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Entropy generation analysis of nanofluids flow in various shapes of cross section ducts☆

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ABSTRACT

The selection of flow passage's cross section shape is important in thermal system design such as compact heat exchanger. A variety of duct's shapes can be used to enhance the thermal performance. However, it must be noted that different thermal and friction characteristics can be initiated due to this approach. Therefore this paper investigates the entropy generation characteristics of three types of duct's cross section subjected to constant heat flux. The considered shapes are circular, square and triangle (equilateral). Al_2O_3 and MWCNT based nanofluids are used as working fluids in the analysis. The study found that the total entropy generation of Al_2O_3 based nanofluids decreases with the increase of particle volume fractions. However, this parameter increases when working fluid's mass flow rate and heat flux applied to the duct increase. On the aspect of cross section's shape, circular duct exhibits lowest total entropy generation compared to other considered shapes. Moreover, it was also found that MWCNT based water nanofluids exhibit lower total entropy generation compared to Al_2O_3 based nanofluids due to its high thermal conductivity value.

1. Introduction

Heat transfer and friction losses usually occurred in internal forced convective heat transfer. The heat transfer losses are due to temperature differences, while friction losses were attributed to the fluid friction. Evaluation of these two losses is important to justify the effectiveness of the flow passage design. Entropy generation analysis can be implemented for this purpose as this method was developed by Bejan [1] and is often used in the preliminary design of flow passage or thermal system. It uses the first and second laws of thermodynamic approaches [2] and optimum design is achieved when entropy generation is minimized [1].

Since the introduction of this method, there are remarkable studies done to assess the performance of flow passage and thermal system. For instance, Sahin [3] compared the entropy generation of several cross section duct geometries (circular, square, equilateral triangle, rectangle and sinusoidal with aspect ratio of ½) under constant wall temperature. The study implied that circular duct is the most preferred among the selected shapes especially when the frictional entropy generation plays a dominant effect. Dagtekin et al. [4] investigated the entropy generation of circular duct attached with internal longitudinal fins. Thin, triangular and V-shaped fins were chosen in their analysis. The authors concluded that the number of fins, Reynolds number, fin's length, dimensionless temperature difference and fin's angle have considerable effects on the dimensionless entropy generation. Both Sahin [3] and Daqtekin et al. [4] used water as heat transfer fluid in their studies. Another researcher, Ko [5] studied the entropy generation and optimum Reynolds number of forced convection in a double sine ducts applied with heat flux. The results obtained from thermodynamic analytical analysis were compared with numerical analysis in which, air was used as working fluid in their study. Entropy generation of water and engine oil flow in a hexagonal duct applied with constant heat flux was considered by Jarungthammachote [6]. The authors reiterated that fluid properties strongly affect the entropy generation. On the aspect of geometry configuration, it is found that entropy generation decreases when aspect ratio of the hexagonal duct is increased. Apart from that, Petkov et al. [7] used extended performance evaluation criteria to evaluate the performance of laminar flow through bundle of ducts with non-circular shape. They found that the selection of geometry configuration depends on the applied boundary and also its objective pursued.

Recently, there are considerable entropy generation studies focused on nanofluids' flow. Nanofluids are known as heat transfer fluid that posses improved thermal conductivity characteristics compared to conventional fluids. For instance, Singh et al. [8] evaluated entropy generation of alumina-nanofluids in micro, mini and conventional channel. The authors revealed that there is optimum diameter at which entropy generation is minimized. On the other hand, Leong et al. [9] compared the alumina and titanium dioxide based nanofluids flow in a circular tube subjected to constant wall temperature. They found that titanium dioxide nanofluids offer lower total dimensionless entropy generation

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Nomenclatures

Al_2O_3	aluminum oxide
A_c	cross section area (m^2)
c_p	specific heat (J/kg K)
D_h	hydraulic diameter (m)
f	friction factor
k	thermal conductivity (W/m K)
L	length (m)
MWCNT	multiwalled carbon nanotube
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number
P	perimeter (m)
$\dot{q}''$	heat flux (W/m^2)
Re	Reynolds number
$\dot{s}_{gen}$	entropy generation (W/K)
T_i	inlet temperature (K)
T_o	outlet temperature
u	velocity (m/s)

