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## Original Research Paper

## Entropy generation in a heat exchanger working with a biological nanofluid considering heterogeneous particle distribution

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## ABSTRACT

Entropy generation rates considering particle migration are evaluated for a biologically produced nanofluid flow in a mini double-pipe heat exchanger. The nanofluid is used in tube side and hot water flows in annulus side. Silver nanoparticles synthesized through plant extract method from green tea leaves are utilized. Particle migration causes non-uniform concentration distribution, and non-uniformity intensifies by increase in Reynolds number and concentration. The results indicate that at high concentrations and Reynolds numbers, particle migration can have a great effect on entropy generation rates. For water inlet temperature of 308 K, the contribution of friction in nanofluid entropy generation is much more than that of heat transfer. However, as the water inlet temperature increases to 360 K, the heat transfer contribution increases such that at low Reynolds numbers, the thermal contribution exceeds the frictional one. For total heat exchanger, Bejan number is smaller than 0.2 at water inlet temperature of 308 K, while Bejan number has a large value at water inlet temperature of 360 K. Furthermore, entropy generation at the wall has an insignificant contribution, such that for  $Re = 1000$  and  $\phi_m = 1\%$ , the total entropy generation rates for the nanofluid, wall, and water are 0.098810, 0.000133, and 0.041851 W/K, respectively.

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## 1. Introduction

Heat transfer by the use of fluid flow has a vital role in various industries such as power plants, refineries, electronics, and so forth [1]. Enhancing the performance of conventional heat transfer has become an important challenge for scientists and engineers [2]. This is an era of developing high heat flux devices such as optoelectronics, heat exchangers, computing chips, energy dense laser applications, nuclear reactors, advanced aerospace equipment, and super conducting magnets. The cooling rates for these devices are enormous and require new techniques including the use of new coolants. Suspending highly conducting solid particles in the fluids is one of the methods to this problem; however, such suspensions have many practical limitations, chiefly arising from the sedimentation of particles and the related blockage problems. These limitations can be overcome by applying nanometer-sized particles (nanoparticles) in liquids, known as 'nanofluids' [3–7].

In recent years, silver nanoparticles have been widely used in many applications such as medical devices, thermal systems, and clothing due to their unique properties. Usually, the technique

for the synthesis of silver nanoparticles involves the reduction of silver ions in the solution or in high temperature in gaseous environments [8]. However, the reducing reagents, such as sodium borohydride, can intensify the environmental toxicity or biological dangers [9]. In addition, the high temperature increases the production cost. Therefore, the development of green preparation methods for silver nanoparticles by applying eco-friendly solvents and nontoxic reagents is very important. Sun et al. [10] developed a simple, environmentally friendly and cost-effective method to synthesize silver nanoparticles using tea leaf extract. The silver nanoparticles were synthesized using silver nitrate and tea extract, and the reaction was carried out for 2 h at room temperature. Sarafraz and Hormozi [11] applied this method to synthesize the nanofluid containing silver nanoparticles. They focused on forced convective heat transfer coefficient of this biologically produced nanofluid flowing in a heat exchanger. Particles were produced using plant extract method from green tea leaves and silver nitrate. Influence of the nanofluid on pressure drop and friction factor was experimentally investigated. The results demonstrated a remarkable enhancement of heat transfer coefficient up to 67% at the concentration of 1%.

It is noticed in the relevant literature that most of researchers in the field of nanofluids have focused on the theoretical, experimen-

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tal and numerical study of thermophysical properties and heat transfer [12–17]. Tripathi et al. [18] studied theoretically the electrokinetic pumping of nanofluids with heat and mass transfer in a micro-channel under peristaltic waves. The microchannel walls were deformable and transmitted periodic waves. Some expressions were presented for the surface shear stress function at the wall, wall heat transfer rate and wall solute mass transfer rate. Bolus formation was also visualized and analyzed in detail. Nayak et al. [19] focused on the influence of transverse magnetic field as well as thermal radiation on three-dimensional free convective flow of nanofluid over a linear stretching sheet. It was found that the presence of magnetic field slows down the fluid motion while it enhances the fluid temperature leading to a reduction in heat transfer rate from the surface. It was also concluded that enhancing thermal radiation parameter causes a reduction in heat transfer rate.

However, the novel design for a thermal system should pursue not only the heat transfer enhancement, but also the minimal destruction of useful work. Entropy of a thermodynamical system means the unavailability of useful work. In fact, entropy generation is related to thermodynamical irreversibility, which is a usual phenomenon in all types of heat transfer systems. Higher rate of entropy production in any heat transfer system destroys the useful work and significantly diminishes the efficiency. A modern technique for optimizing a thermal system is based on the second law of thermodynamics in which the entropy generation is implemented as the parameter for assessing the system efficiency. Indeed, the system with minimum entropy production is considered as the optimum design.

