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Performance analysis of turbulent convection heat transfer of Al_2O_3 water-nanofluid in circular tubes at constant wall temperature

Vincenzo Bianco [a], Oronzio Manca [b, *], Sergio Nardini [b]

[a] University of Genoa, DIME/TEC, Division of Thermal Energy and Environmental Conditioning, Via All'Opera Pia 15/A, 16145 Genova, Italy
[b] Seconda Università degli Studi di Napoli, Dipartimento di Ingegneria Industriale e dell'Informazione, Via Roma 29, 81031 Aversa (CE), Italy

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ABSTRACT

The present paper analyzes the turbulent convection of Al_2O_3-water nanofluid inside a circular section tube subjected to constant wall temperature. The analysis is developed numerically by using the mixture model, which has been proved to be a convenient method to simulate nanofluids behavior. The numerical model is successfully validated by means of analytical equations and experimental correlations. The study is focused on the analysis of the performance of Al_2O_3-water nanofluid within the considered device. Performance indicators based on the first and second law of thermodynamics are taken into account and analyzed. At the increase of nanofluid concentration, the Nusselt number increases, but entropy generation and pumping power also increase, therefore the penalties overcome the benefits.

The results reported in the present paper are believed to be useful for the thermal optimization of nanofluids flow inside tubes.

1. Introduction

The aim of the present paper is to analyze the performance of a nanofluid inside a circular section tube subjected to constant wall temperature boundary condition, in order to establish the optimal thermal conditions for the system under investigation.

Nanofluids are a new category of heat transfer fluid [1] composed by a base fluid, for example water, and a dispersed phase, represented by highly conductive nanoparticles. The idea to increase the thermal conductivity of liquids by dispersing solid particles is not new, in fact it was proposed by Maxwell [2] more than one century ago. At that age the manufacturing capabilities were limited and only particles with a diameter in the order of micrometers could be produced, limiting the applicability of such kind of fluids, because of the very high viscosity due to the particles dimensions. On the contrary, nanofluids do not show an extreme penalty on the viscosity, that is why their popularity among the researchers is increasing.

In the recent years, nanofluids have attracted the interests of many researchers around the world, who developed various investigations on the topic.

Buongiorno [3] developed a complete analysis of the different mechanisms involved in the nanofluid convection. He proposed a correlation for the determination of the Nusselt number for the turbulent convection of nanofluids. Pak and Cho [4] proposed the first experimental study on the turbulent convection of nanofluids. They investigated different kinds of mixtures and they proposed an experimental correlation for the Nusselt number. Also Xuan and Li [5] experimentally investigated the turbulent convection of nanofluids. They were the first to propose a correlation for the Nusselt number, which is explicitly function of the nanoparticles concentration.

Sheikhbahai et al. [6] proposed an experimental investigation of the pool boiling of Fe_3O_4/ethylene glycol-water nanofluid in an electric field. They determined that heat transfer coefficients deteriorate by increasing nanoparticle concentration, whereas their addition delays nucleate boiling incipience and increases CHF (critical heat flux). Jacob et al. [7] performed an experimental and numerical investigation on the microwave heating of nanofluids. Their study demonstrates that additional fluid flow behavior in nanofluids is induced by the heated nanoparticles due to particle migration effects.

Other authors proposed a numerical approach for the study of nanofluids convection, by employing different techniques.

Bianco et al. [8] and He et al. [9] proposed for the first time the application of the discrete phase model to the simulation of nanofluids convection. They performed a full two phase simulation, modeling the nanoparticles with a Lagrangian approach and the base fluid by means of the usual Eulerian methodology. Subsequently,

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* Corresponding author. Tel.: +39 081 5010 217; fax: +39 081 5010 204.
E-mail addresses: oronzio.manca@unina2.it, oronzio.manca@gmail.com (O. Manca).

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Nomenclature

a	acceleration, $m^2 s^{-1}$
Be	Bejan number
Cp	specific heat of the fluid, $J kg^{-1} K^{-1}$
D	diameter, m
d	particles diameter, m
f	friction factor
f_{drag}	drag function
g	gravity acceleration, $m s^{-2}$
h	heat transfer coefficient, $W m^{-2} K^{-1}$
L	channel length, m
$\dot{m}$	mass flow rate, $kg s^{-1}$
Nu	Nusselt number, $Nu = h \times D \times \lambda^{-1}$
k	turbulent kinetic energy, $m^2 s^{-2}$
k_b	Boltzmann's constant, $1.38066 \times 10^{-23} J K^{-1}$
p	pressure, Pa
P	pumping power, W
PEC	performance evaluation criteria index, Eq. (25)
Pr	Prandtl number, $Pr = \mu \times Cp \times k^{-1}$
q	wall heat flux, $W m^{-2}$
R	tube radius, m
Re	Reynolds number, $Re = V_0 \times D \times \upsilon^{-1}$
S_{gen}	entropy generation, $W K^{-1}$
T,t	time-averaged and fluctuating temperature, K
V,v	time-averaged and fluctuating velocity, $m s^{-1}$
$\vec{V}$	velocity, $m s^{-1}$
$\dot{V}$	volumetric flow rate, $m^3 s^{-1}$

