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Using nanofluids in enhancing the performance of a novel two-layer solar pond

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ABSTRACT

A novel two-layer nanofluid solar pond is introduced. A mathematical model that describes the thermal performance of the pond has been developed and solved. The upper layer of the pond is made of mineral oil and the lower layer is made of nanofluid. Nanofluid is known to be an excellent solar radiation absorber, and this has been tested and verified using the mathematical model. Using nanofluid will increase the extinction coefficient of the lower layer and consequently will improve the thermal efficiency and the storage capacity of the pond. The effects of other parameters have been also investigated.

1. Introduction

The solar pond is a body of fluid that collects and stores thermal energy within its mass. In order to store heat within the body of solar pond, salt is used to create salinity gradient that inhibits the convection currents to prevent heat loss. Solar ponds are old natural phenomenon discovered a long time ago in Medve Lake in Transylvania in Hungary in 1902 where the temperatures recorded up to 70 °C at depth of 1.32 m at the end of the summer [1]. In Tibet, China, Nie et al. [2] studied a natural brine lake that acts as a solar pond.

Middle-east area is one of the richest areas in solar energy. Jordan, for example, has an average annual global solar radiation of 2080 kWh/m^2 [3]; this encourages further investigations and studies concerning the use of solar energy in that country. Concerning the solar ponds, Saleh et al. [4] developed a model to predict the performance of an SGSP coupled with desalination plant under Jordanian climate conditions.

Solar ponds have the potential to be used as large thermal energy storage, where heat can be extracted and used for different purposes. Bozkurt and Karakilcik [5] studied the performance of integrated flat-plate solar collectors to a cylindrical solar pond; the pond was of 0.8 m in diameter and 2 m deep. The flat-plate collectors have an area of 1.9 × 0.9 m^2 each. The heat collected by the flat-plate collectors is transferred and stored using heat exchanger to the solar pond. Finally, they evaluated the overall efficiency of the system and found that the number of collectors mainly affects the performance. Leblanc et al. [6] presented a novel system of heat extraction that improves the efficiency of solar ponds. They draw heat from the gradient zone (not only from LCZ as in conventional methods) using in-pond heat exchanger made of polyethylene pipes, and they found that the overall efficiency of solar pond using that extraction method reached up to 55%.

Sukhatme [7] mentioned several problems concerning the operation and maintenance of SGSPs. These problems vary from establishing the salt concentration gradient to washing the upper surface of the pond due to salt diffusion. In addition, rain, biological growth, the fouling due to dirt and leaves is a problem as well since they will settle at the bottom of the pond, and winds all considered problems associated with the operation and maintenance of solar ponds. Not mentioning the stability issue of the SGSP, which affects the performance of the pond, Karim et al. [8] studied experimentally on mixing the NCZ, and how to preserve the stability of the salinity gradient. Busquets et al. [9] investigated the effect of temperature applied on the stability of the pond. They have found that at low and constant temperature, the NCZ is more stable than when higher and variable ambient temperatures were applied.

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Nomenclature

A	Reflection fraction
a	Depth of upper layer, m
b	depth of lower layer, m
Bi	Biot number
C_p	heat capacity, J/kg °C
D	Particle diameter, m
E	Energy, J
Fo	Fourier number
Fo'	Elapsed time
g	Heat generation, W/m^3
G_{ij}	Green's function
h_c	Combined heat transfer coefficient, W/m^2 °C
I	Radiation intensity, W/m^2
I_s	Incident solar radiation, W/m^2
k	Thermal conductivity, W/m °C
k^*	Dimensionless thermal conductivity
LCZ	Lower convective zone
NCZ	Non-convective zone
q	Total rate of heat generation, W
Q_{abs}	Absorption coefficient
SGSP	Salinity gradient solar pond
SSP	Shallow solar pond

Greek symbols

α	Diffusivity, m^2/s
β	Fraction of the energy absorbed at the surface
β_n	Eigenvalue
Γ	Dimensionless time solution component for the problem
δ	Dimensionless diffusivity
θ	Dimensionless temperature distribution for the non-homogeneous problem
θ_h	Dimensionless temperature distribution for the homogeneous problem
μ	Absorption or extinction coefficient, m^{-1}
φ	Volume fraction of nanofluid
Φ	Dimensionless heat generation
Ψ	Dimensionless x-component solution for the problem
ρ	Density, kg/m^3

