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An open-access database of the thermophysical properties of nanofluids

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Abstract

The collection, scope, utility, and development of a comprehensive database with published experimental thermophysical properties of nanofluids is described in this paper. The collected data target nanofluids composed of a base fluid, which can be a pure compound or a binary mixture, and a single type of nanoparticle. The available experimental data in published scientific literature up to date in the field of nanofluids has been collected and organized to provide easy access to knowledge on the thermophysical behavior of nanofluids. The database contains a total of 307 datasets with 8118 data records of thermophysical properties of nanofluids, covering 13 types of base fluids, and 19 nanoparticle types. The collected experimental data include five thermodynamic properties (i.e. density, isobaric heat capacity, vapor pressure, speed of sound, and vaporization enthalpy) and two transport properties (i.e. thermal conductivity, and dynamic viscosity). The first release of this database is accesible for free under the host of the Dortmund Databank. An analysis of the consistency of the data, and challenges encountered during the data collection is provided.

Keywords:
database; nanofluids; thermodynamic properties; transport properties; open access.

Nomenclature

Abbreviations

bf	base fluid
CNC	cellulose nanocrystal
EG	ethylene glycol
MWCNT	multi-walled carbon nanotubes
nf	nanofluid
np	nanoparticle
PG	propylene glycol
sWCNT	single-walled carbon nanotubes

Greek letters

μ	dynamic viscosity, Nms^{-1}
ω	acentric factor
ρ	density kgm^{-3}
k	thermal conductivity $Wm^{-1}K^{-1}$
u	sound speed ms^{-1}
H_{vap}	vaporization enthalpy Wkg^{-1}
c_p	specific isobaric heat capacity, kJ/kmol K
p	pressure, bar
T	temperature, K
b	boiling
c	critical
exp	experimental
pred	predicted

1. Introduction

Nanofluids are colloidal dispersions of nanoparticles in fluids, where nanoparticles are defined as solid objects which dimensions are within the range of 1 nm to 100 nm [1] (although in some cases nanoparticles may exceed this range slightly). Their use was proposed in the early 90s as a new generation of heat transfer fluids thanks to their expected improved thermal properties [2]. Since then, the number of published research works exploring their heat transfer and thermal properties, and their potential industrial and pharmaceutical applications, have increased exponentially, reaching to more than 10,000 publications that contain the keyword *nanofluid* in their title (among ISI-index publications). The investigation of the thermophysical properties of nanofluids has also been a topic of growing interest, but to a much smaller extent that the works regarding heat transfer properties, despite their crucial importance for the development of practical applications for nanofluids.

The high and fast production of scientific literature on nanofluids, boosted by their promising potential in a number of applications, soon started to show contradictory results regarding their performance, which is still the case as of today. Stability issues during the preparation of the nanofluids, settling,

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and clogging of the nanoparticles during measurements have been attributed as the main factors for the observed unexpected behavior of nanofluids [3]. Besides, incomplete reporting of the nanofluid system parameters, preparation methods, and measuring conditions in a large number of publications has been pointed out [4]. The lack of information covering all the influencial parameters of the nanofluid system in available publications, despite the proven dependance of nanofluids behavior on the preparation method, nanoparticle features, and time evolution, has generated high uncertainty on the reliability of nanofluids among large parts of the scientific community [5]. This uncertainty strongly affects the published data on heat transfer and thermophysical data, despite their crucial importance for the development of industrial applications.

A high number of review works aiming at sheding light on the uncertain thermophysical behavior of nanofluids, and its dependance on specific factors, have been published in the recent years. Figure 1 shows the yearly number of reviews targeting the thermophysical properties of nanofluids during the last few years, and the number of publications on nanofluids thermophysical properties. It is interesting to observe, how review studies have proliferated at the same rate as the number of publications on nanofluids thermophysical studies, accounting approximately for a review paper every nine new publications. Among the review studies, the study of thermal conductivity of nanofluids outnumbers studies of other properties. While some provide a general overview of the thermal conductivity of nanofluids [6–9], others target specific nanoparticle types [10], influencial factors [11], or review the available prediction models for thermal conductivity prediction [12]. Reviews on nanofluids viscosity are also abundant, covering experimental studies and theoretical studies [13], the evaluation of predictive models [14], and providing general overviews [15–17]. Besides, a number of review studies provide more comprehensive overviews of the thermophyscial behavior of nanofluids, including other properties such as density and specific isobaric heat capacity [18–20], and the trends in modeling their behavior [21].

