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Effects of delta winglet vortex generators on flow of air over in-line tube bank: A new empirical correlation for heat transfer prediction☆

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ABSTRACT

The present work performs an experimental study addressing the effects of delta winglet vortex generators on convective heat transfer rate at in-line tube bank in external cross flow. The main goal of the work is to evaluate a study assessing the influences of the following parameters on convective heat transfer enhancement: the distance from the vortex generators to the tube bank, the pitch and the incidence angle of the delta winglet, as well as the free-stream velocity inside the wind tunnel (Reynolds number). The validation of the experimental methodology employed was performed by comparing the present results with empiric correlations available in the literature. The main results indicate that Nusselt number was enhanced when using turbulence promoters, being the maximum increment around 30%. Otherwise, the pressure drop through the tube bank was enhanced accordingly, being the maximum increment around 40%. Finally, it is worth mentioning that all the experimental results for the Nusselt number were condensed in a new empirical correlation for practical applications with good accuracy (maximum error around $\pm 6.0\%$).

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1. Introduction

There are several techniques commonly used to increase the heat transfer rate by improving thermal contact between the heat exchanger fluid and wall. The most common methods typically manipulate the surface, including its roughness, use of coiled tubes and vortex generators [1–9]. Vortex generators are solid objects that obstruct the flow causing flow separation (interrupt the boundary layer development) leading to an enhancement of the heat transfer rate [5]. Different vortex generators have been proposed in the literature, being the most common the cubical and delta winglets [1]. Apart from enhancing the heat transfer rate, the insertion of the vortex generators also produces substantial increase in pressure drop [5].

In recent years, several investigations have been made to examine the effects of the parameters of vortex generators on heat transfer and friction factor behaviours. Focusing only on experimental works (with interesting practical applications) that make use of vortex generators, one finds the following: (i) Gunes et al. [2] studied the effects of turbulence promoters in a channel flow; the main findings indicate that a triangular promoter produces a maximum increment of around 35% on the local convective heat transfer coefficient. (ii) Chompookhan et al. [3] analyzed the effects of wedge ribs and winglet type vortex generators on convection heat transfer rate and friction loss behaviours in a channel; the main results indicate increments around 20% on the Nusselt number when the wedge rib promoter was used. (iii) Promvonge et al. [4,5] studied experimentally the turbulent heat transfer characteristics in a square duct fitted both with angle finned-tape promoters [4] and combined twisted tape/winglet vortex generators [5]; the experimental results indicate that smaller fin pitch spacing provides the highest heat transfer rates. Besides, the application of combined (twisted tape/winglet) vortex generators gives thermal performance around 17% higher than the twisted tape alone. (iv) Allison and Dally [6] investigated experimentally the effects of the delta winglet vortex generators on the performance of a heat exchanger; it was found by the authors that a delta angle of 39^0 gave the best flow structure. (v) Eiamsa-ard et al. [7] investigated experimentally the effects on flow friction and thermal performance of the oblique/straight delta winglet twisted tape arrangements; the author's results show that mean Nusselt number and friction factor in the tube with delta winglet twisted tape increase with decreasing twisted ratio; Finally, new empirical correlations for predicting Nusselt number and friction factor have been developed by the authors. (vi) Caliskan [8] studied experimentally the channel flow with punched triangular and rectangular vortex generators; the presence of the vortex generators produced higher heat transfer coefficients than the smooth plate surfaces, being all the results compiled in a new correlation for the average Nusselt number. (vii) Li et al. [9] analyzed numerically and experimentally the thermal-fluid characteristics of a heat sink with a pair of delta winglet vortex generators installed in a cross flow channel; the results obtained by the authors indicate that an attack angle of 30^o is preferred to optimise both the thermal resistance and pressure drop.

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Nomenclature

A_s	heaters surface area (m^2)
B	length of the delta winglet (m)
D	diameter of the cylindrical heaters (m)
$\overline{h}_{conv}$	average convective heat transfer coefficient (W/m^2K)
H	height of the delta winglet (m)
k	molecular thermal conductivity (W/mK)
L	length of the cylindrical heaters (m)
L_{pc}	distance from the vortex generators to the tube bank (m)
$\overline{Nu}_D$	average Nusselt number, $\overline{\mathrm{Nu}}_D = \frac{\overline{h}_{conv}D}{k}$
N_L	rows of tubes ( )
P_{el}	electric power input (W)
P	pitch of the delta winglet (m)
p	static pressure (Pa)
q_{conv}	convection heat transfer rate (W)
q_{rad}	thermal radiation heat transfer rate (W)
R_{el}	electric resistance of the heaters (Ω)
$\mathrm{Re}_{D,\max}$	Reynolds number based in the maximum velocity in the tube bank, $\mathrm{Re}_{D,\max} = \frac{\rho V_{\max} D}{\mu}$
S_L	longitudinal pitch of the tube bank arrangement (m)
S_T	transverse pitch of the tube bank arrangement (m)
T_∞	free-stream temperature (K)
$\overline{T}_s$	average temperature of the heaters surface (K)
U_∞	free-stream velocity in the wind tunnel (m/s)
V	electric voltage (V)
V_{max}	maximum velocity in the tube bank (m/s)

