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Experimental thermal evaluation of a novel solar collector using magnetic nano-particles

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ABSTRACT

A novel solar thermal collector using magnetic nano-particles to create a special array structure to capture solar light to enhance the thermal efficiency is put forward. The Gradient-Index Optics Theory is used to explain the physics of the proposed system. A set of experimental facility is set up to test the thermal collecting efficiency and a comparison between the coating vacuum tube and the conventional vacuum tube is conducted. 180 nm sphere iron nanoparticles were used under the stagnation experiment with water as the working medium. Results show that the magnetic tube performs as well as the coating tubes in lower temperatures and better than ordinary tubes all the time. Heat loss analysis shows the magnetic array structure has a larger ability to capture solar light while a lower ability to prevent heat loss due to the low emissivity layer in the coating. The normalized temperature difference instantaneous efficiency analysis shows that the magnetic tube has a higher top instantaneous efficiency as well as a higher heat loss coefficient, thus resulting a lower thermal efficiency as time passes and temperature rises. The temperature when the efficiency for the coating tube equals to that for the magnetic tube is about 53.8 °C and the temperature when the coating tube and the magnetic tube reach the same is about 73 °C. A comparison between the experimental results and what was available in literatures on the application of nanofluids to solar energy and a similar performance was observed.

1. Introduction

The growing population and energy demand are urgent issues that the whole world must face. As well, the environmental pollution and disruption caused by over-consumption of resources are posing a significant threat to human survival [1]. In the total global social energy consumption, building energy consumption accounted for about 40% [2]. The use of renewable energy in buildings can significantly reduce building energy consumption, which is also significant to reduce the total social energy consumption. As a result of its renewability, pollution-free and wide availability nature, solar energy is an important way to deal with energy crisis and improve the environment. The application of solar energy can be used to meet the demand of heating, cooling, domestic hot water and lighting in buildings depending on the different technologies [3].

The application of solar Energy can be divided into two parts: solar thermal utilization and solar photovoltaic [4]. The first application of nano-particles in the solar field appeared in the solar photovoltaic area and researchers found that nano structure could help improve the photovoltaic conversion efficiency [5]. However, what is to be discussed in this paper is the most common solar utilization, the solar thermal. Solar thermal collectors consist of two ways: the indirect absorption and the direct absorption [6]. Both approaches have been extensively studied and have yielded significant results [7]. Research for indirect absorption mainly focuses on the solar absorption coating, which means the surface of the collector is painted with a special spectral selective coating. The coating has a high absorption coefficient for solar light and low emission coefficient (from the black nickel plating/black chromium plating in early times to the cermet films in recent times [8–10]). "Indirect" means the working fluid doesn't absorb heat directly but the coating on the surface absorbs solar heat and transfers to the medium in the collector. Vacuum tubes are typically used to reduce heat losses. However, the complicated process, high cost and poor durability for spectral selective coating in its practical application mean a longer payback period and more pollution in the production process [11]. As for the application of nanoparticles in the indirect absorption of solar energy, the current work is still very limited. The most recent work seems to be by Gupta [12] who created a spectrally selective surface by laser sintering of tungsten micro & nano particles and measured a solar absorptance of ~83% and a thermal emittance of ~16%. There is no more significant

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Nomenclature

η	thermal efficiency	n	refractive index
T	temperature, °C	ε_1, ε_2	emissivity of the inner and outer tube respectively
G	irradiation intensity, W/m^2		
c	specific heat capacity, J/(kg·K)	*Subscript*	
m	mass of water, kg	i	inside water in the tube
Q	heat gain, J	a	environment
A	shining area, m^2	w	water
L	length, m	c	convection heat transfer
D	diameter of the tube, m	r	radiation heat transfer
t	time, s	w1	inner tube wall
R	reflectivity	w2	external tube wall

work on nano particle utilization in solar indirect absorption, especially in the case of magnetic nano-particles.

