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The significant effect of turbulence characteristics on heat transfer enhancement using nanofluids: A comprehensive review☆

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ABSTRACT

In this article, turbulent flow characteristic of nanofluids is thoroughly reviewed. Turbulent flows have unique characteristics and are preferred in many industrial applications. Therefore, this paper reviews different techniques used to enhance heat transfer using nanofluids within turbulent regime. This paper also presents the effects of some important parameters such as nanoparticle type, nanoparticles concentration, and Reynolds number on heat transfer rate. Studies on numerical techniques are also discussed. Finally, the conclusions and important summaries are presented according to the data collected.

1. Introduction

Since the first attempt to study the characteristics of turbulent by Leonardo da Vinci [1], a great deal of theoretical and experimental studies has been dedicated to investigate this phenomenon [2–5]. The fundamental interest arises from the concern to understand the mixing mechanism [6–9] and its characteristics when interacting with the surroundings [10–15]. Turbulence occurs nearly everywhere: in the oceans (the wake of a ship or submarine), in the air currents in the atmosphere, in the swirls and eddies of a fast-flowing river, and even in stars and galaxies. On the other hand, a similar interest has been provoked by the wide range of engineering applications utilizing this type of phenomenon [16–20]. Among the problems related to turbulent flow, many researchers have focused their investigations on the enhancement of heat transfer by the turbulent characteristics of flow [21–23].

Even though the research on nanofluid only begun in 1993, it has attracted vast attention due to its high potential to enhance heat transfer. A nanofluid can be produced by dispersing metallic or non-metallic nanoparticles or nanofibers with a typical size of less than 100 nm in a base liquid [24–26]. The presence of nanoparticles in base fluid contributes to better mixing of flow and higher thermal conductivity compared to pure fluid. A novel study by Matsuda [27] revealed that the dispersion of γ-$A1_2O_3$ particles at 4.3 vol% can increase the effective thermal conductivity of water by almost 30%. Table 1 shows the thermal conductivity and specific heat of well-known nanoparticles. Since its first introduction to real engineering applications, nanofluid has been successfully applied to enhance heat transfer in many cases such as electronics components, nuclear reactor, building heating and cooling, water boiling, and many more [28–32].

A few review papers have discussed the performance of nanofluids in turbulent flow conditions [33,34]. In the present paper, we attempt to review the application of nanofluids in enhancing heat transfer with the help of turbulent characteristics with much more details. To the best of the authors' knowledge, there is no comprehensive literature on the subject.

2. Heat transfer augmentation by corrugated and roughened surface

The flow characteristics in a channel are extremely dependent on the geometry of the surface. Many techniques have been proposed/introduced in order to generate transverse/longitudinal, three-dimensional vortices of the flow in the channel. These flow characteristics are more crucial when there is a need for efficient heat transfer from the channel surface to the flowing fluid. Corrugated surface geometry is one of the passive techniques to enhance the heat transfer rate near the wall by disturbing the flow and increase the mixing of fluids. Many literature records have indicated that the corrugated channel resulted in a more complex flow structure and improved the heat transfer efficiency [35–42]. Corrugated surface can be introduced by roughened elements such as grooves and ribs in various shapes (rectangular, triangular, square, and circle).

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Nomenclature

AR	aspect ratio of longitudinal strip inserts (W/H)
D	inner tube diameter (m)
f	friction factor
GPR	geometrical progression ratio
H	pitch of twist tape (m)
k	thermal conductivity (W/m·K)
Nu	Nusselt number
p	pitch of dimple (m)
P	pitch of wire coil (m)
PEC	performance evaluation criteria index
Pr	Prandtl number
Re	Reynolds number
T	temperature (°C)
TR	twist ratio (twist length/tape width)
Greek symbols	
η	thermal factor
ρ	density (kg/m^3)
ϕ	volume concentration (%)
Ω	weight fraction (%)
Subscripts	
cal	calculated
h	hydraulic
np	nanoparticle
s	smooth

One of the earliest works on the use of corrugated channel for the enhancement of heat transfer was conducted by Goldstein and Sparrow [41]. They revealed that the average coefficient increased up to a factor of three compared to conventional straight channel. Years later, Murata and Mochizuki [42] compared the performance of roughened surface channel to the angled ribs under laminar and turbulent flow conditions. They confirmed that the turbulence characteristics of flow attributed more heat transfer due to more disturbances on the flow. To gain a better understanding of the turbulence characteristics, Kamali and Binesh [43] numerically analyzed turbulent heat transfer in a square duct with four different types of ribs mounted on the internal surface. They found that the trapezoidal rib with decreasing height in the flow direction provided the highest heat transfer enhancement than other shapes.

