ANALYTICAL STUDY OF PARAMETERS AFFECTING ENTROPY GENERATION OF NANOFLUID TURBULENT FLOW IN CHANNEL AND MICROCHANNEL

by

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In this study, thermo-physical and geometrical parameters affecting entropy generation of nanofluid turbulent flow such as the volume fraction, Reynolds number, and diameter of the channel and microchannel with circular cross-section under constant flux are examined analytically. Water is used as a base fluid of nanofluid with nanoparticles of Ag, Cu, CuO, and TiO_2. The study is conducted for Reynolds numbers of 20000, 40000, and 100000, volume fractions of 0, 0.01, 0.02, 0.03, and 0.04, channel diameters of 2, 4, 6, and 8 cm and microchannel diameters of 20, 40, 60, and 80 micrometers. Based on the results, the most of the generated entropy in channel is due to heat transfer, and also, with increasing the diameter of the channel, Bejan number increases. The contribution of entropy generation due to heat transfer in the microchannel is very poor and the major contribution of entropy generation is due to friction. The maximum amount of entropy generation in channel belongs to nanofluids with Ag, Cu, CuO, and TiO_2 nanoparticles, respectively, while in the microchannel this behavior is reversed, and the minimum entropy generation happens in nanofluids with Ag, Cu, CuO, and TiO_2 nanoparticles, respectively. In channel and microchannel, for all nanofluids except for the water-TiO_2, with increasing volume fraction of nanoparticles, the entropy generation decreases. In channel and microchannel, the total entropy generation increases as Reynolds number augments.

Key words: *nanofluids, analytical solution, turbulent flow, entropy generation, channel, microchannel*

Introduction

Nanofluids are colloid of metal particles, metal oxide or a polymer with a base fluid such as water or ethylene glycol. The higher thermal conductivity of nanoparticles in the nanofluids increases heat transfer compared to the common fluid. Nanofluids can be used for cooling supercomputers, machines, and developed engines. For instance, it is predicted in 2018 that the processor integrated circuit will be produced that generates heat 100 to 300 watts per square meter. For cooling these circuits, air cooling systems are not suitable and nanofluids can be apposite substitute to cool them.

With the aim of the second law of thermodynamics, the amount of the irreversibility which is the same as the entropy generation during a process can be calculated. Entropy analysis

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is a powerful means to determine the efficiency of a process or system [1]. Adding nanoparticles into the fluid leads to an increment of heat transfer and pressure drop simultaneously. Enhancing heat transfer also reduces irreversibility. On the other hand, an increase of the pressure drop causes more irreversibility and decreases the exergy in the system. According to the principles of minimizing entropy generation [2], when the entropy generation is at minimum, the optimum condition of design of a thermal system happens. In other words, when the increasing thermal efficiency and reducing the pressure drop are taken into account concurrently, the best design for a heat exchanger is achieved [3]. Since a few studies on the entropy generation of turbulent flow of nanofluids has been performed in the channels and microchannels, the entropy generation in the channel and microchannel is more considered while the mentioned articles maybe associated with fluid or nanofluids, laminar flow or turbulent. In the following sections, studies that have been investigated the entropy generation in the channels, and then studies that are associated with the entropy generation in microchannels will be proposed. Bianco *et al.* [4] investigated the second law analysis of Al_2O_3-water nanofluid turbulent forced convection in a circular cross-section tube with constant wall temperature. The results show that according to the inlet condition, there is a substantial variation of the entropy generation, whereas when mass flow rate or velocity are taken constant, entropy generation decreases. Ko and Cheng [5] conducted a numerical study of entropy generation in a laminar fluid flow in a channel with wavy walls. According to their results, when the amplitude of the wavy wall is at minimum, the entropy generation is at minimum. Tshehla and Makinde [6] examined the entropy generation of the fluid in the space between two concentric circular channels. They observed that with decreasing the Brinkman number, entropy generation decreases too. In another numerical investigation, Bianco *et al.* [7] explored heat transfer and entropy generation of water-Al_2O_3 nanofluids in a turbulent flow thorough a channel with a square cross-section. According to their results, in order to minimize the entropy generation, the Reynolds number should be optimized. They also reported that at a constant volume fraction, with increasing the Reynolds number, the entropy generation due to heat transfer reduces and the entropy generation due to friction increases. The entropy generation of ethylene glycol-Al_2O_3 and water-TiO_2 nanofluids in the space between two circular channels is examined by Mahian *et al.* [8]. They demonstrated that the entropy generation decreases as the volume fraction of nanofluids increases. Moghaddami *et al.* [9] employed the finite volume method and SIMPLE algorithm to study entropy generation of the water-Al_2O_3 nanofluids in laminar and turbulent flow in a channel. They observed that the entropy generation is at minimum in the optimal Reynolds number. Mahian *et al.* [10] have been investigated the effects of six different predictor models of thermo-physical properties of ethylene glycol-Al_2O_3 nanofluids on entropy generation in a space between two coaxial channels. Based on their results, the critical radius is the same for all models which are examined and for this radius, by increasing the volume fraction of nanoparticles, the entropy generation decreases. The entropy generation in a tube with circular cross-section in a turbulent flow of water-TiO_2 and water-Al_2O_3 nanofluids is examined by Leong *et al.* [11]. They indicated that the use of water-TiO_2 nanofluids causes less entropy generation in a similar situation in comparison with water-Al_2O_3 nanofluids. Mahian *et al.* [12] studied the effect of magnetic fields on entropy generation of water-TiO_2 nanofluids in a space between two coaxial channels. They suggested that nanofluids just should be used for small amounts of Brinkman numbers in the presence of magnetic field. In this way, their using is justifiable as heat transfer and entropy generation increase. Bianco *et al.* [13] numerically investigated the entropy generation of turbulent flow of water-Al_2O_3 nanofluids in a pipe with circular cross-section. They proved that the minimum entropy generation at a constant Reynolds number occurs in low volume fractions of nanoparticles in nanofluids.

