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Technical Note

An experimental study on cool-down of a heterogeneous porous body in throughflow

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1. Introduction

Knowledge of time-dependent convective heat transfer characteristics between porous solid matrix and fluid throughflow constitutes a vital element in thermal storage systems. Several analytical models have been proposed, and they utilize the empirically-derived heat transfer correlations as well as the experimental data for pressure drop that occurs in the porous media [1–4].

The majority of past studies dealt with the cases of a single-medium homogeneous porous material of spatially-uniform physical properties [5,6]. In modern environmental and geophysical applications, however, the porous media of concern are invariably spatially-heterogeneous in thermophysical properties. Also, the material properties of an initially homogeneous porous medium tend to become spatially nonuniform with time while in service.

The objective of the present study is to probe into the time-dependent thermal response characteristics in a heterogeneous porous body. As a paradigmatic representation, an assembly of two sections of homogeneous porous matrix of different properties, which are coupled in tandem, is considered (see Fig. 1 and Table 1 for detailed arrangements). An extensive experimental program was undertaken, and the thermal energy storage capabilities and attendant pressure drop are delineated.

2. Experimental facilities

The experimental facilities and procedures are the same as in the previous undertaking [7]. The specific task is to monitor the cool-down process of a porous body of two-section configuration, as shown in Fig. 1, initially at temperature T_{in}, subjected to an instantaneous switch-on of the throughflow of cold air at temperature T_0, $T_0 < T_{in}$. For all the runs, $T_{in} = 100°C$ and $T_0 = 24°C$. Packed beds of spheres of carbon steel and of glass are used for the porous media. The density ρ_s, specific heat c_s and thermal conductivity κ are respectively 7850 kg m^{-3}, 500 J (kg K)$^{-1}$, and 52 W (m K)$^{-1}$ for the carbon steel, and 2530 kg m^{-3}, 820 J (kg K)$^{-1}$, and 1.0 W (m K)$^{-1}$ for the glass. The dimension of the test section was 50 mm in diameter (D) and 100 mm in length (L).

Measurements were made, by using T-type thermocouples, of evolutions of local temperatures of fluid in the interior of the porous body. For this purpose, each thermocouple bead inserted in the porous body was prevented by a helix-shaped guard from being in direct contact with the packed spheres [7]. The pressure drop over the whole length of the porous body was measured by employing an inclined manometer with a resolution of 1/100 mm in water height.

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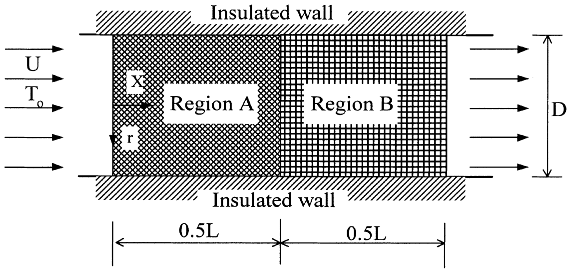

Fig. 1. The physical model of a heterogeneous porous body.

3. Experimental results and discussion

The particulars of the porous media that were employed in the experiment are listed in Table 1. For clarity, HMa, HMb and HMc refer to the homogeneous porous body and HTa, HTb, HTc and HTd indicate the heterogeneous porous body of two-section combination, pictured in Fig. 1. The measured bulk porosities of the packed beds were 0.38 and 0.40 for the spheres of diameter d = 3.00 and 6.35 mm, respectively.

Guided by preceding reports [1], the temperature evolutions are depicted in Fig. 2, plotted in dimensionless temperature $\theta\,[\equiv (T - T_0)/(T_{\rm in} - T_0)]$ versus scaled time $\tau\,[\equiv \rho_f c_f U t/(1-\varepsilon)\rho_s c_s L]$. In the above, subscripts s and f denote respectively the solid matrix and fluid, ε the porosity and t the dimensional time. The free stream velocity is represented in the Reynolds number, $Re \equiv Ud/\nu$, where U is the inlet velocity and ν the kinematic viscosity. In the previous study [7], the experimental data for the homogeneous porous body HMa were found to be consistent with the predictions of the modified dispersion–concentric model [2], and this favorable comparison provided credence to the reliability and accuracy of the present experimental apparatus and procedures.

