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Numerical model for non-equilibrium heat and mass exchange in conjugate fluid/solid/porous domains with application to evaporative cooling and drying

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ABSTRACT

A numerical formulation capable of simulating fluid flow and non-equilibrium heat and mass transfer in three-dimensional conjugate fluid/solid/porous domains is presented. The governing transport equations are presented for the fluid, solid, and porous regions, with special consideration given towards the manner in which moisture is accounted for in the air–water vapour mixture. Mathematical conditions are also presented to ensure that heat and mass transfer occurs smoothly across fluid–porous, fluid–solid and porous–solid interfaces. The developed formulation is validated by simulating direct and indirect evaporative cooling problems. The results demonstrate that the formulation is capable of simulating evaporative cooling in conjugate three-dimensional domains, with and without the addition of sensible heat. Moreover, different simulated cases show that the results are accurate compared to available experimental results, and are physically realistic throughout the domain and at interfaces between conjugate regions. The unsteady problem of drying of an initially saturated porous material is also simulated to demonstrate the non-equilibrium mass transfer feature of the developed formulation. The results show the correct trends in drying time with respect to the flow Reynolds number and the relative humidity of the inlet air–water vapour mixture.

1. Introduction

Fluid flow and heat transfer problems involving conjugate fluid/porous/solid regions have many applications in thermal management, drying, curing, filtration, etc. Thus, there is a need for robust numerical models capable of simulating such classes of problems. The developed formulation must be capable of modeling fluid flow, and sensible and latent heat exchange in conjugate fluid/porous/solid regions, and be accurate and robust at interfaces between these regions where sudden changes can occur in flow characteristics.

With respect to numerically modeling of fluid flow and heat transfer in conjugate domains, a significant amount of work has been reported (see reference [1] for comprehensive literature review). Costa et al. [2] proposed a finite-element approach to simulate flows in conjugate fluid/porous domains. Their approach considered local thermal equilibrium in the porous region, which assumes that the total energy of a porous continuum comprised of fluid and solid can be characterized by a single temperature. While this is reasonable for solid materials of low conductivity, it is not appropriate for highly conductive metals, or for cases where the temperature of the fluid (or solid) is important for determining physical thresholds, such as in evaporative cooling. In addition, because of the discretization approach used at the interfaces between fluid–solid regions, their model was restricted to very low Reynolds numbers (<10). The most comprehensive recent work in conjugate domain modelling of heat and fluid flow was carried out by Betchen et al. [1]. Their work describes a conjugate domain model, based upon the finite-volume approach that accounts for fluid flow and non-equilibrium (sensible) heat transfer in porous regions. One key contribution of their work was interface treatment between regions of the conjugate domain. Robust mathematical conditions were developed and discretized that enable stable, smooth transitions across fluid–porous interfaces over a wide range of Reynolds numbers (up to 1000) in the laminar regime.

A new class of diverse problems such as drying, fluidized bed reactors, chemical reactors, evaporative cooling, produce refrigeration, etc. can be numerically modeled if, in addition to flow and heat transfer, mass transfer is considered in the conjugate fluid/porous/solid framework. A significant amount of work has been

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Nomenclature

A	area, m^2
A_{fs}	specific surface area of porous media, m^{-1}
c_E	inertia coefficient of porous media
c_p	specific heat at constant pressure in fluid region, J/(kg K)
c_{ps}	specific heat in solid region, J/(kg K)
D	binary diffusivity coefficient, m^2/s
$\mathbf{f}$	body force per unit mass, m/s^2
h	specific enthalpy, J/kg
H	channel height, m
h_{fg}	latent heat of evaporation at 0°C in fluid region, J/kg
h_{fs}	interfacial heat transfer coefficient in porous media, W/(m^2 K)
h_{fsm}	interfacial mass transfer coefficient in porous media, m/s
k	thermal conductivity, W/(m K)
K	Darcy permeability of porous media, m^2
l_d	ligament diameter, m
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
$\boldsymbol{n}$	outward normal unit vector
Nu	Nusselt number
P	pressure, Pa
Pr	Prandtl number
R	gas constant, J/(kg K)
Re	Reynolds number
S	source in a transport equation
Sc	Schmidt number
Sh	Sherwood number
T	temperature, °C
t	time, s
$\mathbf{v}$	fluid velocity [=(u,v,w)], m/s
V	volume, m^3
y	distance in y-direction from origin, m
Y	mass fraction
α	volume fraction
μ	dynamic viscosity, N s/m^2
ρ_s	density of solid, kg/m^3
ρ_f	density of fluid mixture, kg/m^3
ω_{spec}	specific humidity, kg of H_2O/kg of dry air
ω_{rel}	relative humidity, %
ε	porosity
φ	a quantity
$\langle\varphi\rangle$	extrinsic volume-average of φ
$\langle\varphi\rangle^x$	Intrinsic volume-average of φ (x is fluid or solid constituent of porous media)