Despite these review works are indeed based on selected data collections gathered by their authors up to the publication date, and may contain reliable and carefully verified data, the raw data are not accessible to the reader, hindering researchers from performing alternative data analyses. Moreover, to the best of our knowledge, there are no comprehensive studies analyzing the uncertainties and discrepancies of the measured experimental data for nanofluids. This is a direct consequence of the lack of an open experimental database compiling all the published thermophysical data for nanofluids.

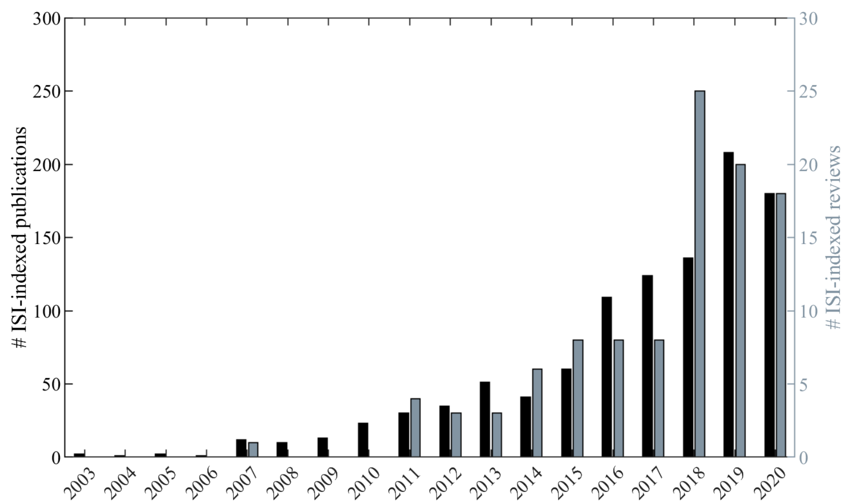

Figure 1: Number of reviews and articles with the keywords *nanofluid* and *thermophysical*, per year of publication.

Recognizing that there was a clear need for a comprehensive database of thermophysical properties for nanofluids, that can be used as a reference source, for correlations development, and evaluation of potential applications of nanofluids, effort has been made during the last two years to collect experimental data of the relevant thermophysical properties of nanofluids, in order to compile the first comprehensive database of thermophysical properties for these heat transfer fluids. A preliminary assessment of the data collection phase was presented in Ref. [4]. The properties of most interest for the application of nanofluids as heat transfer fluids are the thermal conductivity k and their dynamic viscosity μ . Nevertheless, density data ρ and specific isobaric heat capacity c_{p} are also essential for their evaluation in thermal systems. Besides these fundamental properties for heat transfer fluids, some other properties including the vapor pressure p_{sat} , the speed of sound u , and the enthalpy of vaporization H_{vap} have also been reported, but to a much lesser extent. While the primary goal of this database was the collection of data with the intention of developing newer more accurate thermophysical property correlations, the relatively low number of data available does not provide the necessary basis for this development. Instead, this database is intended to support researchers in the field of thermophysical properties of nanofluids, providing quick access to reference data for comparison and evaluation of predictive correlations. This comprehensive database has a special focus on providing a complete description of the systems (to the extent possible), including data about their preparation and uncertainties, whenever possible.

The current database contains 8118 data records for 13 chemical compounds as base fluids and 19 nanoparticle types. More complex systems such as hybrid nanofluids (i.e. containing more than one type of nanoparticle) or metal organic heat carriers (i.e. nanofluids containing metal organic frameworks) are not included.

This paper presents the characteristics of the developed database, discusses the details of the data collection, and its content. A discussion on the potential applications and expected benefits of this database is provided. Based on the analysis of the data available, directions for future research are suggested.

