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Research Paper

Generation of entropy and forced convection of heat in a conduit partially filled with porous media – Local thermal non-equilibrium and exothermicity effects

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HIGHLIGHTS

- Local and total entropy generations in endothermic/exothermic channels are investigated.
- Convection interface boundary condition has been incorporated into the modelling.
- Partial filling of the channel with LTE and LTNE for energy equations are considered.
- Bifurcation phenomena for temperature and local entropy generation are observed.
- Analytical solutions for temperature and entropy generation rates are obtained.

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ABSTRACT

The performance of a two-dimensional, axisymmetric channel with porous inserts attached to the walls is analyzed from the perspective of the first and second laws of thermodynamics. In this analysis, the flow is assumed to be fully developed with a constant heat flux imposed on the external surfaces of the walls, while heat could be internally generated by the fluid and solid phases. Using a Darcy-Brinkman model of momentum transport along with a two-equation thermal energy model, a convective model was developed to describe the thermal boundary conditions on the porous-fluid interface. The so-called Model A was employed on the walls of the channel and semi-analytical solutions were developed for the hydrodynamic, temperature, entropy generation fields and the Nusselt number, and an extensive parametric study was subsequently, conducted. The results indicated that the inclusion of exothermicity leads to significant modifications in the thermal and entropic behaviour of the system. In particular, through comparison with the recent literature, it was demonstrated that exothermicity can significantly impact the influence of the porous-fluid interface model upon the generation of both the local and total entropy within the system.

1. Introduction

Traditionally, improvement in the performance of thermal systems has focused primarily on the heat transfer aspects [1]. Although this approach is fundamentally sound, it does not account for the degradation of the energy within the system. The key thermodynamic parameter determining the level of energy degradation is the entropy, which can be used to indicate the level of irreversibility within the system [2]. Calculation of the entropy generation rate requires a knowledge of the temperature and flow fields and therefore typically builds upon the heat transfer analysis [3,4]. Entropy generation has been investigated in a number of different types of thermal systems [3–8]. Nevertheless, second law analyses of complex media, such as porous materials are still in the development phase. Currently, there exists a large volume of literature on the heat transfer analysis in porous media [9–11], and a large portion of this work is based on the concept of local thermal equilibrium (LTE). Even though the LTE assumption results in a reasonably good approximation for many applications, there are groups of problems in which LTE may be either inappropriate or inadequate [9,10]. For example, systems with low internal Biot

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Nomenclature

a_{sf}	interfacial area per unit volume of porous media, m^{-1}
Bi	Biot number
Bi_{int}	interface Biot number
Br	Brinkman number
c_p	specific heat at constant pressure, $\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$
Da	Darcy defined in Eq. (13)
h	one half of the channel height, m
h_c	one half of the thickness of the clear section, m
h_{sf}	fluid-to-solid heat transfer coefficient, $\mathrm{W \cdot m^{-2} \cdot K^{-1}}$
k	ratio of effective solid thermal conductivity to that of fluid
k_{ef}	effective thermal conductivity of the fluid (εk_f), $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$
k_{es}	effective thermal conductivity of the solid ($(1-\varepsilon)k_s$), $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$
N'''_{f1}	dimensionless local entropy generation rate within the clear fluid region
N'''_{f2}	dimensionless local entropy generation rate within the fluid phase of the porous medium
N'''_{s}	dimensionless local entropy generation rate within the solid phase of the porous medium
N_t	dimensionless total entropy generation rate within the medium
Nu	Nusselt number
Pe	Peclet number
$\dot{S}'''_{f1}$	local entropy generation rate within the clear fluid region, $\mathrm{W \cdot m^{-3} \cdot K^{-1}}$
$\dot{S}'''_{f2}$	local entropy generation rate within the fluid phase of the porous medium, $\mathrm{W \cdot m^{-3} \cdot K^{-1}}$
$\dot{S}'''_{s}$	local entropy generation rate within the solid phase of the porous medium, $\mathrm{W \cdot m^{-3} \cdot K^{-1}}$
s_f	energy source in fluid phase per unit volume, $\mathrm{W \cdot m^{-3}}$
s_s	energy source in solid phase per unit volume, $\mathrm{W \cdot m^{-3}}$
T	temperature, K
T_{f1}	temperature of the fluid within clear region, K
T_{f2}	temperature of the fluid phase of the porous medium, K
$T_{f,m}$	mean temperature of fluid, K
T_s	temperature of the solid phase of the porous medium, K
T_w	lower wall temperature, K
U_{f1}	dimensionless velocity of the fluid in the clear region
U_{f2}	dimensionless velocity of the fluid in the porous medium
U_m	dimensionless mean velocity of the fluid
u_{f1}	velocity of the fluid in the porous medium, $\mathrm{m \cdot s^{-1}}$
u_{f2}	velocity of the fluid in the clear region, $\mathrm{m \cdot s^{-1}}$
u_m	mean velocity of the fluid, $\mathrm{m \cdot s^{-1}}$
w_f	dimensionless energy source in fluid phase per unit volume, $\mathrm{W \cdot m^{-3}}$
w_s	dimensionless energy source in solid phase per unit volume, $\mathrm{W \cdot m^{-3}}$
X	dimensionless axial distance
x	axial distance, m
Y	dimensionless vertical distance
Y_c	dimensionless one half of the thickness of the clear section
y	vertical distance, m

