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Enhancing energy harvest in a constructal solar collector by using alumina-water as nanofluid

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ABSTRACT

We have developed a network of pipes of dendritic geometry in a solar collector with a disc-shaped body. The fluid in the network pipes is a nanofluid composed of a mixture of nanoparticles of alumina (Al_2O_3) and water as a base fluid in order to harvest a greater amount of thermal energy from incoming solar radiation. The sizes of the network pipes are obtained by using constructal theory methods. Thermal conductivity was obtained by the Hamilton-Crosser model; physical properties such as density and specific heat capacity were described as a function of the volumetric fraction of nanoparticles in the fluid. Optimal size of the network presented for every level of construction was established by the condition of minimal thermal resistance. Temperature profiles and the aspect ratio of the construction elements were defined as a function of the volumetric fraction of nanoparticles. Results show that by increasing the volume fraction of nanoparticles, thermal energy gain also increases, reaching a higher outlet temperature of the fluid when alumina nanoparticles are used.

1. Introduction

The increase in world energy demand and the progressive depletion of fossil fuels necessitate the development of technologies based on alternative energy sources. Solar energy is widely used for heating water for domestic and industrial purposes through solar collectors (Kalogirou, 2004). Solar collectors are classified as low temperature devices with operation ranges of 20–150 °C. The flat-plate solar collector is the most widely used. The working fluid flowing in the pipe network is generally water. It is possible nowadays to use, as a working fluid a colloidal suspension with nano-sized solid particles (1–100 nm). Such suspensions are composed of metal particles (oxides) dispersed uniformly, and a base fluid. This combination can present higher thermo-physical properties, such as thermal conductivity values superior to conventional working fluids like water; these particular features are used to improve heat transfer processes (Puliti et al., 2012).

The modification of the thermal properties of a colloidal suspension is possible by adding nano-sized metal particles in a base fluid. The resulting fluid is known as a nanofluid (Buongiorno et al., 2009; Keblinski et al., 2005). The increase of thermal conductivity is due to physical factors such as the Brownian movement of particles in the fluid, a liquid layer at the liquid-particle interface, nanoparticle clustering and concentration of the nanoparticle in the base fluid (Angayarkanni and Philip, 2015; Keblinski et al., 2002). Theoretical and experimental work on the thermal and rheological properties of nanofluids, for different particle materials, is reported mainly in fluid mixtures with oxide particles in convective heat transfer processes (Buongiorno, 2006; Daungthongsuk and Wongwises, 2007; Ghanbarpour et al., 2014). The particular thermal properties of these fluids represent an option for the design of cooling systems in electronic, aerospace and automotive industries through the design of microchannel devices (Chen and Ding, 2011; Khaleduzzaman et al., 2014; Koo and Kleinstreuer, 2005), in designing techniques of drug delivery in the human body (Abbasi et al., 2015; Kleinstreuer et al., 2008), heating, ventilation and air conditioning systems (Hatami et al., 2017), refrigeration systems (Sözen et al., 2014) and optical filters for thermo-photovoltaic solar systems (Taylor et al., 2012). A numerical study for a solar collector with a nanofluid as a working fluid is reported by Nasrin and Alim (2014), identifying the influence of the characteristic dimensionless numbers of the problem as a factor to improve the efficiency collector. Experimental nanofluid applications in conventional flat-plate solar collectors are reported widely by Sarsam et al. (2015), where the main topic is the improved efficiency and performance.

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Nomenclature

A	area of the semi-circular sector (m^2)
C	specific heat capacity (J/kg K)
D	diameter (m)
H	height of the constructal element (m)
k	thermal conductivity
L	length of the constructal element (m)
R	radius (m)
t	physical time (seg)
V	volume of the constructal element (m^3)
w	width of the constructal element (m)
$\dot{q}$	heat flux (W/m^2)

Greek symbols

ω	frequency of the solar signal (1/seg)
ϕ	volumetric fraction of the particle
ρ	density (kg/m^3)

Subscripts

p	particle
f	fluid
nf	nanofluid
0	refers to the first construction
1	refers to the first level ramification
2	refers to the second level of ramification

Applications of nanofluids in thermal systems are reported mainly to improve the performance of the heating systems. Lu et al. (2011) conducted an experiment of an open thermosyphon applied in an evacuated tubular solar heating system with an evaporator tube and two working fluids, deionised water and a water-based copper oxide nanofluid in order to evaluate the thermal performance of the system under steady operative conditions, such as pressure and temperature under indoor conditions. The point of operation of heat transfer enhancement of the system was found for a specific value of the mass concentration of the nanoparticles.