Singh *et al.* [14] examined the entropy generation of laminar and turbulent flow of water-Al_2O_3 nanofluids in a microchannel. According to their results, using nanofluids in microchannel turbulent flow reduces the entropy generation. Li and Kleinstreuer [15] employed the finite volume method to investigate entropy generation of water-CuO nanofluids in a trapezoidal microchannel. They demonstrated that in an optimal volume fraction of nanoparticles, the entropy generation is at minimum. In an analytical study, Mah *et al.* [16] examined the effects of viscosity on entropy generation of water-Al_2O_3 nanofluids in a microchannel with circular cross-section. They observed that in all models, with increasing the volume fraction of nanoparticles, the entropy generation increases. Elazhary and Soliman [17] conducted a research about the entropy generation of force convection of laminar fluid flow in a microchannel with two parallel plates in a fully developed region. Based upon their finding, the entropy generation due to heat transfer has the major part of entropy generation. Entropy generation of laminar fluid flow in a microchannel with blades is explored by Zhai *et al.* [18]. They indicated that use of fins can improve heat transfer and reduce the entropy generation.

Considering the previous literature, it is clear that few studies have been conducted about the entropy generation of the nanofluids in turbulent flows in channels and microchannels. Furthermore, analytical study of parameters that influence the entropy generation of turbulent flow of nanofluids and their comparison in channels and microchannels is not performed and remains to be addressed. So in this study, geometrical and thermo-physical parameters affecting the entropy generation of turbulent flow of nanofluids such as the type of nanofluids, volume fraction, Reynolds number, and diameter of the channel and microchannel with circular cross-section under a constant heat flux are analytically examined and the results were compared.

Description of the problem

The schematic of this problem is depicted in fig. 1. The problem is evaluated in two cases, channel and microchannel, with the circular cross-section. This study has been done for water-based nanofluids with nanoparticles of Ag, Cu, Cu_2O, and TiO_2, Reynolds numbers of 20000, 40000, and 100000, nanoparticles volume fraction of 0, 0.01, 0.02, 0.03, and 0.04. The diameters which have been considered for the channel are 2, 4, 6, and 8 cm and for the microchannel are 20, 40, 60, and 80 mm. Channel length is considered 1 m. Nanofluids at 300 K entered and the lateral surface of studied geometry is under constant 250 W/m heat flux. The turbulent flow in the channel is fully developed. Thermo-physical properties of water as a base fluid and nanoparticles are given in tab. 1.

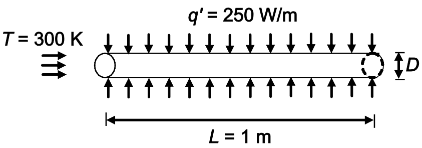

Figure 1. Schematic of the geometry

Table 1. Thermo-physical properties of the base fluid (at 300 K) and nanoparticles [19]

Thermo-physical properties	Water	Ag	Cu	Cuo	TiO_2
c_p [$Jkg^{-1}K^{-1}$]	4179	235	385	535.6	686.2
ρ [kgm^{-3}]	997.1	10500	8933	6320	4250
k [$Wm^{-1}K^{-1}$]	0.613	429	401	76.5	8.95
$\beta\cdot 10^{-5}$ [K^{-1}]	21	1.89	1.67	1.8	0.9
μ [Pa·s]	0.001	–	–	–	–

Classification of channels in terms of diameter

Categorizing the channels in terms of the size is not easy. So it is possible for some applications that the channels are classified as microchannels and for other applications are considered normal channels. For example, in the boiling process a channel with a diameter of 1 mm is not classified as normal channels while in a single phase flow, channel with a diameter of 500 mm are categorized as normal channels. According to Kandlikar [20] segmentation, channels based on the diameter can be classified into three groups as normal channels, minichannels, and microchannels:

(1) normal channels $D_h \geq 3$ mm
(2) minichannels $200\ \mu\text{m} \leq D_h \leq 3$ mm
(3) microchannels $10\ \mu\text{m} \leq D_h \leq 200\ \mu\text{m}$

