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Impact of Nanofluids and Specific Frequency Absorbers in Parabolic Trough Collector Solar Furnaces

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1: Abstract

This meta-study aims to identify methods of optimising efficiency of upcoming parabolic trough collector (PTC) solar furnace technology by analysing thermodynamic properties of both: solar absorbers SiC, Pyromark 2500, Polychromic Al-AlN and C54-TiSi2 nanoparticles; and heat transfer nanofluids SiO_2, TiO_2, Al_2O_3, Cu and Al_2O_3-Cu with a 50:50 ratio. The thermodynamic properties investigated are energy absorbance and emittance, melting point, thermal conductivity and viscosity. Our study revealed that the optimal transfer fluid is the hybrid nanofluid Al_2O_3-Cu of 50:50 ratio with a 1-2% volume fraction in an ethylene glycol base. The optimal solar absorber for use in combination with this nanofluid was found to be polychromic Al-AlN cermet absorber.

Keywords: Parabolic trough collector; solar power; nanofluids; nanoparticles; high absorption materials; meta-analysis

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Nomenclature

η: viscosity

Nu: Nusselt Number

k: Thermal Conductivity

D: Pipe Diameter

A: cross sectional area for heat transfer

m: mass flow rate

ΔT: Temperature at heat transfer boundary

Q_u: Useful Energy

Q_s: Available Energy

h: Convection Coefficient

Pr: Prandtl number

nf: nanofluids

bf: basefluids

p: nanoparticle

2: Introduction

Due to the increasing demand for reliable and renewable energy sources, higher efficiency power generation technology is essential to meet increasing electrical energy requirements. Solar energy is one of the most abundant sources of renewable energy available on earth, with areas in Africa, America, Asia and Australia commonly receiving upwards of 7 kilowatt hours per square meter of direct normal irradiation per day [1]. Taking advantages of this energy has been the focus of countless technological advancements since the industrial revolution and continues to be one of the most popular fields of research to date.

An advancing technology in the harnessing of solar power is the Parabolic Trough Collector (PTC). In this system, solar radiation is reflected by a parabolic mirror onto the surface of the absorber tube as shown in Figure 1. A transfer fluid within the tube then absorbs the heat conducted through the surface of the tube. Modern PTCs use a variety of transfer fluids, such as molten salts with high specific heat capacity, synthetic oils with low viscosity, and aqueous solutions that carry heat utilising evaporative techniques [2]. This transfer fluid then transports generated heat to an engine which produces electricity.

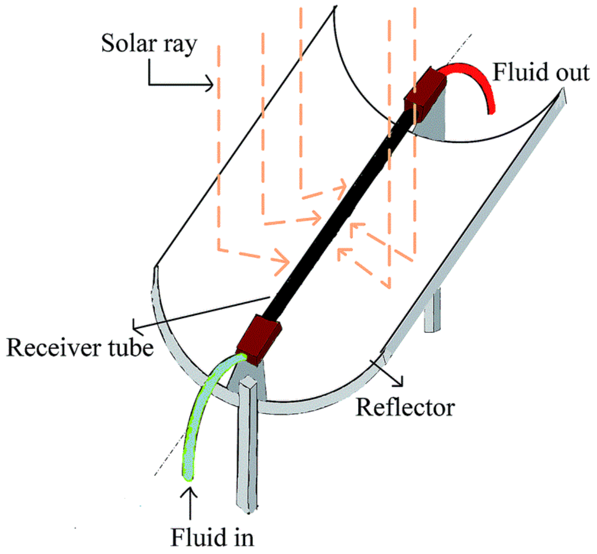

Figure 1. Design of the pipe & mirror components of a parabolic trough collector. Credit to Soroush Dabiri (Dabiri, Rahimi 2016, 3rd International Conference and Exhibition on Solar Technology)

The particular component of the system that this paper will be focusing on is the tube system. Despite the simplicity of the core concept, advanced technologies can be applied to these systems that drastically increase their efficiency. These technologies come from fields such as nanomaterials, photonics, optics and advanced materials. This meta-analysis focuses on the potential improvements that can be made to the tube system using advanced black body and specific frequency absorption coatings and nanofluid-enhanced transfer fluids. Advanced absorbers are investigated as they have become increasingly popular over the last few years and, as a result, have experienced substantial improvements to the feasibility and efficiency [3]. For similar reasons, nanofluid based non-evaporative PTC systems have been analysed. Advancements in nanomaterial synthesis processes have facilitated study in a wide variety of nanofluid applications, thus over time research has shown that nanofluids are better heat carriers than normal heat transfer fluids [4].

