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Study of pressure drop-flow rate and flow resistance characteristics of heated porous materials under local thermal non-equilibrium conditions

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ABSTRACT

Porous materials are used as pneumatic components in a wide range of industrial applications. Such porous materials contain thousands of interconnected irregular micro-pores that produce a large pressure drop (ΔP) between the upstream and downstream sides of the porous material when a fluid flows through it. The relationship between the pressure drop and flow rate (i.e., the $\Delta P - G$ characteristic) and the relationship between flow resistance (γ) and flow rate (the $\gamma - G$ characteristic) are two very important basic characteristics. One factor affecting them is temperature, whose variation changes the viscosity and density of the fluid. In this study, we experimentally and theoretically analyzed the effect of temperature on $\Delta P - G$ and flow resistance characteristics of porous materials by heating them under constant electric heating power. The resulting experimental $\Delta P - G$ and flow resistance curves shift upward relative to their counterparts at room temperature owing to the increase in fluid temperature, but remain within the adiabatic and room temperature curves. The temperature-effect ratio η at constant heating power increases from 1.3 to 1.7 as the flow rate decreases from 21.53×10^{-5} kg/s to 5.80×10^{-5} kg/s, indicating that $\Delta P - G$ and flow resistance characteristics and pumping power change significantly when a porous material is heated. Furthermore, temperature distributions were obtained numerically to gain deeper understanding of the temperature effect. The effects of heating power values, characteristic porous material coefficients, and average fluid density on $\Delta P - G$ and flow resistance characteristics were also investigated.

1. Introduction

A porous material contains thousands of interconnected irregular micro-pores that produce a large pressure difference between the upstream and downstream sides of the material when a fluid flows through it. Such porous materials are used in a wide range of industrial applications. For example, on a large LCD glass production line, porous material is placed in the air flotation rail system, allowing compressed air to flow out of the porous material uniformly; this significantly reduces stress in the thin glass substrate caused by the air flow and enhances suspension stability [1–3]. Another typical application of porous material is in air bearings. Porous materials, fabricated from sintered metal or ceramic powders, replace conventional orifices in applications where high load capacity, stiffness, and stability are critical [4,5]. To study the use of porous materials as pneumatic components, we focus on the relationship between the pressure difference (ΔP) and flow rate (G), i.e., the $\Delta P - G$ characteristics, of porous materials [6–10]. Many studies on the $\Delta P - G$ characteristics of porous materials have been conducted. Lage et al. investigated two types of nonlinear pressure-drop-versus-flow-rate relations [11]. Meanwhile, Mancin and Simone et al. focused on the experimental and theoretical analysis of pressure losses during air flow in aluminum foams with different numbers of pores per inch and different porosity values [12]. Wei et al. proposed a new charge method to determine permeability and inertia coefficients from $\Delta P - G$ characteristics [13]. Calamas studied flow behavior and pressure drops in porous disks with bifurcating flow passages. The effects of the bifurcation angle, porosity, and pore size on the pressure drop across a porous disk were examined computationally [14]. Naaktgeboren investigated inlet and outlet pressure drop effects on permeability and form coefficient of a porous medium [15]. Jin studied porous medium flow of highly compressible gas near a wellbore; in the study, a model with an acceleration effect was used to predict $\Delta P - G$ characteristics [16]. Dukhan and Nihad et al. presented a new set of experimental data for water flow in metal foam to establish various flow regimes (from pre-Darcy to turbulent), and to assess the

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Nomenclature

A_{fs}	specific surface area, m^{-1}
$a/2$	viscosity flow resistance, Pa/(kg s^{-1})
b	inertia flow resistance, Pa/(kg s^{-1})
C_{pf}	specific heat capacity, J K^{-1} kg^{-1}
D_a	Darcy number
d_p	diameter of particles, m
G	mass flow rate, kg/s
H	length of the material, m
h_{fs}	fluid-to-solid heat transfer coefficient, W m^{-2} K^{-1}
K	permeability coefficient, m^2
K_{eff}	effective permeability coefficient, m^2
$k_{f,eff}$	effective conductivity of the solid, W m^{-1} K^{-1}
$k_{s,eff}$	effective conductivity of the fluid, W m^{-1} K^{-1}
k_s	conductivity of the solid phase, W m^{-1} K^{-1}
k_f	conductivity of the fluid phase, W m^{-1} K^{-1}
m	mass of the material, kg
P	pressure of air, Pa
P_1	inlet pressure, Pa
P_2	outlet pressure, Pa
ΔP	pressure drop, Pa
ΔP_T	pressure drop at constant heating power at temperature T, Pa
$\overline{\Delta P_T}$	pressure drop at isothermal conditions at temperature T, Pa
P_r	Prandtl number
q_w	heating power, W
R	gas constant, J kg^{-1} K^{-1}
R_1	inner radius of the material, m
R_2	outer radius of the material, m
Re_p	particle Reynolds number
$Re_{p,in}$	inlet particle Reynolds number
Re_T	inlet Reynolds number at a given temperature T
r	radius, m
T	temperature of air, K
T_f	temperature of the fluid phase, K
T_s	temperature of the solid phase, K
$T_{f,in}$	temperature of inlet air flow, K
$T_{f,out}$	temperature of outlet air flow, K
$T_{s,in}$	temperature of inlet surface of porous material, K
$T_{s,out}$	temperature of outlet surface of porous material, K
T_0	room temperature, K
$\bar{T}$	average temperature of air, K
T_a	adiabatic temperature of air, K
$\dot{V}$	volumetric flow rate, m^3/s
v	radial mean flow velocity, m/s
W	pumping power, W
W_T	pumping power at temperature T, W