2. Overview of the database

The database of thermophysical properties of nanofluids presented in this work contains four main elements: (i) a bibliographic database; (ii) the data entry system; (iii) the querry system; and (iv) the collected thermophysical property experimental data.

Data were included in the database by introducing their bibliographic information, the sets of experimental data, the description of the nanofluid systems, preparation method, and the measuring conditions. The description of the nanofluid system includes the following features: the base fluid composition, the nanoparticle material, the nanoparticle shape (*e.g.*, spherical, semispherical, cylindrical), its dimensions (*i.e.*, minimum, average and/or maximum nanoparticle diameter, for spherical and quasispherical particles, and minimum, maximum and average lenght for nanotubes), and the nanoparticle concentration (which can be given in mass, mole, or volume fraction).

Moreover, although Buongiorno et al. [5] indicated that thermal conductivity enhancement was consistent among different measurement techniques at the same conditions in a benchmark study, it is well known that the preparation method, its parameters, and the time after preparation can have an impact on the measured properties of nanofluids if stability is not sufficient [3]. Therefore, information on the nanoparticle or nanofluid supplier, the preparation method (*e.g.*, one-step method, two-step method), and the utilized surfactants is also included, if reported in the source. Although ultrasonication times used in the two-step method have been reported to affect the stability and properties of the nanofluids [3], data evolution with time is rarely reported, and therefore not included in the database.

The temperature and the pressure under which the measurements were performed are not always explicitely reported. In these cases, meaningful values were assumed (*i.e.*, in case of ambient temperature and atmospheric pressure 298 K and 1 bar were chosen). This kind of data was always labeled accordingly and can easily be distinguished from directly measured results. The thermophysical properties included in the database (*i.e.*, density ρ , specific isobaric heat capacity c_p , dynamic viscosity μ , thermal conductivity k , vapor pressure p_sat , speed of sound u , and vaporization enthalpy H_vap) were collected together with their uncertainty or estimated deviation, if reported in the source. It needs to be pointed out that, in some cases, it is unclear whether the reported uncertainty value is, in fact, the measuring instrument resolution or the estimated deviation. Data reported without uncertainty should be considered to have high uncertainty. Comments on possible innaccuracies, such as those in the reported units, have been corrected and this is indicated on the affected datasets.

The rheological behavior of nanofluids is reported only in a few sources, despite its importance especially for high concentration of nanoparticles. Nevertheless, it was found that for the reporting sources, the behavior was mostly Newtonian, and non-Newtonian behavior was only found at very high concentrations, which in turn could present stability issues. Of all data sets reporting viscosity data, approximately 18% contain information about shear stress and shear rate, which should allow statements about the Newtonian behavior of the nanofluids. For the rest, users should consider carefully the viscosity data reported for highly concentrated nanofluids without rheological data.

2.1. Data collection

Data collection was done primarily within the project NanoORC (`www.nanoorc.mek.dtu.dk`), and was completed with additional data by the Dortmund Data Bank. The data input software developed by the Dortmund Data Bank was used to structure the data, which were initially allocated in the form of spread sheets. The collection environment was enhanced to allow for the full description of parameters of the nanofluid systems, as well as the inclusion of comments (*e.g.*, system preparation). This was needed since the inclusion of solid nanoparticles in a fluid extends the system degrees of freedom beyond those of fluid mixtures, as not only composition is added as an adjustable variable, but also the intrinsic properties of the nanoparticles, and their geometry. For instance, it is generally accepted that the material, shape and dimensions of nanoparticles have a measureable effect on the thermal and thermophysical behavior of nanofluids. As a consequence, the most recent studies reporting thermophysical and heat transfer measurements of nanofluids always describe these variables. However, despite it is well known that the stability affects the nanofluid properties, it is difficult to evaluate, and only a few studies have analyzed their impact in individual systems.