This meta-analysis aims to collate a wide variety of data on recent advancements in the fields of advanced absorbers and nanofluids. These advancements are assessed and discussed in relation to the properties that make them useful in PTC. The information found is used to summarise recent advancements in PTC research. Additionally, the information is combined with thermodynamic principles in order to propose a combination of new technologies that could be used to construct an optimally efficient solar collection, transformation and transport system.

3: Methodology

This meta-analysis was conducted using research that investigates the properties of two components of the PTC system: the absorbers used to convert sunlight into heat, and the thermal fluids used to transport that heat. The results of each study were collated in respect to their component of focus so that broad and reliable figures could be drawn for conclusions. These figures were then used to propose the properties of an ideal PTC design. For the sake of validity, only papers from the last ten years were used as sources and papers with little to no recorded citations for the duration of their availability were excluded.

Papers were drawn from multiple scientific databases. These were: Science Direct (Elsevier), The Journal of Applied Physics, Research Gate, Springer Link, and the American Institute of Physics. Some statistics, constants and designs were also drawn from industrial databases such as The World Bank's solar research program, Solargis, and Tempil temperature indication technologies. These sources have been chosen as the cited parties would likely be involved in the development and distribution of the technology examined in this meta-analysis.

The scope of this meta-analysis has been limited to strictly thermodynamic perspectives for the ease of the reader. Social, political, cultural, economic and logistical perspectives have not been formally assessed, as these aspects are either too problematic or nuanced to be commented on by non-field-experts. The thermodynamic perspective has been chosen primarily in order to assess the ideal and achievable efficiencies of PTC systems by analysing the properties of their individual components and the thermal interactions between them.

When collecting and using data, various similar experimental results were sampled and averaged to provide more practically expectable results. Equations and data (from figures) were also taken from reputable papers and used to calculate required values and create original figures for analysis. This data includes specific heat capacities, thermal conductivity, density, emissivity, viscosity, optimal operating temperature, and boiling point. Using this data, the thermal properties of the PTC pipe system were modelled based on our interpreted superior materials and properties. As this meta-analysis focuses on the pipe system only, the attached solar furnace and respective engine efficiency. Instead the system was modelled with focus on its ability to retain heat. This model incorporated thermal radiation and heat transfer theories and equations to describe the processes the energy generated by this system undergo.

4: Results

4.1: High Absorption Coatings

Black body absorbers and selective frequency absorbers were studied to assess the efficiency of precision absorption bandwidths compared to standard black body absorption techniques. These absorbers take the form of layered materials that can be used to treat a surface and nanoparticles that are grown on a substrate. Many absorbers were researched for this meta-analysis, but only four were selected to be analysed in relation to the rest of the system. These absorbers are Silicon Carbonate, Pyromark 2500, Polychromic Al-AlN cermet and C54-TiSi2 Nanoparticles. These materials were selected for their high absorbances (either theoretically or measurably) over specific operation temperatures. This way the right absorber may be applied to a system based on its other thermal requirements. Figure 2 lists the chosen materials and their properties at optimum output.

Material	**Absorbance (*e*)**	**Power (Suns)**	**Temperature (K)**
SiC	90%	500	292
Pyromark 2500	95%	500	1228
Polychromic Al-AlN	94.2%	n/a	353
C54-TiSi2 Nanoparticles	94.4%	1000	1023

Figure 2. The names and relevant properties of the final four selected solar absorbers (X. Wang et al, 2018; D. Bellas, E. Lidorkis, 2017; K. Burlafinger, A. Vetter, C.J. Brabec, 2015; C. Wang et al, 2016; Hofmeister et al, 2009). At the time of writing, no substantial data could be sourced on the optimal incident solar intensity for polychromic aluminium.

Parabolic trough collector based solar furnaces tend to favour high operating temperatures due to Carnot efficiency principles and heat retention ability [3]. For this reason, multiple absorbers were assessed with very high heat thresholds and optimum absorption temperatures. However, the operating temperature of the system is limited by the thermal robustness of the transfer fluid used to store generated heat. Considering this meta-analysis assesses a wide variety of nanofluids, some with lower temperature thresholds than others, several low-optimum-temperature absorbers were assessed as well.

The emission spectra of nano-C54-TiSi2 was compared to the spectra of the remaining three absorbers on account of the nanoparticles ability to be added to various other materials. C54-TiSi2 was found by X. Wang et al. to be extremely useful in this regard due to it's thermal robustness and high percentage absorbance in specific frequencies. This analysis found that, in conjunction with Silicon Carbide [5] or Pyromark [3] based absorbers, overall absorbance could potentially be increased due to the difference in absorbance wavelengths and similarities in operation temperatures. This potential is not shared with the Al-AlN cermet however, as it does not possess the same thermal robustness as nano-C54-TiSi2 [6]. Furthermore, polychromic Al-AlN cermet out-performs nano-C54-TiSi2 over low operating temperatures.

