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Entropy generation analysis of nanofluid flow over a spherical heat source inside a channel with sudden expansion and contraction

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ABSTRACT

The present paper deals with entropy generation study of CuO/water nanofluid flow over a spherical heat source that is installed inside a cylindrical channel with sudden expansion and contraction. To estimate the entropy generation rate; first, the governing equations are solved numerically to find the velocity and temperature fields in the domain where the flow is steady and laminar. Next, using the simulation data, the entropy generation number is calculated theoretically. The effects of nanofluid concentration, nanoparticle size, blockage ratio, and Reynolds number on the entropy generation have been investigated. The outcomes of this research elucidate that entropy generation number rises with an increase in the nanoparticle volume fraction and surface temperature of the heat source. On the other hand, it was found that the entropy generation is diminished by implementing finer nanoparticles and lowering the blockage ratio. In this study, a new correlation has also been presented to calculate the Nusselt number that is a function of Reynolds number, Prandtl number, and blockage ratio.

1. Introduction

During the last decade, "Nanofluid" has always been an engrossing term for academics and engineers in the field of heat transfer and thermal engineering. The potential of nanofluids has been evaluated for performance enhancement of various thermal systems such as photovoltaic/thermal systems [1–3], solar collectors [4–9], desalination systems [10], microchannels [11,12], car radiators [13], and machining processes [14]. There are many review papers in the literature on the properties and applications of nanofluids that could be suitable sources for interested researchers (see for example [15–18]). With the development of nanofluids applications, thermodynamic analysis of nanofluid-based systems has become an essential part of the system design process. Entropy generation minimization is a thermodynamic approach to optimize the performance of thermal equipment. Singh et al. [19] started the study on the entropy generation in nanofluid-based systems in 2010 by investigating the entropy generation of Al_2O_3/water nanofluids in channels with three different orders of magnitude including micro, mini and conventional. They indicated that using nanofluids in microchannels where the flow is laminar is not advantageous from the second law viewpoint. On the other hand, it was found that entropy generation rises when nanofluid flows in conventional channels at high Reynolds numbers (turbulent regime). Mahian et al. [20,21] have summarized the main studies (from 2010 to 2014) on entropy generation of nanofluid flows in different structures and regimes. Here, a brief review of more recent studies is presented. In 2015, Anand [22] analytically investigated the entropy generation of Al_2O_3-based nanofluids flowing in a tube under immersed in an isothermal fluid for Reynolds numbers up to 4500. They considered two base liquids including water and ethylene glycol in the study. The results showed that particle loading is not advantageous from the second law viewpoint at high Reynolds numbers and the base fluid with high viscosity. Siavashi et al. [23] studied the effects of both porous media and Al_2O_3/water nanofluids on the heat transfer and entropy generation in an annulus. They indicated that to minimize the entropy generation in each nanofluid concentration an optimal thickness of the porous layer

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Nomenclature

A	surface area of heat source, m^2
C_p	specific heat, J/kg K
D	heat source diameter, m
d	nanoparticle diameter, m
D_h	hydraulic diameter of inlet port, m
g	gravity, m/s^2
h	heat transfer coefficient, W/m^2 K
k	conductivity, W/m K
L	channel side, m
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number, $Nu = \frac{h_{avg}D}{k}$
P	pressure, Pa
Pr	Prandtl number, $\Pr = \frac{\mu C_p}{k}$
$\dot{Q}$	heat transfer rate of heat source, W
Re	Reynolds number, $Re = \frac{\rho V_{in} D_{in}}{\mu}$
S	entropy, J/K
$\dot{S}_{gen}$	rate of entropy generation, J/K s
T	temperature, K
T_0	ambient temperature, K
u	internal energy, J/kg
V	velocity, m/s
v	specific volume, m^3/kg
x, y, z	axial coordinates, m

Greek symbols

ρ	density, kg/m^3
μ	dynamic viscosity, kg/m s
ϕ	volumetric concentration of particles, %
β	thermal expansion coefficient, 1/K
κ	Boltzmann constant, 1.381×10^{-23} J/K
λ	blockage ratio, D/L
ψ	viscous dissipation, kg/m s^3
θ	dimensionless heat source temperature