The current database contains 7639 data points (with 8118 experimental data records) for 7 thermophysical properties of nanofluids formed by the combination of 13 base fluids and 19 nanoparticle materials. Figures 2 and 3 show the distribution of the collected data for different properties, base fluids, and nanoparticle types. As it can be observed, most of the measured property values correspond to density ρ , dynamic viscosity μ , and thermal conductivity k , accounting for 45%, 47%, and 12% of the data, respectively. This distribution reflects the needs from the study of heat transfer fluids, where these properties are essential to evaluate the impact of nanoparticles on the heat transfer and pressure drop of the nanofluids. Water-based nanofluids are, by far, the most studied systems, as pointed out in previous works [19, 22]. This is because the use of water may counteract the increase in cost derived from the addition of nanoparticles, but also, because water has the highest thermal conductivity among liquids. Besides, there is a significant number of data for ethylene glycol and polyethylene glycol, or their mixtures with water, as these are common heat transfer fluids in industry. Despite the interest that refrigerant-based nanofluids may have as coolants [23], data for these kind of systems is scarce. In this regard, Nair et al. [24] pointed out that controlling the composition during the laboratory preparation of nanofluids is easier when the base fluid has a low saturation pressure, as minimal vaporization of the fluid is to be expected during the preparation. However, base fluids with high volatility may result in nanofluids with unreliable composition, and therefore may require specific setups for ultrasonication using low-temperatures to ensure minimum sample loss.

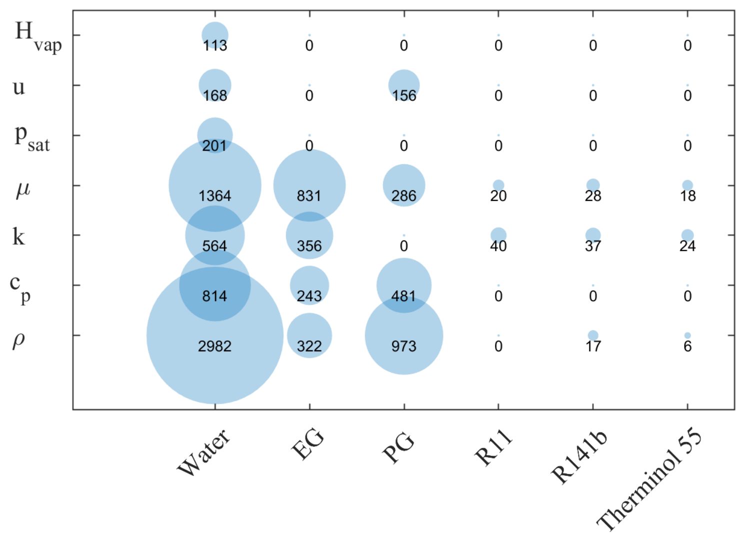

Figure 2: Distribution of the experimental data available in the database, per base fluid and thermophysical property. The number of available data is indicated in numbers.

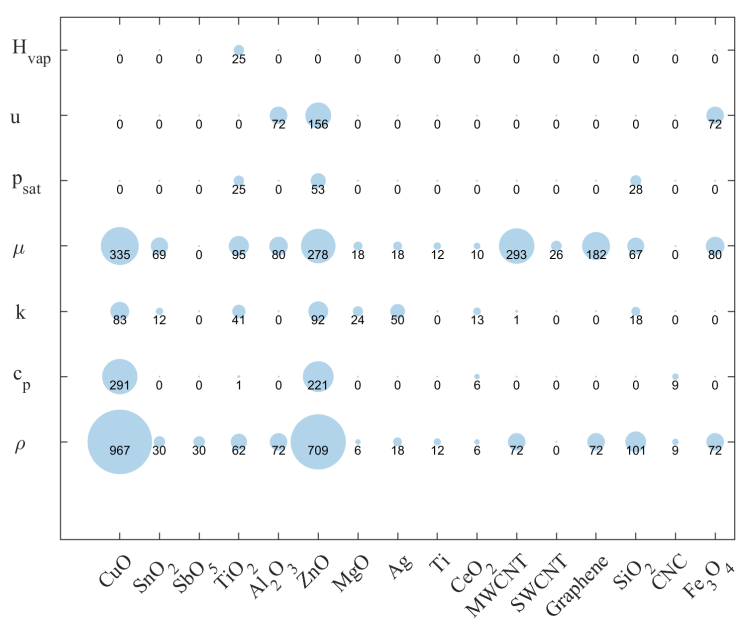

Figure 3: Distribution of the experimental data available in the database, per nanoparticle type and thermophysical property. The number of available data is indicated in numbers.