4.2: Heat Transfer Fluids

Nanofluids are more recently being investigated as the transfer fluid for use in PTCs. These nanofluids consist of a base fluid such as water containing nanoparticles usually made up of metals, oxides or carbon nanotubes. The most common nanoparticles used in PTC technology are Al_2O_3, TiO_2, Cu, and SiO_2 and for base fluids, the most commonly used are water, ethylene glycol and Syltherm800 thermal oil. Because of the breadth of research on these particular materials, they have been decided on as the focus of our study on transfer fluids.

Properties of these base fluids and nanoparticles were analysed to determine the most suitable for use in PTCs. Values collected from the papers along with equations 1 and 2 were used to create the figures below, that facilitated simple comparison of the thermal properties of nanofluids under study. It also allowed us to find the most efficient heat transfer fluid to be used in PTC systems.

4.2.1: Base fluids

Figure 3 below shows the thermal conductivity of the base fluids (water, ethylene glycol and Syltherm800) at different temperature based on the collected results. Also, in Figure 4 we plotted the viscosity versus temperature graph of the same base fluids.

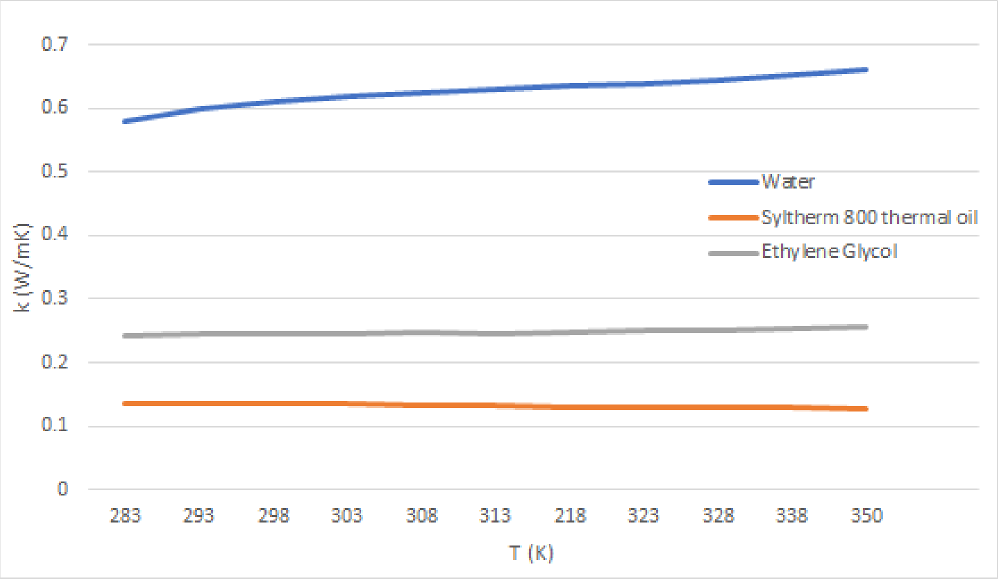

Figure 3. Thermal conductivity (k) of the base fluids water, Syltherm 800 and ethylene glycol as a function of temperature (T) (Allouhi et al. 2018; Bellos & Tzivanidis 2018; Syam Sundar, Singh, & Sousa 2014; Pastoriza-Gallego et al. 2011)

