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Conjugate heat transfer during oscillatory laminar flow in porous media

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ABSTRACT

Hydrodynamics and conjugate heat transfer in porous media subject to unidirectional-steady state as well as steady-periodic flow conditions were numerically studied. Two-dimensional flows in porous media composed of periodically configured arrays of square cylinders were simulated using a computational fluid dynamics tool, with sinusoidal time variation of inlet and exit boundaries and conjugate heat transfer between the solid and fluid domains. The simulated domain contained seven unit cells, with each unit cell representing a square cylinder. Simulations showed that the end effects did not persist more than two unit cells. Simulations were conducted for flow oscillation frequencies of 0–60 Hz, and low and high velocity amplitudes (representing tidal fluid penetration amplitudes of 8 and 2 times the hydraulic diameter, respectively, at inlet) for a 75% porous domain. Using the simulation results, pore-scale volume-average Darcy permeability, Forchheimer coefficient, and Nusselt number associated with the standard volume-average porous media momentum and thermal energy equations were calculated. These parameters were calculated in instantaneous as well as cycle-averaged forms. The Forchheimer coefficient and Nusselt number were significantly different in unidirectional-steady and oscillatory flow conditions. These parameters strongly depend on the flow oscillation frequency and amplitude. Furthermore, significant phase lag occurs among velocity, pressure, temperature and heat transfer processes. The results confirm that unidirectional-steady flow models and correlations are not suitable for applications involving flow oscillations.

1. Introduction

Periodic flows in porous media are encountered in a number of important industrial applications, including conventional heat exchangers, microchannels, and the regenerators and heat exchangers of Stirling and pulse tube cryocoolers. The regenerator is a vital component of Stirling and pulse tube cryocoolers which is subject to periodic flow of a cryogen (usually helium) during the operation of the cryocoolers. Frictional losses and other types of irreversibility in the regenerators and heat exchangers of Stirling and pulse tube cryocoolers adversely impact their performance, and can even render them dysfunctional. An understanding of the hydrodynamics and thermal transport phenomena in porous media during periodic flow is thus necessary for the development of reliable analytical or numerical design tools for these cryogenic systems.

Transport phenomena in oscillatory flow in porous media are currently not well understood. Design and analysis tools addressing periodic flow in porous media should evidently use tractable model conservation and transport equations that are often derived based on the homogenization technique, volume-averaging, or simple postulation. Volume-average conservation and transport equations for unidirectional-steady and quasi-unidirectional-steady flows in porous media have been rigorously derived by several authors [1–5], and postulated and discussed by others [6,7]. Sözen and Vafai [8], who were interested in the thermal storage behavior of packed beds under low frequency (0.05–0.2 Hz) oscillatory compressible flow conditions, applied standard macroscopic porous media conservation equations with closure relations borrowed from unidirectional-steady flow literature. These standard model equations are often applied to relatively fast transient flow in porous media, even though their applicability to fast transients is not certain. The volume-average equations, furthermore, need closure relations for solid–fluid interactions which must be found from experiment or pore-level numerical simulations. Several experimental investigations have been reported for periodic flow in porous media that are of interest for cryocooler applications [9–12]. These investigations in general have shown that unidirectional-steady flow closure relations are not always suitable for application to periodic flow. There appears to be no systematic investigation about heat or mass transfer phenomena in porous media during fast transients.

Reliable closure parameters for volume-average transient flow in porous media can be rigorously obtained when the details of

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Nomenclature

a	flow pulsation amplitude [–]
a_f	specific solid–fluid interface area [1/m^2]
A	area [m^2]
b	inertial resistance coefficient [m^2]
c_f	Forchheimer coefficient [–]
C_{pf}	specific heat [J/kg K]
D	cylinder diameter [m]
D_h	cylinder hydraulic diameter [m]
D_T	thermal dispersion [W/m^2]
$\langle \frac{dT}{dx} \rangle$	volume-average unit cell temperature gradient [W/m]
h	heat transfer coefficient [W/m^2 K]
k	thermal conductivity [W/m K]
K	permeability coefficient [m^2]
L	unit cell longitudinal dimension [m]
n_j	component of the unit normal vector [–]
Nu_L	unit cell length-based Nusselt number [–]
Nu_K	permeability-based Nusselt number [–]
Re_K	permeability-based Reynolds number [–]
t	time [s]
T	temperature [K]
$\langle T \rangle^f$	unit cell volume-average fluid temperature [K]
T_S	solid surface temperature [K]
$\langle \vec{u} \rangle$	volume-average fluid velocity [m/s]

