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Radiative properties of ionic liquid-based nanofluids for medium-to-high-temperature direct absorption solar collectors

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ABSTRACT

Here the radiative properties of the ionic liquid [HMIM][NTf_2] and its nanofluids are investigated for the first time by the experimental and theoretical methods. [HMIM][NTf_2] is almost transparent in the visible light range, while its optical absorption property can be significantly enhanced by dispersing a very low volume fraction of nanoparticles in it. At the volume fraction of 10 ppm, the extinction coefficient of the nanofluid containing the Ni nanoparticles with an average size of 40 nm is higher than that of the one containing the Cu nanoparticles with the similar average size, owing to their different complex refractive indexes. The nanofluid containing the carbon-coated Ni (Ni/C) nanoparticles exhibits lower transmittance and higher extinction coefficient, compared with the one containing the Ni nanoparticles with the similar average size. The radiative properties of the Ni/C nanofluids increase with the volume fraction of the nanoparticles. As the volume fraction is increased to 40 ppm, the absorbed energy fraction by the Ni/C nanofluid reaches up to almost 100% after the incident light only penetrate 1 cm. The excellent radiative properties of the IL-based nanofluids make them show promising to be used as the absorbers for medium-to-high-temperature direct absorption solar collectors.

1. Introduction

Solar thermal utilization is one of the most popular and effective means to utilize solar energy. Solar thermal collectors that capture the incoming solar radiation, convert it into heat, and then transfer the heat to a heat transfer fluid (HTF) by a cycling system [1] are pivotal devices in solar thermal systems. The performance of a solar collector plays a significant role in the whole solar energy utilization efficiency. Traditional solar collectors such as flat-plate solar collectors, which absorb the solar radiation by black-surface absorbers, have been widely used to collect heat for space heating, domestic hot water, etc. [1] Nonetheless, one inherent drawback in the traditional solar collectors is that the maximum temperature spot appears on the black surface, leading to a large temperature difference between the surface and the HTF [2]. As a result, the absorbed heat ineluctably losses to the surroundings, decreasing the performance of the traditional solar collectors [3]. To overcome this drawback in the traditional solar collectors, direct absorption solar collectors (DASCs) were originally proposed in the 1970s [4]. In a DASC, solar energy is directly absorbed by a black liquid that functions as both the absorber and the HTF. The complete elimination of the temperature difference between the absorber and the HTF makes DASCs a novel type of high-performance solar collectors [2]. However, the initially used HTFs, prepared by adding black inks or dyes into some base liquids such as water, ethylene glycol, etc., show serious shortcomings such as the light-induced degradation and thermal degradation at the operating temperatures as well as low thermal conductivity. Consequently, the DASCs based on these black liquids do not exhibit high performance, inhibiting the development and application of the DASCs.

Since 1990s, nanotechnology has been providing new development space for HTFs. Nanofluids, first coined by Choi in 1995 [5], is a kind of uniform suspension prepared by dispersing nanosized particles, fibers, or tubes with a definite proportion into base fluids. Numerous studies have demonstrated that nanofluids exhibit enhanced thermo-physical properties as compared to the corresponding base fluids, especially their thermal conductivity and convective heat transfer coefficients [6–10]. On the other hand, nanoparticles dispersed into base liquids offered a sharp enhancement in optical properties through absorption and scattering [11]. Furthermore, theoretical predictions and experimental investigations have proven that the receiver efficiency of the DASCs equipped with nanofluids is superior to that of the flat-plate

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Nomenclature

D	diameter of the particle (nm)
F	the absorbed energy fraction (dimensionless)
f_v	volume fraction (%)
$I(\lambda)$	the total incident solar irradiance (W/m^2)
k	absorption index of the particle (dimensionless)
$K_{e\lambda}$	extinction coefficient (1/cm)
$K_{a\lambda}$	absorption coefficient (1/cm)
m	relative complex refractive index (particles to base-fluid) (dimensionless)
$m_{particles}$	complex refractive index of the nanoparticle (dimensionless)
n	refraction index of the particle (dimensionless)
Q_{abs}	absorption efficiency (dimensionless)
Q_{ext}	extinction efficiency (dimensionless)
Q_{scat}	scattering efficiency (dimensionless)
$T(\lambda)$	spectral transmittance (dimensionless)
X	thickness of the fluid layer (cm)
y	optical path (mm)

Greek symbols

α	particle size parameter (dimensionless)
λ	wavelength (nm)