Subscripts

∞	Ambient state
eff	Effective
f	Fluid
h	Homogeneous
i, j	Pond layer, it takes values 1 and 2
nf	Nanofluid
0	Initial state
p	Particle
ref	Reference

There are many different types of solar ponds mentioned by El-Sebaii et al. [10]; researchers have tried to design and develop salt-free solar ponds. Shaffer [11] made a patent study on a viscosity stabilized solar pond; in Shaffer's pond, the NCZ is made of water that is thickened by some gelling material, which has a good transparency and can handle high temperatures, to inhibit convection. Furthermore, the water is subdivided into cell-like partitions using honeycombs, vertical separator, or horizontal separators. This distance between these separators or the size of the honeycomb must be designed such that the natural convection is kept minimum to reduce losses. Thus, the pond proposed by Shaffer is considered to be a possible alternative for the conventional SGSP.

Lin [12] introduced a saltless solar pond in 1984; the pond uses only water and a transparent cover made of honeycombs. The convection is inhibited by dividing the pond using the honeycombs as in Shaffer pond. In 1985, Lansing [13] invented a two-layer pond that uses two different liquids such that the density of the upper liquid is lesser than the density of the lower liquid. The lower liquid acts as thermal energy storage while the upper liquid acts as an insulator. He proposed that the lower liquid to be darker than the upper liquid in order to absorb more solar radiation. Some experiments were conducted in the 1980s and 1990 on the performance of honeycomb solar ponds [14,15], another conducted on a solar pond with one semi-transparent air-filled surface insulation layer [16].

Recently, shallow solar pond (SSP) became a topic of interest. The SSP has depth between 4 cm and 15 cm only, and it uses only the water that has been stored in a bag. During day, the water is heated by the sun, and when the heat collection drops to zero, the water is withdrawn [1]. Ali [17] modelled an SSP and validated his model experimentally. The experiment showed that the 10 cm deep SSP is more suitable to operate as thermal storage during summer than winter. The pond reached a temperature of 95 °C during summer. El-Sebaii et al. [18] conducted an experimental testing an SSP covered with glass, under continuous heat extraction. The pond reached maximum temperature around 55 °C.

During the last few years, and due to their much better thermal characteristics, nanofluids have been utilized extensively in large number of energy systems and applications. Using nanoparticles in fluids enhances the thermal conductivity. Adding nanoparticles (CuO) to water enhances its thermal conductivity [19]; for 1% volume fraction of CuO in water, the thermal conductivity increases by 5.8%; for 7.5% volume fraction of CuO in water the enhancement is 32.25%. In addition, nanoparticles enhance the thermal efficiencies of thermal energy storage systems [20]. Nanofluids enhance the convection in heat exchangers as well [21,22].

Using nanofluids in heat pipes enhanced the thermal efficiency by ~15% for a 0.5 wt.% Cu [23]. Another study concerned with the size and concentration of nanoparticles in a heat pipe reported enhancement in thermal efficiency [24]. The thermal resistance of micro-pipe decreased when nanoparticles (Al_2O_3) are used, i.e., the thermal performance increased [25]. Using (Al_2O_3) has increased the thermal performance by 35.1% in 0.6 m heat pipe [26]. Karunamurthy et al. [20] investigated the use of nanoparticles in enhancing the efficiency of an SGSP using a nanoparticle thermal energy storage. They simulated the SGSP and they heated it by a heater; the hot saline water was pumped to a storage that contains a phase change material (paraffin) mixed with nanoparticles (CuO). The result of this simulation is enhancing the thermal conductivity of paraffin, which led to improvement in store and discharge time of heat.

Water is used in many thermal absorption systems, yet it is weak absorber since it absorbs only 13% of the solar energy [27]. Yousefi et al. [28] reported an increase in the efficiency of the flat-plate solar collector when Al_2O_3–H_2O is used as working fluid. For 0.2 wt%, the efficiency increased by 28.3%. Using graphite in solar collectors enhances the direct solar energy absorption. Ladjevardi