Greek symbols

β	inertia coefficient
γ	flow resistance, Pa/(kg s^{-1})
γ_T	flow resistance at constant heating power at temperature T, Pa/(kg s^{-1})
$\overline{\gamma_T}$	flow resistance at isothermal conditions at temperature T, Pa/(kg s^{-1})
η	temperature-effect ratio of ΔP, γ, and W
η_T	temperature-effect ratio of ΔP, γ, and W at temperature T
μ	air viscosity at a given temperature T, Pa·s
μ_0	viscosity at room temperature, Pa·s
ρ	air density, kg/m^3
ρ_0	air density at room temperature, kg/m^3
ρ_s	density of steel alloy, kg/m^3
φ	porosity

behavior of pressure drops in each regime [17]. However, these studies were conducted under room temperature conditions. As the temperature of a fluid changes, the viscosity and density of the fluid change accordingly.

Many researchers have studied temperature variations and heat transport phenomena in porous materials. Odabaee et al. experimentally examined the heat transfer enhancement from a thin metal foam layer sandwiched between two bipolar plates of a cell. Effects of the key parameters including the free-stream velocity and metal foam characteristics such as porosity, permeability, and form drag coefficient on temperature distribution, heat and fluid flows were investigated [18]. Dukhan and Nihad Direct et al. measured actual air temperatures inside a commercial aluminum foam cylinder whose wall was heated by a constant heat flux and cooled by forced air flow using a specially designed technique. The volume-averaged analytical method was used to analyze temperatures of the solid and fluid phases inside the foam. Comparison showed good agreement between experimental and analytical air temperatures [19]. Zhang discussed compressed air energy storage and described a program in which it is applied to a wind turbine system for leveling power supplied to the electrical grid. Pressure drop, heat transfer, and temperature distribution characteristics were presented [20]. Aboelsoud et al. numerically studied hydraulic and thermal characteristics of V-shape corrugated carbon foams in air flows. The pressure drop, overall heat transfer coefficient, and temperature contours across the foam wall for four geometries were calculated [21]. Carpenter et al. experimentally investigated aluminum foam test sections with discrete pore-size gradients. The pressure drop, thermal performance, pumping power, etc. were discussed [22]. However, while they discussed pressure drop-flow rate characteristics, they aimed to analyze heat transfer between porous materials and the fluid rather than the effect of temperature variation on pressure drop-flow rate characteristics.

In practical applications, the effects of temperature variation on pressure drop-flow rate characteristics is of great importance, for example, in the pumping power of metal foam heat exchangers designed for fuel cells or other cooling systems [18,23,24]. The pumping power is determined by temperature-dependent pressure drop-flow rate characteristics, indicating that pumping power is another parameter affected by temperature. Thus, research into temperature effects on pressure drop-flow rate characteristics is very important to cooling systems. On the other hand, temperature effects on pressure drop-flow rate characteristics are also far-reaching. For instance, Yeo studied the effect of gas temperature on the flow rate characteristics of an averaging pitot-tube-type flow meter [25,26]. Based on the principle of using two hot wires, Lange investigated the characteristics of a micro-mechanical thermal flow sensor operating at constant-temperature in a small channel and considered temperature-based $\Delta P - G$ characteristics [27].

However, few studies have dealt with the effects of temperature variation on pressure drop-flow rate characteristics of porous materials. Narasimhan performed a theoretical analysis to predict the effects of a fluid with temperature-dependent viscosity flowing through an isoflux-bounded porous medium channel. The pressure drop, heat transfer, and temperature profiles of this system were obtained by solving numerically the differential balance equations [28,29]. Vanderlaan studied heat-flow-induced pressure drops using superfluid helium (He II) contained in porous media. In his