Renewable and Sustainable Energy Reviews 55 (2016) 739–755

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

An investigation into the thermophysical and rheological properties of nanofluids for solar thermal applications

Owen Arthur, M.A. Karim *

Faculty of Engineering and Science, Queensland University of Technology, Brisbane, Queensland 4001, Australia

ARTICLE INFO

Article history:
Received 19 December 2014
Received in revised form
26 May 2015
Accepted 23 October 2015

Keywords:
Nanofluid
solar energy
molten salt
specific heat capacity
thermal conductivity
viscosity

ABSTRACT

Considered to be the next generation of heat transfer fluids, nanofluids have been receiving a growing amount of attention in the past decade despite the controversy and inconsistencies that have been reported. Nanofluids have great potential in a wide range of fields, particularly for solar thermal applications. This paper presents a comprehensive review of the literature on the enhancements in thermophysical and rheological properties resulting from experimental works conducted on molten salt nanofluids that are used in solar thermal energy systems. It was found that an increase in specific heat of 10–30% was achieved for most nanofluids and appeared independent of particle size and to an extent mass concentration. The specific heat increase was attributed to the formation of nanostructures at the solid–liquid interface and it was also noted that the aggregation of nanoparticles has detrimental effects on the specific heat increase. Thermal conductivity was also found to increase, though less consistently, ranging from 3% to 35%. Viscosity was seen to increase with the addition of nanoparticles and is dependent on the amount of aggregation of the particles. An in-depth micro level analysis of the mechanisms behind the thermophysical property changes is presented in this paper. In addition, possible trends are discussed relating to current theorised mechanisms in an attempt to explain the behaviour of molten salt nanofluids.

Contents

* Corresponding author. Tel.: +61 7 3138 6879; fax: +61 7 3138 1529.
E-mail address: azharul.karim@qut.edu.au (M.A. Karim).

http://dx.doi.org/10.1016/j.rser.2015.10.065
1364-0321/

1. Introduction

With fossil fuels expected to deplete at the turn of the next century, finding alternative methods of energy production is an ever increasing necessity. Utilizing solar energy to produce electricity has shown great potential to compete with fossil fuels and ultimately replace them as the amount of energy the sun provides is estimated to be 120,000 TW every hour [1]. Currently there are two main methods of converting solar energy to electricity, namely; photovoltaic (PV) and concentrated solar thermal power (CSP). For large scale production of electricity CSP systems is the more cost effective option as they concentrate solar energy as thermal energy source to be used in a general thermodynamic cycle, whilst also possessing thermal storage capabilities [2,3]. The concentrated energy is captured in a heat transfer fluid (HTF) which is in turn used to produce steam and run a turbine to generate electricity [4].

HTFs are critical to CSP plants and their selection is paramount to the overall efficiency of the system. As CSP systems generate electricity through the use of a general thermodynamic cycle, be it Rankin, Stirling etc., the efficiency of the system is thus limited by the operating temperature of the HTF. By increasing the operating temperature from 300 to 400 °C to 560 °C the Carnot efficiency can increase from 50% to 65% [5]. CSP systems currently cannot compete with fossil fuels as they are greatly limited by the HTF [6]. Starace et al. [7] stated that to reach an unsubsidised parity with fossil fuels, a HTF fluid with a heat capacity of 2.25 J/gK and the ability to operate over at temperatures of 600–800 °C is needed. Currently state of the art CSP plants consist of a molten nitrate salt that has a heat capacity of 1.5 J/gK and operates over a range of 228–565 °C [7]. HTFs used today in solar applications are molten salts, glycol, water and synthetic oil. Water while having a high thermal conductivity and specific heat is limited to its boiling temperature and therefore cannot be used in high temperature CSP applications. Glycol is again limited by its boiling temperature, which is generally 177 °C [8]. The fluids capable of reaching high temperatures are synthetic oils and molten salts. A commonly used synthetic oil as a HTF is Therminol VP-1, which is a eutectic mixture consisting of biphenyl and diphenyl oxide, has a relatively high vapour pressure and can break down into H2 upon decomposition, both of which are undesirable properties for a HTF. It is also has a relatively low boiling point of 390 °C [9]. Molten salts on the other hand can reach temperatures as high as 600°C and are relatively cheap, naturally abundant and environmentally safe. However their shortcomings are evident in their poor thermophysical properties, most notably the specific heat which is generally less than 2 J/gK [10].

Nanofluids have recently emerged as a new alternative heat transfer fluid. Nanofluids are rapidly gaining interest and are viewed as the next generation HTFs [11]. Defined as colloidal suspensions, otherwise known as the suspension of nano-sized solid particles in a liquid, nanofluids unlike micron-sized suspensions were found to form stable systems with next to no settling under static conditions [12]. These stable suspensions were found to even at small concentrations of nanoparticles ($\sim$1% mass fraction) anomalously increase the thermal conductivity compared to that of the base fluid and in some cases increases in specific heat capacity have been observed [13].

Numerous experimental studies have been conducted on high temperature nanofluids; however to the authors' best knowledge a comparative review of these results does not yet exist. This paper aims to address this by gathering together the experimental results of molten salt nanofluids and comparing them to identify any trends. This is important as the majority of studies have focussed on aqueous nanofluids which act differently to molten salt nanofluids and cannot be applied to high temperature CSP systems. This paper will help to identify which mechanisms are the most likely cause of the anomalous enhancements in molten salt nanofluids as well as identifying the critical areas that still require investigation. It should be noted that there are also several other important properties that must be taken into account when considering nanofluids. These properties include the vapour pressure, corrosion, melting and boiling points, heat transfer coefficient and capital cost of the nanofluid and are affected by the addition of nanoparticles to some degree. However these properties are not considered in this study as this paper is focussing only on the thermal conductivity, specific heat and viscosity increases of molten salt nanofluids. The consideration of the other properties is a good topic for future research.

2. Potential of nanofluids in solar energy technologies

There is great potential for nanofluids in concentrating solar power systems as discussed by Taylor et al. who identified a number of possible advantages over traditional heat transfer fluids [14].

1. Due to the incredibly small size of the particles they are essentially fluidized. Allowing them to pass through pumps, micro-channels and piping without any adverse effects.
2. Nanoparticles act as the absorption medium allowing the nanofluid to directly absorb solar energy.
3. Optically selective, allowing for high absorption in the solar range while obtaining low emittance in the infrared. Allowing for a volumetric receiver instead of a selective surface system, which is favourable as selective surfaces have an poorer temperature profile resulting in higher emissive losses [2].
4. Enhancement of efficiency and uniformity of receiver temperature is possible by tuning nanoparticle size and concentration.
5. Enhanced heat transfer may result in improved receiver performance.
6. Absorption efficiency can be altered by tuning the size, shape and concentration to suit conditions.

Taylor et al. went on to conduct a conservative, simplified analysis of how a nanofluid CSP system would perform compared to a conventional one. It was found that an efficiency improvement on the order of 5–10% was possible when using a nanofluid receiver [14]. For a 100 MW nanofluid thermal plant such an improvement in efficiency can equate to an addition of $3.5 million to the yearly revenue.

Not only are the optical properties of a HTF enhanced by nanoparticles its thermophysical properties are also affected. Investigating this, the majority of attention has been paid to the enhancement of thermal conductivity of water and glycol based