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Heat transfer and optimization studies on layered porous stackings under an imposed pressure drop☆

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ABSTRACT

This work reports the results of a study to augment the performance of layered porous heat sinks under forced or mixed convection. A two dimensional computational domain is used in the study which involves a rectangular channel consisting of a layered porous stacking. The temperature and flow fields are obtained for different configurations and inlet velocities with the Local Thermal Equilibrium (LTE) model using the commercially available software Fluent 14.0. The solver was validated with in-house experiments and the predictions from the solver were found to be in good agreement with the experimental results. The data obtained from the numerical experiments were used to train a BRANN (Bayesian-regularized artificial neural network). This, in turn, is used to drive a genetic algorithm (GA) to determine the optimal porosity distribution across the layers and the inlet velocity, maximizing the heat transfer with the simultaneous consideration of minimizing the pressure drop. The study reveals that factoring in the pressure drop during design results in a deviation from the optimal configuration obtained by minimizing only the hot-spot temperature. The optimal configuration has been determined and the benefit of an appropriate porosity distribution on the thermal performance has been investigated, giving qualitative insights into the performance of layered porous media.

1. Introduction

With increasing miniaturization of electronic devices there is an ever increasing need to improve the thermal control solutions. While several techniques are available for augmenting heat transfer to achieve temperature control, baffles and fins [1] are popular as there is little increase in pumping power required for employing them. However, with further miniaturization, more compact heat sinks are required. Porous stackings, with their increased surface area for heat-transfer and compact nature have been recognized as a highly compact replacement for fins.

Fluid-flow and heat-exchange through porous media have been studied extensively, both experimentally and analytically [2–9]. Even so, studies on multi-objective optimization on layered porous media that take into account both heat-transfer and pressure drop are scarce. In view of the above, this study reports the results of heat-transfer and optimization on a vertical channel filled with a layered porous medium considering both of the above objectives.

2. Model and governing equations

A multi-layered porous stacking adjacent to a hot wall acting as a heat source, generating a constant heat-flux and cooled by air is considered.

The porous stacking is made of 6 layers with varying porosities and thicknesses. The total width (L) of the stacking is 10 cm and the length (H) along the direction of flow is 40 cm (See Fig. 1). One wall of the stacking is uniformly heated to result in a constant heat flux over the surface. Gravity acts in the negative X-direction. The boundary opposite to the heat-source is assumed to be adiabatic. The porous matrix here is assumed to be made of copper (25 pores per inch) and the fluid used for cooling, as mentioned earlier, is air.

The fluid enters the inlet with a constant velocity (plug flow) and passes through the porous media. Following [5], the porous media is modeled as an array of circular cylinders. The porosity and the thickness of the layers are assumed to vary continuously. Darcy's flow is assumed.

Reynold's number, defined below varies from 0 to 500, much below the transition Reynolds number [10].:

$$Re = \frac{\rho_f u D_p}{\mu} \tag{1}$$

The governing equations for two dimensional steady flow are given by the following:

Mass-conservation (continuity equation)

$$\nabla . \rho_f v = 0 \tag{2}$$

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Nomenclature

c_s	specific heat capacity of the solid(J/kgK)
c_f	specific heat capacity of the fluid(J/kgK)
D_p	particle diameter (m)
g	acceleration due to gravity vector (m/s^2)
H	length of the channel along the direction of flow (m)
k_s	thermal conductivity of the solid phase(W/mK)
k_f	thermal conductivity of the liquid phase(W/mK)
L	width of the channel(m)
P	static pressure(Pa)
Q_{input}	heat influx W/m^2
Re	Reynolds number
v	velocity vector (m/s)
$\in$	porosity
μ	dynamic viscosity of the fluid($Pa.\ s$)
ρ'	modified fluid density (kg/m^3)
ρ_f	fluid density at room temperature(kg/m^3)
ρ_s	density of the solid(kg/m^3)

Momentum conservation (Darcy's law)

$$\nabla P + g\rho_f' = -\frac{\mu}{K}v \tag{3}$$

Further buoyancy is considered by invoking the Boussinesq approximation [11].

$$\rho_f' = \rho_f(1-\beta(T-T_\infty)) \tag{4}$$

The temperature field is determined by solving the energy Eq. (5):

$$\left(\rho_f' c_f\right)v.\nabla T = \nabla.(k_e \nabla T) \tag{5}$$

where

$$(\rho c)_e = (1-\in)(\rho c)_s + \in\left(\rho'_f c_f\right) \tag{6}$$

$$k_e = (1-\in)k_s + \in k_f \tag{7}$$

The boundary conditions are given by:

$$\forall x = 0, v_x = C_1, v_y = 0 \tag{8}$$

$$\forall x = H, p = 0 \tag{9}$$

$$\forall y = 0, q'' = 0 \tag{10}$$

$$\forall y = L, q'' = C_2 \tag{11}$$

The outlet is set to zero pascal gauge pressure.

