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Flow pattern construction-based tubular heat transfer intensification using calculus of variations

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HIGHLIGHTS

- The flow pattern construction-based approach is applied to intensify heat transfer.
- The optimal flow pattern is constructed from the thermodynamic point of view.
- The vortex structure is generated to improve heat transfer performance.
- The enhanced heat transfer tube with porous inserts is obtained.

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ABSTRACT

The flow pattern construction-based optimization approach was applied to tubular heat transfer intensification. As the first step in the optimization, the flow pattern was constructed from the thermodynamic point of view, with the heat transfer entropy generation set as the optimization objective and the viscous dissipation set as the constraint. The necessary conditions for the conditional extremum were determined to constitute a CFD model for the flow pattern construction. The hydrodynamic and heat transfer characteristics of the constructed optimal flow pattern are shown to be significantly different from those of the ordinary flow pattern. In particular, a flow structure containing multiple vortices appeared in the optimal flow pattern to improve the heat transfer performance. The second step of the proposed optimization was to design the internal geometric structure of the heat transfer tube to construct a real flow pattern that produces a larger heat transfer rate. The results of the geometry optimization indicate that porous inserts arranged near the tube wall can be a useful strategy for practical heat transfer intensification.

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1. Introduction

With the ever-increasing demand for energy, energy conversion and management have been the center of attention of both researchers and engineers. Energy utilization critically depends upon heat transfer, so how to intensify heat transfer has become an important subject to achieve energy savings.

In recent decades, there has been a growing interest in the research of heat transfer intensification (Bergels, 1997, 2002; Liu and Sakr, 2013; Sheikholeslami et al., 2015). The primary mechanism of the intensification is to change the velocity field to form a specific flow pattern, because the hydrodynamic characteristics have been shown to be of extreme importance for heat transfer performance (Li et al., 2011). Of particular interest is the establishment of secondary flows and chaotic advection by curved channels (Metwally and Manglik, 2004; Rosaguti et al., 2005, 2007; Lasbet et al., 2006; Geyer et al., 2007; Zheng et al., 2014; Kumar and Nigam, 2007; Kumar et al., 2007), vortex generators (Lei et al., 2010; Tian et al., 2009; Wang et al., 2015a; Lin et al., 2015; Zhang et al., 2016), ribs/structured surface patterns (Desrues et al., 2012; Tang and Zhu, 2013; Siddique et al., 2013; Tohidi et al., 2013; Xie et al., 2014a, 2014b; Meng et al., 2005a; Li et al., 2009) and inserts (Leng et al., 2014; Solano et al., 2012; Mohammed et al., 2013), to promote the liquid mixture and intensify the heat transfer. Commonly, the physical configuration of the equipment is the unknown in a design, and in principle, the global heat transfer performance is entirely dependent upon the heat transfer equipment, so the optimization of the configuration of the equipment is the route to maximum system performance. Therefore, engineers tend to design heat transfer equipment carefully to create a specific flow pattern to accomplish heat transfer intensification. The conventional design method begins with the assumption of

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Nomenclature

A_0, B_0, C_0	Lagrange multiplier
Br	Brinkman number
C_P	specific heat capacity, J/(kg K)
$\boldsymbol{F}$	body force, N/m^3
h	heat transfer coefficient, W/(m^2 K)
$\boldsymbol{I}$	unit tensor
L	tube length, m
P	pressure, Pa
Q	heat flux, W/m^2
R	universal gas constant, J/(kg mol)
Re	Reynolds number
S_{tube}	heat transfer area, m^2
S_{gen}	entropy generation rate per unit volume, W/(m^3 K)
T	temperature, K
ΔT_m	log-mean temperature difference, K
$\boldsymbol{U}$	velocity vector, m/s

Greek symbols

α	permeability of porous media, m^2
α_{flu}	volume fraction of the “fluid phase”
α_{sol}	volume fraction of the “solid phase”
$\alpha_{sol}{}^*$	equilibrium volume fraction of the “solid phase”
ε	porosity of porous media
λ	thermal conductivity, W/(m K)
μ	viscosity, kg/(m s)
ρ	density, kg/m^3
ϕ	viscous dissipation rate, W/m^3