Greek symbols

ε	porosity
γ	ratio of the heat flux at porous-fluid interface to that of channel's wall
κ	permeability, m^2
μ_f	fluid viscosity, $\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$
μ_{eff}	effective viscosity of porous medium, $\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$
θ	dimensionless temperature
θ_{f1}	dimensionless temperature of the fluid within clear region
θ_{f2}	dimensionless temperature of the fluid phase of the porous medium
$\theta_{f,m}$	dimensionless mean temperature of the fluid
θ_s	dimensionless temperature of the solid phase of the porous medium
ρ	fluid density, $\mathrm{kg \cdot m^{-3}}$

number or those with very different fluid and solid conductivities feature strong non-equilibrium behaviour. Under such circumstances, the more general approach of local thermal non-equilibrium (LTNE) may be preferable. Yet, this approach continues to be challenged by the unresolved issues associated with the definition of the proper thermal boundary conditions at the interface of the porous material [12–14]. Recent studies have indicated that LTNE predictions of the thermal behaviour for a given system is significantly dependent upon these assumed boundary conditions [15–17].

Over the last decade, partially-filled porous conduits have attracted considerable attention mainly due to the hydraulic superiority when compared with fully-filled channels [17–19]. The assumption of LTE has been used extensively to analyze heat transfer processes in the partially-filled systems [11]. Recently, LTNE analyses of these systems have also appeared in the literature. Forooghi et al. [18] conducted a numerical study on a channel, partially filled with a porous insert attached to the walls of the duct. In this investigation, the hydrodynamic field and the Nusselt number were calculated and indicated that the change in Nusselt number with porous thickness is not monotonic [18]. Yang and Vafai [15] considered a channel with a central porous insert and analyzed the effects of thermal dispersion and the inertia parameter on the temperature fields and heat transfer enhancement. The results demonstrated that when the condition of temperature gradient equality at the porous interface is not imposed, the heat flux can bifurcate [15]. In a separate work, Yang and Vafai [19] investigated the validity of LTNE in a partially filled conduit under five different interface models to understand the influence of each of these models. Further theoretical investigations were conducted by Xu et al. on a parallel-plate channel [20] and a pipe, partially filled with porous media attached to the inner walls of each geometry [21]. Analytical expressions were developed for the velocity and temperature fields through solution of the hydrodynamic equations in the clear and porous regions and the two-equation energy model [20,21]. Following the work of Ochoa-Tapia and Whitaker [22], Xu et al. [20,21] considered the convective boundary conditions at the porous material-fluid interface. The temperature distributions were calculated under varying thermo-physical parameters and showed that Nusselt number decreases if the channel is fully filled with the porous media [20,21]. Recently, Karimi et al. [23] conducted an analytical study on a channel with a central porous insert, in which both phases included internal heat sources. These authors [23] applied Models A and B [15,19] to the porous-fluid interface and found the temperature distributions in the solid and fluid phases. In keeping with the earlier findings of