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Improvement in field synergy principle: More rigorous application, better results

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A R T I C L E I N F O

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A B S T R A C T

Basing on the original derivation of field synergy principle, we propose two rigorous rules for its applications with respect to incompressible flow in conventional-scale duct: (1) the synergy angle should be evaluated in the thermal boundary layer for laminar flow; (2) the FSP analysis must be refined to the viscous sublayer for turbulent flow in the strict sense. These two rules are verified by two specific computational fluid dynamics cases of forced convection in two-parallel plates with irregular boundary condition in laminar and turbulent flow regimes, respectively. By making elaborate post-processing, the local synergy angles in the very near-wall region are clearly visualized. It is found that the patterns of synergy angle distribution in laminar boundary layer/turbulent viscous sublayer are able to accurately reflect the local heat transfer ability, which provides an opportunity to directly visualize the local variation of convective heat transfer coefficient. Quantitative analysis also shows that the local Nusselt number variations are in perfect agreement with the local synergy angle variations according to the rules we proposed. This work also can be regarded as a verification for field synergy principle from a new aspect.

1. Introduction

In convective heat transfer problems, it is meaningful to understand the relationship between fluid flow and energy flow. However, convection takes place in the vicinity of the wall, which is difficult to be visualized. In 1998, Guo and his co-workers proposed the concept of field synergy principle (FSP) [1], which provided an opportunity to see the relationship between fluid flow and energy flow. The FSP emphasized the role that intersection angle between velocity vector and temperature gradient vector plays on the heat transfer performance. Here, we give a brief introduction of the FSP concept:

The derivation of FSP was started with the two-dimensional laminar-boundary-layer flow over flat plate [1]. The relevant energy equation is:

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

In FSP, convective heat transfer was regarded as heat conduction with heat sources between two plates. Thus, the integration of Eq. (1) over the thermal boundary layer yielded:

$$\rho c_p \int_0^{\delta_{t,x}} (U \cdot \nabla T)\, dy = -k\left.\frac{\partial T}{\partial y}\right|_w = q_w(x) \tag{2}$$

where $U \cdot \nabla T$ can be expressed as:

$$U \cdot \nabla T = |U||\nabla T| \cos\theta \tag{3}$$

Eqs. (2) and (3) indicated that convective heat transfer can be enhanced by reducing the intersection angle θ (also called "synergy angle"). Tao et al. [2] also summarized that the conventional explanations of the mechanism of enhancing single phase convective heat transfer, i.e., the decreasing of thermal boundary layer, the increasing of flow interruption and the increasing of velocity gradient near a solid wall, can be unified by FSP. Intrinsically, the intensity of single phase convective heat transfer depends on the synergy between the velocity and temperature fields. In other words, the FSP can directly demonstrate the intensity of convective heat transfer.

In the past dozen years, the FSP has been improved and extended to a much broader scope. Tao et al. [3] extended the FSP to the elliptic flow and heat transfer problems. Shen et al. [4] applied FSP to analyze the natural convection in unsaturated porous media. The applicability of FSP in turbulent flow were verified numerically [5,6]. Recently, the FSP has been extended to analyze compressible flow or heat transfer problem [7,8]. The FSP, as an analytical tool, were widely used to analyze the heat transfer intensity in a device or system and ultimately helping understand the heat transfer mechanism and in this way seeking to improve

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Nomenclature

c_p	specific heat capacity, J/(kg K)
C_μ	turbulent viscosity
D_h	hydraulic diameter, $2H$, m
G_κ	rate of turbulent kinetic energy
G_b	rate of buoyancy force
H	width between the two plates, m
k	thermal molecular diffusivity, W/(m k)
Nu	Nusselt number
Pr	Prandtl number
q	heat flux, kW/m^2
Re	Reynolds number, $\rho\|U\|D_h/\mu$
S_{ij}	strain rate tensor
T	temperature, K
u	velocity component in x-direction, m/s
U	velocity vector, m/s
$\|U\|$	velocity magnitude, m/s
v	velocity component in y-direction, m/s
x, y	Cartesian coordinate, m
$\tilde{y}$	scale factor, $y/(H/2)$