The local thermal equilibrium (LTE) model has been used where the temperature of the solid and the liquid phases is assumed to be in local equilibrium. The equivalent thermal conductivity is estimated as a volume average of the conductivities of the solid and fluid thermal conductivities following (7).

For the porous medium under consideration, the permeability and the porosity are closely related. For the study the relation proposed in [9,12] is used to determine the permeability from the porosity. Large-pore diameters imply greater permeability but at larger-pore diameters the LTE assumption fails to hold [13].

3. Solution methodology

The two-dimensional equations governing the flow are discretized on a uniform square grid using the finite-volume formulation. Eqs. (3), (5), and (2) are solved using the semi-implicit pressure linked equation solver algorithm (SIMPLE) [14] iteratively using Fluent 14 [15]. The second order upwing scheme is used for the spatial discretization of the temperature and the velocity fields. Convergence is reached when the residuals for the energy, momentum and mass-conservation do not change by 0.1% over 100 iterations. The under-relaxation factors for the continuity and momentum equations are 0.3 and 0.7 respectively. The energy equation is fully relaxed.

A grid independence study showed that the difference in hot-spot temperature between the grid with 160,000 nodes and that with 250,000 nodes is less than 1.3 °C and hence the grid with 160,000 nodes is adequate for all subsequent calculations.

3.1. Experimental validation

A test-section whose outer walls are made of hard-wood is mounted on top of a vertical wind-tunnel. On the inside, four wooden boxes made from 12 mm plywood and placed adjacent to each other form a vertical rectangular duct at the center. The walls of the vertical duct are made with non-rubberized cork (low thermal conductivity of 0.07 W/mK) of 25 mm thickness and are supported on the inner boxes. The cork wall is covered with thin aluminum foils to minimize emission from it. A heater-plate assembly is placed adjacent one of the larger-sides of the vertical duct. An aluminum metal-foam is placed in the duct. The aluminum metal-foam has the dimensions 250 mm × 150 mm × 20 mm. The foam is tightly packed between the heater and the cork-wall. The rubber-cork also ensures that air-leakage is minimized along the sides. A curved bell-mouth at the entrance minimizes entry-losses. The pressure-drop across the metal-foam is measured using a digital

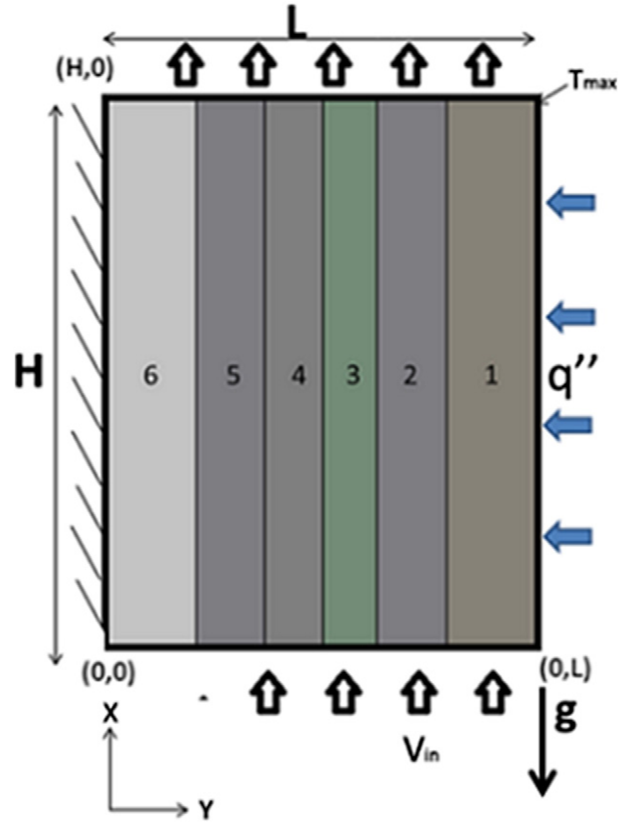

Fig. 1. Schematic of the problem geometry.