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Multi-objective genetic optimization of the heat transfer for tube inserted with porous media

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ABSTRACT

This work is aimed at determining the best configurations of porous media inserted in a tube to achieve the excellent performance of fluid flow and heat transfer. Both geometry parameters and property parameters are the variables to be optimized. In order to evaluate the performance of tube, two conflicting objectives, Nusselt number *Nu* and friction factor *f*, are simultaneously considered. In the optimization process, computational fluid dynamics (CFD) and multi-objective genetic algorithm are coupled to obtain the numerical solutions of two-dimensional calculation model and Pareto front composed of non-inferior solutions. Besides, an attempt of utilizing limited resources is made by applying the penalty function instead of adding or modifying governing equations to restrain the flow resistance. Subsequently, technique for order preference by similarity to an ideal solution (TOPSIS) is employed to help decision makers determine the best alternative from the Pareto front. The results selected by TOPSIS are compared with the alternative which has the maximum Nusselt number. It is found that TOPSIS is effective to balance deferent objectives and determine compromise parameters.

1. Introduction

With the development of modern industry, the performance of heat exchangers becomes more and more important. In recent decades, considerable studies of heat transfer enhancement technologies and theories by disturbing fluid or increasing heat transfer area [1–3] in tubes have been made to meet the requirements of the energy saving. Recently, performances of tube with porous inserts have received some attention with experimental, analytical and numerical studies [4–7]. Mohamad [4] investigated heat transfer enhancement for a flow in a pipe or a channel fully or partially filled with porous media and found that partially filling has a better performance on both heat transfer and pressure drop. Huang et al. [5] studied the heat transfer enhancement for the flow in a pipe filled with annular porous ring and found that high porosity was recommended when using performance evaluation criteria (*PEC*) [6] as decision criteria. Zheng et al. [7] applied genetic algorithm (GA) to optimize the configurations of porous media which was divided into several layers and partially inserted in a tube. It was found that multiple layers of porous inserts can further increase the *PEC*.

When optimizing a heat transfer unit or a system, the flow resistance often has an increase with the enhancement of heat transfer. Therefore, evaluation criteria play a significant role in assessing the performance or determining the economic benefit of heat exchangers for many practical applications, such as *PEC*, *JF* factor [8], efficiency evaluation criterion (*EEC*) [9]. In existing studies, most of the evaluation criteria are composed of several parameters affecting the heat transfer and pressure-drop in a certain form. However, it is sometimes difficult to establish a general selection criterion to be applied in the industry. Recently, more and more optimizations attempt to apply multi-objective optimization techniques to obtain the non-inferior solutions, and choose the most feasible solution to meet the requirements for practical applications. This approach has been proven effective, and extensively applied in optimization design of different fields, such as thermodynamic cycle [10], power system [11].

In spite of the widespread application of multi-objective optimization techniques, there is limited published literature about optimizing the performance of tube with porous ring inserted. The purpose of this paper is to determine the optimal parameters of the porous media by means of a multi-objective genetic algorithm (MOGA) [12]. The geometrical shape and property configuration of porous ring jointly decide the performance of tube. Meanwhile, two conflicting objectives, Nusselt number *Nu* and friction factor *f*, are considered to be optimized at the same time. In

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Nomenclature

C	relative closeness to the ideal solution
c	specific heat
Da	Darcy number, K/r_0^2
F	inertia coefficient
H	convective heat transfer coefficient
f	friction factor
J	objective function
K	permeability
L_1	dimensionless entrance length
L_2	dimensionless exit section length
Nu	local Nusselt number, $2hr_0/\lambda_f$
P	dimensionless pressure
p	pressure
Pr	Prandtl number of the fluid, $c\mu_f/\lambda_f$
q	heat flux
R	dimensionless radius
R_1	dimensionless distance between the internal wall of porous ring and the centerline
R_2	dimensionless distance between the exterior wall of porous ring and the centerline
r	radial position measured from the centerline
r_0	radius of the tube
Re	Reynolds number, $2\rho ur_0/\mu_f$
T	temperature
U	dimensionless axial velocity
u	axial velocity
V	dimensionless radial velocity
v	radial velocity
X	dimensionless axial coordinate
x	axial position measured from the inlet

Greek symbols

ε	porosity
θ	dimensionless temperature
λ	thermal conductivity
μ	dynamic viscosity
ρ	fluid density

Superscript

e	effective
f	fluid domain properties
p	porous domain properties
R	the ratio of a parameter in porous domain to the same parameter in fluid domain
m	mean
s	solid matrix propertied
w	wall

present study, an effective design method [13] coupling GA and computational fluid dynamics (CFD) analyzes is applied to solve the multi-objective problems mentioned above. Subsequently, all the non-inferior solutions (Pareto solutions) obtained by MOGA are ranked by a famous decision making technique, TOPSIS (technique for order preference by similarity to an ideal solution) [14]. Besides, an attempt is made to restrain the flow resistance by employing the penalty function instead of adding or modifying governing equations.

