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Convective heat transfer optimization based on minimum entransy dissipation in the circular tube

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ABSTRACT

Convective heat transfer optimization based on minimum entransy dissipation is studied in this paper. By setting entransy dissipation as optimization objective and power consumption as constraint condition, optimized fluid momentum equation with additional volume force for convective heat transfer are deduced by variational principle. Numerical investigations for convective heat transfer in a straight circular tube based on optimized governing equations are conducted. The results show that there exist longitudinal swirl flows with multi-vortexes in the tube, which leads to heat transfer enhancement at relatively small flow resistance. The present analysis for heat transfer and flow shows that this kind of optimized flow field can realize a far greater increase in heat transfer than that in flow resistance, which indicates that the investigated optimization method is useful in design of heat transfer enhancement.

1. Introduction

As far as heat transfer enhancement [1,2] is concerned, many researchers focus on whether heat transfer is enhanced and to which degree it is enhanced, while ignoring the increase in flow resistance which sometimes may exceed the degree of heat transfer enhancement. With growing concern about energy saving in heat exchangers which are widely used in industry, more and more researchers are devoted to developing heat transfer enhancement unit which can work efficiently with low power consumption. Since the overall performance of convective heat transfer is heavily dependent on heat transfer process, great emphasis should be laid upon the process optimization [3]. However, the currently used methods in heat transfer enhancement are more technical and lack of theoretical optimization to guide the design for various enhancement techniques.

Bejan et al. [4–7] proposed the constructal theory, which simplified the complicated geometric construction into the assembly of a series of fundamental units, and made the transport process optimization possible. Guo et al. [8] proposed the field synergy principle in analyzing the relationship between the local behavior and the overall performance of convective heat transfer in two-dimensional laminar flow. They pointed out that the performance of convective heat transfer was dependent on the synergy between temperature and velocity fields. With the same velocity and temperature boundary conditions, the larger the synergy degree was, the better the convective heat transfer would be. Based on the field synergy principle, Liu et al. [9–11] considered multi-field synergy in convective heat transfer by reexamining the physical mechanism of convective heat transfer between fluid and solid wall in the laminar and turbulence flows. They revealed how heat transfer enhancement was influenced by multi-field synergy relation associated with temperature, velocity and pressure and explained physical essentials on enhancing heat transfer and reducing flow resistance. According to the field synergy principle, we can know that the performance of convective heat transfer is dependent on the organization of fluid field, and what we need to do is to find an optimized fluid field. After finding it, a heat transfer enhancement solution which is closest to this optimized fluid field can be identified and implemented.

Bejan deduced entropy generation expression and analyzed optimization parameters in heat exchangers or heat transfer systems by taking minimum entropy generation as optimization objective [12,13] induced by heat transfer and viscous dissipation. Xia [3] set thermal potential loss as the evaluation objective and used viscous dissipation to denote the loss in mechanical energy. With fixed mechanical energy loss, the optimized velocity field equation can be derived through functional analysis, in which a scalar item was unknown. Meng [14] furthered Xia's analysis by using Lagrange multiplier to make functional analysis. The field synergy equation was derived, and each term in the equation

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Nomenclature

A, B, C_0	Lagrange multipliers
c_p	specific heat at constant pressure, J/(kg K)
e_h, ϕ_h	entransy dissipation, W K/m^3
E_{vh}	entransy, J K
$\boldsymbol{F}$	volume force vector, N
J	functional
p	pressure, Pa
Q_{vh}	heat capacity, J
T	temperature, K
$\boldsymbol{U}$	velocity vector, m/s
V	volume, m^3
W_p	power consumption, W
Greek symbols	
λ	thermal conductivity, W/(m K)
ρ	fluid density, kg/m^3
μ	viscosity coefficient, kg/(m s)
Ω	control volume, m^3
Γ	control surface, m^2

was identified. Based on his analysis, the heat-transfer enhanced tubes with two longitudinal vortexes were designed, which exhibited better heat transfer performance. Guo et al. [15] proposed a new physical quantity – entransy to describe the capability of heat energy transportation. They also proposed the principle of entransy dissipation extremum [16–21] to optimize heat transfer process by setting fixed viscous dissipation as constraint condition. Compared with the principle of minimum entropy generation, the principle of entransy dissipation extremum is more suitable in heat transfer process optimization. Chen et al. [22–27] optimized heat exchanger, constructal problems of variable cross-section channel, "volume-point" heat conduction, and so on, with minimum entransy dissipation rate as optimization objective.