Subscripts

avg	average
bf	base fluid
in	inlet
nf	nanofluid
np	nanoparticle
s	solid (heat source)
w	wall

can be obtained. Ebrahimi et al. [24] found that using nanofluids in microchannel heat sinks with rectangular cross-section and equipped with vortex generators can reduce the entropy generation. Siavashi and Jamali [25] investigated the entropy generation due to turbulent flow of titanium oxide/water nanofluids in an annulus using two-phase mixture model. The work concludes that entropy generation minimization can be achieved by regulating the mass flow rate of nanofluid. Cho et al. [26] found that with increasing the volume fraction of Al_2O_3 nanoparticles dispersed in water the entropy generation due to natural convection inside a wavy cavity decreases. Bahiraei and Alighardashi [27] studied the entropy generation of TiO_2 based non-Newtonian nanofluids flowing inside a narrow annulus under constant heat flux boundary condition. They reported entropy generation reduction by particle loading at high heat fluxes while for low values of heat flux the pure base fluid provides lower levels of irreversibility. Ibáñez et al. [28] minimized the entropy generation due to Al_2O_3/water nanofluid in a porous microchannel under magnetohydrodynamic (MHD) flow by considering thermal radiation, suction and injection, and slip flow. Cho [29] evaluated the effect of MHD flow on the entropy generation due to free convection of Cu/water nanofluids inside a wavy cavity.

Malik and Nayak [30] numerically examined the effects of MHD flow on the entropy generation in a square cavity filled with Cu/water nanofluid and porous media. They considered time-dependent temperature for a portion of left wall while the right wall was kept cold partially. They found that the ratio of heat transfer rate to entropy generation rate increases with increasing the nanofluid concentration. Torabi et al. [31] investigated Al_2O_3/water nanofluid in porous channels equipped with ribs with different arrangements. They found that increasing the nanoparticle volume fraction decreases the irreversibility. The interested readers may refer to other studies on the effects of nanofluids on entropy generation in different geometries and flow regimes, for example see Refs. [32–37].

The present study, for the first time, deals with the entropy generation due to CuO/water nanofluid flow over a hot spherical block in a channel with sudden expansion and contraction through combined numerical and theoretical approaches. This type of flow has many applications in industry, especially in chemical reactors [38]. The effects of various parameters such as Reynolds number, nanofluid concentration, nanoparticle size, and blockage ratio on entropy generation have been studied. Besides the entropy generation analysis, a new correlation has been derived and presented to estimate the Nusselt number in the channel by considering different blockage ratios.

2. Problem description and numerical solution

The problem under consideration is shown in Fig. 1 where a spherical heat source of diameter D is placed inside a cylindrical channel of length $2L$ with sudden expansion and contraction. The entrance and exit regions are two pipes with a length of $L/2$ and diameter of $D/2$. For the analyses in this study, the length of the channel is assumed to be fixed while the diameter of the heat source is varied.

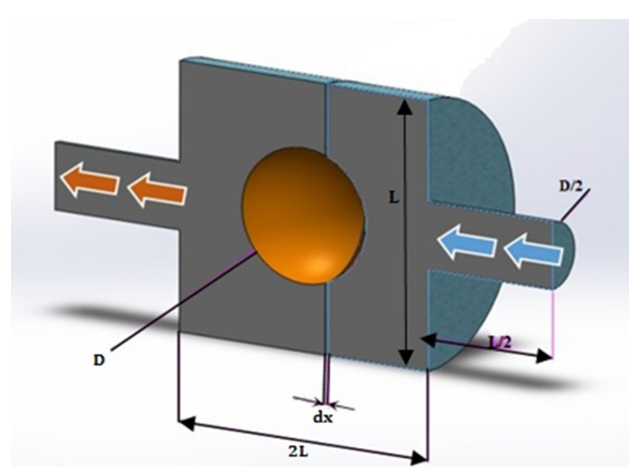

Fig. 1. Configuration of the geometry, a channel with a spherical heat source in the middle of it.