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Convective heat transfer optimization in a circular tube based on local exergy destruction minimization

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ABSTRACT

In this study, the equilibrium equation of available potential, which reveals the relation of available potential and local exergy destruction rate, is determined, and the expressions of available potential and local exergy destruction rate are given. To improve heat transfer enhancement and reduce increase amplitude of flow resistance, a method termed as fluid-based heat transfer enhancement is proposed relative to surface-based heat transfer enhancement. An optimal mathematical model by constructing Lagrange function with exergy destruction corresponding to irreversibility loss of heat transfer process and fluid power consumption to flow loss of fluid is adopted to validate this method. To obtain the optimal flow structure in a tube, the tube flow is divided into two parts: core flow and boundary flow. For reducing the irreversibility loss in the core flow, we take fluid exergy destruction as optimization objective with prescribed fluid power consumption. For reducing the flow resistance in the boundary flow, we take fluid power consumption as optimization objective with prescribed fluid exergy destruction. The optimization equations for the convective heat transfer in laminar flow are derived, which are solved numerically. The longitudinal swirling flows in the tube are found at different parameters. In the optimized flow, heat transfer is enhanced greatly while accompanied with a little increase of flow resistance. Comprehensive performance, the ratio of increases in heat transfer and flow resistance, reaches at 3.65 after optimization.

1. Introduction

The enhancement and optimization of heat transfer are essential for energy conservation and environment protection, because heat transfer is related to almost 80% of total energy consumption in industry. Convective heat transfer is one of the common transport processes in industry. It is highly important to develop a theory and corresponding technology for enhancing convective heat transfer.

Through numerical simulation and experimental analysis, researchers have developed many technologies to enhance the heat transfer in tube flow. Correspondingly, certain heat-transfer-enhanced tubes are exploited, such as inner-finned tubes [1], spiral corrugated tubes [2], and micro-finned tubes [3]. Bejan et al. [4] divided the tube flow into two parts: boundary flow and core flow. The flow near the wall of tube is defined as boundary flow and the remaining is core flow. In the aforementioned heat-transfer-enhanced tubes, the surfaces in the boundary, which dominate the convective heat transfer between fluid and tube wall, are designed or improved to enhance heat transfer. The mechanism for heat transfer enhancement includes [5]: disturbing the boundary layer, extending the heat transfer surface, and changing the physical properties of the heat transfer surface. Therefore, this kind of method can be designated as surface-based heat transfer enhancement (abbreviated as the surface-based method). This method effectively enhances the convective heat transfer coefficient, but the increase in flow resistance may become significant and the comprehensive performance can be weakened.

For reducing the increase in flow resistance while maintaining satisfactory heat transfer, researchers have developed certain new heat-transfer-enhanced tubes, such as center-cleared twisted tape [6], multiple regularly spaced twisted tapes [7], and conical strip inserts [8]. Furthermore, Mohamad and Pavel [9,10] conducted a numerical simulation for heat transfer enhancement in a fully developed tube with porous media partially filling the center. Ming et al. [11] and Huang et al. [12] conducted a brief numerical and experimental study of the heat transfer performance of a tube filled with porous media in the core flow. Wang et al. [13] added fiber fines in a fully developed laminar rectangular channel,

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Nomenclature

A_1, B_1, C_1	Lagrange multipliers
A_2, B_2, C_2	Lagrange multipliers
c_p	specific heat capacity, J/(kg K)
e	available potential, J/kg
e_d	local exergy destruction rate, W/m^3
E_d	exergy destruction, W
f	flow resistance coefficient
F	additional volume force, N/m^3
h	enthalpy, J/kg
J_1, J_2	Lagrange functions
Nu	Nusselt number
p	pressure, Pa
P_w	fluid power consumption, W
$\boldsymbol{q}$	heat flux, W/m^2
$\boldsymbol{q}_e$	exergy flux, W/m^2
$\boldsymbol{q}_s$	entropy flux, W/(m^2 K)
$\dot{\boldsymbol{q}}'''$	inner heat source, W/m^3
$\dot{\boldsymbol{q}}_e'''$	analogical exergy source, W/m^3
$\dot{\boldsymbol{q}}_s'''$	analogical entropy source, W/(m^3 K)
Q	heat, J
s	entropy, J/(kg k)
s_g	local entropy generation rate, W/(m^3 K)
t	time, s
T	temperature, K
U	velocity, m/s
V	volume, m^3