Subscripts

abs	absorption
ext	extinction
EXP	experimental result
MOD	model result
scat	scattering

collectors [2,3,12–14], making nanofluids show great potentials for use as the absorbers in DASCs. To further increase the performance of DASCs until they can be commercialized, it is necessary to optimize the thermo-physical and optical properties of nanofluids, which are influenced by the material, size, shape, and volume fraction of nanoparticles [15]. Compared with thermo-physical properties of nanofluids, their optical properties have not been paid much attention yet [16], which are more important to the absorbers for DASCs. Taylor et al. [17] combined experimental and theoretical methods to investigate the optical properties of the water- and oil-based nanofluids, in which Al, TiO_2, Cu, and graphite nanoparticles were used as the nanoadditives. They found that the extinction coefficients from the model predictions agree well with the spectroscopic measurements for the water-based nanofluids containing graphite nanoparticles, but less well for metallic nanoparticles and/or oil-based nanofluids. Sani et al. [18–20] used a novel carbon nanomaterial, carbon nanohorns, to prepare water- and glycol-based nanofluids, and investigated their thermal and optical properties. They demonstrated that carbon nanohorn-based nanofluids not only possessed enhanced thermal properties as compared with the base liquids, but also showed more promising for use as the direct sunlight absorbers than the nanofluids containing amorphous carbon black. More recently, Saidur et al. [21] calculated the extinction coefficient of the water-based aluminum nanofluids with varying sizes and volume fractions of the Al nanoparticles, and presented that the particle size had minimal influence on the optical properties of the nanofluids. All above results uniformly indicate that the optical properties of nanofluids dramatically increase by adding a low volume fraction of nanoparticles. However, all the aforementioned researches involve the nanofuids based on the traditional base liquids such as water, ethylene glycol, and thermal oil. The nanofluids based on water and ethylene glycol can be only applied in low-temperature solar thermal collectors. Although the thermal oil can keep the liquid phase up to about 300 °C, their applications are limited by some intrinsic disadvantages such as low decomposition temperature, inflammability, high vapor pressure, and low chemical stability. Therefore, novel nanofluids with excellent thermo-physical and optical properties are needed to be developed for medium-to-high-temperature direct absorption solar collectors.

Ionic liquids (ILs), composed of organic cations and organic or inorganic anions, are the group of salts with a wide liquid temperature range from room temperature to a maximum temperature above 400 °C [22]. A certain of convincing researches indicate that ILs can be used as a promising replacement of the current HTFs, especially in medium- and high-temperature heat transfer systems, due to their favorable physical properties such as wide liquid temperature range, good thermal and chemical stability, low vapor pressure, and non-harmfulness [23–27]. Furthermore, several kinds of IL-based nanofluids (Ionanofluids) have been prepared and shown enhanced thermo-physical properties as compared with the pure ILs [28–33]. Note that the optical properties of Ionanofluids are more crucial to the performance of medium-to-high-temperature DASCs. In the current work, the radiative properties of Ionanofluids have been systematically investigated for the first time by varying particle material, volume fraction, and optical path length. The extinction coefficients of the Ionanofluids have been obtained based on theoretical predictions and experimental investigations. Moreover, the light absorbing capability of the Ionanofluids has been evaluated based on their measured spectrally-resolved optical properties.

2. Experimental section

2.1. Materials

[HMIM][NTf_2] (CAS number 916729-96-9), provided by Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences, was selected as the base liquid due to its high initial decomposition temperature of more than 400 °C. Ni and Cu nanoparticles with average sizes of 40 nm were supplied by Xuzhou Jiechuang New Material Technology Co., Ltd., China. Carbon-coated Ni (Ni/C) nanoparticles with an average size of 40 nm were purchased from NanoAmor, USA. The morphology of the Cu, Ni, and Ni/C nanoparticles was observed using a transmission electron microscope (Hitachi H-7650, Japan). TEM images of the Cu, Ni, and Ni/C nanoparticles are displayed in Fig. 1. It can be seen that all the nanoparticles are almost spherical, except a few larger particles, which are likely aggregates of the smaller ones. The average diameters of all the nanoparticles are estimated to be ca. 40 nm.

2.2. Preparation of Ionanofluids

Ionanofluids were prepared by the two-step method [32,33]. A certain amount of nanoparticles were added into [HMIM][NTf_2], followed by magnetic stirring for 15 min. The obtained suspensions were thoroughly dispersed for 30 min by an ultrasonic apparatus at 90 W (KQ2200DE, Kunshan of Jiangsu Equipment Company, China). All the obtained Ionanofluids without any