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A combined numerical and experimental study on graphene/ionic liquid nanofluid based direct absorption solar collector

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ABSTRACT

Novel heat transfer fluids with very low vapor pressure and high thermal stability are highly desirable for both high temperature direct solar collectors and concentrated solar collector. Herein a combined analytical and experimental study has been conducted on high temperature direct solar thermal collectors using graphene/ionic liquid nanofluids as the absorbers. A one-dimensional transient heat transfer model has been used to predict the receiver temperature and efficiency with varying parameters such as solar and graphene concentration and receiver height. The results show that the experimental temperature is in good agreement with numerical results under the same conditions. Based on the model, it is shown that the receiver efficiency increases with the solar concentration and receiver height, but decreases with the graphene concentration. The receiver efficiency could be maintained 0.7 under the conditions of 0.0005 wt% of graphene in 5 cm receiver under 20 × 1000 W m^{-2} at 600 K. This work provided an important perspective to the graphene/ionic liquid nanofluids for use as a kind of novel heat transfer fluid in direct solar thermal collectors under concentrated solar incident radiation.

1. Introduction

Solar thermal utilization, one of the most practical and effective way in solar energy applications, is expected to solve the energy crisis without harm to the environment. In solar thermal systems, one major component is the solar collectors, which are special kind of heat exchangers that transform solar radiation energy to internal energy of the transport medium. Since their discovery in the early 1970s, direct absorption solar collectors (DACs) [1], where heat transfer fluid (HTF) directly and volumetrically absorb solar incident radiation, have been demonstrated to be efficient than surface receivers owing to a reduction in temperature difference between the surface and the fluid, consequently minimizing convective heat losses [2]. Moreover, increasing the operating temperature of HTF is crucial in solar thermal systems because higher temperature can significantly reduce the electricity cost and improve the conversion efficiency of power generation. Consequently, a variety of concentrated solar receivers such as parabolic troughs [3] and power tower [4], have been developed to increase the temperature of HTF. Such solar thermal technologies show great potential in solar thermal-to-electrical power conversion. This emerging technology gets stuck because its improvements require a new HTF that must have a very low vapor pressure at the hot operating temperature and combined with a high thermal stability, higher than 400 °C. Further, the piping layout of trough plants dictates that the fluid not be allowed to freeze, which dictates the use of extensive insulation and heat tracing unless the fluid has a freezing point near 0 °C [5]. Unfortunately, traditional HTFs have limitations: water [6], ethylene glycol [7], oil (Therminol VP-1) [8] are instable at high temperature and molten inorganic salts [5] have freezing points above 200 °C, limits the thermal conversion efficiency of the power cycle.

Ionic liquids, composed of organic cations and organic or inorganic anions [9], have been demonstrated to have a wide range temperature of liquid [10]. For example, 1-hexyl-3-methylimidazolium tetrafluoroborate ([HMIM]BF$_4$) has a freezing point even down to -80 °C and a decomposition temperature of 420 °C [11]. The remarkable property indicates that ionic liquids are better candidates of HTF in concentrated solar thermal systems. Furthermore, the properties of ionic liquids can be tuned by altering cations and anions, making ionic liquids more attractive for thermal utilization [12]. The thermophysical properties of ionic liquids have been broadly reported at present [13–15], and the results confirm ionic liquids are superior to traditional HTFs. However, the investigations on ionic liquids based solar collectors are rarely reported [16].

In DACs, the HTFs directly absorb solar incident radiation and storage to heat, the sunlight absorptivity of HTFs is important for photo-thermal conversion. Although most of ionic liquids have

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Nomenclature

A	surface area of the receiver [m^{-2}]
C	solar concentration factor
C_{pl}	specific heat of liquid [J g^{-1} K^{-1}]
C_{pg}	specific heat of air [J g^{-1} K^{-1}]
C_0	speed of light [m s^{-1}]
G_s	incident radiative heat flux [W m^{-2}]
h	convective heat loss coefficient [W m^{-2} K^{-1}]
H	nanofluid height [m]
I	radiative intensity [W m^{-2} nm^{-1}]
$I_{b\lambda}$	incident solar radiation at the top of the receiver [W m^{-2} nm^{-1}]
k_l	thermal conductivity of liquid [W m^{-1} K^{-1}]
k_g	thermal conductivity of air [W m^{-1} K^{-1}]
K_e	extinction coefficient [cm^{-1}]
k_B	Boltzmann constant [1.3807×10^{-23} J K^{-1}]
m	weight of nanofluid [kg]
q	heat flux [W m^{-2}]
S_{scat}	attenuation constant of sunlight [0.73]
T	temperature [K]
t	time [s]
x,y	coordinate [m]
Ωs	solid angle of sun as seen from Earth [6.80×10^{-5}]