Nanofluids properties

To calculate the nanofluids density, heat capacity, viscosity [21], and thermal conductivity [22], respectively, eqs. (1) to (4) are used:

$$\rho_{\text{nf}} = (1-\varphi)\rho_{\text{f}} + \varphi\rho_{\text{s}} \tag{1}$$

$$(\rho c_p)_{\text{nf}} = (1-\varphi)(\rho c_p)_{\text{f}} + \varphi(\rho c_p)_{\text{s}} \tag{2}$$

$$\mu_{\text{nf}} = \mu_{\text{f}}(1-\varphi)^{-2.5} \tag{3}$$

$$\frac{k_{\text{nf}}}{k_{\text{f}}} = \frac{k_s + 2k_{\text{f}} - 2\varphi(k_{\text{f}} - k_s)}{k_s + 2k_{\text{f}} + \varphi(k_{\text{f}} - k_s)} \tag{4}$$

Nanofluids entropy generation

Entropy generation relations were introduced by the Bejan [2] already. In the following, the entropy generation in circular channel is proposed. Two major procedures to generate entropy of fluid flow are entropy generation due to heat transfer, $S'_{\text{gen},\Delta T}$, and entropy generation due to pressure drop, $S'_{\text{gen},\Delta P}$:

$$S'_{\text{gen}} = S'_{\text{gen},\Delta T} + S'_{\text{gen},\Delta P} \tag{5}$$

where S' is the entropy generation per unit length. According to the relation of energy conservation, for an element length dx of the tube under constant heat flux, eq. (6) is used:

$$q'\text{d}x = \dot{m}\text{d}h \tag{6}$$

whrere q' is the heat transfer rate per unit length, and dh is the enthalpy change of nanofluids. The second law of thermodynamics can be explained:

$$S'_{\text{gen}} = \dot{m}\frac{\text{d}s}{\text{d}x} - \frac{q'}{T + \Delta T} \tag{7}$$

where ΔT is the temperature difference between the wall and the flow of nanofluids. Enthalpy change is given by:

$$\text{d}h = T\text{d}s + v\text{d}p \tag{8}$$

$$\mathrm{d}s = \frac{\mathrm{d}h - v\mathrm{d}p}{T} = \frac{q'\,\mathrm{d}x}{\dot{m}T} - \frac{v\mathrm{d}p}{T} \tag{9}$$

By substituting eq. (9) in eq. (7), eqs. (10) and (11) are obtained:

$$S'_{\mathrm{gen}} = \frac{q'}{T} - \frac{q'}{T+\Delta T} - \frac{v}{T}\frac{\mathrm{d}p}{\mathrm{d}x} \tag{10}$$

$$S'_{\mathrm{gen}} = \frac{q'\Delta T}{T^2\left(1+\dfrac{\Delta T}{T}\right)} + \frac{\dot{m}}{\rho T}\left(-\frac{\mathrm{d}p}{\mathrm{d}x}\right) \tag{11}$$

Because $\Delta T/T$ is smaller than one, eq. (11) can be rewritten in the form of eq. (12):

$$S'_{\mathrm{gen}} = \frac{q'\Delta T}{T^2} + \frac{\dot{m}}{\rho T}\left(-\frac{\mathrm{d}p}{\mathrm{d}x}\right) \tag{12}$$

The first and second sentences in the right side of eq. (12) indicate the entropy generation due to heat transfer and pressure drop, respectively. The Bejan number which is the proportion of entropy generation due to heat transfer to the total entropy generation is defined:

$$\mathrm{Be} = \frac{S_{\mathrm{gen},\Delta T}}{S_{\mathrm{gen}}} \tag{13}$$

Friction coefficient, Stanton number, mass rate, and hydraulic diameter are:

$$f = \frac{2\rho D_h}{G_2}\left(-\frac{\mathrm{d}p}{\mathrm{d}x}\right),\quad \mathrm{St} = \frac{\dfrac{q'}{\Gamma\Delta T}}{c_p G} = \frac{\mathrm{Nu}}{\mathrm{Re}\,\mathrm{Pr}},\quad G = \frac{\dot{m}}{A},\quad D_{\mathrm{h}} = \frac{4A}{\Gamma} \tag{14}$$

where A is the cross-section of the channel. If we include relations (14) into eq. (12), the final entropy generation is:

$$S'_{\mathrm{gen}} = \frac{q'^2}{\pi T^2 k\ \ \mathrm{Nu}} + \frac{8\dot{m}^3 f}{\pi^2\rho^2 T D^5} \tag{15}$$

In a developed turbulent flow, Nusselt number and f are obtained from eqs. (16), [23], and (17), [24], respectively:

$$\mathrm{Nu} = \frac{\dfrac{f}{8}(\mathrm{Re}-1000)\,\mathrm{Pr}}{1+12.7\left(\dfrac{f}{8}\right)^{0.5}(\mathrm{Pr}^{2/3}-1)} \tag{16}$$

$$f = [0.79\ln(\mathrm{Re}) - 1.64]^{-2} \tag{17}$$

Results and discussion

In this section, the effect of various parameters such as the type of nanofluids, Reynolds number, volume fraction, and changes of diameter on entropy generation of nanofluids in channel and microchannel are discussed.