The power consumed in incompressible fluid flow is partly stemmed from the fluid viscosity reflecting frictional resistance and profile resistance, and partly from the momentum change. In order to reach a maximum amount of heat transfer without excessive power consumption, we can set minimum entransy dissipation as optimization objective and fixed power consumption as constraint condition in developing optimization method.

2. Convective heat transfer optimization

Based on the analogies between thermal and electrical conductions, Guo defined the entransy as half of the product of heat capacity and temperature:

$$E_{vh} = \frac{1}{2} Q_{vh} T \tag{1}$$

where T is temperature, Q_{vh} is heat capacity at constant volume in general. The entransy dissipation function which represents entransy dissipation per unit time and per unit volume was deduced as [15]:

$$\phi_h = \lambda(\nabla T)^2 \tag{2}$$

where λ is thermal conductivity, and ∇T is temperature gradient.

By setting entransy dissipation as optimization objective and viscous dissipation as constraint condition, optimization flow field equation for convective heat transfer was constructed by Meng [14] as:

$$\rho \boldsymbol{U} \cdot \nabla \boldsymbol{U} + \nabla p - \mu \nabla^2 \boldsymbol{U} - \left(\frac{\rho c_p}{2C_0} A \nabla T + \rho \boldsymbol{U} \cdot \nabla \boldsymbol{U} \right) = 0 \tag{3}$$

where μ is viscosity coefficient, $\boldsymbol{U}$ is velocity vector, ρ is fluid density, p is pressure, c_p is specific heat at constant pressure, C_0 is constant Lagrange multiplier. Scalar Lagrange multiplier A satisfies the following equation:

$$\rho c_p \boldsymbol{U} \cdot \nabla A + \lambda \nabla^2 A - \lambda \nabla^2 T = 0 \tag{4}$$

3. Optimized field equations

As we know that heat transfer enhancement is usually accompanied by an undesirable increase in flow resistance. So when dealing with problems of heat transfer enhancement, we need to take both thermal and flow resistances into consideration. As it is mentioned from above, entransy dissipation which can also be defined as entransy dissipation to represent the irreversibility of a heat transfer process, is a physical quantity to measure the loss of heat transfer capability, so we can use it to evaluate the intensity of convective heat transfer enhancement, which is expressed as [15]:

$$e_h = \lambda(\nabla T)^2 \tag{5}$$

The entransy dissipation can be regarded as an expression of the irreversibility of heat transfer process, which is similar as the entropy generation to that of thermodynamics process. Entransy always decreases in heat transfer process, while entropy always increases. The smaller the entransy dissipation, the smaller the temperature difference of the fluid is, and thereby the smaller the irreversibility of the heat transfer process is [28].

In the flow of incompressible fluid, the power consumption, partly from the fluid viscosity and partly from the momentum change, can be expressed as:

$$W_p = -\boldsymbol{U} \cdot \nabla p = \boldsymbol{U} \cdot [\rho(\boldsymbol{U} \cdot \nabla)\boldsymbol{U} - \mu \nabla^2 \boldsymbol{U}] \tag{6}$$

From Eq. (6), it can be seen that the power consumption is correlated with the velocity field, meanwhile heat transfer characteristics and thermal resistance of the fluid are correlated with the temperature field coupling with velocity distribution. Therefore, optimizing a convective heat transfer process is to find an optimal velocity field with fixed power consumption which satisfies minimum entransy dissipation leading to small thermal resistance. This is a typical problem of functional variational. Its deduction is described below.

(1) Optimization target: fluid velocity field
(2) Optimization objective: entransy dissipation extremum expressed as variation:

$$\delta \int_\Omega e_h dV = 0 \tag{7}$$

(3) Constraint conditions:

Fixed power consumption:

$$\int_\Omega W_p dV = const \tag{8}$$

Mass conservation of incompressible fluid:

$$\nabla \cdot \boldsymbol{U} = 0 \tag{9}$$