2.2. Data quality

A number of challenges were faced during the collection and organization of the data, concerning the data availability and reporting characteristics [4]. If the quality of the reported data is evaluated following the standards defined by Chirico et al. [25], it was found that in a great part of the included sources the reported data lacked enough quality. The main quality issues found in the published literature on thermophysical properties of nanofluids are enumerated as follows, by order of severity (starting with the most severe issue):

- The majority of the experimental data were reported only in the form of plots, some of which had very low resolution. This was found as a common practice in the field, also observed in the field of heat transfer research, where numerical data was not provided in tables within the manuscript, appendixes, or supporting information. However, some works do provide the raw data, and a few authors in more recent publications provided the raw data when contacted during the collection process, which contribution is gratefully acknowledged in the Acknowledgments (Section 6). It must be pointed out that only data from plots with sufficient resolution were included in the database, so that small deviations during the graphical collection of the data points did not have a significant impact in the reported value.

- Another common practice in this field is the use of a volume fraction based scale for specification of nanoparticle concentrations. Reasons for this may be the fact that the first equations evaluating the increase of thermal conductivity of nanofluids by Choi and Eastman [2] was reported as a function of the nanoparticle volume fraction. Similarly, the first equations to predict the viscosity of nanofluids were based on Einstein's law for solid suspensions [26], which was also expressed as a function of volume concentration. Moreover, since most of the experiments up to date have been carried out at ambient temperature, significant volume changes due to temperature variation are not expected. Additionally, some sources dealing with blends as base fluid reported their composition also on a volume basis. It is important to remark that concentrations of components in a mixture should be reported in mass fractions, as these are independent from temperature and pressure.

- A few sources contained errors in the units of the reported values (especially in the case of dynamic viscosity). These unit errors were assumed to be typos and corrected in the database.

- A number of sources, especially those investigating also the heat transfer behavior of nanofluids, reported thermophysical properties in the form of ratios with respect to the properties of the base fluid. While the use of ratios is a very intuitive way to show if nanoparticles enhance or not a certain property, the ratios should always be accompanied with the raw data obtained during measurements, or at least the measured data for only the base fluid (*i.e.*, this is of special importance in cases were base fluids are not well defined, such as commercial synthetic oils).

- A few sources, especially those published earlier in time, provided an incomplete definition of the characterized nanofluid system (*e.g.*, information on nanoparticle shape or dimensions are missing). Since it has been proved that the inherent properties of the nanoparticles can influence the thermal conductivity and dynamic viscosity, it is important that new publications with thermophysical data of nanofluids provide the complete description of the fluid system.

The importance of good quality data for the thermophysical properties of nanofluids is critical to reduce the uncertainty on their reliability and avoid overestimation of their favorable thermal characteristics, which could lead to under dimensioned heat exchanger equipment, or failure in the design of lubricating systems using nanofluids. Therefore, it is necessary to establish a standard for the reporting of thermophysical properties of nanofluids, as defined in Section 4.1.

The development of a database with experimental data supports quick checks for quality control of the data, where the comparison of values among different datasets and systems may allow identifying potential outliers, as explained in Section 4.2.

3. First release

The first release of this database accounts for data from publications up to year 2020. The collection contains 307 datasets from 59 sources, including original journal publications and conference proceedings published during the time period from 1998 to 2019. To the best of our knowledge, this database collects the most relevant thermophysical experimental data for nanofluids of different base fluids and nanoparticle types. Some data may have not been included due to poor readability in the graphical collection or lack of description of the system (see Section 2.1). The database can be accessed through the free explorer version of the Dortmund Data Bank at http://www.ddbst.com/explorer_version.html?. The data related to nanofluids can be found in the databank 'X-Different Thermodynamic properties' and under Property type 'nanofluids'. Figure 4 shows a screenshot of the list of nanofluids references in the explorer version.