Effect of changing diameter on entropy generation in the channel and microchannel

(A) Channel

In fig. 2, the total entropy generation variations, [WK^{-1}], *vs.* the channel diameter for water and different nanofluids in Re = 20000 and φ = 0.02 is depicted. The entropy generation decreases with increasing the diameter of channel. The strongest decline in total entropy generation by increasing the channel diameter from 2 cm to 4 cm is 50.72% and takes place for water-TiO_2. With further increment of diameter, the reducing trend of entropy generation decreases, so that the reduction of entropy generation for water-TiO_2 nanofluids with augmentation the diameter from 6 cm to 8 cm becomes 3.74 %.

In fig. 3, the variations of entropy generation, [WK^{-1}], due to friction against the channel diameter for water and different nanofluids in Re = 20000 and φ = 0.02 is illustrated. The change of entropy generation due to friction is similar to the total entropy generation and has reducing behavior with diameter augmentation.

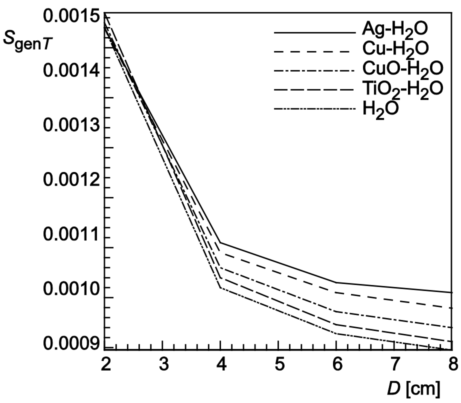

Figure 2. Total entropy generation variations in terms of the channels diameter for water and different nanofluids in Re = 20000 and φ = 0.02

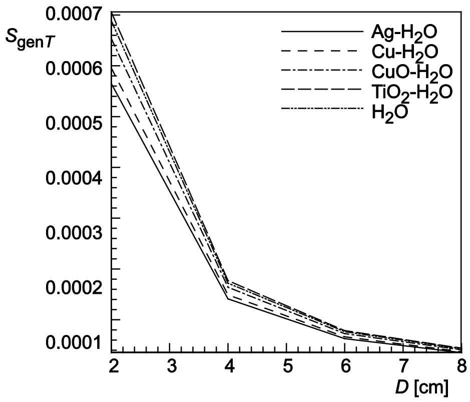

Figure 3. Entropy generation due to friction variations in terms of the channel diameter for water and different nanofluids in Re = 20000 and φ = 0.02

In tab. 2, the Bejan number values in various diameters for water and different nanoparticles in Re = 20000 and φ = 0.02 are presented.

Table 2. Bejan number in different diameters for water and different nanofluids Re = 20000, φ = 0.02

Diameter	Ag	Cu	CuO	TiO_2	Water
2	0.6322	0.6123	0.5789	0.5513	0.5529
4	0.8730	0.8633	0.8461	0.8309	0.8318
6	0.9393	0.9343	0.9252	0.9171	0.9175
8	0.9649	0.9619	0.9565	0.9516	0.9519

In regard to Bejan number is the proportion of entropy generation due to heat transfer to the total entropy generation, and by considering the Bejan number values in tab. 2, it is proved that in the most part of channel, heat transfer is the cause of entropy generation.

For all of the nanofluids that have been used, with increasing the diameter of the channel, the Bejan number increases. Among the mentioned nanofluids in all diameters, maximum and minimum Bejan numbers belong to water-Ag and water-TiO_2, respectively.

(B) Microchannel

In fig. 4, variations of total entropy generation, [WK^{-1}], in terms of the microchannel diameter for water and different nanoparticles in Re = 20000 and φ = 0.02 is displayed. The entropy generation decreases as diameter of the microchannel augments, but this behavior is not uniform with increasing diameter. Furthermore, when the microchannel diameter increases from 20 μm to 40 μm for water and all of nanoparticles which are used, the total entropy generation reduces about 300%. However, with augmentation the microchannel diameter from 40 μm to 60 μm and 60 μm to 80 μm, the total entropy generation reduces about 125% and 78%, respectively.

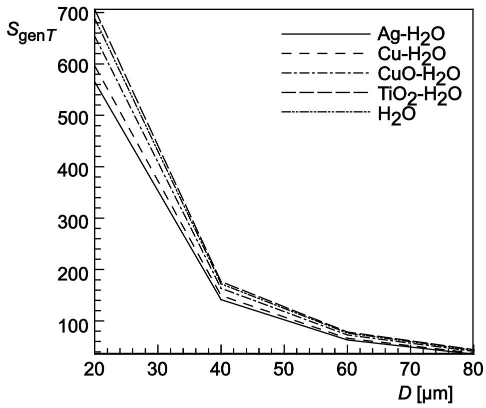

Figure 4. Total entropy generation variations in terms of the microchannel diameter for water and different nanofluids in Re = 20000 and φ = 0.02

