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Research Paper

Local field synergy analysis of conjugate heat transfer for different plane fin configurations

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HIGHLIGHTS

- Thermal performance enhancement of a plane fin by only modifying the solid fin.
- Exhaustive local analysis of field synergy principle in the thermal boundary layer.
- Local heat transfer in accord with the field synergy of regions close to the fin.

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ABSTRACT

The aim of the present study is to achieve conjugate heat transfer enhancement in a finned heat exchanger by only modifying the isotherms distribution in the fins. A three-dimensional numerical study of a flat plate and its geometric variants is therefore carried out for a steady incompressible laminar flow. The results are analyzed by carrying out an extensive analysis of the local field synergy which shows the effect of local velocity and local temperature gradient vectors on the heat transfer process. Depending upon the magnitudes of the field synergy parameters, in general, it is found that the local heat transfer coefficient is in accordance with the field synergy principle for the regions in the thermal boundary layer very close to the heated surface. Gain in thermal performance is obtained due to orientation of the velocity and the temperature gradient vectors in the same direction near the upstream fin modification as well as due to the enhancement of the modulus of the inner product of velocity and temperature gradient. For one of the tested configurations, the results show an increase of 7% of *PEC* associated with about 14.4% less aluminum material used.

1. Introduction

Heat transfer enhancement for heat exchangers stems from increasing constraints of less cost, smaller size, reduced pumping power, lesser material and high heat transfer capacity. Depending upon the need of the user, an enhanced heat exchanger configuration can mean physical size reduction of the heat exchanger for a given heat duty, operation at lower temperature difference for fixed heat duty and fixed size, increased heat transfer rate for the same size and similar temperature conditions and low frictional losses for a fixed heat duty [1]. Heat transfer enhancement methods can be mainly classified into active and passive methods: the active methods are those which need a power source for their operation while the passive methods are those which do not require an external power source for their operation [1]. Active and passive methods for heat transfer enhancement applied to industrial heat exchangers have been widely studied and have produced improvements of heat transfer efficiency in a myriad of heat exchanger configurations [1–3]. Siddique et al. [2] gave a summary of the mechanisms behind heat transfer enhancement, such as enhanced mixing due to secondary flows, reduced thermal resistance due to boundary layer thinning, increased temperature difference between solid and the fluid media, changes in the separation/attachment behaviour of the boundary layers, etc. In order to explain the physical mechanism of conjugate heat transfer enhancement from a different perspective, Guo et al. [4] proposed Field Synergy Principle (*FSP*) to quantify the convection heat transfer by relating the velocity and temperature gradient fields. Tao et al. [5] stated that for a single phase convective heat transfer, the field synergy principle could be used to unify three known

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Nomenclature

Principle notations

A	heat transfer area (m^2)
c_p	specific heat capacity at constant pressure ($J\,kg^{-1}\,K^{-1}$)
Ci	geometric configurations, ($i = 0, 1, 2$) ($-$)
D_h	hydraulic diameter (m)
f	friction factor, $\frac{2\Delta P}{(\rho U_m^2 L_c/D_h)}$ ($-$)
g	acceleration due to gravity (ms^{-2})
Gr	Grashof number, $\frac{\beta g \rho^2 \Delta T L_c^3}{\mu^2}$ ($-$)
h	heat transfer coefficient, $\frac{Q}{A\Delta T}$ ($W\,m^{-2}\,K^{-1}$)
H and $tb/2$	height and half thickness of the mounting walls/base surface (m)
j	Colburn factor, $StPr^{2/3}$ ($-$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
L_c	characteristic length (m)
L, W and tf	length, breadth and thickness of the fins (m)
Lp and Wp	length and breadth of the punch (m)
Nu	Nusselt number, $\frac{hD_h}{k}$ ($-$)
P	static pressure (Pa)
Pr	Prandtl number, $\frac{\mu c_p}{k}$ ($-$)
Q	heat transfer rate (W)
q	heat flux ($kW\,m^{-2}$)
$\dot{q}$	heat flux ($W\,m^{-3}$)
$R1, R2$	region 1 and region 2 ($-$)
Re	Reynolds number, $\frac{\rho U_m D_h}{\mu}$ ($-$)
St	Stanton number, $\frac{h}{\rho U_m c_p}$ ($-$)
T	temperature (K)
$\vec{U}$	velocity vector (ms^{-1})
u, v and w	velocity components along x, y and z respectively (ms^{-1})
x, y and z	cartesian coordinates (m)
X^*, Y^* and Z^*	normalized cartesian coordinates ($-$)
X^{**}	modified normalized coordinate X^* ($-$)

