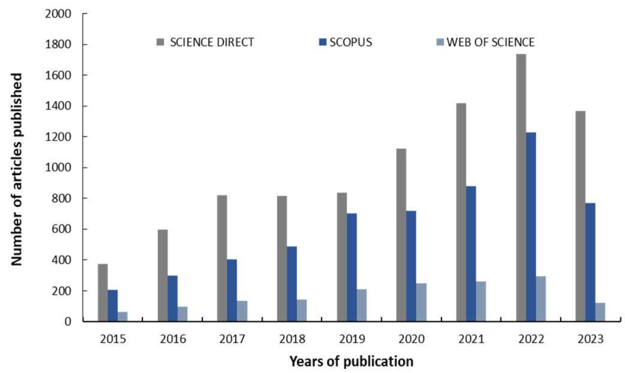

Fig.3. Number of articles published in different databases (keyword: Thermal oil nanofluids)

2. THERMAL OILS

Thermal oils are a must for most of the heat transfer processes that occur at medium to high temperatures and we are outlining temperature ranges up to 300 °C [21-35]. There are a lot of thermal oils that are in use at this moment in most of the solar thermal applications and some of them are outlined, together with their properties in Table 1.

Table 1.

Few thermophysical properties of heat transfer fluids [18, 30, 31, 35].

Fluid	ρ, g/cm^3	Cp, J/g°C	K, W/mK	μ, Pa s
Diathermic oil	No data	1.615 at 25 °C	0.133	0.047
Poly-alpha olephin pur (PAO)	No data	1.9 at 60 °C	0.137	0.075

PEG 200	1.121 at 25 °C	No data	0.19	0.0497
PEG 400	1.125 at 25 °C	2.35 at 25 °C	0.184	0.0704
IL 1	1.218 at 60 °C	1.281 at 100°C	0.200	0.043
IL 2	1.181 at 60 °C	1.627 at 100°C	0.186	0.104
IL 3	1.384 at 60°C	1.430 at 100°C	0.127	0.041

where ρ, Cp, K and μ represent the density, heat capacity, thermal conductivity (at ambient temperature) and viscosity (at ambient temperature) of the fluid.

Also, IL 1, IL 2 and IL 3 means: ionic liquid 1-ethyl-3-methylimidazolium tetrafluoroborate, ionic liquid 1-butyl-3-methylimidazolium tetrafluoroborate and Ionic liquid 1-butyl-3-methyl-imidazolium bis (trifluoromethylsulfonyl) imide.

In order to improve the performances of these thermal oils, a similar technique that was successfully applied for low temperature fluids can be adopted.

Thus, introducing solid nanoparticle with considerable higher thermal conductivity was studied lately by a number of research groups (see for example: Bretado-de los Rios et al. and Tavousi et al.) [13, 14].

Nanoparticles used for these new fluids can be of most of the classical categories, as was outlined before. [15], as for example: metals (Cu, Fe, Al, Ag), oxides (CuO, Al_2O_3, Fe_2O_3, Fe_3O_4) carbon based (SWCNT, MWCNT, grafen) or MXene [16].

Some research groups studied thermal conductivity of thermal oils, as for example Diathermic oil, Dowtherm A, Therminol 66, Therminol 55, as well as silicone oil or other natural oils (i.e seed oils that can be used at high temperatures applications) [12-35].

Figures 4 and 5 outline the thermal conductivity and the specific heat range of several heat transfer fluids, including thermal oils.