Table 3. Heat entropy generation values for water and different nanofluids in D = 40 μm

Nanoparticle	Heat entropy
Ag	$9.72 \cdot 10^{-4}$
Cu	$9.42 \cdot 10^{-4}$
CuO	$9.00 \cdot 10^{-4}$
TiO_2	$8.68 \cdot 10^{-4}$
Water	$8.52 \cdot 10^{-4}$

Since entropy generation due to friction has the major contribution of the total entropy generation, and with increasing the diameter of the microchannel the frictional effects diminishes, this behavior is justifiable. Moreover, the most reduction in entropy generation for nanofluids rather than pure water is 21.83% and appertains to Ag nanoparticles in microchannel with 20 μm diameter. Unlike nanofluids containing Ag, Cu, and CuO nanoparticles, by using the water-TiO_2 nanofluids, the entropy generation increases 2.54% in comparison to pure water. The maximum increment occurs in 60 μm diameter. According to tab. 3, the contribution of entropy generation due to heat transfer is negligible and the main contribution of entropy generation in microchannel belongs to the friction entropy.

The entropy generation of nanofluids in microchannel and channel have similar behavior that with increasing diameter, the entropy generation decreases, but as regards the type of nanoparticles, there is a significant difference between the behavior of microchannel and channel. In channel, the maximum amount of entropy generation is for nanofluids with nanoparticles of Ag, Cu, CuO, and TiO_2, respectively, while this behavior is reversed in microchannel and the lowest entropy generation appertains to nanofluids with nanoparticles of Ag, Cu, CuO, and TiO_2. The maximum decreasing percentage in entropy generation with increasing the diameter in microchannel is six times more than those of in channel.

Effect of volume fraction variation on entropy generation in channel and microchannel

(A) Channel

In fig. 5, the variation of total entropy generation, [WK^{-1}], *vs.* the volume fraction in different Reynolds number of water-Cu nanofluids in channel with D = 4 cm is elucidated. As can be seen, the total entropy generation increases with augmentation Reynolds number. In Re = 20000, with increasing the volume fraction up to 0.04, the entropy generation increases 12.86%, while for the other Reynolds numbers, the entropy generation reduces as the volume fraction of nanoparticles augments. The maximum reduction in entropy generation with increasing the volume fraction is 21.2% and occurs at Re = 100000. In figs. 6 and 7, the variation of entropy generation due to heat transfer and friction in terms of the volume fraction in different Reynolds number of water-Cu nanofluids with D = 4 cm is illustrated.

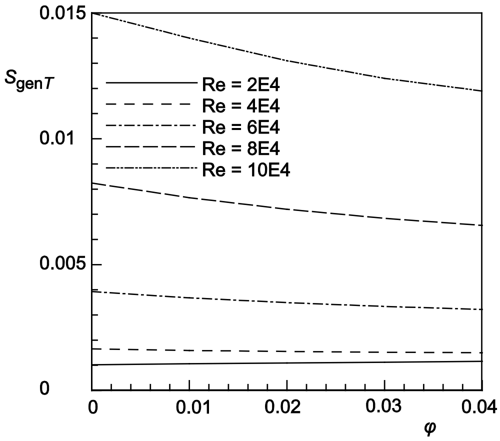

Figure 5. The variation of total entropy generation in terms of the volume fraction in different Reynolds number of water-Cu nanofluids in channel with D = 4 cm

According to these figures, it is clear that the friction entropy generation decreases when the volume fraction increases (with the exception of Re = 20000). The variation of entropy generation due to friction is in contrast to the behavior of entropy generation due to heat transfer for water-Cu nanofluids. It means that the entropy generation due to heat transfer increases as the volume fraction increases, except for Re = 20000 when it decreases.

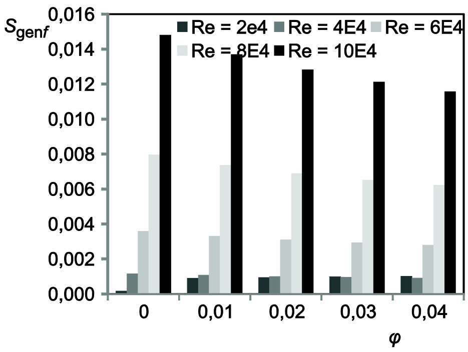

Figure 6. The variation of entropy generation due to friction in different Reynolds number of water--Cu nanofluids with D = 4 cm

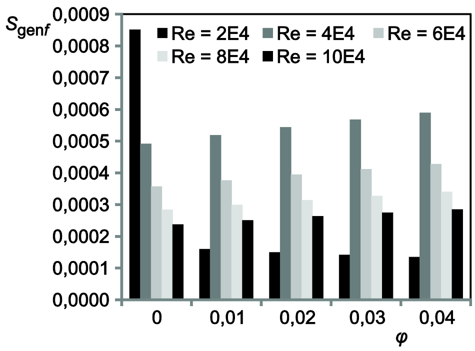

Figure 7. The variation of entropy generation due to heat in different Reynolds number of water-Cu nanofluids with D = 4 cm

In figure 6, with increasing the volume fraction, entropy generation due to friction increases too. Because by increasing the volume fraction of nanoparticles, the viscosity of nanofluid increases and thus, the friction effects and entropy generation due to friction increase.