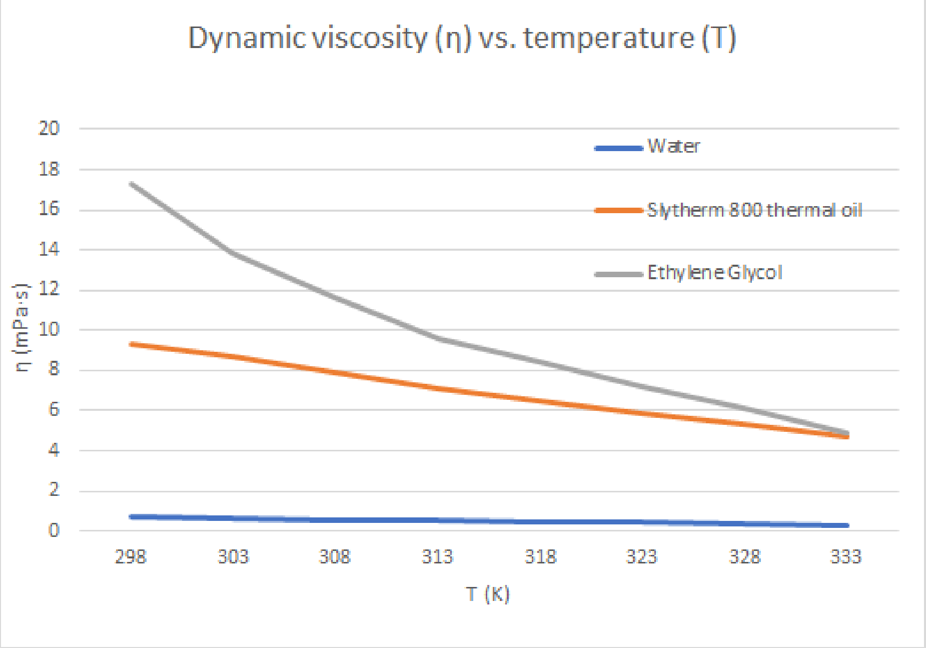

Figure 4. Viscosity (η) of the base fluids water, Syltherm 800 and ethylene glycol as a function of temperature (T) (Allouhi et al. 2018; Bellos & Tzivanidis 2018; Madhesh, Parameshwaran, & Kalaiselvam 2014; Syam Sundar, Singh, & Sousa 2014; Pastoriza-Gallego et al. 2011)

As seen in Figure 3 water held the highest thermal conductivity which increase proportional to temperature over the given range. Syltherm800 and ethylene glycol had much lower average thermal conductivity with Syltherm800 as the lowest overall. Water can be seen (Figure 4) to have the lowest viscosity, nearly constant with change in temperature over the given range at around 1mPa·s approaching 0. Ethylene glycol has very high viscosity at low temperatures, but this quickly drops as temperature increases to approach the viscosity of Syltherm800 at 333K. Hence, it can be said that ethylene glycol is the most optimal base fluid to be used.

In order to judge the appropriateness of each base fluid for use in the PTC a relation was derived between the system efficiency and the parameters in question, thermal conductivity and viscosity. Reynolds number (Re) is given by:

$$\mathrm{Re} = \frac{4 \cdot \mathrm{m}\pi}{\mathrm{D} \cdot \eta}$$

Therefore, by eliminating the constants we can write the proportionality relationship:

$$\mathrm{Re} \propto \frac{1}{\eta}$$

Also, the efficiency of the PTC system is given by the ratio of Q_u (useful energy), and Q_s (available energy).

$$efficiency = \frac{Q_u}{Q_s}$$

$$Q_u = h \cdot A \cdot (\Delta T)$$

$$h = \frac{Nu \cdot k}{D}$$

$$\mathrm{Nu}=0.023\mathrm{Re}^{0.8}\mathrm{Pr}^{0.4}$$ [6]

Therefore

$$efficiency = \frac{0.023\left(\frac{4 \cdot \mathrm{m}\pi}{\mathrm{D} \cdot \eta}\right)^{0.8} \mathrm{Pr}^{0.4} \cdot k \cdot (D)^{-1} \cdot A \cdot (\Delta \mathrm{T})}{Q_s}$$

All terms except η and k are constant for constant flow rate for a specific fluid in a constant state (see nomenclature for definitions). Therefore, by eliminating the constants we can write the proportionality relationship:

$$efficiency \propto \frac{1}{\eta} \propto k \qquad [1]$$

As a result, it is preferable to choose a base fluid with low viscosity as this increases the flow turbulence which in turn increases the efficiency of the PTC. A high thermal conductivity is also important in maximising the efficiency of energy transformation. Water showed maximum values in both these properties but was decided against due to its low boiling point. It is possible to use water as a base fluid as high temperatures using a pressurised system, however Coccia et al. (2016) reports this leads to many complications and additional costs and is not recommended. Furthermore, the authors of Coccia et al conclude that only minor improvements to system efficiency can be yielded by the addition of nanoparticles. Therefore, water was decided against to be used as the base-fluid in the study.