The temperature evolutions for HTa and HTb are depicted in Fig. 2(a). Both HTa and HTb consist of the same spheres, but the sequences of spatial arrangement of regions A and B are opposite in the above two runs. At small times, i.e., $\tau \leq 0.35$, the cold fresh air arrives at upstream zones, and this cold fluid flushes out the original hot fluid in the void. In this process, the cold fluid that occupies the void becomes hot and the spheres are cooled since convective heat transfer takes place between the fresh cold air and the hot steel spheres. As time progresses, the temperature of the steel spheres falls appreciably. The incoming cold fluid replaces the original hot fluid, and most of the void region is occupied by the cold fresh fluid. However, this process of filling the void by the cold fluid and the subsequent lowering of temperature in the upstream region is more effective for HTb than for HTa, since the smaller spheres packed in this region for HTb have larger surface area to volume ratio. This trend is clearly illustrated in the early-time temperature evolutions of HTa and HTb in Fig. 2(a).

The temperatures at further downstream locations fall off more mildly since much of the cooling-off action occurs in the upstream region. Near the exit, since the incoming fluid has already gone through the full course of heat transfers with both large and small spheres, the difference between HTa and HTb becomes very small.

The time histories for HTc and HTd are exhibited in Fig. 2(b). Note that the sizes of the spheres are identical (d = 3.00 mm), but the sequence of packing in the upstream–downstream regions is glass–steel and steel–glass for HTc and HTd, respectively. At small and intermediate times, in the upstream region, the convective heat transfer between the incoming cold air and the spheres is more intense for HTd than HTc, since the thermal capacity of steel is nearly twice that of glass. Therefore, the temperature of the fluid for HTd is higher than for HTc. This trend is discernible over the whole length of the porous body. As expected, at

Table 1
Porous media configuration: d denotes the sphere diameter, and ε porosity

Homogeneous porous body	$0.0 \leq x/L \leq 1.0$	
HMa	Steel spheres, d = 3.0 mm, $\varepsilon = 0.38$	
HMb	Steel spheres, d = 6.35 mm, $\varepsilon = 0.40$	
HMc	Glass spheres, d = 3.0 mm, $\varepsilon = 0.38$	
Heterogeneous porous body	$0.0 \leq x/L \leq 0.5$ (region A)	$0.5 \leq x/L \leq 1.0$ (region B)
HTa	Steel, d = 6.35 mm, $\varepsilon = 0.40$	Steel, d = 3.0 mm, $\varepsilon = 0.38$
HTb	Steel, d = 3.0 mm, $\varepsilon = 0.38$	Steel, d = 6.35 mm, $\varepsilon = 0.40$
HTc	Glass, d = 3.0 mm, $\varepsilon = 0.38$	Steel, d = 3.0 mm, $\varepsilon = 0.38$
HTd	Steel, d = 3.0 mm, $\varepsilon = 0.38$	Glass, d = 3.0 mm, $\varepsilon = 0.38$

further downstream locations, the difference between HTc and HTd narrows, since for both cases, the fluid at the exit has undergone combined heat transfers with both steel and glass spheres.

Cross-comparisons of the temperature histories of the experimental runs point to the preponderance of the influence of upstream-side on the behavior of downstream-side. For instance, in the upstream region A, the differences in temperature evolutions between HMa and HTb are very small. In contrast, in the downstream region B, significant deviations are in evidence between HMb and HTb. Similar findings are observed in the experiments using HTa, HTc and HTd. These imply that, in a heterogeneous body, the impact of the upstream-side features on the downstream-side is appreciable, but not vice versa.

It is useful to compute the ratio of the accumulated heat transported Q_L from the porous material to the air flow over the time duration t since start-up [3]:

$$Q_{\mathrm{L}} = \frac{\rho_{\mathrm{f}} c_{\mathrm{f}} U \int_0^t \left\{ T(X = 1.0\ t) - T_0 \right\} \mathrm{d}t}{\left\{ \left[0.5\rho_{\mathrm{s}} c_{\mathrm{s}} (1-\varepsilon) L\right]_{\mathrm{A}} + \left[0.5\rho_{\mathrm{s}} c_{\mathrm{s}} (1-\varepsilon) L\right]_{\mathrm{B}} \right\} (T_{\mathrm{in}} - T_0)}.$$

The denominator of the above represents the total available sensible heat that is contained over the entire length L of the porous material. The numerator indicates the heat transferred to air from the whole porous body up to time t.