Greek Letters

ε	surface thermal emissivity ( )
σ	Stefan–Boltzman constant ($W/m^2\ K^4$)
α	incidence angle of the delta winglet (rad)
ρ	specific mass (kg/m^3)
μ	molecular dynamic viscosity (Ns/m^2)
Δp	pressure drop (Pa)

Finally, in order to conclude the introduction section, it is worth to mention that developing more efficient thermal systems is one of the research areas of the present authors. Some previous author's results dealing with applications of turbulence promoters in thermal systems may be found in Zdanski et al. [10]. Besides, it is important to emphasise that most literature works dealing with turbulence promoters (vortex generators) are focused on assessing their effects in finned surfaces of heat exchangers and heat sinks. Otherwise, to the best author's knowledge little attention is devoted on applying vortex generators in the flow over tube bank without fins (where the external flow layers are mixed and highly three-dimensional). Within this framework, the main focus of the present work was to study experimentally the effects of delta winglet vortex generators on convective heat transfer enhancement at in-line tube bank arrangement. The main results indicate a maximum increment around 30% in the global Nusselt number, whereas the pressure drop through the tube bank was enhanced around 40%. Most importantly, it was found that all the experimental results for the global Nusselt number collapse in a new empirical correlation for heat transfer prediction with good accuracy (maximum error around ±6.0%).

2. Experimental setup and procedure

The experimental setup used in the present work is showed in Figs. 1 and 2. The tube bank is composed of six cylindrical heaters positioned inside the test section of the wind tunnel on the Teflon support, being the winglet vortex generators placed upstream (see Fig. 1). The in-line arrangement is used, being the cylinders positioned in two rows and three columns. An open circuit wind tunnel of the suction type (range of velocities 4.0–15.0 m/s) was used to accomplishes the experiments. The wind tunnel contraction ratio is 1:6 with a test section of 25 cm × 25cm, being the turbulence intensity of the oncoming flow in the empty test section less than 1%.

The main purpose of the present experimental work was to evaluate the average convective heat transfer coefficient, and accordingly the global Nusselt number. Therefore, according to the Newton's law of cooling one finds [11]

$$\overline{h}_{conv} = \frac{q_{conv}}{A_s\left(\overline{T}_s - T_\infty\right)}, \tag{1}$$

$$\overline{Nu}_D = \frac{\overline{h}_{conv}D}{k}, \tag{2}$$

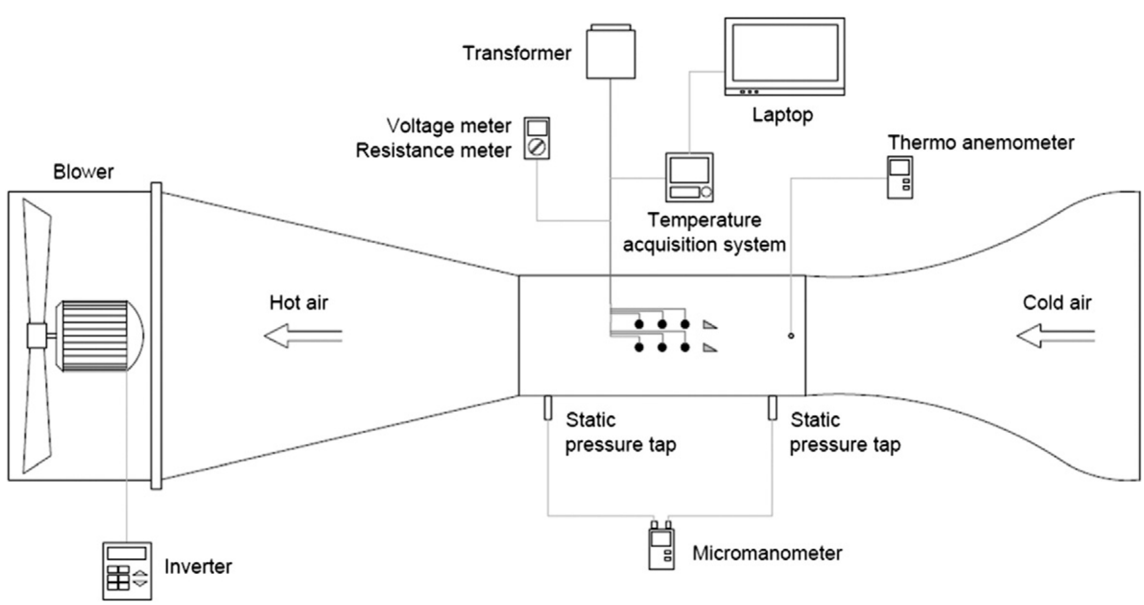

Fig. 1. Illustration of the experimental apparatus.

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