Greek symbols

μ	dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
δ	thermal boundary layer ($-$)
ρ	density ($kg\,m^{-3}$)
θ	synergy angle (deg)
β	coefficient of thermal expansion (K^{-1})

Abbreviations

FSP	Field synergy principle
PEC	Performance evaluation criteria, $\frac{(j/j_o)}{(f/f_o)^{1/3}}$

Subscripts

m	average
o	reference geometry
w	wall
x	local values
∞	free stream conditions

enhancement mechanisms which are: (1) decreasing the thermal boundary layer thickness, (2) increasing the flow interruption and (3) increasing the velocity gradient near the wall. A comprehension of heat transfer mechanism which can unify the known methods of heat transfer enhancement is of significant importance so as to scientifically design heat exchangers with enhanced performance.

One of the principle postulate of the *FSP* is that the synergy between the velocity and temperature gradient fields or, in other words, the included angle between these parameters is also an important factor to ascertain the degree of the heat transfer enhancement. Since its introduction, several researchers have used this concept in different ways such as: verification studies [6], correlation between Nusselt number and field synergy principle for variety of configurations namely: a discrete parallel duct, discrete staggered plates, two-dimensional wavy channel, corrugated duct [7], circular tube [8–12], fin-and-tube heat exchangers [13,14], shell-and-tube heat exchanger [15,16], vortex generators [14,17–21] to [21] and fins [22,23]. Subsequent to its introduction, several developments were made in *FSP* which contributed to widen its scope [7,9,24–27].

Several studies have been performed on the utilisation of *FSP* to charaterize heat transfer enhancement, but the major part of these studies was dedicated to either analyze synergy angles over the entire computational domain resulting in volumetric average values of synergy angles, and/or did not include the synergy modulus in the analysis. Simple average values of the thermal quantities and synergy angles do not give the actual picture of flow dynamics, thermal field and the underlying physics in heat transfer enhancement which is actually very local. Recently, several researchers have focused on the points mentioned above. Saha et al. [20] asserted that favourable conditions for heat transfer enhancement are given by small synergy angles values combined with large synergy modulus. The importance of local synergy analysis and of including the scalar product of velocity and temperature gradient in the analysis was also highlighted by Habchi et al. [19] in their study of turbulent flow for different configurations of vortex generators. Bejan [28] notes that in a multi-dimensional flow the local angles between heat flux lines and streamlines are not accessible for a designer to obtain an enhancement in heat exchange. Recently, Zhu and Zhao [29] compared local Nusselt numbers with local synergy angles in near wall regions for laminar and turbulent boundary layers for forced convection between two parallel plates. They concluded that the variation of the local Nusselt number inside the thermal boundary layer for a laminar flow is in accordance with *FSP*. However, for a turbulent flow, it was noted that *FSP* is only available in the viscous sub layer of the turbulent boundary layer because of negligible eddy viscosity in that region. Keeping in mind these significant developments in the latest literature concerning a local analysis of synergy, it is important to find a relation between heat transfer enhancement and the local flow and local temperature fields for a better application of field synergy principle.

The aim of this study is to achieve heat transfer enhancement in a model of plate fin heat exchanger by simply modifying the fin. This means modifying the isotherm distribution in the base configuration and modification of the main flow due to the geometric change. The objective is to achieve improvement in thermal and hydrodynamic performance solely based on geometric changes in the fin or in other words, without external addition of secondary flows, i.e., for example, without adding artificial vortices by vortex generators. To this end, a plate fin is considered as a base case and two geometrically modified configurations of the base geometry are numerically studied to analyze their global thermal performances and friction losses. An exhaustive post processing is then carried out to locally analyze the flow and temperature gradient fields in relation to local field synergy principle to find a correlation between heat transfer and field synergy principle for the modified configurations in relation to the base configuration.