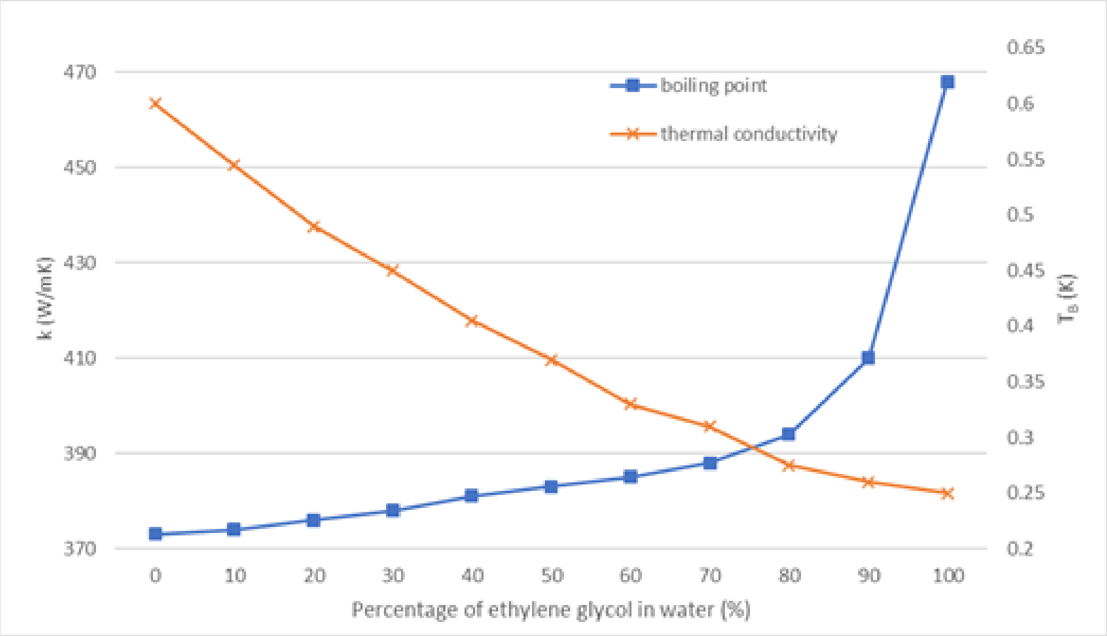

Figure 5. Boiling point (TB) thermal conductivity (k) as independent functions of percentage of ethylene glycol in water, (Pastoriza-Gallego et al. 2011), (The MEGlobal Group of Companies 2008)

A mixture of ethylene glycol and water was considered in order to draw on both the high boiling point of ethylene glycol and the high thermal conductivity and low viscosity of water. Figure 5 was constructed to find the optimal ratio of the two fluids. It can be seen however that the boiling point of the fluid rises exponentially with increased ethylene glycol concentration. This means that even a small addition of water causes a large decrease in boiling point. It was decided for this reason that any gain in thermal conductivity by adding water is not worth the subsequent decrease in boiling point.

Ethylene glycol was chosen as the optimal fluid. As it has a relatively high thermal conductivity and at high temperatures its viscosity drops dramatically.

4.2.2: Nanoparticles

Many nanoparticles are in use for PTC technology but the four most common were found to be SiO_2, TiO_2, Al_2O_3 and Cu [4]. These were chosen for analysis as there is a wider range of research on these materials from which to collect data, leading to more reliable and consistent results. The properties of the nanomaterials in question are displayed in Figure 6.

Nanoparticles	Density (kg/m^3)	Specific heat (J/kg·K)	Thermal conductivity (W/m·K)
SiO_2	2200	0.97	1.4
TiO_2	4240	689	8.7
Al_2O_3	3963	769	40
Cu	6000	551	383

Figure 6. properties of the studied nanoparticles SiO2, TiO2, Al2O3 and Cu (Allouhi, Benzakour Amine, Saidur, Kousksou & Jamil 2018), (Bellos & Tzivanidis 2018), (Rafati, Hamidi & Shariati Niaser 2012), (Patel, Sundararajan & Das 2010), (Donghyun & Debjyoti 2011)

It can be seen from the above table that Cu and Al_2O_3 possess superior thermal conductivity. Al_2O_3 also exhibits highest specific heat. Although Cu has slightly lower specific heat compared to TiO_2, its thermal conductivity is far greater.

4.2.3: Nanofluids

Nanofluids comprising of the nanoparticles listed in figure 3 were analysed through their properties of thermal conductivity and viscosity in order to find the most efficient in accordance to equation (1). Both mono and hybrid nanofluids were investigated.