Greek symbols

ρ	density [kg m^{-3}]
σ	Stefan–Boltzmann constant [5.670×10^{-8} W m^{-2} K^{-4}]
λ	spectral wavelength [nm]
η	receiver efficiency
μ	viscosity of air [Pa s]

Subscripts

amb	ambient
in	receiver inlet
out	receiver outlet

superior thermophysical properties, they are too transparent to adequately absorb sunlight especially in visible range of wavelength (400–800 nm). The poor sunlight absorptivity of ionic liquids limits their receiver efficiency for solar thermal collectors. Recent years, the drawback is ameliorated by dispersing nanosized particles in HTFs, forming 'nanofluid' [17], previous research show that tiny dispersed metal, metallic oxide or carbon materials can sharply improve the solar absorptive capability of HTFs, leads to the increasing efficiency of receiver, and thermal performance of HTFs. For example, the radiative property of a number of metallic or carbon materials based nanofluids were reported experimentally [7,18–23] and a few theories were proposed for optimizing the sunlight absorptive capability [6,24], while in other works, the temperature and photo-thermal conversion efficiency of nanofluids based receivers were experimentally tested or theoretically estimated [25–29]. Among these, carbon materials such as carbon nanotubes show the greatest sunlight absorptive enhancement than other nanoparticles [7,23].

Graphene, a single layer of monocrystalline graphite with sp^2-hybridized carbon atoms, exhibits remarkable electronic, mechanical, optical, and transport nature [30–32] and reveals a great number of potential applications with possible uses in capacitors [33], fuel cells [34], batteries [35] and flexible electronics [36]. With its excellent extinction capability [37], graphene is believed to be an ideal nanoaddictive in ionic liquids to form matrix materials as HTFs for direct absorption solar collectors. Hence, in this paper, we theoretically and experimentally investigated a stationary DAC based on graphene/ionic liquid. First, a transient one-dimensional numerical model based on the extinction coefficient of graphene/ionic liquid was used to predict the temperature distribution of this new kind of HTF inside the receiver under 2300 W m^{-2}, then, a cylindrical simulative receiver was used to test the temperature under the same incident solar light intensity. The results of experiment were compared to aforementioned numerical results to demonstrate the concept of attenuation of sunlight in DAC. Furthermore, the model was used to predict the temperature of graphene/ionic liquid with various geometrical parameters and operating conditions such as graphene concentration, HTF height and solar concentration. In addition, the effects of above parameters on the receiver efficiency were systematically investigated via further calculation.

2. Experimental section

2.1. Graphene/[HMIM]BF$_4$ preparation and characterization

In this section, different mass of graphene (Nanjing XFNANO Materials Tech Co) was readily dispersed in [HMIM]BF$_4$ (244193-50-8, Lanzhou Institute of Chemical Physics) after 30 min of sonication without any surfactant, forming stable nanofluid with different concentrations (range from 0.0005 wt% to 0.01 wt%). To determine the radiative properties of the graphene in suspensions, a differential measurement technique [19] was performed using a spectrophotometer (Lambda 950, Perkin-Elmer). For this measurement, quartzose cuvettes of equal pathlengths (10 mm) were used, and the difference in transmission between graphene/[HMIM]BF$_4$ and pure [HMIM]BF$_4$ was determined. The effects of scattering and multiple reflections through media of different optical thicknesses are assumed to be negligible. The extinction coefficients were calculated according to the Beer Lambert law based on the above experimental results of transmission with six different mass fractions.

2.2. Experimental solar receiver

To experimentally demonstrate the concept of graphene/[HMIM]BF$_4$ based DAC, a setup was used to test the temperature profile which was compared to the numerical model result under the same conditions. Fig. 1a shows the main components of the setup, including the solar simulator, beam-down mirror, receiver, thermocouple array and data acquisition system. A 700 W solar simulator (SOLAREDGE700, Perfectlight Inc.) was used as the radiative source for the experiments. As compared with a normalized solar black body spectrum, the solar simulator matches with the AM1.5 spectrum well and meets ASTM Class A standards for spectral match, temporal stability and spatial uniformity [38]. Before the experiments, the average radiative heat flux incident on the receiver was measured with an irradiatometer (ST-80C Peifbnu Inc.) to be 2300 W m^{-2}. A custom thin-walled cylinder insulated by low-density foam was machined to hold the graphene/[HMIM]BF$_4$. A high-purity quartz window (Perfectlight Inc.) sealed the top of the cylinder. During the experiments, the radiation from the solar simulator was beamed down to the receiver and temperature measurements were taken using type-K thermocouples, the probes extended to the centerline of the receiver and