subscripts and superscripts

a	air
e	energy
eff	effective property in porous media
f	fluid
fl	fluid side of interface
o	value at previous time level
P	control volume over which the equation is being integrated
por	porous side of interface
s	solid
sol	solid side of interface
t	total
v	vapour
w	water

reported focused on the numerical modelling of the problems involving heat and mass transfer. In this respect, simple heat and mass balance equations have been proposed to model different heat and mass transfer problems, such as dehumidification of air through desiccant drying, indirect evaporative cooling, and Maisotsenko cycle cooling [3–7]. A novel desiccant evaporative cooling system (DES) capable of providing conditioned-air by utilizing low grade thermal energy [8], which involves dehumidification of air through desiccant drying followed by evaporative cooling process to lower its temperature, has also been modeled previously using mass and energy balance equations [9–12].

More sophisticated finite-volume and finite-difference numerical formulations have been proposed to model different types of heat and mass transfer problems inside porous media. However, most of these studies have considered local thermal-equilibrium to model heat transfer [13–19]. For the problems related to produce refrigeration, only a few studies have considered the thermal non-equilibrium approach to model heat transfer [20,21]. Moreover, few studies have proposed specifically formulated non-equilibrium heat and mass transfer models to study desiccant drying process [22,23]. Very few studies have proposed air flow and heat transfer numerical models in conjugate fluid/porous domains. In this respect, Moureh et al. [24,25] focused solely on air flow modeling, and relied on a commercial Computational Fluid Dynamics (CFD) package to deal with the complexities associated with the fluid/porous interface. Zou et al. [26,27] presented an air and heat transfer numerical model in conjugate fluid/porous/solid domains for the problem of produce packaging. However, no information pertaining to the interface treatment was provided.

It can be concluded from the above literature that no study, as yet, has proposed a non-equilibrium heat and mass transfer numerical formulation for porous materials. Moreover, no study, as yet, has considered such a formulation in a conjugate fluid/solid/porous domain framework. The aim of the present work is to develop a numerical formulation capable of modeling fluid flow, heat and mass transfer in conjugate fluid/solid/porous domains. The key objective of this work is to extend the work of Betchen et al. [1] by incorporating latent heat and mass transfer in the existing formulation. In this regard, special attention will be given to ensure that heat and mass transfer occurs smoothly across all the interfaces. Moreover, to accurately capture the physics of the heat and mass transfer problems, non-equilibrium heat and moisture transport equations will be introduced. To achieve the present objective, an in-house CFD code will be described. The assessment of the developed formulation will be made by simulating problems related to evaporative cooling. In this respect, direct and indirect evaporative cooling simulation results will be validated against available experimental results to comprehensively test the different features of the developed formulation. In addition, a transient problem of drying of a porous material initially saturated with water will also be simulated to further assess the formulation.

Another novel feature of the present study is the manner in which the latent energy of the moist air flow is accounted in the transport equation of energy. Previously, studies focused on modeling the phenomenon of evaporative cooling in porous media have accounted for the latent heat of evaporation of water in energy equation by utilizing a source term [15–17]. In the present formulation, a more general approach has been taken to account for this latent energy in the energy equation. Further discussion regarding this approach will be made later in the section describing the numerical formulation.