Subscripts

in	inlet
out	outlet
wall	wall
λ_1, λ_2	related to thermal conductivity
μ_1, μ_2	related to viscosity
ρ_1, ρ_2	related to density

certain configurations, followed by building the model and evaluating the performance such that in the end, the engineer selects the best configuration from the assumed ones. If the heat transfer performance is shown to improve in the designed equipment, a correlation is then developed to serve as a standard guide for the related heat transfer equipment design. Thus far, equipment development in thermal systems is mainly based on the conventional method. Because this sort of conventional method depends upon the engineer's experience, and practical heat transfer systems are very complex, the utility of the design is typically limited.

To make progress in the research of heat transfer intensification, many researchers have proposed various novel concepts and principles that are of both engineering and scientific significance. Guo et al. (1998) proposed the field synergy principle, which indicates that the performance of a single-phase convective heat transfer process depends upon the velocity field, temperature field and their synergy. The field synergy principle has been further substantiated in the studies of Tao et al. (2002) and Guo et al. (2005) and extended to the areas of fluid flow (Chen et al., 2008a; Zhang et al., 2014) and convective mass transfer (Guo et al., 2015a; Chen and Meng, 2008; Chen et al., 2008b). In addition to the field synergy principle, researchers have applied other principles to intensify heat transfer, including the minimum entropy generation principle (Li et al., 2014), the entransy dissipation extremum principle (Chen et al., 2009), the minimum power consumption principle (Jia et al., 2012), the minimum heat consumption (Liu et al., 2013), the exergy destruction minimization (Wang et al., 2015b) and the minimum temperature gradient (Guo et al., 2015d). These principles reveal the heat transfer intensification mechanism from a different perspective. It has been demonstrated that the heat transfer performance improves significantly via optimizing flow patterns using these principles. Consequently, it is supposed that an efficient or even optimal heat transfer unit can be developed based on flow pattern optimization.

Our group attempts to develop a systematic approach for transfer process intensification based on the previous studies, with particular attention focused on the flow pattern construction. Not limited to the flow pattern construction, how to design the internal geometric structure of the equipment is also considered in the proposed approach. In contrast to the conventional design method, the proposed approach begins by constructing a flow pattern and then relates the equipment configuration to the flow pattern construction and ultimately produces a practically applicable design for the equipment structure. Currently, the approach has been successfully applied to fluid flow (Guo et al., 2015c), “area to point” heat conduction (Guo et al., 2016) and gas mixture (Guo et al., 2015b). The purpose of the present study is to extend the flow pattern construction-based optimization approach to tubular heat transfer that is a classical problem with wide engineering applications. Specifically, the first step of this study is to propose a strategy for flow pattern construction (optimization) from an entropy generation optimization point of view. To construct the flow pattern, the convective heat transfer is optimized as a conditional extremum problem with the heat transfer entropy generation set to be the optimization objective and the viscous dissipation set to be the constraint. By using the calculus of variations, the necessary condition for the conditional extremum is determined to constitute a CFD model. As the core of the CFD model, a virtual body force is applied in the momentum equations to construct an optimal flow pattern. This optimal flow pattern is equivalent to the necessary condition for the conditional extremum. The second step is to design the internal geometric structure of the heat transfer tube based on the constructed flow pattern, using porous media model and a scalar transport equation.

2. Problem description

2.1. Tubular heat transfer

Tubular heat transfer in the heat exchanger and reactor is governed by the conservation of mass, momentum and energy or the continuity equation, momentum equation and energy equation.

$$\nabla\cdot(\rho\boldsymbol{U}) = 0 \tag{1}$$

$$-\rho C_P\boldsymbol{U}\cdot\nabla T + \nabla\cdot(\lambda\nabla T) = 0 \tag{2}$$

$$\nabla\cdot(\rho\boldsymbol{U}\boldsymbol{U}) = -\nabla P + \nabla\cdot\mu[(\nabla\boldsymbol{U} + \nabla\boldsymbol{U}^T) - \frac{2}{3}(\nabla\cdot\boldsymbol{U})\boldsymbol{I}] \tag{3}$$

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