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A thermodynamic analysis of forced convection through porous media using pore scale modeling

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ABSTRACT

The flow thorough porous media is analyzed from a thermodynamic perspective, with a particular focus on the entropy generation inside the porous media, using a pore scale modeling approach. A single representative elementary volume was utilized to reduce the CPU time. Periodic boundary conditions were employed for the vertical boundaries, by re-injecting the velocity and temperature profiles from the outlet to the inlet and iterating. The entropy generation was determined for both circular and square cross-sectional configurations, and the effects of different Reynolds numbers, assuming Darcy and Forchheimer regimes, were also taken into account. Three porosities were evaluated and discussed for each cross-sectional configuration, and streamlines, isothermal lines and the local entropy generation rate contours were determined and compared. The local entropy generation rate contours indicated that the highest entropy generation regions were close to the inlet for low Reynolds flows and near the central cylinder for high Reynolds flows. Increasing Reynolds number from 100 to 200 reveals disturbances in the dimensionless volume averaged entropy generation rate trend that may be due to a change in the fluid flow regime. According to Bejan number evaluation for both cross-section configurations, it is demonstrated that is mainly provoked by the heat transfer irreversibility. A performance evaluation criterion parameter was calculated for different case-studies. By this parameter, conditions for obtaining the least entropy generation and the highest Nusselt number could be achieved simultaneously. Indeed, this parameter utilizes both the first and the second laws of thermodynamics to present the best case-study. According to the performance evaluation criterion, it is indicated that the square cross-section configuration with $\phi = 0.64$ exhibits better thermal performance for low Reynolds number flows. A comparison between the equal porosity cases for two different cross-sectional configurations indicated that the square cross-section demonstrated a higher performance evaluation criterion than the circular cross-section, for a variety of different Reynolds numbers.

1. Introduction

The investigation of fluid flow in porous media has been of considerable interest for engineers and scientists for several decades. Various applications, such as fluid flow and heat transfer in compact heat exchangers, packed beds, aerosol transport and blood flow in vessels, are all dependent on the behavior of the flow in the porous media [1,2]. The heat transfer augmentation in thermal systems that utilizes porous media can be evaluated using the second law of thermodynamics. The second law, namely the entropy generation principle, has previously been used to optimize and/or minimize the entropy generation, i.e., exergy destruction, in heat transfer processes. Bejan's pioneering work [3] provided significant insight on the associated relationships. The concept of entropy generation minimization (EGM) [4] was first proposed as an energy-saving approach for thermal processes. Following the initial introduction, a number of investigators extended the concept of entropy generation-based designs to other areas such as thermal/fluid engineering systems [5]. In the present study, a literature review is divided into two categories. First, the investigations related to the entropy generation in free flow and thermal systems are considered, and second, a review related to entropy generation investigations inside porous media is presented.

A number of studies have investigated the entropy generation within fluid flow and thermal systems, but only a relatively few have examined or considered the entropy generation in porous

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Nomenclature

A	surface area of control volume, M^2
T	temperature, K
D	circle diameter, square length, M
H	REV length scale, M
k	fluid conductivity, W M^{-1} K^{-1}
S_{gen}	local entropy generation rate, W M^{-3} K^{-1}
u_D	Darcy velocity, M s^{-1}
T_w	wall temperature, K
T_B	bulk temperature, K
q''	wall heat flux, W M^{-2}
p	pressure, N M^{-2}
u_i	velocity vector, M s^{-1}
u	X-direction velocity, M s^{-1}
v	Y-direction velocity, M s^{-1}
x	flow direction, M
y	flow perpendicular direction, M
ρ	density, kg M^{-3}
c_p	specific thermal capacity, J kg^{-1} K^{-1}
K	permeability, M^2
Re	Reynolds number, $\frac{u_D \cdot D}{v}$
Pe	Peclet number, $\frac{\mu c_p}{k}$
Pr	Prandtl number, $\frac{v}{\alpha}$
Br	Brinkman number, $\frac{\mu u_D^2}{k(T_w - T_f)}$
Be_s	local Bejan number, $\frac{\text{HTI}}{\text{HTI+FFI}}$
Be	Bejan number, $\frac{1}{A}\int_A Be_S dA$
N_S	dimensionless local entropy generation rate, $\frac{S_{gen}D^2\Delta T}{\mu u_D^2}$
N_t	dimensionless volume-averaged entropy generation rate, $\frac{1}{A}\int_A N_S dA$
Nu	Nusselt number, $\frac{q''D}{k(T_w - T_B)}$
Ha	Hartman number
Bi	Biot number
Da	Darcy number

