International Journal of Heat and Mass Transfer 82 (2015) 373–387

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Optimization of winglet-type vortex generator positions and angles in plate-fin compact heat exchanger: Response Surface Methodology and Direct Optimization

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ARTICLE INFO

Article history:
Received 1 April 2014
Received in revised form 29 October 2014
Accepted 31 October 2014
Available online 6 December 2014

Keywords:
Heat transfer enhancement
Optimization
Vortex generator
Genetic Algorithm

ABSTRACT

Augmentation of heat transfer has been an important research topic for many years. Although many heat transfer enhancement techniques have been proposed over the years, few researches deal with thermal optimization considering vortex generators (VG). This work is related to optimization of VG position and angles in a fin-tube compact heat exchanger using the Genetic Algorithm (GA). Two approaches were evaluated: Response Surface Methodology (RSM) applying Neural Networking method, and Direct Optimization (DO). Numerical analyses based on the finite-volume methodology was performed to analyze heat transfer and pressure drop of a fin-tube heat exchanger with two row of tubes in staggered tube arrangement applying two delta winglet type longitudinal vortex generators with aspect ratio 2. Turbulent flow simulation was performed for Reynolds number 1400 (based on fin pitch). Four vortex generator parameters which impact heat exchanger performance were analyzed: longitudinal vortex generator position in x–y directions, attack angle (θ) and roll angle (φ). The present work is the first to study the influence of VG roll angle on heat transfer enhancement. Therefore, eight independent input parameters were considered, four VG parameters for each tube. Four performance evaluation criteria (PEC) based on Colburn factor (j) and Friction factor (f) were chosen as objective function. The optimized VG configurations led to heat transfer enhancement rates higher than reported in the literature. Direct Optimization reported better results than Response Surface Methodology for all objective functions. Important flow interactions were found between vortices generated by VG1 and VG2, which influenced the results of Colburn factor (j) and Friction factor (f). The best results for each objective functions were achieved when VG1 was not symmetrical to VG2. Regarding global pressure drop, VG1 does not contribute to its mitigation, whereas VG2 is very important to flow separation delay in tube 2. The main contribution of VG1 is to increase the heat transfer rate, whereas VG2 increases the heat transfer rate and decreases the pressure drop. Roll angle has a strong influence on friction factor (f), especially for VG1.

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1. Introduction

Several applications in the automotive and chemical industries, residential air-conditioning and refrigeration have used compact heat exchangers (CHE). According to an estimation of the US Department of Energy, air-conditioning and heating ventilation systems have accounted for 55% of the energy used in residential buildings and 45% in commercial buildings around the world [1]. Heat transfer enhancement has gained interest for developing CHE to meet the need of high efficiency and low cost. Many investigations have been carried out in this area since the 1960s [2]. The main thermal resistance in a solid–fluid interaction results from the formation of the boundary layer, and efforts towards heat transfer enhancement should be directed to artificially interrupting or disturbing the boundary layer.

Convective heat transfer enhancement is accomplished by active or passive methods. The active methods require additional external energy, such as electric or ultrasonic fields, vibrating surfaces, etc. The passive techniques generate main flow destabilization and disturbance of the boundary layer. Vortex generators (VGs) are recognized as passive enhancement techniques that have shown good results for heating, ventilation, air-conditioning and refrigeration applications. In this passive technique, the heat transfer surface is modified to intentionally introduce secondary vortices that are carried through the main flow [3–5]. Although

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.10.072
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Nomenclature

A_c	minimum free flow area (m^2)
A_o	total flow area (m^2)
c_p	specific heat (J/kg K)
D_o	tube diameter (m)
e_{mean}	mean relative error (%)
e_{max}	maximum relative error (%)
F_p	fin pitch (m)
h	heat transfer coefficient (W/m^2 K)
L	depth of the CHE (m)
$\dot{m}$	mass flow rate (kg/s)
N	number of tube row
$N_{training}$	number of NN training data
N_i	number of input variable
P_L	longitudinal pitch (m)
P_T	transverse pitch (m)
Q	heat transfer (W)
R^2	regression
r	radius (m)
T	temperature (K)
U	velocity component (m/s)
U_c	velocity at inlet domain (m/s)
x	position in x-direction (mm)
y	Position in y-direction (mm)
ΔP	pressure drop (Pa)
ΔT	temperature difference (K)