A review of the literature reveals that few studies have been performed about the entropy generation in the thermal systems in which nanofluids are working fluid. Yarmand et al. [20] investigated the entropy generation based on the second law of thermodynamics for turbulent forced convection flow of  $\text{ZrO}_2$ -water nanofluid through a square pipe. Contributions from frictional and thermal entropy generations were evaluated, and the optimal working condition was obtained. The results revealed that the optimal concentration to minimize the entropy generation increases when the Reynolds number reduces. Moreover, it was found that the thermal entropy generation increases by increase of nanoparticle size whereas the frictional entropy generation decreases.

Sarkar et al. [21] evaluated the entropy generation due to mixed convection of water-based  $\text{Al}_2\text{O}_3$  and Cu nanofluids flowing past a barrier located in the middle of two parallel plates. Their results showed that the total entropy production decreases by about 25% by increasing the volume fraction from 0 to 20%. They also concluded that the entropy generation due to fluid friction is negligible in comparison with the thermal irreversibility.

Li and Kleinstreuer [22] evaluated numerically entropy production of CuO–water nanofluid with concentrations less than 4% in trapezoidal microchannels, assuming steady laminar developing flow. They found that adding nanoparticles to the base fluid decreases entropy generation while there is an optimum concentration for which entropy generation is minimized.

In the investigations reported thus far, a nanofluid was frequently assumed to be a homogeneous fluid, and its properties were considered to be constant in all points of the system. These assumptions are not realistic, and can lead to misunderstandings in the phenomena related to nanofluids. Even if nanoparticles are in a motionless medium, they can have Brownian displacements due to their small mass and size. Hence, consideration of nanoparticle motion is essential to analyze nanofluids as heat transfer mediums. Additionally, the results reported in the relevant literature about the flow and heat transfer characteristics of nanofluids are full of contradictions. These contradicting results verify that the interactions between base liquid and nanoparticles can significantly

affect the heat transfer rate which are currently less disclosed. Although many possible mechanisms such as ballistic conduction of phonon, Brownian motion, liquid layering, and so forth have been introduced, there is no overall approach to determine the thermal behavior of nanofluids.

Taking into account the effects of particle migration is one of the important ways which can be effective in better recognition of nanofluid behavior. In other words, if the effects of particle migration are considered properly, more accurate results closer to the problem physics will be reachable. The nanoparticle migration may lead to the non-uniform concentration in nanofluids, and hence, can modify distribution of the thermophysical properties such as thermal conductivity and viscosity.

About the particle migration effects on nanofluids characteristics, a very few surveys have been conducted. Ding and Wen [23] investigated motion of the nanoparticles in laminar pressure-driven pipe flows for dilute suspensions. It was found that the concentration near the wall is significantly lower than that at the pipe centre. Bahiraei [24] evaluated flow and heat transfer features of the suspensions containing  $\text{Fe}_3\text{O}_4$  magnetic nanoparticles in turbulent flow regime. The effects of Brownian motion, shear rate and viscosity gradient were considered. The value of concentration at the wall vicinity was lower than that at the tube centre by applying the effects of particle migration. Their results showed that non-uniformity of the particle distribution was more significant for the larger particles and intensified by increasing mean concentration and Reynolds number.

Assessment of the related literature shows that the research studies about the effect of nanoparticle migration on entropy generation in nanofluids is very sparse. In the current study, an effort is made to evaluate entropy generation for a biological nanofluid flow in a double-pipe heat exchanger locally and globally considering particle migration. The effects of parameters such as particle concentration, inlet temperature and Reynolds number are reported and discussed. To the best knowledge of the authors, this study is the first survey that reports entropy generation of a nanofluid in a heat exchanger considering particle migration.

## 2. Definition of the nanofluid

The analysis is carried out on a biologically produced nanofluid containing silver nanoparticles. The base fluid is ethylene-glycol/water (50:50 by volume). The method for preparation of this nanofluid has been fully presented in [11], and is summarized in Fig. 1. This technique is a green and simple way to synthesize nanofluids containing Ag nanoparticles by tea extract. The nanoparticles will be with functional groups from the tea extract capped on the surface. Sun et al. [10] have proved that the silver ion release from the tea extract synthesized silver nanoparticles is lower in comparison with the other methods. Moreover, this method displays a good stability caused by the functional groups from the tea extract capped on the nanoparticles.

## 3. Definition of the heat exchanger

As per Fig. 2, the mini heat exchanger under study is a double-pipe counter-flow one. The length of the heat exchanger is 1 m, and diameters of the inner and outer pipes are 1 mm and 2 mm, respectively. Moreover, the wall thickness is 0.2 mm and its material is copper. The nanofluid is used as the coolant in the tube side and the hot water flows in the annulus side. The flow directions of both hot water and nanofluid in the heat exchanger have been depicted in Fig. 2.

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