Greek letters

ε	dissipation of turbulent kinetic energy, $m^2 s^{-3}$
φ	particle volume concentration
λ	thermal conductivity of the fluid, $W m^{-1} K^{-1}$
μ	fluid dynamic viscosity, $kg m^{-1} s^{-1}$
ρ	fluid density, $kg m^{-3}$
τ	wall shear stress, Pa

Subscripts

av	average value
b	bulk value
bf	refers to base-fluid
dr	drift
f	friction
fr	freezing
k	the *k*th phase
m	mixture
nf	refers to nanofluid property
p	refers to particle property
r	refers to ‘nanofluid/base-fluid’ ratio
w	value at wall channel
t	turbulent
T	total
th	thermal
0	refers to the reference (inlet) condition

Tahir and Mital [10] successfully utilized this approach to simulate the developing laminar forced convection flow of alumina-water nanofluid in a circular tube subjected to a uniform wall heat flux. They analyzed the effects of particle diameter, Reynolds number and volume fraction of the particles on the average heat transfer coefficient.

Other research groups utilized the mixture model to simulate nanofluids convection. Behzadmehr et al. [11] were the first to apply the mixture model to the simulation of nanofluid convection. They showed the higher accuracy of the two phase mixture model with respect to the single phase model. This approach was successfully implemented by many other researchers [12–14].

Different authors performed comparisons about the different numerical models to be used in the simulation of nanofluids convection. Hejazian and Moraveji [15] proposed a comparison between single phase model and mixture model, showing that the mixture model guarantees a better agreement with experimental results. Moraveji and Esmaeili [16] compared single-phase and two-phases CFD (computational fluid dynamics) modeling of laminar forced convection flow of nanofluids in a circular tube under constant heat flux. They detected a good agreement between the numerical results and experimental data. Minea [17] proposed a numerical investigation of nanofluid turbulent convection inside a microtube. She investigated the influence of the microtube length providing some correlations. Kamyar et al. [18] reviewed and summarized the numerical studies performed in the field of nanofluids, concluding that most of the employed computational simulations are in acceptable concordance with the results from experiments.

Many researchers focused their attention on the study of the thermophysical properties of nanofluids, proposing different constitutive models, especially for the thermal conductivity and for the viscosity. Khanafer and Vafai [19] proposed different models to determine thermal conductivity and viscosity for alumina based nanofluids. They used a large amount of experimental data available in the literature to build their models. Also Corcione [20,21] utilized the same methodology as in Ref. [19], but he proposed correlations valid for different kinds of nanofluids. Minea and Luciu [22] proposed an experimental analysis of the thermal conductivity of Al_2O_3-water based nanofluids, detecting a strong enhancement with respect to the base fluid. A complete review of thermophysical models for nanofluids is proposed in Ref. [23].

Many applications employing nanofluids are presented in the literature, which illustrate the practical advantages that can be achieved. In Refs. [24–26], it is described the application of nanofluids within heat pipes, showing that a reduction of the dimensions can be achieved and that the maximum capillary limit is enhanced. Instead, Mital [27] applied nanofluids to the cooling of electronic devices. He performed an optimization of the parameters by means of a genetic algorithm. Recently Kazemi-Beydokhti and Heris [28] utilized nanofluids in a CHP (cogeneration of heat and power) system. They used nanofluids in the heat exchanger to recover waste heat, demonstrating that the use of nanofluids increases the CHP performances.

As previously noticed, nanofluids are characterized by a higher thermal conductivity and also by a higher viscosity with respect to the base fluid; therefore it is important to find a balance between these two opposite behaviors, in order to establish optimal working conditions.

Entropy generation analysis [29] is one of the most utilized criteria to face such a kind of problem, because its minimization, i.e. the minimization of the irreversibility of a system, allows to obtain more convenient working conditions. This approach was successfully employed to pursue the optimization of thermal system, as reported in Refs. [30–32].

Recently some authors studied the entropy generation in nanofluid flow. Bianco et al. [33] analyzed the average entropy generation in the turbulent convection of nanofluids within a square section tube. They found the Re number which minimizes entropy generation for a given concentration. Mahian et al. [34,35] analyzed entropy generation between two co-rotating cylinders using nanofluids. They found that the TiO_2-water nanofluid represent the optimal choice for this kind of configuration.