It is seen in Fig. 3(a) that the difference in the Q_L curves is very small between HTa and HTb. The experimental results for heterogeneous porous bodies, HTa and HTb, are shown to lie intermediate between the homogeneous media, HMa and HMb. This is not unexpected since both HTa and HTb are composed of the spheres used in HMa and HMb, and a higher heat transport is realized when the packed spheres are of smaller size. Also, the Q_L–τ curves for HTc and HTd do not show much difference, and they are similar to those of the homogeneous porous media, HMa and HMc. Note that, for all these runs, the size of the packed spheres is identical, i.e., d = 3.00 mm, although they differ in material. It can be inferred that the total heat transport, not the local heat transfer characteristics, is determined principally by the size of the packed spheres, and the physical properties and compositional layout have little impact on the behavior of Q_L.

The pumping work for air flow $W(t)$, and the accumulated total heat transported $Q_L^*(t)$ from the entire body of the porous media over the time duration t since start-up, can be defined as

$$W(t) = \int_0^t (\Delta P \cdot A \cdot U)\, \mathrm{d}t$$

and

$$Q_{\mathrm{L}}^*(t) = \rho_{\mathrm{f}} c_{\mathrm{f}} U A \int_0^t \left\{ T(L, t) - T_0 \right\} \mathrm{d}t,$$

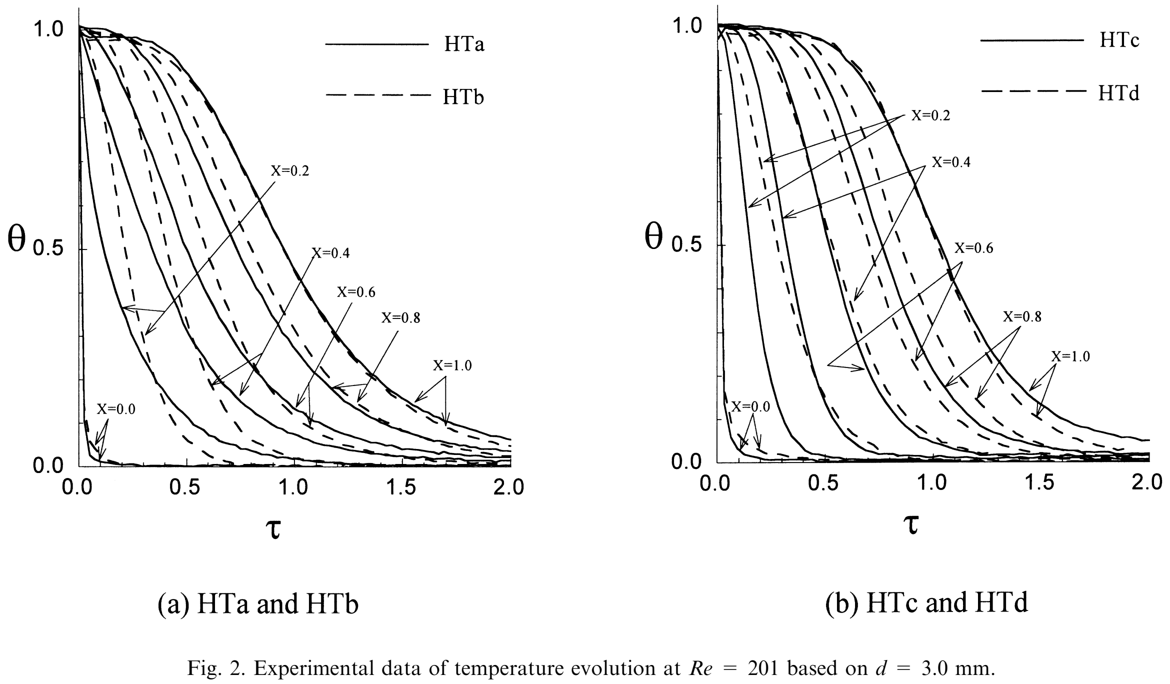

Fig. 2. Experimental data of temperature evolution at Re = 201 based on d = 3.0 mm.