The heating system mentioned previously established the experimental conditions for an outdoor experiment applied to a simplified compound solar concentrator as a solar air collector with the same working fluids. The main results are efficiency improvement with a nanofluid with the mass concentration determined previously (Liu et al., 2013). These works provide important information about the experimental procedures in collector systems and demonstrate the existence of an optimal point of operation for a thermal system for a specific value of the concentration of nanoparticles in a fluid base.

The design of nanofluids with suitable thermo-physical properties (high thermal conductivity) will allow the design of efficient systems for heat removal, miniaturisation of the devices and the consequent energy savings (Godson et al., 2010).

The constructal theory, proposed by Bejan (2000), develops transport networks to imposed physical flows (heat, fluid) with the principal characteristic of obtaining a minimal resistance to flow, under local restrictions, that satisfy a main objective. The design methodology allows networks with different geometrical configurations (shape and structure) to have optimal transportation between a point and an infinite number of points, area or volume.

In an effort to apply the constructal theory to designing nanofluids, Fan and Wang (2010) report the microstructure of a single nanoparticle immersed in the base fluid, which is defined by the minimal thermal resistance. The elemental system is a nanoparticle with a source of uniform heat in a disc-shaped element; the particle is defined as plates of slabs of a thermal conductivity value, higher than the base fluid. The system optimisation is determined by the freedom within the three-shaped nanostructures.

On the other hand, Bai and Wang (2011) developed the expressions for the thermal resistance of constructal building blocks composed of a base fluid and nanoparticles with blade configuration. The constructal theory is applied to describe the optimal shape for the blades, cylinder-shape and prism-shape of the particle, that offers minimum thermal resistance. Both studies focus on the design of the microstructure of the nanoparticle from the principles of optimisation of the constructal theory. The same group developed the design of the microstructure of a nanofluid by comparing two geometric configurations—quasi-rhombus and quasi-sector shapes—identifying a proper nanofluid configuration for better heat transfer performance (Bai and Wang, 2013). An important parameter for increasing the thermal conductivity of a nanofluid is the geometry of the particle. This aspect is considered as a shape factor in theoretical models.

In the present work we develop a pipe network with a dichotomous branching characteristics following the constructal methods by treating the nanofluid as a medium that flows to remove heat in a disc-shaped body system. The nanofluid properties such as thermal conductivity, density and specific heat capacity are modelled as a function of the physical properties of the alumina nanoparticle, water as a base fluid and volumetric fraction.

2. First element or construction

The first element of construction takes into account the physical and geometrical variables and considers the finite size volume that is initially found at a uniform temperature T_0. This element is a semi-circular sector with area A_0 and volume V as constants, which are local constraints. These assumptions are the restrictions that are frequently assumed by the constructal theory. The solar incident area is given by $A_0 \approx H_0 L_0$, where the height and length of the disc-shaped body are unknown and determined from the optimisation process.

The constructal theory considers the total volume of the pipe network system as a building block of elements, optimised in shape and form; the optimisation process begins with the first element of construction (Wechsatol et al., 2002). Fig. 1 provides a sketch and the dimensions of this first element.

The top of the element is separated by an infinitesimal wall with negligible thermal conductivity. In the transverse direction, at $y = H_0$, the element receives the solar energy; the limits of the constructal element are at temperature T_m. For simplicity, we consider that the warming effect of air trapped in the cavity comes from the signal $\dot{q} = \dot{q}_0 sin(\omega t)$, where $\dot{q}_0$ is the reference amplitude of this periodic heat flux for the present system, ω is the frequency of the solar signal and t is the physical time. The space between the surface exposed to solar radiation and the pipe of diameter D_0 is considered a cavity filled with air at temperature T_c.

Inside the pipe, a nanofluid is circulating in the x direction in a steady-state regime. This hypothesis is justified below. The nanofluid flow is considered Newtonian and fully developed, and is considered to be stable (no chemical reactions) with nanoparticles of