International Communications in Heat and Mass Transfer 63 (2015) 41–48

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

The numerical assessment of volume averaging method in heat transfer modeling of tissue-like porous media ☆

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ARTICLE INFO

Available online 8 March 2015

Keywords:
Porous media
Vascular tissue
Counter-current network
Numerical assessment
Volume averaging
Local thermal non-equilibrium

ABSTRACT

In this paper, the heat transfer characteristics of a tissue-like capillary porous media are investigated, using the realistic and volume averaging methods. For this purpose, a cylindrical medium is introduced with counter-current vascular network, including longitudinal parallel vessel pairs and numerous interconnect capillaries. The energy equations of solid and fluids phases are derived based on one realistic and two volume averaging methods. Accordingly, the thermal behavior of this capillary porous media was modeled in three cases: constant temperature of solid phase, uniform moderate heat generation in solid phase, and local intensive heat generation in solid phase. The comparison of results for various lengths and densities of interconnect capillaries indicates the inaccuracy of volume averaging method, especially if the supply and return fluids are considered as single integrated phase. Thus, despite much anatomical dissimilarities between the present medium and real living tissues, the occurrences of such errors can be expected if the volume averaging method is used. In addition, the predicted temperature of solid phase at the end of various interstitial heating processes shows that the constant delivery of focused energy in shorter time can increase the maximum temperature of solid phase and its heat affected zone.

1. Introduction

Determination of thermal interaction between blood and tissue is one of the most important objectives of researches in a bioheat transfer issue. For these purpose, many scholars tried to develop accurate models for the description of heat exchange phenomena in perfused tissues, but up to now, only the Pennes' bioheat model has been accepted widely [1–3]. The main reason is probably the complexity of other models, including detailed anatomical knowledge. One of the most important steps in developing applicable bioheat models is the implication of porous media concepts [3,4]. However, the porous media-based bioheat models have some differences in their basic assumptions, so the assessment of these models can provide valuable insights into this area. As found in the literature, two major differences exist among porous media bioheat models, all of which use volume averaging method [5–31]. One of these differences is the absence or presence of perfusion term in blood and tissue energy equations, and the other is the consideration of blood as the integrated fluid phase or separated arterial and venous phases. Accordingly, the porous media-based studies of living tissue heat transfer can be categorized into four groups: two equation models without perfusion term [5–18], two equation models with perfusion term [19–27], three equation models without perfusion term [27,28], and three equation models with perfusion [29–31]. For better understanding and evaluation of these important differences, this paper establishes a vascular tissue with cylindrical geometry and relative anatomical similarity to human muscle tissues. The vascular network consists of main parallel longitudinal vessels and numerous interconnect capillaries between each pair of them. One of the vessels in each pair includes supply fluid and the other includes return fluid. The capillaries each include supply fluid in their first half and return fluid in their second half. Accordingly, the governing heat transfer equations of supply and return fluids as well as the solid are derived based on realistic or volume averaging methods. After the completion of models, they are used to heat transfer modeling of this porous medium in three case studies. The results of these case studies indicate that the volume averaging method can be inaccurate in heat transfer modeling of capillary porous media such as living vascular tissues.

2. Porous media and volume averaging method

It can be said that the living the tissue is a capillary porous media whose solid phase consists of cells, vessel walls and extracellular fluid, whereas the fluid phase consists of blood in arterial, venous, and capillary vessels [4]. The method of volume averaging is usually a technique which is used to derive continuum conservation equations of mass, momentum, and energy for porous media systems [5]. In this

☆ Communicated by W.J. Minkowycz.

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2015.02.006
0735-1933/

Nomenclature

c	specific heat (J kg^{-1} K^{-1})
D	diameter (m)
h	interstitial heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
L	length (m)
N_{pair}	vessel pair density (m^{-2})
N_{cap}	capillary vessel density (m^{-2})
q	volumetric heat source (W m^{-3})
r	radial coordinate (m)
s	coordinate along path of capillary vessel (m)
T	temperature (°C)
x	axial coordinate (m)

Greek symbols

ε	porosity
ρ	density (kg m^{-3})
τ	time (s)
ω	blood perfusion rate (m^3 m^{-3} s^{-1})

Subscripts and superscripts

c	convection
cap	capillary
f	fluid phase
g	generation
p	perfusion
ret	return fluid
RS	realistic solution
s	solid phase
sup	supply fluid
VA	volume averaging

method, a representative elementary volume (REV) must be selected for a macroscopic description of system behavior. This REV has a characteristic length much greater than that of the pores (vessel diameters) and much smaller than that of the system under study [19]. The intrinsic (i-phase) volume averaged values of a certain variable in REV is defined by Eq. 1.