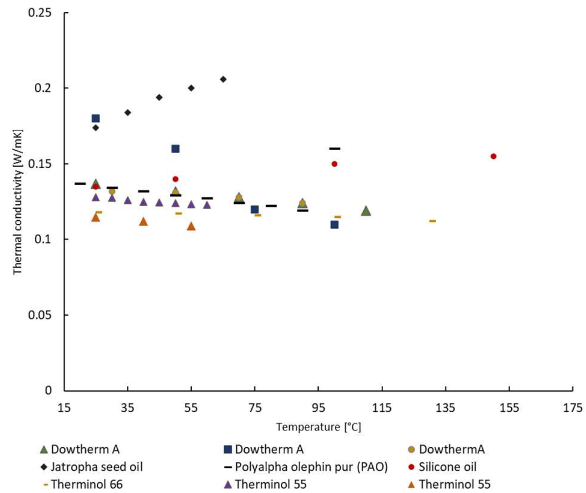

Fig.4. Thermal conductivity variation of several thermal oils

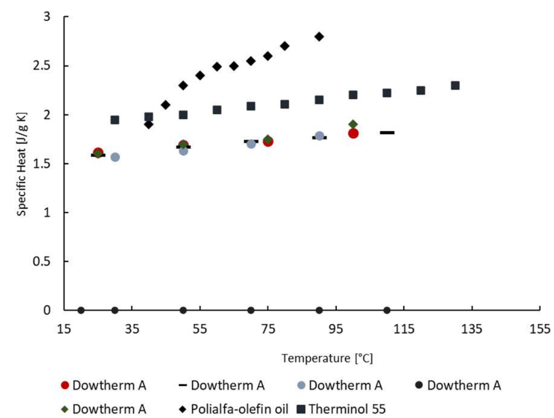

Fig.5. Specific heat variation of several thermal oils

If it looks to Figure 4 it can see that the temperature increase goes in a moderate increase in thermal conductivity, while the specific heat clearly upsurges when heating (see Figure 5).

3. THERMOPHYSICAL PROPERTIES OF OIL BASED NANOFLUIDS

3.1 Thermal conductivity

There are a number of theories that are trying to estimate the thermal conductivity values; however, the ost comprehensive method remains the experimental one, even if the Maxwell model remains as reference. Several accepted theories to explain the thermal conductivity variation mechanisms are: classical effective medium theory, nanoscale layer models or Brownian motion [17].

The Maxwell model writes [17]:

$$\lambda_{nf} = \frac{\lambda_{np}+2\lambda_{bf}+2(\lambda_{np}-\lambda_{bf})\phi}{\lambda_{np}+2\lambda_{bf}-(\lambda_{np}-\lambda_{bf})\phi}\,\lambda_{bf} \qquad (1)$$

where λ_{bf} – thermal conductivity of the base fluid; λ_{np} – thermal conductivity of the nanoparticles; ϕ – nanoparticle volume fraction.

On the other hand, Bruggeman, proposed a model that can be applied in certain conditions for large fractions of nanoparticles:

$$\phi\left(\frac{\lambda_{np}-\lambda_{nf}}{\lambda_{np}-2\lambda_{nf}}\right)+(1-\phi)\left(\frac{\lambda_{bf}-\lambda_{nf}}{\lambda_{bf}-2\lambda_{nf}}\right)=0 \quad (2)$$

where factor λ_{nf} can be used for introducing new parameters, as for example the nanoparticle geometry [17].

Nevertheless, as was affirmed previously, experimental tests remain the most accurate option and, in this regard, several results will be presented further on.

Wei et al. [18] studied Diathermic oil and added SiC + TiO_2 nanoparticles and noticed an increase in thermal conductivity when the volume concentration increases. Authors developed 3 classes of nanofluids and measured the thermal conductivity, demonstrating an increase of up to 8.4%. This increase is the maximum attained for the hybrid nanoparticles in concentration of 1 %vol. Results for the single nanoparticles are close to the hybrid and, in this author opinion, hybridization cannot be a solution due to high costs.

Carrillo-Berdugo et al. [19] manufactured Dowtherm A thermal oil enhanced with Au nanoparticles in different concentrations. The thermal conductivity was found to decrease with the addition of nanoparticles, up to 3%.

Also, other research groups proposed different oil based nanofluids and their main conclusion was that the thermal conductivity is increasing with nanoparticle addition and with temperature, that being a normal behavior that was noticed for most of these new fluids. Explanations can rely on the Brownian motion, specifically (see [1, 17, 19] for details).

In Figure 6 it is inserted a comparison in terms of thermal conductivity for several studied suspensions.

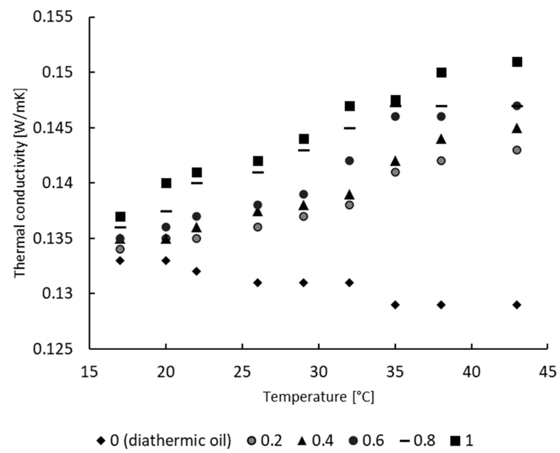

Fig.6. Diathermic oil with nanoparticles [19]

Table 2.