Greek symbols

γ	specific ratio
δ	thickness, m
ε	turbulent dissipation rate, m^2/s^2
ϵ_H	thermal eddy diffusivity, W/(m k)
θ	synergy angle, °
κ	turbulence kinetic energy, m^2/s^2
μ	dynamic viscosity, kg/(ms)
μ_t	turbulent molecular viscosity
σ_t	constant of turbulent Prandtl number
σ_κ	turbulent Prandtl numbers for κ
σ_ε	turbulent Prandtl numbers for ε
ρ	density, kg/m^3
Γ	diffusivity
∇	gradient

Subscripts

c	computational cell
f	fluid
t	thermal boundary layer
vsl	viscous sublayer
w	wall
x	x-direction
y	y-direction
0	*uniform boundary condition*

Averages

–	time-average

the heat transfer technique [9–27]. Generally, the FSP analysis was implemented in two manners: Either evaluating the overall average synergy angle in entire flow domain [9–21], or displaying the distribution contours of synergy angle in entire flow domain [11,22–27]. Particularly, Guo et al. [11] reviewed the state-of-art application of FSP as well as its contributions to the heat transfer enhancement techniques, wherein readers can get a glimpse of the conventionally analytical methods of FSP. Until now, the synergy angle analytical method still followed the conventional manner. For instance, Lotfi et al. [21] recently applied FSP to analyze the thermal performance of a novel type of vortex generators. They integrated the synergy angle in the entire computational domain. Hamid et al. [27] recently introduced FSP to interpret the turbulent heat transfer in a ribbed solar air heater by depicting the synergy angle distribution in the entire field. However, they did not show any relationships between the Nusselt number distribution and the calculated synergy angle contours.

As mentioned above, the FSP was derived basing on the heat equation of thermal boundary layer, as shown in Eqs. (1) and (2). However, in the latter application process, the synergy angle was always weighed or analyzed over the entire flow domain [9–27], which was not in accordance with the original derivation of FSP concept. This defect was questioned by Bejan [28], who pointed out that the synergy angle at the centerline of the straight duct was a paradox since the intense heat transfer was impossible to appear at duct centerline. Indeed, the analysis of synergy angle in the main stream region is pointless since the convection happens at the near wall region. Besides, from the paper review, we noticed that there was little work interested in the local average synergy angle distribution, as well as its relationship with the local heat transfer performance. The numerical study of Habchi et al. [29] indicated that the local synergy angle of the entire flow field was insufficient for local analysis of the heat transfer performance.

The present work aims to verify the feasibility of using FSP to precisely analyze and visualize the variation of local heat transfer in a two-dimensional duct caused by irregular thermal boundary condition. The flow is assumed to be incompressible with negligible viscous dissipation. To accord with the original derivation of FSP, we give insight into the synergy angle distribution in the vicinity of the wall by performing elaborate post-processing. The local synergy angle distribution and the local-average-weigh synergy angle in the thermal boundary layer/viscous sublayer are shown in detail, which are then compared with the local Nusselt number distribution.

2. Model and solution methodology

2.1. Model descriptions

The problem we considered is the hydrodynamically and thermally developed flow through two parallel plates with infinite depth, width of $H = 0.01$ m and total length of $100H$ as depicted in Fig. 1(a). As shown, the computation domain is segmented into two parts. The first 4/5 length duct is used for the development of flow while the last 1/5 length duct is the numerical test section. Due to the symmetrical configuration of the model, the calculation is reduced to one half of the domain. The grid structure is partially shown in Fig. 1(b). To simplify the model, several assumptions are made: (1) The flow is incompressible and in steady state; (2) The effects of viscosity dissipation and body force are neglected; (3) The effect of wall conduction is neglected.

Pure water is selected as the working fluid for the present study. The temperature-dependent properties of water are acquired from Ref [30].

2.2. Governing equations and numerical solution

We consider the fully developed flow in both laminar and turbulent flow regimes, under a specified Reynolds number of 200