2. Problem description and constraint conditions

2.1. Physical model

The schematic of the tubes inserted with porous ring in current study is shown in Fig. 1. A two-dimensional, centrosymmetric numerical model for convection heat transfer of steady laminar flow in a tube with constant heat flux is considered. In order to give function boundary conditions at the inlet and eliminate the influence of backflow at the outlet, an entrance section and an exit section are applied, respectively. The total length L is fixed at 24, with the entrance length L_1 = 1 and exit section length L_2 = 3. At the end of entrance section, a porous ring is placed in porous section with its length L_p = 20. As shown the Fig. 1, the position of porous ring can be determined by two parameters, R_1 and R_2. To simplify the analysis, other assumptions are listed as follows: (1) the porous media is regarded as homogeneous and isotropic; (2) the heat generated by the viscous effects is negligible; (3) the gravitational effect of the air flowing through the tube is negligible; (4) the gas phase and the solid phase in porous media exist in a state of local thermal equilibrium.

2.2. Mathematical model

The governing equations including the continuity, momentum, and energy can be expressed as follows [15]:

Continuity equation:

$$\frac{\partial(\rho u)}{\partial x}+\frac{1}{r}\frac{\partial(r\rho v)}{\partial r}=0 \tag{1}$$

Momentum in x-direction:

$$\begin{aligned}&\frac{\partial}{\partial x}\left(\frac{\rho}{\varepsilon}uu\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\rho}{\varepsilon}vu\right)\\&=-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\frac{\mu}{\varepsilon}\frac{\partial u}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\mu}{\varepsilon}\frac{\partial u}{\partial r}\right)-\delta\frac{\mu_e u}{K}-\delta\frac{\rho F\varepsilon}{\sqrt{K}}|u|u\end{aligned} \tag{2}$$

Momentum in r-direction:

$$\begin{aligned}&\frac{\partial}{\partial x}\left(\frac{\rho}{\varepsilon}uv\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\rho}{\varepsilon}vv\right)\\&=-\frac{\partial p}{\partial r}+\frac{\partial}{\partial x}\left(\frac{\mu}{\varepsilon}\frac{\partial v}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\mu}{\varepsilon}\frac{\partial v}{\partial r}\right)-\delta\frac{\mu_e v}{K}-\delta\frac{\rho F\varepsilon}{\sqrt{K}}|u|v-\frac{\mu v}{\varepsilon r^2}\end{aligned} \tag{3}$$

where ε is the porosity and K is the permeability. In this study, the parameter δ is set to unity for flow in porous medium and to zero for flow in a clear region. The inertia coefficient F is related to porosity as described by Ergun [16]:

$$F=\frac{1.75}{\sqrt{150\varepsilon^3}} \tag{4}$$

Energy equation:

$$\begin{aligned}&\frac{\partial}{\partial x}(\rho cuT)+\frac{1}{r}\frac{\partial}{\partial r}(\rho crvT)\\&=\frac{\partial}{\partial x}\left\{[\delta(\lambda_e-\lambda)+\lambda]\frac{\partial T}{\partial x}\right\}+\frac{1}{r}\frac{\partial}{\partial r}\left\{r[\delta(\lambda_e-\lambda)+\lambda]\frac{\partial T}{\partial r}\right\}\end{aligned} \tag{5}$$

where λ_e is the effective thermal conductivity of the porous media, $\lambda_e=\varepsilon\lambda_f+(1-\varepsilon)\lambda_s$ [17].

The boundary conditions are used as follows:

(1) at $r = 0$: $\frac{\partial u}{\partial r}=0,\ v=0,\ \frac{\partial T}{\partial r}=0$;
(2) at $r = r_0$: $u=0,\ v=0,\ \frac{\partial T}{\partial r}=-\frac{q}{\lambda_f}$;
(3) at $x = 0$: $u(r)=u_c\left[1-\left(\frac{r}{r_0}\right)^2\right]$, $v=0$, $T(r)=T_c+\frac{qr_0}{\lambda_f}\left[\left(\frac{r}{r_0}\right)^2-\frac{1}{4}\left(\frac{r}{r_0}\right)^4\right]$;
(4) at $x = 24r_0$: $\frac{\partial u}{\partial x}=0,\ v=0,\ \frac{\partial T}{\partial x}=0,\ p=0$.