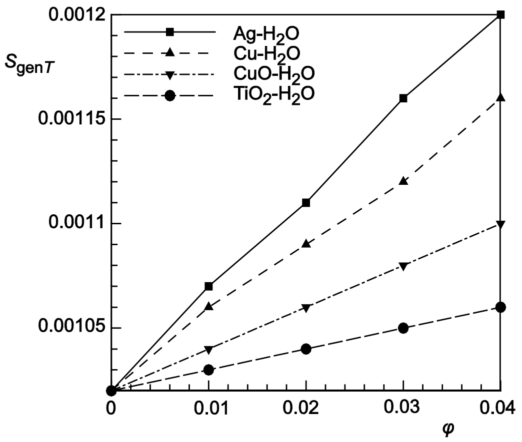

Figure 8. The variation of total entropy generation in terms of volume fraction for different nanofluids in Re = 20000 and *D* = 4 cm

In fig. 8, the variation of total entropy generation against the volume fraction for different nanofluids in Re = 20000 with D = 4 cm is displayed. The total entropy generation increases with augmentation of the volume fraction for all the nanofluids in all Reynolds numbers and diameters which are considered. The maximum and minimum entropy generation within the nanofluids belong to water-Ag and water-TiO_2, respectively. In tab. 4 the values of entropy generation due to friction for different nanoparticles in Re = 20000 and φ = 0.02 are shown. For all the nanofluids, the entropy generation due to friction decreases as the volume fraction augments expect for water-TiO_2. In tab. 5, Bejan number for nanofluids with different nanoparticles are presented in Re = 20000 and φ = 0.02. The Bejan number behavior for all nanofluids that are examined is similar to the behavior of the entropy generation due to friction when the volume fraction increases.

Table 4. Entropy generation due to friction for different nanoparticles in Re = 20000 and φ = 0.02

Nanoparticles	Ag	Cu	CuO	TiO_2
$\varphi = 0$	$1.72\cdot10^{-4}$	$1.72\cdot10^{-4}$	$1.72\cdot10^{-4}$	$1.72\cdot10^{-4}$
$\varphi = 0.01$	$1.55\cdot10^{-4}$	$1.59\cdot10^{-4}$	$1.67\cdot10^{-4}$	$1.74\cdot10^{-4}$
$\varphi = 0.02$	$1.41\cdot10^{-4}$	$1.49\cdot10^{-4}$	$1.64\cdot10^{-4}$	$1.77\cdot10^{-4}$
$\varphi = 0.03$	$1.31\cdot10^{-4}$	$1.41\cdot10^{-4}$	$1.61\cdot10^{-4}$	$1.80\cdot10^{-4}$
$\varphi = 0.04$	$1.23\cdot10^{-4}$	$1.35\cdot10^{-4}$	$1.59\cdot10^{-4}$	$1.83\cdot10^{-4}$

Table 5. Bejan number for nanofluids with different nanoparticles in Re = 20000 andφ = 0.02

Nanoparticles	Ag	Cu	CuO	TiO_2
$\varphi = 0$	0.8318	0.8318	0.8318	0.8318
$\varphi = 0.01$	0.8551	0.8494	0.8379	0.8317
$\varphi = 0.02$	0.8730	0.8633	0.8461	0.8309
$\varphi = 0.03$	0.8870	0.8745	0.8541	0.8297
$\varphi = 0.04$	0.8981	0.8836	0.8555	0.8278

(B) Microchannel

In fig. 9, the variations of total entropy generation, [WK^{-1}], in terms of volume fraction is elucidated for water-Cu nanofluids and D = 20 μm. In constant volume fraction, the

Table 6. Total entropy generation due to heat for water-Cu nanofluids in φ = 0.02

Reynolds number	Entropy generation due to heat
$2\cdot10^4$	$8.98\cdot10^{-4}$
$4\cdot10^4$	$5.44\cdot10^{-4}$
$6\cdot10^4$	$3.94\cdot10^{-4}$
$8\cdot10^4$	$3.14\cdot10^{-4}$
$10\cdot10^4$	$2.63\cdot10^{-4}$

total entropy generation increases with Reynolds number augmentation for all of the nanofluids with the exception of water-TiO_2. In constant Reynolds number, total entropy generation decreases as the volume fraction increases. The maximum amount of this reduction is 27.28% and takes place in Re = 80000 and by increasing volume fraction from zero to 0.04. In tab. 6 the total entropy generation due to heat transfer for water-Cu nanofluids in φ = 0.02 is presented. When Reynolds number increases, entropy generation due to heat transfer decreases in constant volume fraction. As indicated in tab. 6, the contribution of entropy generation due to heat transfer is insignificant and the major contribution of entropy generation in microchannel appertains to friction entropy. In fig. 10, the variation of the total entropy generation in terms of the volume fraction is displayed for different nanofluids in Re = 20000 and D = 40 μm. The maximum amount of reduction in the total entropy generation with increasing the volume fraction is 40.47% and belongs to water-Ag.