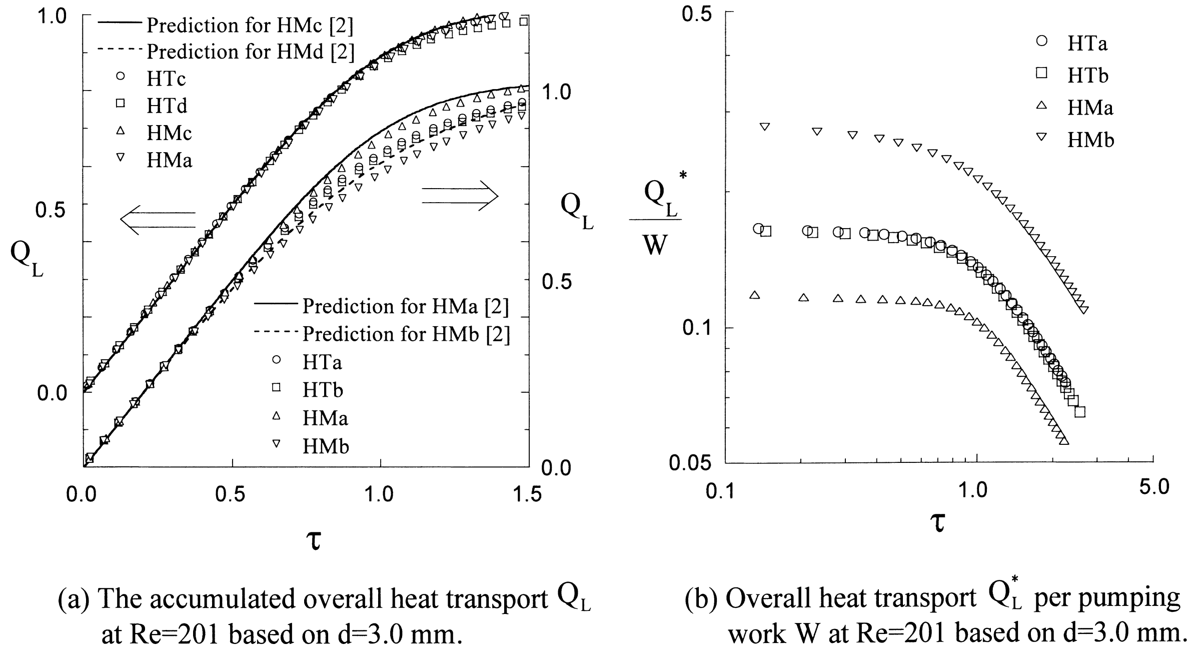

Fig. 3. The overall performance characteristics of heterogeneous porous bodies.

respectively. In the above, ΔP denotes the pressure drop over the length L of the porous material and A the frontal area of the porous body. In an effort to describe the effectiveness of the heterogeneous porous media, the ratio Q_L^*/W is displayed in Fig. 3(b). The values of Q_L^*/W for HTa and HTb are intermediate between the results of HMa and HMb, largely due to the differences in pressure drops. In addition, the values of Q_L^*/W remain nearly unchanged until $\tau \approx O(1)$, and Q_L^*/W decreases at large times. This trend is little affected by the variations in Reynolds number. From the standpoint of actual operational cost, it is recommended that the porous media should be run slightly longer than the characteristic time period, until $\tau \approx O(1)$ after the start-up, since the major transient process is accomplished over the time scale $\tau \approx O(1)$. This suggests that approximately 85% of the heat initially stored in the packed bed is retrieved in times up to $\tau \approx O(1)$.

4. Conclusion

The cool-down characteristics of heterogeneous bodies are strongly affected by the geometrical and compositional arrangement and thermophysical properties of the component porous materials. The impact of the conditions in the upstream-side region on the behavior of the downstream-side region is noticeable, but not vice versa. Small spheres packed in the upstream region allow a more effective heat transfer with the throughflow. The total heat transfer between the entire porous body and the throughflow is less affected by the local conditions of the make-up and properties of the media. The pressure loss that is incurred over the whole length of the heterogeneous porous body is seen to be the sum of the pressure losses of the individual component homogeneous porous media. The present heterogeneous porous media should be operated over times until $\tau \approx O(1)$ after the start-up, since the major transient process is accomplished over the characteristic time scale $\tau \approx O(1)$.

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