Greek symbols

β	field synergy angle, degree
ε	dimensionless thickness of equivalent thermal boundary layer
λ	heat conductivity, W/(m K)
ρ	fluid density, kg/m^3
μ	viscosity coefficient, kg/(m s)
ϕ	heat dissipation from fluid viscosity, W/m^3
ϕ_e	analogical exergy flow from fluid viscosity, W/m^3
ϕ_s	analogical exergy flow from fluid viscosity, W/(m^3 K)
Ω	fluid computational domain, m^3
Γ	flow boundary area, m^2

Subscripts

0	reference point, environmental state
1	state 1
2	state 2

and conducted numerical and experimental studies to characterize the heat transfer and pressure drop. Nanan et al. [14] experimentally investigated heat transfer enhancement through perforated helical twisted tapes and indicated that the use of these tapes reduces friction loss, but yields lower thermal performance factors compared with helical twisted tapes. Tu et al. [15] conducted experimental studies on heat transfer and friction factor characteristics of turbulent flow through a circular tube with small pipe inserts. They found that pipe inserts can transfer more heat at the same pumping power for their unique structure when compared with other inserts, and their performance evaluation criterion (PEC) arrived at 2.23–2.7. These technologies focus on the disturbance in core flow and enhance the heat transfer by changing the tube flow. We designate this method as fluid-based heat transfer enhancement (abbreviated as the fluid-based method). Although this method can achieve satisfactory comprehensive performance, the principle for the design of inserts is not clear. Therefore, it is necessary to develop a theory to reveal the mechanism and an optimization method for the design of inserts.

In addition to the development of techniques for heat transfer enhancement, many related theories have been proposed and developed. Guo et al. [16–18] proposed a new physical quantity called “entransy” to express the capability of the thermal energy transport process. Many modeling and numerical investigations have been conducted; the results have proven that entransy dissipation can be used to express the irreversibility loss when optimizing the heat transfer process. Additionally, Guo et al. [19] proposed the field synergy principle to explain and guide the enhancement of convective heat transfer. Based on Guo’s field synergy principle, Liu et al. developed two-field synergy into multi physical quantities synergy, and extended the principle from laminar flow to turbulent flow [20–22]. Based on the principle of multi physical quantities synergy, Liu et al. [23–26] conducted extensive numerical and experimental investigations, which indicated that this theory is an effective method to direct the design of heat transfer processes. Liu et al. [27] also developed a new criterion to evaluate the performance of heat transfer units. Based on entransy, Liu et al. [28] developed a new expression for the second law of thermodynamics and applied it to the optimization of the heat transfer process. Liu et al. [29] performed numerical investigations to assess the effects of different combinations of entransy and power consumption as optimization objectives or constraint conditions. Additionally, Liu et al. [30] proposed a method for achieving minimum heat consumption to optimize the convective heat transfer, and compared three different objectives, i.e. minimum heat consumption, minimum entransy dissipation, and minimum power consumption. The current methods optimize the convective heat transfer based on the reduction of irreversibility loss, whereas the increase in flow resistance is not taken into consideration. For the operation of a heat exchanger at a constant power consumption by a pump, to reduce the flow resistance means increasing the fluid velocity, thereby achieving better heat transfer performance. Therefore, the reduction of flow resistance is also an effective method to enhance heat transfer. Thus, it is important to simultaneously consider heat transfer enhancement and flow resistance reduction for optimizing the convective heat transfer in a tube.

The concept of exergy is applied widely in analysis and evaluation of energy system and lots of studies have been conducted. Farahat et al. [31] conducted an exergetic optimization of flat plate solar collectors and found the optimal performance and design parameters of these solar to thermal energy conversion systems. Lu et al. [32] established a basic physical model of solar receiver pipe with solar selective coating and conducted exergetic optimization. The variation of energy absorption efficiency and exergetic efficiency with system parameters are analyzed. Bindra et al. [33] conducted thermal analysis and exergy evaluation of packed bed thermal storage systems, and proposed that for packed beds, sensible heat storage systems can provide much higher exergy recovery as compared to phase change material (PCM) storage systems under similar high temperature storage conditions. Furthermore, they [34] developed the sliding flow method to decouple thermal behavior and pressure drop effects and improve the exergetic efficiency. It is significant to analyze the relation between exergy and convective heat transfer.

In this study, we proposed a method, termed fluid-based heat transfer enhancement, for improving the comprehensive performance from the perspective of reducing both thermal and flow resistances. Additionally, we obtained the expression of local