Researchers reporting experimental thermophysical property data for nanofluids are encouraged to contact the database managers at Dortmund Data Bank or the corresponding author of this paper (email address: frh@mek.dtu.dk) concerning inclusion of their work in the data collection, which should be provided in a required format. The long-term update of this database will depend on the active participation of the user community. The authors of the present paper intend to keep the database updated and revised when new experimental data are published.

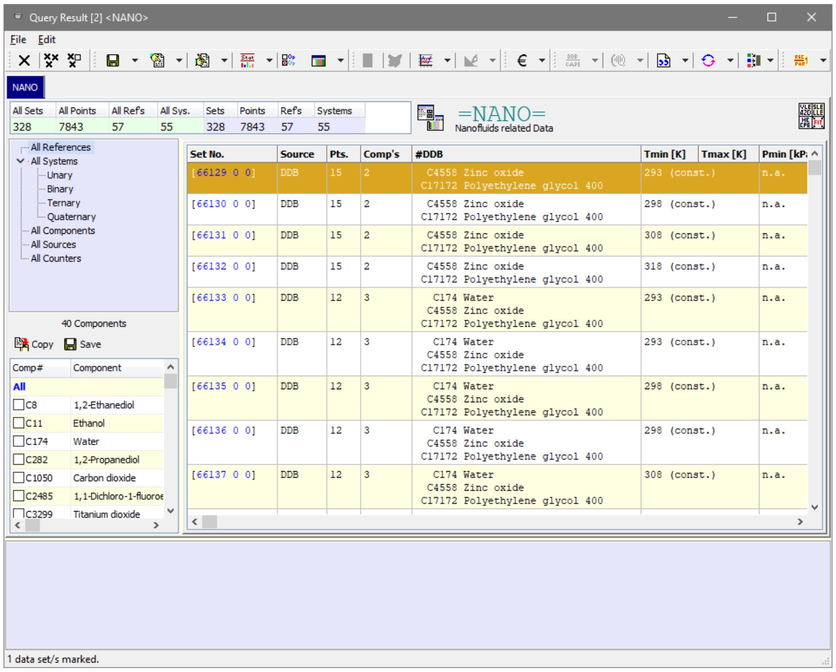

Figure 4: Screenshot of the explorer of the Dortmund Data Bank showing the list of references with nanofluids data.

4. Discussion

The developed database allows for a comprehensive critical evaluation of the measured properties for selected base fluids, nanoparticle material, and other nanoparticle features. Thanks to the inclusion of a complete description of the nanofluid system (where this information was available), it is possible to compare results among different systems, and sources. This database provides a number of main contributions to the research in the field of thermophysical properties of nanofluids, which are discussed as follows.

4.1. Necessity of a standard

First, during the data collection process it became evident that there is a lack of a reporting standard for experimentally determined thermophysical property data of nanofluids. This is not new in the thermophysical properties community, as similar issues were observed some decades ago for other types of fluids. In fact, issues pointed out in Section 2.2, were also found

Table 1: Percentage distribution of the described issues in the data collected from the considered publications.

Description issue	Percentage of data
No nanoparticle diameter	48
No nanoparticle diameter distribution	5
No surfactant information	14
Concentration given on a volume basis	53
Properties reported only as ratio	2
Preparation method not indicated	14
Data reported only in plots	65

in the reporting of thermophysical properties back then [25], motivating the definition of reporting standards, that have resulted in a high quality of the thermophysical data published today. Therefore, we believe that the novelty of the study of nanofluids should not be used as a justification for repeating the same errors.

Following this trend, it is essential that new data meet the quality standards discussed in the present paper, which will contribute to reducing the current uncertainty concerning the thermophysical behavior of nanofluids, facilitate the development of predictive models, and bring confidence from the general public.