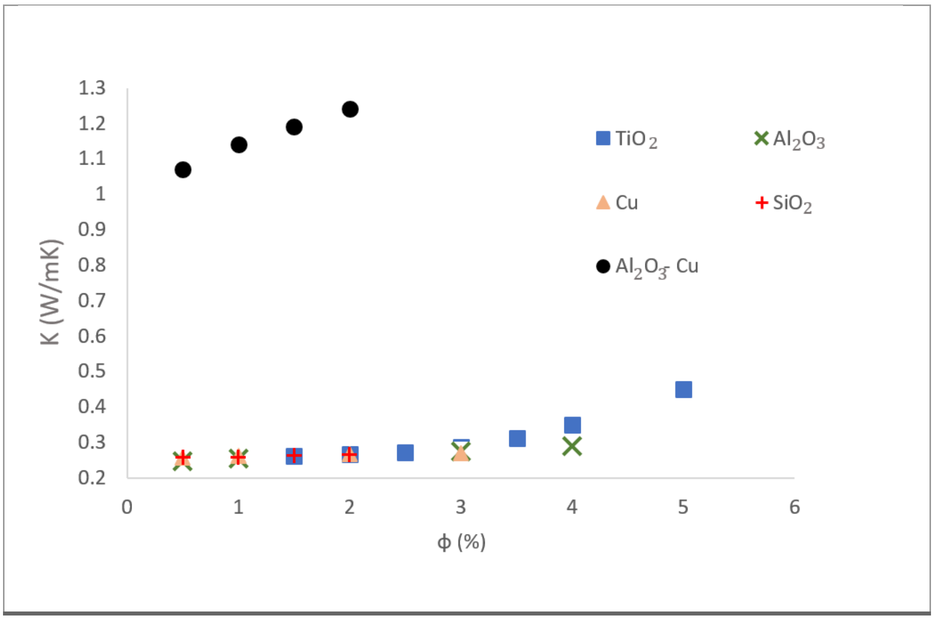

Figure 7. Thermal conductivity (k) as a function of volume fraction (ϕ) for ethylene glycol based nanofluids enhanced by nanoparticles; TiO_2, Al_2O_3, Cu, SiO_2 and Al_2O_3-Cu (hybrid), (Murshed, Leong, & Yang 2008; Pastoriza-Gallego et al. 2010; Garg et al. 2008; Nikkam et al. 2017; Akilu et al. 2017; Parsian, A. & Mohammad, A. 2017)

As seen in Figure 7, the hybrid nanofluid investigated (Al_2O_3-Cu) produced much higher thermal conductivity than the mono nanofluids investigated. The data from Figure 7 is represented on a smaller scale to better represent the trends apparent.

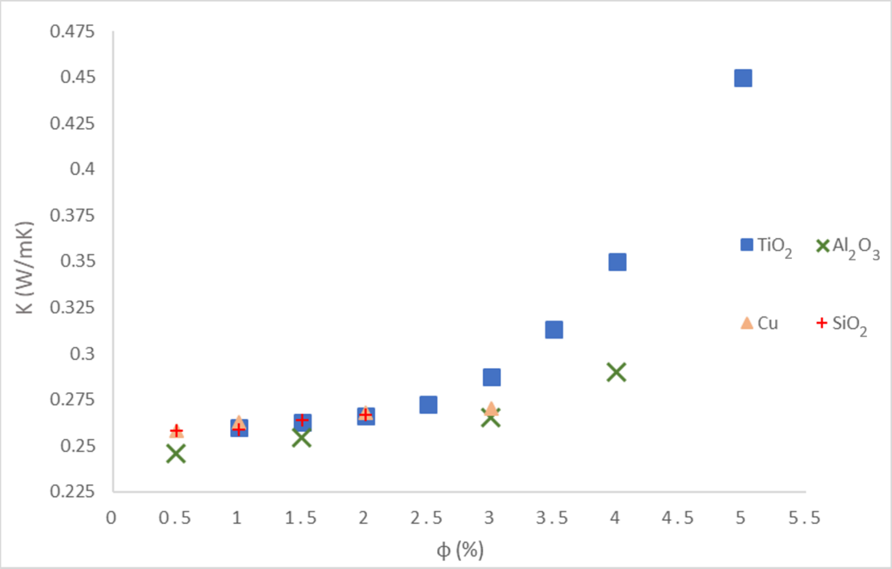

Figure 8. Thermal conductivity (k) as a function of volume fraction (ϕ) for ethylene glycol based nanofluids enhanced by nanoparticles; TiO_2, Al_2O_3, Cu and SiO_2 (Murshed, Leong & Yang 2008; Pastoriza-Gallego et al. 2010; Garg et al. 2008; Nikkam et al. 2017; Akilu et al. 2017)

Figures 7 and 8 present an obvious increasing trend of thermal conductivity with concentration of nanoparticles. Although the thermal conductivity of TiO_2 seems to increase exponentially; all other nanofluids exhibit a more linear relationship between thermal conductivity and volume fraction. This linear relationship is backed up by trends shown by Akilu et al. (2017), Parsian, A. & Mohammad, A. (2017), Nikkam et al. (2017) and Bellos & Tzivanidis (2017). It is further reinforced by Maxwell's equation,

$$k_{nf} = k_f \left(\frac{k_p + 2k_f + 2(k_p - k_f)\phi}{k_p + 2k_f - (k_p - k_f)\phi} \right) \quad [2]\ (2)$$

which describes a linear relationship between the thermal conductivity of the nanofluid and the volume fraction at constant temperature, shown by Mehta, Chauhan, & Kanagaraj (2011).

