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Study on the consistency between field synergy principle and entransy dissipation extremum principle

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ABSTRACT

This paper is aiming at numerically demonstrating the interrelationship and consistency between field synergy principle (FSP) via the field synergy number (Fc) and the entransy dissipation extremum principle (EDEP). Numerical simulation is conducted by using the FLUENT software and the user defined function programs (UDF) for fin-and-tube surfaces (plain plate and slotted fins) and composite porous materials. The thermal boundary conditions include given heat flux and given surface temperature. The flow includes laminar and turbulent. The air properties may be constant or vary with temperature. Based on the numerical data the analyzed results from the FSP via Fc are totally consistent with the results analyzed by the EDEP for all the cases studied. Such consistency between the FSP and the entransy theory can be regarded as a kind of demonstration of the reliability and correctness of both the FSP and the entransy theory.

1. Introduction

The efficient utilization of energy is an important subject of researchers around the world. In all the process of natural energy utilization, about 80% involves thermal energy transmission. So, the efficiency of the thermal energy transmission plays an important role in determining the efficiency of the energy utilization.

In past decades, many enhancement technologies and physical mechanisms for improving heat transfer performance have been proposed and applied, such as constructing fin and ribs, imposing mechanical vibration, appending electromagnetic field, developing secondary flow and increasing turbulence intensity. However, as indicated in [1] there was lack of general theoretical analysis and guidance in the enhancing heat transfer process up to the end of last century.

In 1998, based on the energy equation of convective heat transfer, Guo et al. [2–5] proposed field synergy principle (FSP) for revealing the basic mechanism of enhancing convective heat transfer. For the reader's convenience, the major analysis processes of [2–5] are described as follows. For two-dimensional laminar boundary layer, the energy equation of convective heat transfer can be shown as

$$\rho c_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right) \tag{1}$$

Integrating Eq. (1) along the thermal boundary thickness and noting that at the outer boundary the fluid temperature gradient equals zero, yields:

$$\int_0^{\delta_t}\rho c_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)dy=-\lambda\frac{\partial T}{\partial y}\bigg|_w \tag{2}$$

where δ_t is the thermal boundary layer thickness. Noting that

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\vec{U}\cdot\nabla T \tag{3}$$

Following equation can be obtained:

$$\int_0^{\delta_t}\rho c_p(U\cdot\nabla T)dy=-\lambda\frac{\partial T}{\partial y}\bigg|_w \tag{4}$$

Through non-dimensional treatment, Eq. (4) can be transformed into

$$Nu_x=Re_xPr\int_0^1(\overline{U}\cdot\overline{\nabla T})d\overline{y}=Re_xPr\int_0^1(|\overline{U}|\cdot|\overline{\nabla T}|\cdot\cos\theta)d\overline{y} \tag{5}$$

where $\overline{U}=U/U_\infty$, $\overline{\nabla T}=\nabla T/[(T_\infty-T_w)/\delta_t]$, $\overline{y}=y/\delta$, $T_\infty>T_w$, and θ is the angle between velocity vector and temperature gradient (synergy angle).

Eqs. (4) or (5) is the math expression of the field synergy principle (FSP) which indicates that the intensity of heat transfer depends not only on the temperature difference between flow fluid and solid wall, flow velocity, but also on the intersection angle between velocity vector and fluid temperature gradient. There