As already mentioned in Section 2.2, most of the thermophysical property data in this field are reported only in plots (accounting for approximately 65% of the data), making it difficult to extract the information for their evaluation. Therefore, authors are encouraged also to provide the raw data in tables within the manuscript or as supplementary information.

4.2. Identification of average properties and outliers

Second, the arrangement of all the available experimental data for different systems in the form of a database allows the selection and quick comparison of existing data, therefore facilitating the identification of general trends, the value distribution of the data, and drawing of general conclusions. The observation of all the collected data against a single variable can, therefore, bring insight on the significant scatter for some experimental data for similar systems, and possible outliers. Here it is important to mention that the presence of outliers does not necessarily mean that the quality of the data set is poor, as the outlying value(s) of the property may be due to a specific parameter of the nanofluid system. As an example, Figure 5 represents the ratio of the thermal conductivity of nanofluids with different base fluids to the thermal conductivity of the base fluid at the same conditions, versus the volume-based nanoparticle concentration. As it can be seen, for most of the reported data, the increase in thermal conductivity lies within 20% of the base fluid, and only a few data show increases of up to 60%. Further data analysis reveals that these data correspond to nanofluids in which the base fluid is a refrigerant with high volatility and significantly lower thermal conductivity, which could explain the observed greater thermal conductivity ratio.

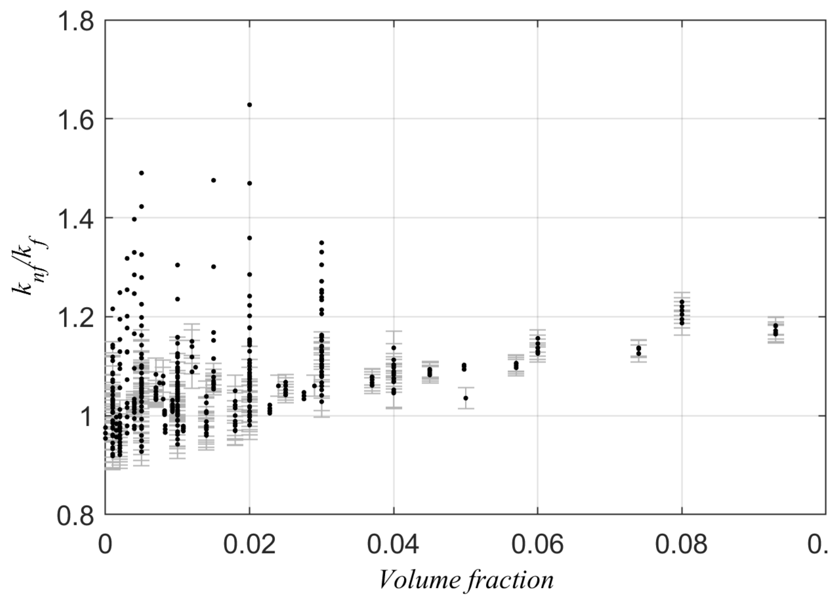

Figure 5: The ratio of the thermal conductivity of different nanofluids to the thermal conductivity of the base fluid at the same conditions k_{nf}/k_f (calculated for the same conditions using Refprop v.10. [27]), versus volume-based concentration. The uncertainty of the reported values is indicated for the data for which it is available.

4.3. Identification of the parameters governing the thermophysical behavior of nanofluids

Third, being able to compare the variation of a specific magnitude against different features of the nanofluid systems allows the identification of the sensitivity of the magnitude to the variation of different parameters. This analysis can provide support in the design of experiments and analysis of systems, identifying the nanofluid features that have a major impact on the studied property. Figure 6 presents the ratio of the dynamic viscosity of aqueous based nanofluids to the dynamic viscosity of water in the same conditions, versus the volume-based nanoparticle concentration. As it can be seen, the dynamic viscosity increases with the addition of nanoparticles. However, the increase rate is different among different data sets. When representing the data colored according to the dimensions of the nanoparticles, it can be seen that smaller nanoparticles cause a greater increase in relative viscosity with concentration. This is in agreement with the observations presented by Rudyak and Krasnolutskii [28], that the viscosity of nanofluids increase with decreasing nanoparticle size.