It is shown by Bellos & Tzivanidis (2017) that the viscosity of a nanofluid can be calculated by the equations:

$$\eta_{nf} = \eta_{bf} \cdot (1 + 2.5 \cdot \phi + 6.5 \cdot \phi^2)$$

and

$$\eta_{nf} = \frac{\eta_{bf}}{(1-\phi)^{2.5}} \quad (3)$$

The above equations show that the theoretical viscosity of a nanofluid is only dependant on the volume fraction of the nanofluid and the regular viscosity of the base fluid. For this reason, this paper does not compare the viscosities of different types of nanofluids with common bases. Instead the nanofluid with the highest thermal conductivity was selected and its conductivity and viscosity over various volume fractions was compared. The chosen nanofluid was a 50:50 mix of Al_2O_3 and Cu. Figure 9 shows the viscosity and conductivity of Al_2O_3-Cu from 0 to 4% volume fractions. Viscosity was calculated using equation (3). Viscosity is graphed in descending order on the second y-axis to better illustrate where the volume fraction minimises viscosity while maximising thermal conductivity. Due to the linear relationship between thermal conductivity and volume fraction (as outlined above and in equation (2) a linear trend line is chosen to show the predicted thermal conductivity over a wider range of volume fraction of nanoparticles. Figure 8 was used to determine the volume fraction of 50:50 Al2O3-Cu that maximises thermal conductivity and minimises viscosity. This volume fraction was found to be in the range 1-2% volume fraction.

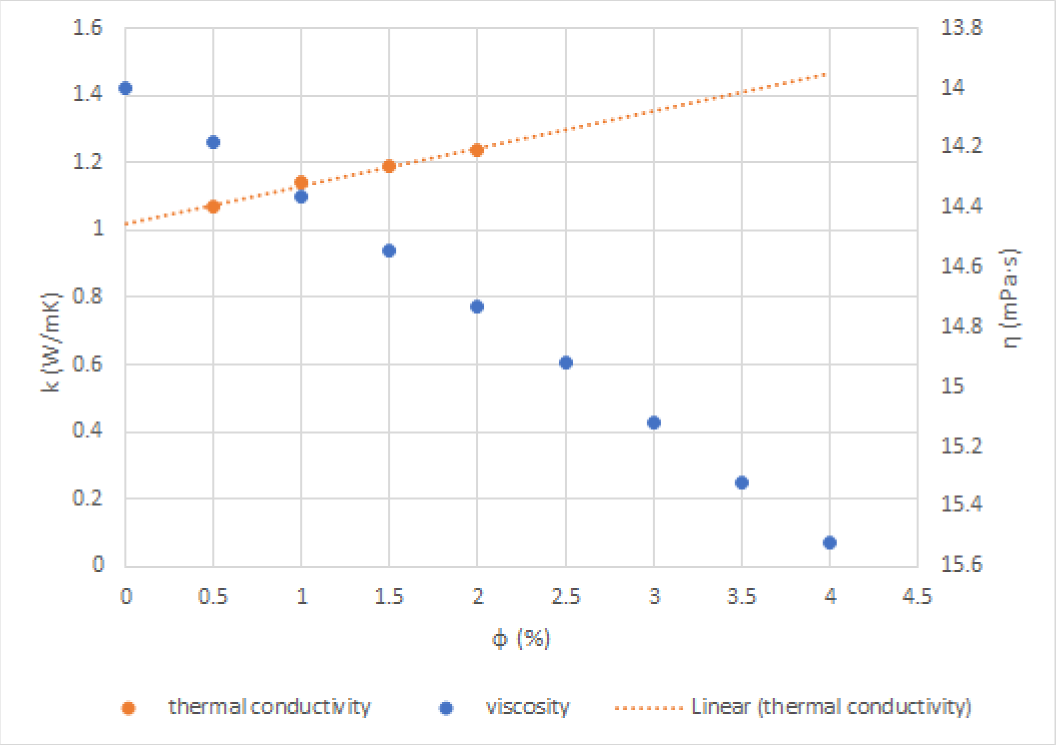

Figure 9. The viscosity axis of this graph has been flipped to create a crossover point near which the properties of the nanofluid will be optimised.

5: Discussion

In this meta-analysis multiple scientific articles were analysed to find the optimal pipe properties that would increase the efficiency of the parabolic trough collector based solar furnaces. In order to achieve that aim papers from past the 10 years were studied and the most reputable and relevant data was compared. Papers were analysed specifically from the fields of nanofluids, black-body absorbers and specific frequency absorbers with the aim of collating a diverse range of materials whose properties could work in conjunction with one-another in order to increase the efficiency and heat retention of the Parabolic Trough Collector system.