Thermal conductivity variation with temperature for Thermal 66 enhanced with CNT nanoparticles and surfactant [20].

Sample	Temperature [°C]				
	25	**50**	**75**	**100**	**130**
Therminol 66	118	117	116	115	112
0.5% CNT/OA (Acid Oleic) = 1:1 + Therminol 66	145	145	145	144	143
0.1% CNT/OA (Acid Oleic) = 1:1 + Therminol 66	132	131	131	130	128
0.05% CNT/OA (Acid Oleic) = 1:1 + Therminol 66	122	122	122	121	120

Besides the mentioned theories, there are a number of other models that take into account the NP sedimentation [21], size and geometry of the nanoparticles.

Taking into account the previously mentioned theories as well as the experimental results regarding nanofluids for heat transfer, it can be stated that the main factors that influence the thermal conductivity are the concentration, size and shape of the nanoparticles, the stability of the dispersion, the addition of surfactants, the pH of the mixture as well as nanofluid preparation methods [16].

3.2 Specific heat

Specific heat is another property of interest in applications such as heat exchange and is defined as the amount of heat required to raise the temperature of a unit mass by one degree [22]. In the case of nanofluids, there are two theoretical models by which the specific heat can be estimated: the model that is based on the specific heat values of the compounds (eq. 3) and the model that takes into account the particle-liquid thermal equilibrium (eq. 4) [13].

$$Cp_{nf} = \phi_v C_{p_{np}} + (1 - \phi_v) C_{p_{bf}} \quad (3)$$

$$Cp_{nf} = \frac{\phi_v C_{p_{np}} \rho_{np} + (1-\phi_v) C_{p_{bf}} \rho_{bf}}{\phi_v \rho_{np} + (1-\phi_v) \rho_{bf}} \quad (4)$$

where: C_p – specific heat; ϕ_v – NP volume fraction; ρ – density; while nf, np, bf – refers to nanofluid, nanoparticles and base fluid.
According to literature outcomes [23]-[29], the specific heat values are decreasing with concentration and this phenomenon occurs due to the low value of the specific heat of nanoparticles if compared to the host fluid. More exactly, if it considers the state of the art on thermal oils enhanced with NP it can see that the specific heat usually increases with nanoparticles addition, as it is outlined in Figure 7.

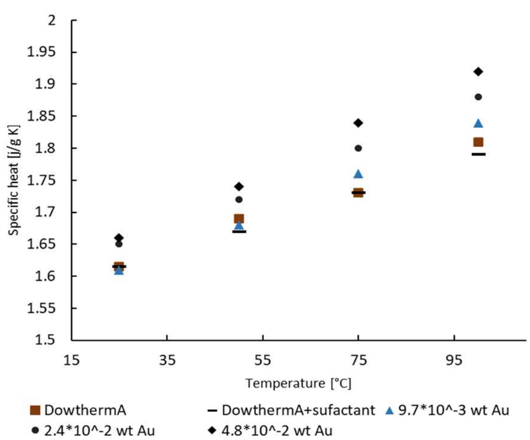

Fig.7. Specific heat variation for nanofluids based on Dowtherm A [30]

If it looks at Figure 7, as well as to other data from the literature it can notice that the addition of nanoparticles clearly influences the specific heat values (see [30] for further details and discussion).
Plus, few other research groups studied the specific heat variation and acknowledged the same trend [18, 30, 35].

Table 3.
Specific heat variation with temperature and NP addition for Dowtherm A with TRX surfactant and BNNT nanoparticles [31].

	Temperature °C			
	30	**50**	**70**	**90**
Dowtherm A	1567.1	1632.9	1703.4	1789.4
Dowtherm A + TRX-100	1535.1	1603.3	1685.3	1765.9
3.4 vol % BNNT	1571.5	1643.5	1703.9	1771.9
5.8 vol % BNNT	1579	1640.4	1700.3	1759.6
8.6 vol % BNNT	1588.8	1646.8	1696.1	1742

Most of the cases outline an increase of specific heat when nanoparticles are added to the suspensions. Nevertheless, a coordinated study is not present in the open literature.