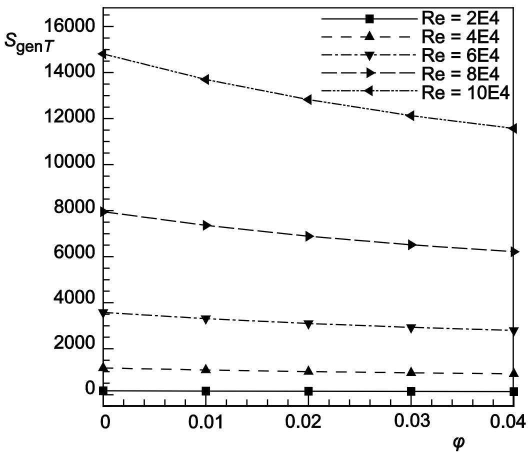

Figure 9. The variation of total entropy generation in terms of volume fraction for water-Cu nanofluids and D = 20 μm

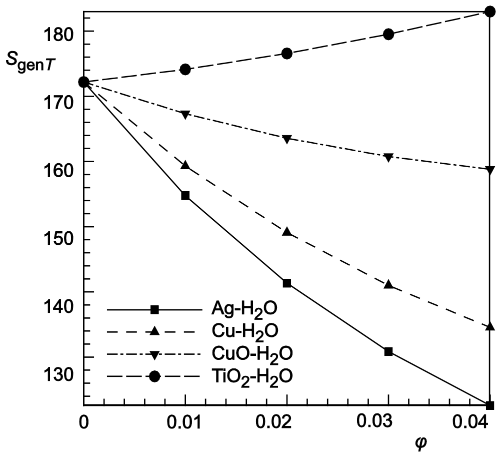

Figure 10. The variation of total entropy generation in terms of volume fraction for different nanofluids, Re = 20000, D = 40 μm

In fig. 9, as the volume fraction increases, entropy generation due to heat transfer decreases. The cause of this behaviour is reducing the heat capacity of nanofluid with increasing the volume fraction.

The total entropy generation decreases as the volume fraction augments for all of the nanofluids except for water-TiO_2. Furthermore, for this nanofluid, with increasing the volume fraction up to 0.04, the entropy generation increases 6%, while in channel, the nanofluids generated entropy increases as the volume fraction augments. Total entropy generation due to heat transfer for various nanofluids in Re = 20000 and φ = 0.02 is presented in tab. 7. Furthermore, the maximum and minimum entropy generation in all of the volume fractions belongs to water-Ag and water-TiO_2, respectively. In tab. 8, the total entropy generation due to

Table 7. Entropy generation due to heat for different nanofluids in Re = 20000 and φ = 0.02

Nanofluids	Entropy generation due to heat
Water-Ag	$9.72\cdot10^{-4}$
Water-Cu	$9.42\cdot10^{-4}$
Water-CuO	$9.00\cdot10^{-4}$
Water-TiO_2	$8.68\cdot10^{-4}$

Table 8. Total entropy generation due to heat for water-Ag nanofluids in Re = 20000

Volume fraction	Entropy generation due to heat
$\varphi = 0$	$8.52\cdot10^{-4}$
$\varphi = 0.01$	$9.13\cdot10^{-4}$
$\varphi = 0.02$	$9.72\cdot10^{-4}$
$\varphi = 0.03$	$1.03\cdot10^{-4}$
$\varphi = 0.04$	$1.08\cdot10^{-4}$

heat transfer for water-Ag nanofluids is presented in Re = 20000 and φ = 0.02. The maximum and minimum entropy generation in all of the volume fractions are for water-Ag and water-TiO_2, respectively.

Effect of the Reynolds number changing on entropy generation in channel and microchannel

(A) Channel

Figure 11 displays the variation of the total entropy generation in terms of the Reynolds number in φ = 0.02 and D = 4 cm for different nanofluids in channel. The total entropy generation increases as the Reynolds number increases. Moreover, this behavior is seen in microchannel but a difference is that in channel the maximum and minimum entropy generation appertain to water-Ag and water-TiO_2, respectively, whereas this behavior is reversed in microchannels and the maximum and minimum entropy generation belong to water-TiO_2 and water-Ag.

(B) Microchannel

The variation of total entropy generation, [WK^{-1}], against Reynolds number in φ = 0.02 and D = 4 μm for different nanofluids in microchannel is shown in fig. 12.