Nano-particles have played an important role in direct absorption, which mainly focuses on the nano-fluid direct absorption collector. A number of work has been carried out to analyze the thermal properties for solar nano-fluid, from the materials selection to the preparation method and the stability analysis, since Choi invented it in 1995 [13–15], including the thermal conductivity, viscosity, convective heat transfer and boiling heat transfer. The results show that nanofluids can significantly improve thermal efficiency in most cases, but efficiency increases are not always positively correlated with volume fraction. It's suggested to carry out more experiments on the volume fraction, the particle size and the theoretical work on the collector efficiency. Nanofluids often work as the coolant or heat transfer medium in the thermal industry due to its excellent thermal properties. In recent years, two more significant applications of nanofluids seem to be promising, the application in micro-channel heat sinks (MCHS) and the application in solar direct absorption. Hatami's [16–18] summarized the work of predecessors and conducted a comprehensive analysis of the heat transfer and flow characteristics of nanofluids in MCHS. The results showed the Nusselt number varied with the channel aspect ratio and the nanoparticles diameter and confirmed the great potential of nanofluids utilization in MCHS.

As for the nanofluid applications in solar collectors, Tyagi et al. [19] found that the thermal efficiency increased remarkably by adding nano-particles at a volume fraction lower than 2%, but for the volume fraction higher than 2% the efficiency nearly remained constant. Otanicar et al. [20] analyzed the thermal performance of different nanofluids both experimentally and numerically. Taylor et al. [14] compared a nanofluid-based concentrating solar collector with a conventional one and found an efficiency improvement of 10%. Corcione [21] carried out a quantity of experiments and proposed two empirical equations to predict the dynamic viscosity and effective thermal conductivity of nanofluids. Yousefi et al. [22] investigated the efficiency variation with the pH value and found that the thermal efficiency increased with the increase of the pH value difference between the nanofluid and the isoelectric point. He also found that by adding surfactants the efficiency could be improved by as high as 15.63%. Xu et al. [23] confirmed that the heat transfer oil had a better thermal performance after adding nano-size CuO, Fe_3O_4 or graphite particles at higher temperatures. Michael and Iniyan [24] tested the performance of copper oxide/water nanofluid in natural and forced circulation and found that largest improvement was observed for the thermosyphon operation rather than forced circulation. Rejeb et al. [25] conducted a numerical and experimental research on the application of nanofluids as the coolant fluid in a PV/T system. Results showed that both the electrical efficiency and the thermal efficiency increased with the increasing nanoparticle concentration.

Despite the significant advantages in increasing the efficiency of heat collection, the nanoparticles dispersion technology and the phenomena of nanoparticles glomeration and sedimentation after certain time still remain a problem to be solved [26,27]. These issues greatly limit nanofluid's development in practical applications and require more work to overcome these shortcomings. This previous research work contributed greatly to the application of nano-fluids in solar energy including the thermal properties, the efficiency enhancement and the coupling with other systems. However, no significant work has been done on the application of magnetic nano-particles in solar collectors.

Based on the characteristics of different solar energy utilization technologies, a new kind of solar thermal collector is put forward in this paper, which uses the magnetic nano-particles in magnetic field to create a "similar blackbody" to capture solar light, thus improving the thermal efficiency. The magnetic nano-particles (iron powder, for example) are driven by the magnetic force to form the ordinal and compact space array along the magnetic lines. At the same time, the effect of tiny particles can reflect and diffuse solar radiation in a spatial array produced by the particles, thereby forming a special light-capturing structure. The layout of the magnetic field can be changed to change the spatial structure, thus controlling the magnetic line layout. By fixing the mentioned magnetic array structure into the evacuated tubes, a new type of solar thermal collector is proposed to enhance the thermal efficiency, in comparison with the conventional coating tubes and the bare tubes. Firstly the physics of the proposed system was discussed to explain why the magnetic array structure can reduce solar reflection and enhance solar thermal absorption. Secondly a set of experimental facility was set up to test the thermal collecting efficiency and the temperature rise trend was tested for all the three kinds of tubes. Then the instantaneous efficiency and the heat loss coefficient for the three kinds of tubes were analyze by linear fitting. Finally the results were compared with what was available in literatures on the application of nanofluids to solar energy.

2. Experiment principle

A block of metals has different metallic lustre, which means metals have different abilities to reflect and absorb light with different wavelengths in the visible light. When the size reaches the nano scale, nearly all kinds of metal particles are black, which means they have a low reflectivity and a high absorptivity in visible light [17]. This is because of the size distribution effect and interfacial effect. The structure of nano-particles can't be arranged and controlled with ordinary methods because of its micro size particularity. So in this paper the nano-particles are supposed to be distributed freely along the magnetic line to form an ordinal and compact array structure to capture light and heat.