Greek symbols

ρ	density (kg/m^3)
μ	dynamic viscosity (Ns/m^2)
Ø	particle volume fraction

Subscripts

nf	nanofluid
f	basefluid, fluid
p	particle
r	radius
l	length
d	diameter

compared to that of alumina nanofluids. Sohel et al. [10] stressed that the addition of Al_2O_3 and Cu nanoparticles in water or ethylene glycol based fluids will decrease its entropy generation. In their analysis, the authors investigated the nanofluids flow in mini and microchannel heat sink. Bianco et al. [11] performed a parametric investigation on the nanofluids turbulent flow in a circular tube where constant heat flux was applied to the tube. It is concluded that, at the constant inlet velocity, the entropy generation increases when the particle concentration is increased. At higher concentration, the viscosity effects started to prevail.

The rationale of the present study is to investigate the entropy generation of nanofluid's flow in circular, square and triangle cross section ducts. As far as the authors' concern, there are limited literatures on this topic, which focused on nanofluids. So far, most of the reported studies emphasized on the use of conventional fluids such as water, oil, or ethylene glycol. It is hoped that the present study will fill the gap in this area. Comparison between Al_2O_3 and carbon nanotube based nanofluids was also considered in this study. Nevertheless, in a comprehensive review on entropy analysis of nanofluids flow, Mahian et al. [12] suggested that more studies on nanofluids' entropy generation should be focused on different types of geometry configurations.

2. Methodology

This study analyzed the entropy generation of the nanofluid flow in various shape of duct cross section. The assumptions used in this study are:

(a) The thermo-physical properties of nanofluids are constant.
(b) The flow is in steady state condition.
(c) All the heat flux is transferred to the nanofluids.
(d) Uniform heat flux is applied to the duct's wall
(e) The cross section area of the duct is constant throughout its length.
(f) The flow is in laminar condition.

The following Sub-section 2.1 discusses the specification of the duct and its operating condition followed by the thermo-physical model of nanofluids in Sub-section 2.2. Lastly, theoretical models of entropy generation are explained in Sub-section 2.3.

2.1. Specification of duct subjected to constant heat flux

Three types of duct's cross section shapes are investigated in this study. The shapes considered are circular, square and triangle (equilateral). Alumina (Al_2O_3) and water are chosen due to its low costs and can be easily purchased. Al_2O_3 nanoparticles have been widely reported in nanofluids' related researches [13–16]. Apart from that, the entropy analysis of Al_2O_3 based water nanofluid is also compared with multiwalled carbon nanotube (MWCNT) based water nanofluids. MWCNT nanoparticles are among the highly thermal conductive materials available in the market. Table 1 depicts the specification of the ducts and its operating conditions. The schematic diagram of the nanofluids flow can be observed in Fig. 1.

2.2. Thermo-physical properties of base fluid and nanofluids

Thermo-physical properties of the nanofluids are evaluated using correlations or models obtained from various sources of literature. Thermal conductivity of the nanofluids is obtained based on Maxwell formula [17] as follows:

$$\frac{k_{nf}}{k_f} = \frac{k_p + 2k_f + 2\varnothing_p\left(k_p - k_f\right)}{k_p + 2k_f - \varnothing_p\left(k_p - k_f\right)}. \tag{1}$$

Thermal conductivity of Al_2O_3 based water nanofluids is determined by using Maxwell model since the Al_2O_3 particle is assumed to be in spherical form. From this model, it is noticed that nanofluid's thermal conductivity depends on thermal conductivity of particle, base fluid and particle volume fraction. For multiwalled carbon nanotube based water nanofluids' thermal conductivity, Hamilton–Crosser [18] model is used as shown in Eq. (2).

$$\frac{k_{nf}}{k_f} = \frac{k_p + 5k_f + 5\varnothing_p\left(k_p - k_f\right)}{k_p + 5k_f - \varnothing_p\left(k_p - k_f\right)} \tag{2}$$

Table 1
Specification and operating conditions.

Num	Specification/Operation conditions	Circular	Square	Triangle (equilateral)
1	Cross section area (m^2)	7855×10^{-5}		
2	Length of the duct (m)	1		
3	Mass flow rate (kg/s)	0.01–0.05		
4	Inlet temperature of the fluid (K)	300		
5	Type of nanoparticle	Al_2O_3 and MWCNT		
6	Base fluid	Water		
7	Volume fraction of nanoparticles	0–0.01		
8	Heat flux (W/m^2)	2000–4500		