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Numerical analysis of forced convection of high-temperature exhaust gas around a metal-foam wrapped cylinder

Yue Wang, Gequn Shu *, Guopeng Yu [1], Hua Tian, Xiaonan Ma, Tianyu Chen

State Key Laboratory of Engines, Tianjin University, 92 Weijin Road, Nankai District, Tianjin 300072, China

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A B S T R A C T

Due to its high volumetric porosity and large specific surface area, open-cell metal foam has considerable advantages in compact heat exchangers for waste heat recovery system of internal combustion engines (ICEs). In order to simulate the forced convection around a metal foam-wrapped tube, a precise macroscopic model using the Darcy-Forchheimer-Brinkman momentum equation and the local thermal non-equilibrium energy equation has been established, and the heat transfer and pressure drop performance are investigated. Effects of key parameters, including porosity, pore density, foam thickness and Reynolds number are numerically studied and analyzed. It is found that the presence of a foam layer around the cylinder changes the flow structure, especially in the rear of the cylinder, and then influences the heat transfer and pressure field. A comparative study has been conducted between foam cylinders and a bare tube for various Reynolds number. The results indicate that, compared to a bare cylinder, the average Nusselt number of metal-foam wrapped cylinders can improve as much as 10 times at $Re = 1000$ and 18 times approximately at $Re = 6000$, which shows significant improvement in heat transfer performance.

1. Introduction

Due to limited resource of fossil fuel and destructive environmental effects resulting from its consumption, it is vital to develop waste heat recovery (WHR) technique in engines which not only reduces the demand of fossil fuels, but also reduces the harmful greenhouse gases (GHG) [1]. In spite of recent improvements in efficiency of internal combustion engines (ICEs), large amount of waste heat is still rejected to the ambient from the exhaust gas, which indicates the need of WHR technology [2]. Plenty of researches have been carried out on WHR aiming at diesel engines [3–5].

Heat-exchangers are commonly employed in such applications to transfer heat from high-temperature exhaust gas to the coolant [6], and the incurred pressure drop also has to be of reasonable magnitude to avoid excessive pumping power losses which have a negative impact on net engine efficiency [7]. For this reason, the exhaust gas is supposed to flow around the tubes and the coolant flows inside them to offer minimum pressure drop across the flow passage, according to Wang et al. [8] and Yang et al. [9]. As for engines, however, the heat transfer coefficient on the exhaust side is much lower than that of the coolant side [7], further leading to poor overall heat transfer performance. Therefore, a highly compact and highly efficient heat-exchange construction for the high-temperature exhaust gas side is in great demand. Technology development brings about several heat transfer enhancement techniques, such as using fins [10], turbulators [11], structured roughness [12], and so forth. Open-cell metal foam is a kind of porous media with novel structural and thermal properties [13]. It is characterized by light weight, high rigidity and strength, high specific surface area and good flow-mixing ability, which make open-cell metal foam able to recycle heat efficiently [14]. As an effective heat transfer enhancement material, open-cell metal foam is widely used in many compact heat-exchanger designs over the years [15]. Odabaee et al. [16,17] have applied this material in air-cooled condensers for air-side heat transfer enhancement, and concluded that the heat transfer rate from a single cylinder in cross-flow can be increased by an order of magnitude by adding a metal foam layer to its outer surface. According to their research, metal foams have shown great potentials in heat transfer enhancement of gas. Therefore, it is necessary and significant to investigate the heat transfer enhancement characteristics of high-temperature exhaust in a metal foam-wrapped cylinder, especially when the pressure drop is acceptable.

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* Corresponding author.
E-mail addresses: sgq@tju.edu.cn (G. Shu), ygp0307@tju.edu.cn (G. Yu).
[1] Co-corresponding author.

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Nomenclature

Abbreviations

GHG	greenhouse gas
ICE	internal combustion engine
LTE	local thermal equilibrium
LTNE	local thermal non-equilibrium
REV	representative elementary volume
WHR	waste heat recovery
PPI	pores per inch