U	velocity [m/s]
u_j	component of the velocity vector [m/s]
V	total volume [m^3]
V_f	fluid volume [m^3]
Greek lettersε	
	porosity [–]
μ	dynamic viscosity [kg/m s]
ν	kinematic viscosity [m^2/s]
ρ	density [kg/m^3]
ϕ	fluid property
$\tilde{\phi}$	spatial deviation of fluid property
$\langle \phi \rangle^f$	volume-average fluid property
ω	angular frequency [rad/s]
*Super/subscripts*f	
	fluid
L	based on unit cell length
s	solid
*Abbreviations*CFD	
	computational fluid dynamics
UDF	user defined function

pore-level processes are known. Direct experimental measurements of pore-level transport phenomena are difficult when very small pores are of interest, for example in the aforementioned cryocooler regenerators. Due to the very small pore size and flow constraints of cryogenic regenerators, even miniature measurement instruments cause unacceptable flow disturbance. Direct numerical simulation can be used instead provided that the exact geometry of the porous structure is known, however porous media often have complex and non-uniform structures. Nevertheless, valuable information can be deduced by the direct numerical simulation of flow in generic porous media composed of periodic arrays of regular-shaped structures such as arrays of parallel square or circular cylinders [13–20]. These and other similar investigations thus far have all addressed unidirectional-steady flow, however.

Two-dimensional flow through arrays of tubes or fins of various shapes is also of great interest in relation to heat exchangers [21–23]. Most investigations that were concerned with heat exchangers are interested in tube friction, drag coefficients, and Nusselt numbers. However, flow in large heat exchangers have been treated as flow in porous media by many investigators as well [24–28]. Past investigations dealing with simulation of flow in heat exchanger tube bundles have mostly addressed unidirectional-steady flow as well.

In this paper we report on numerical simulations aimed at understanding the hydrodynamic resistant parameters and heat transfer during laminar steady-periodic flow in generic porous media composed of a periodic array of parallel square cylinders. The differences between unidirectional-steady and periodic flow are of interest and are described. This study is a follow-up of our earlier work [29–31], in which the hydrodynamic and thermal parameters associated with laminar unidirectional-steady and pulsating flow through the same generic porous media were investigated.

2. Geometric configuration of the simulated system

The generic porous media simulated here are regularly spaced square rods arranged in a linear pattern with rows parallel to the direction of the flow field. The domain is similar to those addressed in [29,30]. Fig. 1 displays the physical configuration of the parallel square rods. Previous researchers typically studied the flow details in a single unit cell, using periodic boundary conditions. However, for periodic flow, a single unit cell is not sufficient due to the entrance effect complications and the development of phase shift which makes simple periodic boundary conditions along the main flow direction unsuitable [29]. Therefore, the generic computational domain for this study is composed of seven consecutive unit cells in series, as depicted in Fig. 2.

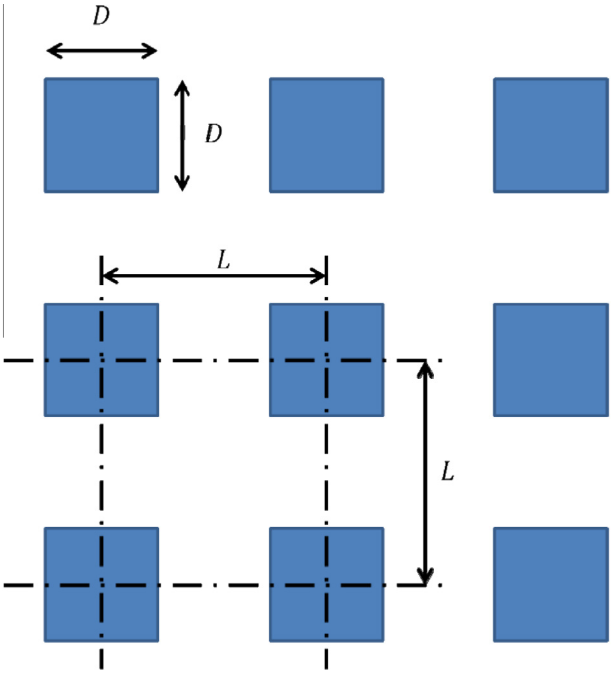

Fig. 1. Generic computational domain.