Dimensionless numbers

f	Friction factor
j	Colburn factor
Pr	Prandtl number
Re	Reynolds number

Greek symbols

δ	fin thickness (mm)
ϕ	generic output
$\bar{\phi}$	generic output mean
$\tilde{\phi}$	generic output by surrogate model
φ	roll angle (°)
λ	thermal conductivity (W/m K)
μ	dynamic viscosity (kg/m s)
θ	attack angle (°)
ρ	density (kg/m^3)

Subscripts

in	inlet
f	fin
out	outlet
ln	logarithmic mean
o	reference to fin-tube
t	tube
W	wall
1	related to tube and VG 1
2	related to tube and VG 2

the surface area of the heat transfer may not be changed before and after the setup of VGs, the fluid flow dynamic can be strongly disturbed due to vortices generated by VG when a fluid flows over it. In the conventional point of view, VG not only disturbs the flow field and disrupts the growth of the boundary layer, but also causes fluid swirling and a intense exchange of core and wall fluid, leading to the enhancement of heat transfer. For the present study, vortex generator of type delta-winglets were adopted, which produce heat transfer enhancement with small pressure drop in comparison to other VGs types [5–7].

According to Yanagihara and Torii [8], three types of longitudinal vortices can be generated by a delta-winglet VG: *Main vortex*, formed due to flow separation at the tip of the delta-winglet and rolling up due to the lower pressure behind the vortex generator, which results in detached shear layers; *Corner vortex*, vortices generated in the corner between the front side of the delta-winglet and the plate, and *Induced vortex*, created between the main and corner vortices. Additionally to those longitudinal vortices, another type of vortical structure can be generated when a fluid flows through a tube, which is called *horseshoe vortex*, also known as a longitudinal vortices. The main characteristic of horseshoe vortexes is that they generate high heat transfer in front of the tube. However, the heat transfer behind the tube is poor due to the flow recirculation in the wake zone.

1.1. Background on augmentation heat transfer in CHE

He et al. [9] studied the heat transfer enhancement on fin-tube exchanger with punched delta-winglet vortex generator in different arrays, the Reynolds number varying between 600 and 2600. They investigated the effects of the attack angle and the VG locations. They concluded that the heat transfer and pressure drop increased with the attack angle. Lemouedda et al. [10] investigated the optimal attack angle of the delta-winglet VG based on the Pareto optimal strategy. The optimization process combined Computational Fluid Dynamics (CFD) analysis, Genetic Algorithms (GA) and the Response Surface Methodology (RSM). The attack angle of a pair of delta-winglet VGs mounted behind each tube varied between −90° and +90° for three circular tube rows considering inline and staggered arrangements for Reynolds numbers between 200 and 1200. For different attack angles, the configuration is either common-flow-down or common-flow-up arrangement. For the inline arrangement, the common-flow-down arrangement was found to be more suitable than the common-flow-up for trade-off heat transfer and pressure drop. The staggered arrangement was found to be better than the inline one for both cases with and without winglets. Still, the researchers pointed out the benefit of the optimization process that could be applied to other kinds of engineering applications with large design space. Numerical studies about the effect of delta-winglet VG (aspect ratio from 1 to 4 and the attack angles between 10° and 50°) on hydrodynamics and heat transfer of a CHE were performed by Lei et al. [5] for Reynolds numbers between 600 and 2600 considering a CHE of two tube rows in staggered arrangement. Both heat transfer coefficient and friction factor showed a growth trend with the increase of the attack angle. The impact of the aspect ratio was evaluated for an unchanged attack angle (20°), and the heat transfer coefficient increased slightly with the growth of aspect ratio. The results for Colburn factor showed an increasing trend with the growth of aspect ratio for the same Reynolds number. The relation between heat transfer and pressure loss was higher for aspect ratio 2. In our work, the aspect ratio was fixed to 2, based on the conclusions provided by Lei et al. [5]. Experimental work by Pesteei et al. [11] aimed at determining the best position of the delta winglet pairs in CHE. The study was carried out by evaluating the local heat transfer coefficient and flow pressure loss in a channel built by parallel

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