Symbols

a_{sf}	surface area density
c_p	specific heat
C_p	pressure coefficient
C_F	Forchheimer coefficient, $C_F = 0.00212(1-\varepsilon)^{-0.132}(d_f/d_p)^{-1.63}$
d	foam layer thickness
$\tilde{d}$	specific diameter, $\tilde{d} = d_f \cdot G$
d_p	pore diameter, $d_p = 0.0254/\phi$
d_f	fiber diameter, $d_f = d_p \cdot 1.18\sqrt{(1-\varepsilon)/(3\pi)} \cdot G^{-1}$
D	cylinder diameter, $D = 2R$
Da	Darcy number, $Da = K/D^2$
E	relative deviation, $E = (Nu_{\mathrm{m,LTE}} - Nu_{\mathrm{m,LTNE}})/Nu_{\mathrm{m,LTNE}}$
G	shape factor, $G = 1 - \exp((\varepsilon - 1)/0.04)$
h	heat transfer coefficient
I	turbulent intensity
k	thermal conductivity
K	permeability, $K = 0.00073(1-\varepsilon)^{-0.224}(d_f/d_p)^{-1.11}d_p^2$
L_R	length of recirculation zone
Nu	Nusselt number
P	pressure
Pr	Prandtl number, $\mathrm{Pr} = \upsilon/\alpha$
r	radial coordinate
R	cylinder radius
R_c	thermal conductivity ratio, $R_c = k_{eff}/k_f$
Re	Reynolds number, $Re = \rho U_\infty D/\mu$
Re_d	local Reynolds number, $Re_d = \rho u\tilde{d}/\mu$
T	temperature
u, v	velocity

Greek letters

μ	dynamic viscosity
υ	kinematic viscosity, $\upsilon = \mu/\rho$
ρ	fluid density
ε	porosity
ϕ	pore density
α	thermal diffusivity
θ	cross-radial coordinate
δ	non-dimensional porous layer thickness, $\delta = d/D$

Subscripts

eff	effective
f	fluid
H	hollow region
i	interface between hollow and porous region
loc	local
p	pressure force
P	porous region
s	solid
v	viscous force
w	wall
∞	free stream

Superscripts

e	effective
n	normal to the interface between hollow and porous region

Models are important tools to investigate enhancing heat transfer. There are some researchers devoting their efforts to the model of heat transfer from a porous layer wrapped solid cylinder. Bhattacharyya and Singh [18] established a numerical model of mixed convection on a solid horizontal cylinder wrapped with a porous layer in cross-flow. Effects of different parameters such as Reynolds number, Grashof number, Darcy number, and effective thermal conductivity of the porous medium were examined. They used the model to investigate the heat transfer augmentation through the inclusion of a porous layer. Odabaee et al. [16] put forward a model of forced convective heat transfer from a metal foam-wrapped cylinder in cross-flow with Forchheimer-extended Darcy momentum equation and LTE energy equation. Effects of key parameters including the free stream velocity and characteristics of metal foam on heat transfer and fluid flow were studied. The model was used to choose the optimal value for the heat transfer augmentation and lay foundations for the heat exchanger designs. Similarly, Rashidi et al. [19] also proposed a model of cross flow and forced convection of a solid cylinder wrapped with a layer of porous media with Brinkman-Darcy-Forchheimer momentum equation and LTE energy equation. A comprehensive parametric study on fluid flow and heat transfer was carried out, and the effects of the presence of porous layers were further investigated to determine the optimal porous layer thickness with the model.

From the perspective of momentum equation, the fluid flow through a porous media is described by the Darcy's law in most early studies [20]. However, Darcy's law neglects some crucial physical effects, such as the viscous loss factor and the inertial loss factor, which is defined as Brinkman term and Forchheimer term, respectively [21]. Hence, for the extension of Darcy's law, the Darcy-Forchheimer-Brinkman flow model considers more factors and is more precise to perform as the momentum equation in our study.

As for energy equation, according to Vafai et al. [22], there are two approaches available in applying the volume-averaging method for heat transfer investigations in porous media: local thermal equilibrium (LTE) model, which neglects the local temperature difference between fluid and solid, and local thermal non-equilibrium (LTNE) model, which considers the interstitial heat transfer between the two phases. For high-conductive foams, according to Zhao et al. [23], thermal conductivity of solid is usually three to five orders of magnitudes higher than that of fluid, and the LTE model neglecting the local temperature difference and interstitial heat transfer in such foams usually overestimates the heat transfer results. Moreover, they also put forward a criterion called the relative deviation of Nusselt number (defined as $E = (Nu_{\mathrm{m,LTE}} - Nu_{\mathrm{m,LTNE}})/Nu_{\mathrm{m,LTNE}}$) to quantify LTNE effect in metal foams, and referring to their conclusion, the LTE model can be roughly used for prediction of heat transfer in metal foam instead of LTNE model in the range of $E \leqslant 20\%$. After calculation with our presumed heat exchange conditions, the relative deviation can reach up to 37.96%, which is much higher than 20%. As a consequence, the LTNE model is necessary for our calculation.

As indicated above, prior researches to the present investigation are those which somewhat neglect viscous loss effect, inertial loss effect or local heat transfer effect in the calculation of metal foams,