$$\langle\psi\rangle^i = \frac{1}{V_i}\int_{V_i}\psi dV \tag{1}$$

3. Geometry description

As shown in Fig. 1, the selected domain was the cylindrical porous medium with counter-current vessel pairs parallel to its axis. One vessel of each pair contains supply fluid and another vessel contains return fluid. In each pair, two main vessels are connected via capillary vessels with equal diameter and length. The flow rate of fluid in capillaries is adjusted in such a way that the velocity of fluid reaches to zero at the end of supply vessels. The capillaries could be assumed with or without perfusion, dependent on the permeability or impermeability of solid phase. In the impermeable tissue phase, the capillaries connected the supply vessels directly to return vessels, but in the permeable solid phase, the fluid was allowed to bleed off from the capillary walls at their mid-length and replace with the same amount from solid side. Then, the temperature of fluid in the second half of capillary length is equal to that of the solid phase.

Table 1 represents the values of used parameters in this work. The density of vessel pairs, diameter of supply vessels, and their inlet velocity were adjusted in such a way that the perfusion rate of fluid into solid phase was close to the anatomical data. Based on the anatomical observations in the human body, in which the volume of venous vessels is greater than that of arterial vessels, the diameter of return vessels was selected 1.5 times greater than the diameter of supply vessels, so the volume of return vessels was more than twice the supply vessels. It must be mentioned again that this porous medium is not a real living tissue, but it can be used in accurate an evaluation of volume averaging method for heat transfer modeling of similar vascular tissues and determination of this methods' shortcomings and inaccuracies. The energy equation of solid phase in cylindrical coordinates is presented below where the last three terms in right hand side are volumetric heat exchange by convection and perfusion as well as the volumetric heat generation.

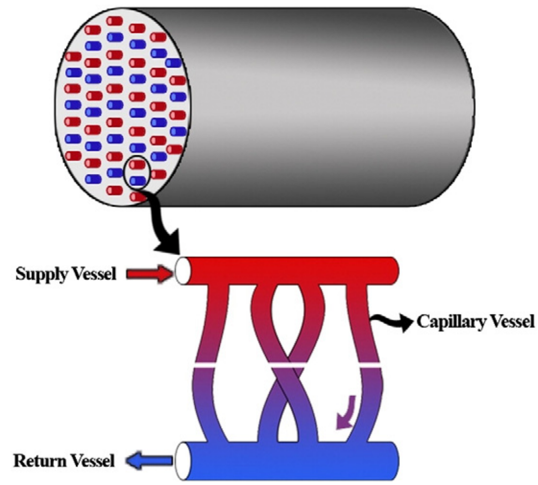

Fig. 1. Porous medium under study with countercurrent vascular network, each vessel pair include one supply vessel, one return vessel and numerous connective capillary vessels.

$$(1-\varepsilon)\rho_s c_s \frac{\partial T_s}{\partial t} = (1-\varepsilon)k_s\left(\frac{1}{r}\frac{\partial T_s}{\partial r} + \frac{\partial^2 T_s}{\partial r^2} + \frac{\partial^2 T_s}{\partial x^2}\right) + q_c + q_p + q_g \tag{2}$$

To calculate convection and perfusion terms, the fluid temperature must be known at every elements of a solution domain. The realistic determination of fluid phase temperatures in supply and return vessels and capillaries is fortunately feasible. The Eqs. (3) to (5) were used to the realistic calculation of supply and return fluids along the main vessels and capillaries, respectively.

$$\rho_f c_f\left(\frac{\partial T_{sup}}{\partial \tau} + u_{sup}\frac{\partial T_{sup}}{\partial x}\right) = k_f\left(\frac{\partial^2 T_{sup}}{\partial x^2}\right) + \frac{4h_{sup}}{D_{sup}}\left(T_s - T_{sup}\right) \tag{3}$$

$$\rho_f c_f\left(\frac{\partial T_{ret}}{\partial \tau} + u_{ret}\frac{\partial T_{ret}}{\partial x}\right) = k_f\left(\frac{\partial^2 T_{ret}}{\partial x^2}\right) + \left(\frac{4h_{ret}}{D_{ret}} - \rho_f c_f\frac{\partial u_{ret}}{\partial x}\right)(T_s - T_{ret}) \tag{4}$$

Table 1
Vessel and capillary characteristics of proposed geometry.

Supply vessels diameter (μm)	100
Return vessels diameter (μm)	150
Capillary vessels diameter (μm)	30
Capillary vessels length (mm)	1
Inlet velocity of arterial blood (cm/s)	5
Density of vessel pairs per cross-section unit area (1/cm^2)	16
Density of capillaries per unit length of vessel pairs (1/cm)	12
Blood perfusion rate per tissue unit volume (m^3/m^3·s)	6.2×10^{-4}