3.3 Viscosity

Viscosity is one of the most relevant properties when it discusses flow behaviour and clearly influences the energy efficiency of a system. An increase in viscosity is going to an upsurge in pumping power, thus decreasing the energy efficiency of the heat exchange application. It is clear that the addition of solid nanoparticles it clearly determines an increase in viscosity. So, the main issue when dealing with nanofluids remain to keep the viscosity in reasonable ranges. In the next lines, a short disvcussion on viscosity of thermal fluids enhanced with naoparticles will be inserted.

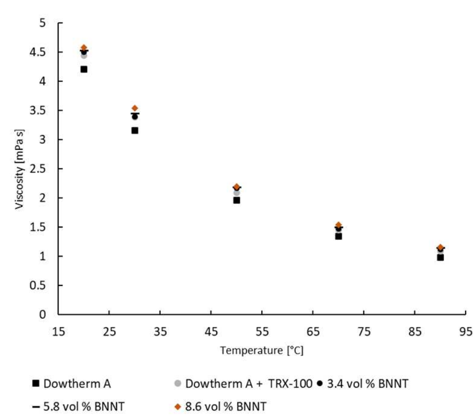

Fig.8. Viscosity variation of Dowtherm A with TRX surfactant and BNNT nanoparticles [31]

Other similar studies were performed by Ilyias et al. [32] who studied Hexatherm oil with hybrid nanoparticles of diamond + graphene and the results are outlined in Table 4.

Table 4.

Specific heat variation with temperature and NP addition for Dowtherm A with TRX surfactant and BNNT nanoparticles [32].

Sample	Temperature °C				
	20	30	40	50	60
HRMO (Texatherm)	0.059	0.038	0.021	0.018	0.017
HRMO + 0.4% wt	0.06	0.039	0.021	0.018	0.017
HRMO + 0.8% wt	0.062	0.04	0.022	0.0185	0.018
HRMO + 1.2% wt	0.064	0.041	0.023	0.019	0.018
HRMO + 1.6% wt	0.066	0.042	0.024	0.02	0.018
HRMO + 2% wt	0.068	0.043	0.026	0.021	0.019

Other authors, as for example Teruel et al. [33], Ahmad [34] found similar trend in the increase of viscosity, of up to 5 % which is extremely reasonable in terms of drawbacks in pumping power.

4. CONCLUSION

Thermal oils are specific heat transfer fluids used at medium to high temperatures and their first use refers to temperature ranges between 60 – 300 °C. Adding nanoparticles is a technique that clearly goes to great benefits in terms of thermal conductivity and specific heat, which are relevant for all heat transfer applications. This increase is going to reduce energy consumption of heat exchanger applications with short drawbacks in terms of increasing the pumping power.

The present overview compares and describes recent research in thermal oils enhanced fluids and creates the referential for future research, especially since it is less explored domain, with a lot of potential.

As a main conclusion from this short overview it can clearly say that adding nanoparticles to thermal oils follows the benefits of nanofluids and more coordinated research is needed.

Acknowledgement

This work was supported by a grant of the Romanian Ministry of Education and Research, CNCS—UEFISCDI, project number NR. PD 36⁄2022, Code project PN-III-P1-1.1-PD-2021–0222 within PN III.

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Prezentare generală a uleiurilor termice îmbunătățite cu nanoparticule pentru aplicații de transfer de căldură

Scopul acestei lucrări este de a explora progresele recente în ceea ce privește aplicațiile nanofluidelor prin utilizarea diferitelor tipuri de nanoparticule adăugate în uleiul termic. În ultimii ani, nanofluidele au fost recunoscute ca un nou fluid de transfer de căldură, în special în aplicațiile de schimb de căldură. În ultimul timp, ionanofluidele sunt delimitate ca o nouă clasă de nanofluide care pot depăși dezavantajele nanofluidelor simple. Pe scurt, punctul de plecare al acestei lucrări a fost studierea diferitelor tipuri de uleiuri termice îmbunătățite cu nanoparticule, studiate anterior în ceea ce privește stabilitatea lor în serviciu și proprietățile termofizice. În concluzie, în această lucrare o parte din rezultatele prezentate în literatura de specialitate au fost discutate în ceea ce privește proprietățile termofizice al uleiului termic pe bază de nanofluide în comparație cu fluidele de transfer termic convenționale.

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