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Technical Note

Transient thermal behavior of porous media under oscillating flow condition

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Abstract

An analytical characterization of the heat transfer in an oscillating flow through a porous medium is presented in this work. Based on a two-equation model, two important dimensionless parameters are identified as the ratio of the thermal capacities between the solid and fluid phases and the ratio of the interstitial heat conductance between the phases to the fluid thermal capacity. The analytic solutions are obtained for both the fluid and solid temperature variations, and the heat transfer characteristics between the phases are classified into four regimes. In addition, a criterion for the validity of the local thermal equilibrium is suggested in a simple form as the ratio of the two time scales intrinsically involved in any transient heat transfer in porous media, namely the time scale relevant to the thermal inertia of porous media and the time scale pertinent to the transient variation of the boundary condition.

Keywords: Transient thermal behavior; Porous media; Oscillating flow; Thermal equilibrium

1. Introduction

Porous media have been widely used in industry as an effective means of transporting and storing thermal energy. Common examples of the industrial applications include thermal regenerators of the Stirling cycles, rotary regenerative heat exchangers, and temporary energy storage units. In such applications, the transient characteristics of the porous media are of importance since the porous media absorb and release thermal energy periodically [1].

One of the early investigations on the transient heat transfer in porous media was performed by Riaz [2]. He analyzed the unsteady response of thermal storage system to a step change in the inlet air temperature. Spiga and Spiga [3] analytically obtained the dynamic response of the thermal storage system to an arbitrary time-varying inlet temperature. Recently, the case where the flow oscillates through a porous medium were investigated by Muralidhar and Suzuki [4], and Klein and Eigenberger [5]. They analyzed numerically or theoretically the periodic heat transfer in porous media for the analysis of thermal regenerators. Most of the studies mentioned above dealt with the problems by means of numerical integrations or complicated series solutions. These means, however, are not very suitable for deduction of fundamental aspects of periodic heat transfer in porous media underlying the apparent complex phenomena.

The main objective of this study is to analyze theoretically the transient heat transfer in porous media under oscillating flow condition. Exact solutions are obtained for both the fluid and solid temperature variations, and the transient thermal characteristics are investigated theoretically based on the solutions. Additionally, the temperature difference between the phases is examined and a simple

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Nomenclature

a	interfacial area per unit volume of porous media (m^{-1})
C_p	isobaric heat capacity ($J\,kg^{-1}\,K^{-1}$)
g	complex amplitude of oscillating temperature
h	interstitial heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
K	thermal capacity ratio defined in Eq. (7)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
L	length of porous media in flow direction (m)
L_s	oscillation distance of flow (m)
S	ratio of interstitial thermal conductance to fluid thermal capacity
T	temperature (K)
T_0	time-averaged temperature (K)
t	time (s)
t_o	time scale of oscillating flow (s)
t_p	characteristic time of porous media (s)
u	fluid velocity ($m\,s^{-1}$)
x	longitudinal coordinate (m)

Greek symbols

θ	non-dimensional temperature
ε	porosity
γ	gradient of the linear temperature distribution ($K\,m^{-1}$)
τ	non-dimensional time
ρ	density ($kg\,m^{-3}$)
ω	frequency (s^{-1})

Subscripts

eff	effective value
f	fluid
s	solid
0	reference point

criterion is prescribed for the validity of the local thermal equilibrium.

2. Theoretical analysis

Fig. 1 shows an infinitely large slab of a porous medium with a thickness of L. The fluid at each side of the slab is maintained at high and low temperatures, respectively. The flow oscillates back and forth through the porous slab and transfers heat from the hot end to the cold end of the slab. This situation commonly happens in the regenerators of the ventilation systems and in the thermal regenerative engines or coolers. The energy equation for each phase can be written as [3]:

Fluid phase:

$$\varepsilon(\rho C_p)_f \frac{\partial T_f}{\partial t} + \varepsilon(\rho C_p)_f u \frac{\partial T_f}{\partial x} = k_{f,eff} \frac{\partial^2 T_f}{\partial x^2} + ha(T_s - T_f). \quad (1)$$

Solid phase:

$$(1-\varepsilon)(\rho C_p)_s \frac{\partial T_s}{\partial t} = k_{s,eff} \frac{\partial^2 T_s}{\partial x^2} + ha(T_f - T_s). \quad (2)$$

The oscillating velocity in the above equation is expressed as

$$u = \frac{L_s \omega}{2}\cos(\omega t), \quad (3)$$

where L_s is the swept distance and ω is the frequency of the oscillating flow.

When the representative pore diameter of the porous medium is sufficiently small compared to the thickness of the slab as is often the case, it is well known that the entrance region near each end of the porous slab is negligibly small compared to the thickness of the slab [6,7]. Neglecting the entrance region, the temperature within the slab has been found to have a linear distribution [4,5,8]. This finding implies a negligible contribution of

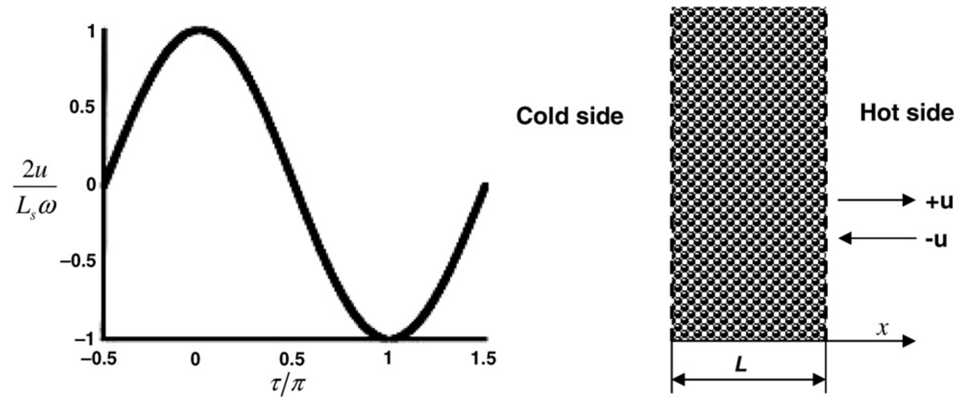

Fig. 1. Schematics of the model.