International Communications in Heat and Mass Transfer 55 (2014) 29–37

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Unified field synergy and heatline visualization of forced convection with thermal asymmetries☆

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ARTICLE INFO

Available online 2 May 2014

Keywords:
Field synergy
Heatline
Thermal asymmetries

ABSTRACT

Forced convection between two parallel plates imposed with thermal asymmetric boundary condition is analyzed by employing a unified field synergy and heatline visualization technique. The heatline visualization is incorporated in the field synergy analysis through the introduction of an included angle between the heatline and the streamline, which is comparable to the well-established synergy angle of the field synergy principle. Inherently, both angles present the common intrinsic characteristics with each other. The heatline plot provides a more explicit visualization of heat flow in convection heat transfer compared to the isotherm plot, which is widely used in the existing field synergy study. Similar to the synergy angle, it is observed that the decrease of the included angle between the heatline and the streamline enhances the synergy between the heat and fluid flow, resulting in higher Nusselt number and field coordination number. The variations of the heat flux ratio induce changes on the field synergy of the flow due to the effects of thermal asymmetries, which concurrently alter the heatline patterns.

1. Introduction

Convection heat transfer is associated with the combined effects of transport phenomena involving fluid motion and heat conduction. The study of any convection heat transfer problem inherently involves the determination of the velocity and temperature distribution in the flow region under investigation. The nature of this field of study is relatively interesting compared to other two modes of heat transfer in the sense that there is a large variation of possible ways to enhance or weaken the internal energy transfer, which is regarded as convection heat transfer. The direction of the fluid velocity vector plays an important role in quantifying the heat transfer rate. Due to the fact that the presence of bulk fluid motion brings warmer and cooler chunks of fluid particles into contact, convection is non-existent if the direction of all the moving particles is along the isotherms and isothermal surfaces for two and three-dimensional flows, respectively. On the other hand, highest convective heat transport rate is obtained if the velocity vectors are perpendicular to the isotherms or isothermal surfaces. To obtain better physical understanding of this intuition, Guo et al. [1] utilized an analog between convection and conduction and proposed a novel concept called "field synergy principle." From the shrewd deduction of this concept, convection heat transfer enhancement can be achieved by reducing the intersection angle between the velocity vector and the temperature gradient, apart from the conventional understanding of increasing the Reynolds number and Prandtl number of the flow field. This concept was then further elaborated and improved by Guo and co-workers [2–4]. It has been shown that the reduction of intersection angle as a representation of energy transfer by convection is valid for both parabolic [4] and elliptic [3] flows. In the existing literature, numerical and experimental investigations have been conducted to verify the synergetic relation between the velocity field and the heat flux field, serving as an effective analytical tool in the design of heat transfer devices involving convection heat transfer [5–18].

Heatline concept is an essential breakthrough in convection heat transfer in providing coherent visualization of heat flow trajectories. The heat flow lines that are perpendicular to the isotherms are essential tool used to analyze and visualize heat flow of conduction heat transfer in isotropic media [19]. The sensible development of heat flow line into the heatline concept in convection heat transfer, through the introduction of the heat function, was first proposed by Kimura and Bejan [20] in 1980s. Heatlines represent the trajectories of heat flow in convection heat transfer, analogous to streamlines that provide an ideal bird's-eye view of a two-dimensional fluid flow domain. Heatline is mathematically represented by heat function of which the dimensionless form is intimately related to Nusselt number. To date, substantial studies of heatline visualization

☆ Communicated by W.J. Minkowycz.

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2014.04.003
0735-1933/

Nomenclature

A_c	cross-sectional area, m^2
c_p	specific heat, J · kg^{-1} · K
D	channel height, m
Fc	coordination number
H	heat function, W · m^{-1}
$\widetilde{H}$	dimensionless heat function
h	convection heat transfer coefficient, W · m^{-2} · K^{-1}
k	thermal conductivity, W · m^{-1} · K^{-1}
Nu	Nusselt number
Pe_D	Péclet number
q	constant wall heat flux, W · m^{-2}
T	temperature, K
$\overline{T}$	bulk mean temperature, K
U	dimensionless fluid velocity
u	fluid velocity, m · s^{-1}
$\overline{u}$	mean velocity of fluid, m · s^{-1}
X	dimensionless longitudinal coordinate
x	axial coordinate, m
Y	dimensionless transverse coordinate
y	transverse coordinate, m

Greek symbols

α	intersection angle between the heatline and the streamline, °
β	synergy angle, °
θ	dimensionless temperature
ρ	fluid density, kg · m^{-3}
Ψ	dimensionless stream function
ψ	stream function, m^2 · s^{-1}
Ω	heat flux ratio

Subscripts

1	of upper plate
2	of lower plate

and applications in convection heat transfer have been documented in the literature [21–40].

