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Review

Challenges and progress on the modelling of entropy generation in porous media: A review

Mohsen Torabi [a,*], Nader Karimi [b], G.P. Peterson [a], Shannon Yee [a]

[a] The George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA
[b] School of Engineering, University of Glasgow, Glasgow G12 8QQ, United Kingdom

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ABSTRACT

Depending upon the ultimate design, the use of porous media in thermal and chemical systems can provide significant operational advantages, including helping to maintain a uniform temperature distribution, increasing the heat transfer rate, controlling reaction rates, and improving heat flux absorption. For this reason, numerous experimental and numerical investigations have been performed on thermal and chemical systems that utilize various types of porous materials. Recently, previous thermal analyses of porous materials embedded in channels or cavities have been re-evaluated using a local thermal non-equilibrium (LTNE) modelling technique. Consequently, the second law analyses of these systems using the LTNE method have been a point of focus in a number of more recent investigations. This has resulted in a series of investigations in various porous systems, and comparisons of the results obtained from traditional local thermal equilibrium (LTE) and the more recent LTNE modelling approach. Moreover, the rapid development and deployment of micro-manufacturing techniques have resulted in an increase in manufacturing flexibility that has made the use of these materials much easier for many micro-thermal and chemical system applications, including emerging energy-related fields such as micro-reactors, micro-combustors, solar thermal collectors and many others. The result is a renewed interest in the thermal performance and the exergetic analysis of these porous thermochemical systems. This current investigation reviews the recent developments of the second law investigations and analyses in thermal and chemical problems in porous media. The effects of various parameters on the entropy generation in these systems are discussed, with particular attention given to the influence of local thermodynamic equilibrium and non-equilibrium upon the second law performance of these systems. This discussion is then followed by a review of the mathematical methods that have been used for simulations. Finally, conclusions and recommendations regarding the unexplored systems and the areas in the greatest need of further investigations are summarized.

Contents

* Corresponding author.
E-mail addresses: Mohsen.Torabi@my.cityu.edu.hk (M. Torabi), Nader.Karimi@glasgow.ac.uk (N. Karimi), Bud.Peterson@gatech.edu (G.P. Peterson).

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Nomenclature

a_{sf}	interfacial area per unit volume of porous media, m^{-1}
B	a dimensionless parameter used in Eqs. (10) and (11) which depends on the thermophysical properties of the system
B_0	magnetic field, T
Bi	Biot number
Br	Brinkman number ($Pr \cdot Ec$)
Da	Darcy number
E	flow strain rate tensor
Ec	Eckert number
h_{sf}	fluid-to-solid heat transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$
h	characteristic length of the system, m
$\mathbf{J}^D$	diffusion flux
$\mathbf{J}^s$	entropy flux
k	thermal conductivity of the medium, $W \cdot m^{-1} \cdot K^{-1}$
k_{ef}	effective thermal conductivity of the fluid (εk_f), $W \cdot m^{-1} \cdot K^{-1}$
k_{es}	effective thermal conductivity of the solid ($(1-\varepsilon)k_s$), $W \cdot m^{-1} \cdot K^{-1}$
N'''	dimensionless local entropy generation rate within the fluid phase of the porous medium
M	Hartmann number
Pr	Prandtl number
Q_L	lower interface heat flux
Q_U	upper interface heat flux
q'''	volumetric internal heat generation rate, $W \cdot m^{-3}$
$\dot{S}'''$	local entropy generation rate, $W \cdot m^{-3} \cdot K^{-1}$
S_L	lower wall-fluid interface entropy generation rate, $W \cdot m^{-2} \cdot K^{-1}$
S_U	upper wall-fluid interface entropy generation rate, $W \cdot m^{-2} \cdot K^{-1}$
T	temperature, K
U	dimensionless velocity
u	velocity, $m \cdot s^{-1}$

Greek symbols

β	temperature jump coefficient
κ	permeability, m^2
φ	porosity
ϕ	nanoparticles volume fraction
μ	dynamic viscosity of the fluid, $Kg \cdot s^{-1} \cdot m^{-1}$, chemical potential, $Joul \cdot Kg^{-1}$
θ	dimensionless temperature
Π	shear stress tensor
σ	electrical conductivity of fluid, $S \cdot m^{-1}$

Subscripts

ef	effective fluid characteristic
es	effective solid characteristic
f	fluid
i	*i*th species
m	mean
s	solid

1. Introduction

The use of porous media in thermal and chemical systems can provide significant operational advantages. This has led to increased interest in potential applications involving promoting a more uniform temperature distribution, increasing the heat transfer rate, controlling reaction rates, and improving heat flux absorption. For this reason there is a renewed interest in the modelling of porous materials for use in scientific and industrial applications [1]. Understanding and formulating the characteristics of porous materials has the potential to significantly impact the thermal performance of a large number of natural and artificial processes. For example, porous material play a significant role in physicochemical and biochemical reactions of methane to carbon dioxide through the bacterial activity in the methane oxidation layer [2,3], which are used in connection with various approaches to waste disposal processes [4]. Porous materials have also been used in solar systems to enhance both the quantity and quality of the absorbed heat flux and temperature within these microstructures [5]. Porous materials have also been proposed for use in battery electrodes and other electrochemical systems [6]. In all of these application, the use of porous media can result in enhanced heat transfer, reductions in system weight, better reaction control, and sound isolation making them highly desirable for a wide range of applications [1,7].

Historically, porous media have been extensively used in thermofluidics, due to their ability to increase the Nusselt number and consequently decrease the temperature of heat transfer systems [8]. To simulate the physical processes occurring inside porous media, a number of different macroscopic and microscopic approaches have been used to capture the requisite engineering characteristics. Among these, the volume averaging theory (VAT) [9] and pore scale modelling (PSM) [10] are most frequently utilized. The well-known VAT was identified and applied by Whitaker in his pioneering article in 1969 [9]. The VAT approach exploits volume averaged quantities, *e.g.* volume-averaged velocity. When the VAT approach is employed, two modelling approaches can be adopted to simulate the porous system. A classical model is the local thermodynamic equilibrium approach, which assumes that at any point the fluid and solid phases of the porous medium are in full thermodynamic equilibrium [11]. This includes thermal, chemical and mechanical local equilibria. Under the local thermal equilibrium (LTE) approach, a single energy equation is used to model the temperature field of the porous system [12,13], since a thermal equilibrium exists between the two phases at any local point. The second approach, local thermal non-equilibrium (LTNE), assumes a local difference between the temperature fields of the two phases and hence two energy equations are required to simulate the system [14,15]. Although LTNE is more accurate, it is computationally more expensive as it relies on two energy equations