Greek symbols

Φ	viscous dissipation function, s^{-2}
∇	gradient, M^{-1}
v	kinematic viscosity, $M^2 \cdot s$
μ	dynamic viscosity, kg M s
α	thermal diffusivity, M s^{-2}
ϕ	porosity

Abbreviations

MHD	magnetohydrodynamic
SIMPLE	semi-implicit pressure linked equation
EGM	entropy generation minimization
REV	representative elementary volume
VAT	volume averaging theory
LTE	local thermal equilibrium
LTNE	local thermal non-equilibrium
PEC	performance evaluation criterion
HTI	heat transfer irreversibility
FFI	fluid friction irreversibility

media. Basak et al. [6] studied the entropy generation resulting from free convection inside a cavity using a finite element approach. Different inclination angles, Prandtl numbers and Rayleigh numbers were considered in order to determine the minimal entropy production for each case considered. Torabi et al. [7] investigated the entropy generation between two co-rotating cylinders with a copper–water nanofluid. By applying the analytical solutions, both the local and total entropy generation rates were obtained. The governing equations were found to consist of two energy equations for the inner and outer cylinders, using a constant heat generation, and the energy equation for nanofluid between the cylinders was also considered. A one-dimensional flow equation approach was utilized, assuming a Brinkman viscosity model. In this study, it was concluded that both the local and total entropy generation rates increased as a result of the presence of the nanofluid. This resulted in a temperature reduction within both the solid and fluid media.

In another investigation, Mahian et al. [8] investigated the entropy generation phenomenon in co-rotating cylinders assuming both the magnetohydrodynamic (MHD) and mixed convection effects. Here, the different parameters, such as the Hartman number (Ha), the radius ratio, the mixed convection parameter, and the local and volume averaged entropy generation ratios were considered. It was suggested that the entropy generation reduction, increases with increasing MHD effects and larger spacing between the two cylinders, and results in a lower entropy generation. In a series of papers, Mahian et al. [9,10] considered the first and the second laws of thermodynamics for nanofluid flow and heat transfer in solar collectors. The investigations discussed the effects of different values of nanoparticle volume fraction, nanoparticle shapes and different relations for thermal conductivity, viscosity and friction factor on the temperature outlet, the Reynolds number (Re), the Nusselt number (Nu), the Prandtl number (Pr), the Bejan number (Be), convection heat transfer coefficient and the entropy generation rate, e.g. heat transfer irreversibility and fluid friction irreversibility. It was observed that for various mass flow rates, the entropy generation rate of steel tubes show higher values compared with the copper tubes Also, the entropy generation rate calculation showed practical importance of tube roughness for high mass flow rates. Mahmud and Fraser [11] surveyed the entropy generation in fundamental steady, forced convection flows such as two-dimensional Poiseuille flow between concentric cylinders, and non-Newtonian fluid flow in tubes and channels. The isothermal and isoflux boundary conditions were discussed and the entropy generation was determined using the available velocity and temperature profiles. A review about the entropy generation of nanofluid flow including different geometries, e.g. heat exchangers, rotating cylinders and cavities was performed by Mahian et al. [12]. This review gathered numerical and experimental correlations of viscosity, thermal conductivity, specific heat capacity, thermal expansion coefficient and density. The entropy generation investigations of nanofluid in microchannels, channels, tubes and natural and mixed convection systems were thoroughly discussed.

In addition to this work, several investigations were performed to approximate the entropy generation for fluid dynamic systems, such as calculating the entropy generation in turbulent flows. Some of the research was focused on the entropy generation using a Reynolds averaging Navier–Stokes (RANS) approach, such as the so called $k-\varepsilon$ model [13,14]. Ghasemi et al. [15] compared the performance of different RANS models, in the bypass-transition boundary layer flow using pressure gradient effects. The new transition model, namely the k–kl–w model, was able to predict the entropy generation in turbulent–laminar transition flow far better than other RANS models. Sheikhi et al. [16] applied a large eddy simulation (LES) approach to calculate the entropy generation in mixing flow. Two parallel flows moving toward each other, which became mixed as a unique flow, were considered. The results indicated that the LES approach was capable of predicting the entropy