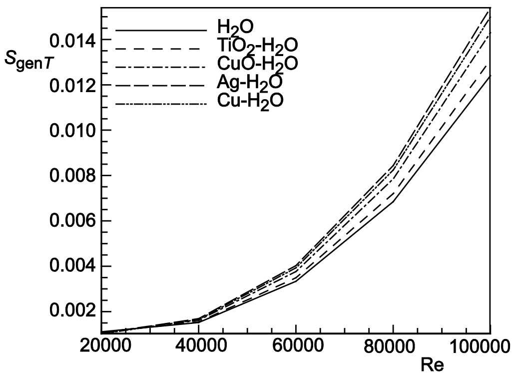

Figure 11. Variation of total entropy generation in terms of Reynolds number in φ = 0.02 and D = 4 cm for different nanofluids in channel

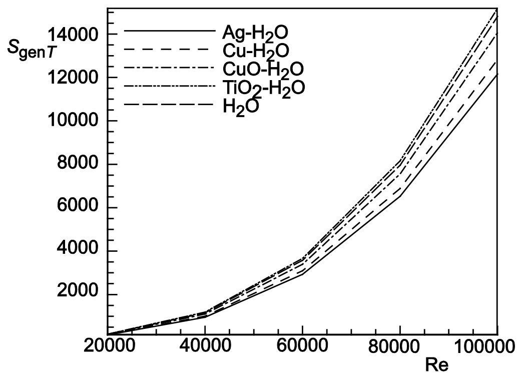

Figure 12. Variation of total entropy generation in terms of Reynolds number in φ = 0.02 and D = 4 μm for different nanofluids

The maximum and minimum entropy generation in all volume fractions and Reynolds numbers is for water-Ag and water-TiO_2, respectively. Furthermore, the maximum augmentation in total entropy generation by changing the type of nanoparticle is 25% and occurs in Re = 60000 when the nanofluid is switched from Cu to TiO_2. The total entropy generation of water is more than other nanofluid except for water-TiO_2.

Conclusions

In this study, the thermo-physical and geometrical parameters which are influenced on the entropy generation of nanofluids turbulent flow such as volume fraction, Reynolds number, and diameter of the channel and microchannel with circular cross-section are analytically investigated under constant heat flux. The study is conducted for different water-based nanofluids with Ag, Cu, CuO, and TiO_2 nanoparticles, Reynolds numbers of 20000 to 100000, volume fractions of 0 to 0.04, channel diameters of 2, 4, 6, and 8 cm and microchannel diameters of 20, 40, 60, and 80 μm. The results are the following.

- As the channel diameter increases, entropy generation decreases. The strongest decline in total entropy generation with increasing the channel diameter from 2 cm to 4 cm is 50.72% and belongs to water-TiO_2.
- The main part of the generated entropy in channel is due to heat transfer, and Bejan number increases with increasing channel diameter. Among the nanofluids which are considered for all diameters, the maximum and minimum Bejan number is for water-Ag and water-TiO_2, respectively.
- The entropy generation decreases with diameter augmentation of the microchannel. When the microchannel diameter increases from 20 μm to 40 μm, the total entropy generation reduces about 300% for water and all of the nanofluids which are used.
- The entropy generation due to the friction has the major contribution of the total entropy generation in microchannel.
- In channel, the maximum amount of entropy generation is for nanofluids with nanoparticles of Ag, Cu, CuO, and TiO_2, respectively, while this behavior is reversed in microchannel and the minimum entropy generation belongs to nanofluids with nanoparticles of Ag, Cu, CuO, and TiO_2.
- In channel, the entropy generation reduces as the volume fraction of nanoparticles increases in all Reynolds numbers with the exception of Re = 20000. The maximum reduction in entropy generation with increasing volume fraction is 21.2% and occurs at Re = 100000.
- In microchannel and in constant Reynolds number, the total entropy generation decreases when the volume fraction augments. The maximum amount of this reduction is 27.28% and occurs in Re = 80000.
- The total entropy generation increases as the Reynolds number increases. This behavior is seen in microchannel with a difference that in channel, the maximum and minimum entropy generation appertain to water-silver and water-TiO_2, respectively, whereas this behavior is reversed in microchannels and the maximum and minimum entropy generation belong to water-TiO_2 and water-Ag.

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Nomenclature

A – cros-section
Be – Bejan number
c_p – specific heat at constant pressure, [$Jkg^{-1}K^{-1}$]

D – diameter, [cm], [μm]
f – friction coefficient
G – mass rate, [kgm^{-2}s^{-1}]
h – enthalpy, [J]
k – coefficient of thermal conductivity, [Wm^{-1}K^{-1}]
$\dot{m}$ – mass flow rate, [kgs^{-1}]
Nu – Nusselt number
p – pressure, [Pa]
Pr – Prandtl number
ΔP – pressure gradient
q' – heat, [Wm^{-1}]
Re – Reynolds number
S_{gen} – entropy generation, [WK^{-1}]
S'_{gen} – entropy generation per unit length, [WK^{-1}m^{-1}]
St – Stanton number
ΔT – temperature difference

Greek symbols

Γ – wet area, [m^2]
μ – viscosity, [kgm^{-2}s^{-1}]
ρ – density, [kgm^{-3}]
φ – volume fraction of nanoparticles

Subscripts

gen – generated
f – fluid
nf – nanofluid
h – hydraulic
s – nanoparticle

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