Table 1
Specific heat and thermal conductivity.

Materials	Specific heat (kJ/kg K)	Thermal conductivity (W/m K)
Ag	0.235	429
Carbon nanotube		3000
Cu	0.385	401
Graphite	0.701	120
Ni	0.445	89
Silicon carbide	1.340	350
Yttria	0.298	5
SiO_2	0.68	1.3
CuO	0.551	32.9
ZnO		21
Al_2O_3	0.773	40
Fe_3O_4	0.67	80.4
TiO_2	0.692	8.4
ZrO_2	0.502	1.7
MgO	0.88	30
Water	4.179	0.609
Glycerine	2.43	0.285
Ethylene glycol	2.2	0.258

These findings were supported by a study done by Bilen et al. [44], who conducted an experimental study on surface heat transfer of a turbulent flow in different grooved tubes. The tests were performed at Reynolds number ranging from 10,000 to 38,000. Fifty-eight percent of the heat transfer enhancement was obtained for trapezoidal grooved when compared with smooth grooved.

The application of nanofluids in grooved or ribbed channel can further enhance the rate of heat transfer from the surface to the turbulent fluid flow. Suresh et al. [45] have introduced dimples on the outer surface of the tube to create roughness and interruption of boundary layer. CuO/water nanofluid with 0.1–0.3 wt% was used as working fluid. The results showed that the enhancement of Nusselt number was about 19% to 39% with a maximum of 10% pressure drop compared to plain tubes. Using least squares regression analysis, they also proposed the following correlations for Nusselt number and friction factor:

$$\mathrm{Nu} = 0.00105\,\mathrm{Re}^{0.984}\,\mathrm{Pr}^{0.4}(1+\phi)^{-80.78}\left(1+\frac{p}{D}\right)^{2.089} \tag{1}$$

$$f = 0.1648\,\mathrm{Re}^{0.97}(1+\phi)^{107.89}\left(1+\frac{p}{D}\right)^{-4.463} \tag{2}$$

Oronzio et al. [46] numerically investigated the forced convection heat transfer behavior of Al_2O_3/water nanofluids in a uniformly heated tube. Square and rectangular shapes of ribs mounted on the lower wall were introduced to create local turbulence characteristics of flow. Their study showed that the highest performance evaluation criteria index, $\mathrm{PEC} = (\mathrm{Nu}/\mathrm{Nu}_s)/(f/f_s)^{1/3}$ was obtained when the ratio of pitch to height was equivalent to 8.

Within the same year, Mohammed and his co-workers [47] conducted a comprehensive numerical investigation on the effect of ribs and grooves on channel wall heated by a uniform temperature. Four different types of nanoparticles (Al_2O_3, CuO, SiO_2, and ZnO) with different volume fractions in the range between 1 and 4 wt% were dispersed in different based fluids (water, glycerine, and engine oil). They concluded that the Glycerin-SiO_2 nanofluid in the channel with rectangular rib-triangular groove gave the best heat transfer enhancement compared to other tested cases.

The effects of detached ribbed channel on the flow and heat characteristics have been numerically investigated by Mohammed et al. [48]in which he considered Al_2O_3, CuO, SiO_2, and ZnO nanoparticles in water-based nanofluid. No significant effect of the gap between the rib and channel wall on heat transfer performance was reported. The presence of rib creates local turbulence due to flow separation and reattachment between consecutive ribs. As a result, the mixture of nanoparticles improved and the heat transfer mechanism was enhanced.

Pongjet et al. [49] numerically studied the turbulent periodic flow and heat transfer in a tube with angle rings using Al_2O_3/water nanofluids. The maximum PEC = 1.8 was obtained when the blockage ratio was 0.025 and the Reynolds number was 3000.

A recent study has been done by Abed et al. [50] regarding the performance of nanofluids flow in a corrugated channel with V-shaped on the lower surface. The study showed some promises on the enhancement of turbulent heat transfer. Numerical analysis using standard k–ε turbulent model has demonstrated the superiority of SiO_2–glycerin nanofluid in predicting the Nusselt number compared to other based fluids. They also concluded that the water-based nanofluids only perform better heat transfer enhancement under low Reynolds number.

Ahmed et al. [51] conducted a series of numerical and experimental studies to investigate the heat transfer enhancement in the corrugated channel using SiO_2/water nanofluid. Three different channels such as trapezoidal, sinusoidal, and straight were fabricated and tested. In the