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Nomenclature

T_h	temperature of hot porous plate (K)
T_c	temperature of cold porous plate (K)
V_w	fluid velocity perpendicular to porous plate ($m \cdot s^{-1}$)
Re	Reynolds number
Pr	Prandtl number
Nu	Nusselt number
ρ	density ($kg \cdot m^{-3}$)
c_p	specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)
T	temperature (K)
u	fluid velocity in the x direction ($m \cdot s^{-1}$)
v	fluid velocity in the y direction ($m \cdot s^{-1}$)
δ	thickness (m)
δ_t	thermal boundary layer thickness (m)
R	channel radius (m)
U	velocity vector ($m \cdot s^{-1}$)
$\overline{U}$	dimensionless velocity vector
$\overline{T}$	dimensionless temperature
$\overline{y}$	dimensionless direction vector y
θ	field synergy angle (°)
Φ_h	heat flux (W)
V	volume (m^3)
Fc	field synergy number
λ	conduction coefficient ($W \cdot m^{-1} \cdot K^{-1}$)
S	surface area (m^2)
a	thermal diffusion coefficient ($m^2 \cdot s^{-1}$)
a_t	thermal diffusion coefficient of the turbulence ($m^2 \cdot s^{-1}$)
Q	heat transfer rate (W)
h	heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
D	characteristic quantity (m)
$\overline{D}$	dimensionless characteristic quantity
$\overline{V}$	dimensionless volume
$\overline{\rho}$	dimensionless density
$\overline{c_p}$	dimensionless specific heat
l	characteristic length (m)
ν	kinematic viscosity ($m^2 \cdot s^{-1}$)
η	dynamic viscosity ($kg \cdot m^{-1} \cdot s^{-1}$)
q	heat flux density ($W \cdot m^{-2}$)
St	Stanton number
E	entransy ($W \cdot K$)
ΔE	entransy dissipation ($W \cdot K$)
ΔT_m	heat transfer temperature difference (K)
Δe	entransy flux dissipation ($W \cdot K \cdot m^{-2}$)
R_E	equivalent weighted thermal resistance ($K \cdot m^2 \cdot W^{-1}$)
A	area (m^2)
m	mass flux ($kg \cdot s^{-1}$)
d	mean cell size of the tetrakaidecahedron unit (m)
L_s	length of column framework in the tetrakaidecahedron unit (m)
d_s	diameter of column framework in the tetrakaidecahedron unit (m)
ε	porosity
Δp	pressure drop (Pa)

Subscript

w	wall
x	direction of vector x
∞	far-field region
a	air
m	mean value
E	entransy
p	per
tr	heat transfer
in	inlet of calculation area
out	outlet of calculation area

Superscript

he	heat exchanger
pm	porous material

are three scalars in the above equations: velocity absolute value, absolute value of temperature gradient and cosine of the angle between them. If three values are simultaneously large, the heat transfer process could be greatly strengthened.

Zhao and Song [6] conducted independently an experimental study where fluid velocity direction coincided with heat flux and obtained results of Nu proportional to RePr. This is the demonstration of the best synergy situation. In [7] it was demonstrated by numerical examples that the existing heat transfer enhancement mechanisms can be unified by FSP. Ma et al. [8] provided experimental results that when fluid flow velocity is normal to fluid temperature gradient flow velocity is nothing to do with heat transfer, and that is the worst situation of synergy. A great number of studies have been published to show the feasibility of FSP [9–13] or the applicability of FSP in guiding the design of enhanced structures [14–23].

In 2007 Guo and his co-workers [24] presented a new concept called entransy whose physical meaning is the ability of a body to transfer its internal energy to the environment. Due to the thermal resistance, this ability is reduced in the heat transfer process. In other words, the entransy is dissipated while thermal energy is conserved in the heat transfer process. Guo et al. [24] further proposed the entransy dissipation extremum principle (EDEP). There are the minimum entransy dissipation principle (MinEDP) and the maximum entransy dissipation principle (MaxEDP) in the EDEP. The MinEDP means that the temperature difference is the minimum when the entransy dissipation is the minimum in the given wall heat flux condition. The MaxEDP means that the heat flux is the maximum when the entransy dissipation is the maximum in the given wall temperature condition.

The EDEP indicates that when the entransy dissipation reaches the extremum the optimum heat transfer performance can be obtained for the above two boundary conditions. Since the proposal of this concept many studies have been conducted in different aspects of thermal science and engineering for optimization and performance improvement. For interesting readers references [25–41] can be consulted.

The present paper is concerned with the interrelationship between FSP and EDEP. What presented above for both FSP and EDEP can be used to guide convective heat transfer enhancement. One question may be naturally raised is that for the same problem when both theories are used are the results consistent? An intuitive consideration for FSP and EDEP leads to following conclusion that synergy between velocity vector and fluid temperature gradient should have inherent consistency with the dissipation of entransy. Up to now there are three related papers [42–44]. Before a brief review on the three papers, one thing should be mentioned, i.e., the indicator of synergy between velocity vector and fluid temperature gradient. As indicated in [4] for the indicator of the entire studied domain both the domain averaged synergy angle and the field synergy number can be used. These two indicators can clearly show how far the studied situation deviates from the ideal situa-