Several absorbers were analysed and considered, but the selection was trimmed down to just the materials that appear in this paper. This was either because the materials did not have properties that would have made them compatible with the system, or because there were other materials found that possessed better absorptions at similar temperature and solar concentration ranges. The four remaining materials then were Silicon Carbide (SiC), Pyromark 2500, Polychromic Aluminium + Aluminium Nitride, and Titanium Silicarbide nanoparticles. Each material has a specific property that makes it stand out from the others. Initially, Silicon Carbide is the only material that does not need to be layered onto another material. Silicon Carbides structural properties make it more than eligible for use as a fluid pipe, as it is used in the Solair Thermal Solar Power Plant in Switzerland. Pyromark 2500 was kept for final analysis as it has the highest operating temperature of all the absorbers analysed. Polychromic Aluminium remained in this paper as it is a low-temperature-operating, high absorption black body with specific high absorption frequencies. Finally, Titanium Silicarbide nanoparticles were further analysed as they can be grown on some other high absorption materials to add their specific absorption frequencies to the resulting composite.

In addition, various papers were analysed to find an ideal nanofluid that would maximize the efficiency of the entire process. To increase the PTC's efficiency, fluids with high thermal conductivity and low viscosity are necessary [7] (as show in equation (1)). Nanofluids were also judged by boiling point. Despite the model of Risi, Milanese & Laforgia (2013) showing that nanofluids can function evaporatively in PTC systems, this meta-analysis focuses on non-evaporative systems on account of a much greater breadth of pre-existing research. In this paper, the thermal conductivity and viscosity of commonly used base fluids: Water, Ethylene Glycol and Syltherm800 were compared. Although water exhibited optimal properties in terms of thermal conductivity and viscosity, Ethylene Glycol was considered the best to use because of its high boiling point which was decided more important in increasing the overall efficiency of the system.

Furthermore, the thermal conductivity and viscosity data of ethylene glycol based nanofluid was obtained with both mono and hybrid nanoparticles. The nanoparticles used to carry out this analysis are TiO_2, Al_2O_3, Cu, SiO_2 and hybrid Al_2O_3-Cu (50:50). Of the many nanofluids investigated it was decided the hybrid nanofluid consisting of Al_2O_3 and Cu with a ratio of 50:50 and volume fraction ranging 1-2% with a base fluid of ethylene glycol would provide the most efficient energy transfer in the system.

For the pipe system to operate non-evaporatively using the ethylene glycol Al_2O_3-Cu nanofluid the operating temperature is restricted to under $\approx$190°C. For this temperature polychromic Al-AlN cermet would provide optimal energy generation as it possesses the best absorption below 500° K of all absorbers analysed by this study [6]. For operating temperatures up to 1383°K this study recommends the consideration of a hybrid of Pyromark 2500 and nano-C_{54}-$TiSi_2$, as hybrid black-body and selective absorbers have shown not only incredibly high but robust thermal conversion efficiencies [3,8]. However, systems with such high temperatures would likely have to operate either conductively or evaporatively, and thus have not been studied in greater detail by this paper.

Despite the increasing popularity of investigated fields, there is still as shortage of sufficient data to make a conclusive statement on the properties of an ideal parabolic trough collector based solar furnace pipe system. Hybrid nanofluids showed great potential in terms of their thermal properties, however due to the lack of data in this area, only one hybrid nanofluid could be properly analysed. Further studies on this technology is highly recommended. In particular, due to the high thermal conductivity enhancement of TiO_2 nanoparticles with increasing volume fraction, it is suggested that the properties of TiO_2 based hybrid nanofluids are investigated.

6: Conclusion

This meta-analysis has assessed several enhancements that can be made to the pipe system of the parabolic trough collector based thermal solar generator. Specifically, these enhancements are the surface-coat absorber used to convert solar energy into heat and the fluid used in the pipe to transfer heat to a furnace or storage unit, we have constructed original figures using data and equations from reputable papers, to gather and reconfigure existing information in a succinct and easily accessible format for the comparison of nanofluids in heat transfer applications (specifically for use in PTCs). It was found that, out of all the assessed possible pipe systems, that a combination of a polychromic Al-AlN cermet absorber and a nanofluid consisting of an ethylene glycol based 50:50 Al_2O_3-Cu hybrid nanofluid with a 1-2% volume fraction would provide the optimum efficiency of heat generation and transfer. The operating temperature of this system constrains the energy generation per meter of pipe that this system possesses, but the optimisation of the process by which this heat is transformed into electricity is beyond the scope of this meta-analysis.

7: Acknowledgements:

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