It is noted that both the synergy principle and the heatline concept are derived based on analogies between conduction and convection heat transfer; intuitively, they present common intrinsic characteristics with each other. To this end, the present study is motivated and aimed to incorporate the heatline visualization in the analysis of convective heat transfer employing the field synergy principle. All existing studies associated with the field synergy principle utilized plots of isotherms and streamlines of convective heat transfer for the visualization of the synergy angle, which is the intersection angle between the fluid flow velocity and the temperature gradient [1,2,4,12,13]. In the present study, for the first time, we propose the evaluation of the angle between heatline and streamline at a particular location in the two-dimensional domain, which is comparable to the synergy angle. The plots of heatlines and streamlines provide a more direct and better visualization method, as well as an alternative technique in identifying the degree of coordination between the fluid velocity and the temperature gradient, which contributes to the convective heat transfer enhancement. In addition, the effect of thermal asymmetries under the imposition of isoflux at the walls is investigated by the unified techniques of field synergy principle and heatline visualization.

2. Mathematical formulation

2.1. Temperature distribution

By assuming negligible body force and constant viscosity μ in an incompressible fluid flow, the vectorial notation of the momentum equation is given by

$$\rho(\mathbf{V}\cdot\nabla)\mathbf{V} = -\nabla P + \mu\nabla^2\mathbf{V}, \tag{1}$$

where $\mathbf{V}$ is the velocity vector, P the pressure, and ρ the fluid density. By neglecting the viscous dissipation and considering the fluid thermal conductivity k as constant, the vectorial notation of the energy equation can be expressed as

$$\rho c_p \mathbf{V}\cdot\nabla T = k\nabla^2 T, \tag{2}$$

where T is the fluid temperature and c_p the specific heat of the fluid. We consider a steady laminar Newtonian fluid flow with constant properties between fixed parallel plates distanced D apart, to be both hydro-dynamically and thermally fully developed. Also as depicted in Fig. 1, we consider flow between the two horizontal infinite parallel plates with fluid particles moving in x direction and there is no velocity in the y direction. By applying the continuity equation and imposing the no-slip condition, Eq. (1) is solved for two-dimensional steady flow with a constant pressure gradient in the xy-plane and the velocity profile is given by

$$u(y) = \frac{3\overline{u}}{2}\left[1-\left(\frac{y}{D/2}\right)^2\right]. \tag{3}$$

The mean velocity over the cross-sectional area of the channel is given by

$$\overline{u} = \frac{1}{D}\int_{-D/2}^{D/2} u\,dy. \tag{4}$$

For two-dimensional steady flow, the energy equation of Eq. (2) can be reduced to

$$\rho c_p u\frac{\partial T}{\partial x} = k\frac{\partial^2 T}{\partial y^2}. \tag{5}$$

Following the assumption of a thermally fully developed flow with uniformly heated boundary wall, the axial conduction term is absent in the energy equation as its contribution to the net energy transfer is negligible [40]. In this case, the temperature gradient along the axial direction is independent of the transverse direction and expressed as

$$\frac{\partial T}{\partial x} = \frac{d\overline{T}}{dx} = \frac{dT_1}{dx} = \frac{dT_2}{dx}, \tag{6}$$

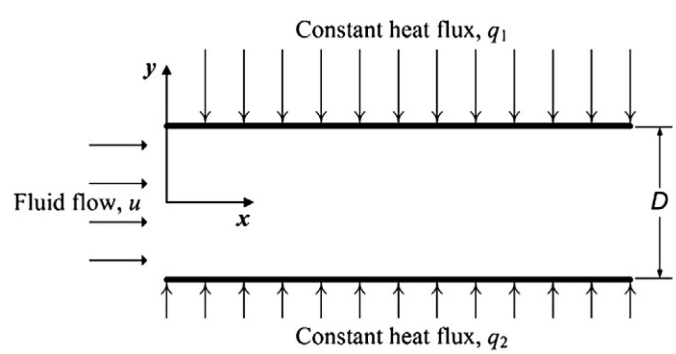

Fig. 1. Schematic diagram of the problem.