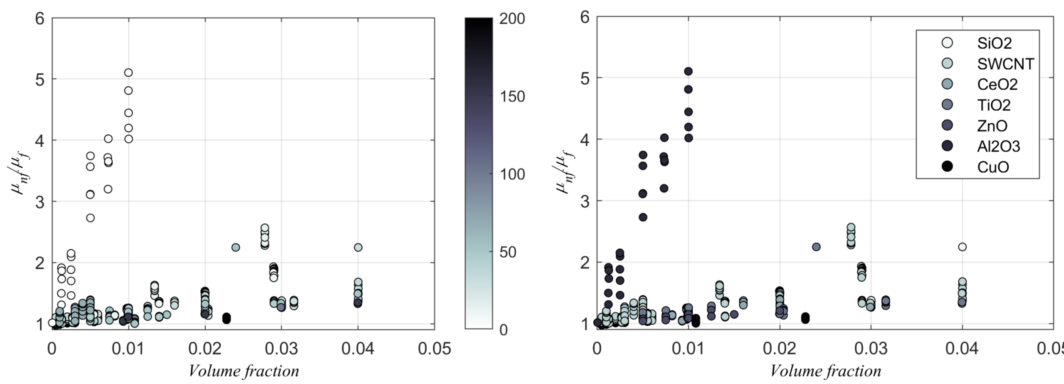

Figure 6: The ratio of viscosity of nanofluids to the viscosity of the base fluid μ_{nf}/μ_f (calculated at the same conditions using Refprop v.10. [27]), versus volume-based concentration. On the left figure, color indicates the size of the nanoparticles, shown in nm in the colorbar. On the right figure, the color indicates different material of the nanoparticles.

4.4. Directions for future research

In view of the statistics on the contents of the database, the data quality, and the analysis possibilities mentioned in the previous section, the following recommendation for future research can be made:

- Although water is the most relevant base fluid for the formulation of nanofluids, due to its high thermal conductivity, availability and low cost, there are indications that nanoparticles can also improve substantially other types of fluids, such as lubricants and thermal oils. In this context, Buongiorno et al. [5] found that the affordable thermal conductivity enhancement by nanofluids increased with decreasing base fluid thermal conductivity. Therefore more experimental data is needed for other base fluids, for which so far, scarce data is available.

- A large part of the nanofluids studies use nanoparticles of dimensions equal or larger than 30 nm. Given the important effect that small nanoparticles can have on viscosity, extending the study towards smaller nanoparticles may be of interest.

- New experimental data should comply with the recommendations discussed in the present paper for the correct description of the fluid system, including as much data as possible for the dimensions and morphology of the nanoparticles, and providing uncertainty estimations for the reported thermophysical properties.

5. Conclusions

This work presents the release of an open-access comprehensive database of experimental thermophysical property data of nanofluids. The considered nanofluid systems consist of a base fluid (which can be a pure compound or binary mixture) and a single type of nanoparticle. The database allows the quick evaluation of the measured properties for selected base fluids, nanoparticle material, and measurement conditions. The following conclusions were drawned from the development process of the database:

- The database presented in this work is the first open access, and comprehensive source of thermophysical property data for nanofluids, and it is freely available through the free version of the Dortmund Data Bank explorer at http://www.ddbst.com/free-software.html.

- Thermophysical property values in the database are characterized with estimated expanded uncertainties, whenever their value was provided in the source.

- Most of the available property data is for water-based nanofluids, although some data exist for common refrigerants, glycol mixtures, and synthetic oils.

- The most studied properties are, by order of number of data, density, dynamic viscosity, thermal conductivity, and heat capacity. A few studies have also reported data of speed of sound, saturation pressures and vaporization enthalpies.

- Despite the amount of collected data may appear high, the higher number of degrees of freedoom of nanofluids results in low amount of data for specific systems.

- Authors reporting experimental thermophysical property data of nanoflu-ids are encouraged to contact the corresponding author of the present paper (email address: frh@mek.dtu.dk) concerning the inclusion of their work in the collection.

6. Acknowledgements

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