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Experimental study on heat transfer in square duct with combined twisted-tape and winglet vortex generators☆

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ABSTRACT

The article presents an experimental investigation on thermal performance enhancement in a constant heat-fluxed square duct fitted with combined twisted-tape and winglet vortex generators. The experiments are carried out for the airflow rate through the tested square duct fitted with both the vortex generators for Reynolds number from 4000 to 30,000. The effect of the combined twisted tape and rectangular winglet inserts on heat transfer and pressure drop presented in terms of respective Nusselt number and friction factor is experimentally investigated. The characteristics of the combined twisted-tape and winglet include two twist ratios ($Y = 4$ and 5), three winglet- to duct-height ratios, ($R_B = 0.1$, 0.15 and 0.2), four winglet-pitch to tape-width ratios, ($R_P = 2$, 2.5, 4 and 5) and a single attack angle of winglet, $\alpha = 30°$. The experimental results reveal that the Nusselt number and friction factor for the combined twisted-tape and V-winglet increase with increasing R_B but decreasing R_P. The inserted duct at $R_B = 0.2$, $R_P = 2$ and $Y = 4$ provides the highest heat transfer rate and friction factor but the one at $R_B = 0.1$, $R_P = 2$ and $Y = 4$ yields the highest thermal performance. The application of combined vortex-flow devices gives thermal performance around 17% higher than the twisted tape alone.

1. Introduction

Many engineering techniques have been devised for enhancing the rate of convective heat transfer from the wall surface. One of the popular passive techniques for increasing thermal performance in cooling/heating duct systems is the application of vortex generators such as fins, baffles, ribs, twisted tapes, wire coils, winglets, etc. to thin or interrupt the boundary layer development in such ducts. Apart from enhancing the heat transfer rate, the insertion of the vortex generators also yields the substantial increase in pressure drop. Therefore, to achieve optimal thermal performance the pertinent parameters of the vortex generators are to be considered such as the blockage height, pitch spacing and angle of attack.

Several investigations have been made to examine the effect of the parameters of vortex generators on heat transfer and friction factor behaviors in tubes/ducts. Promvonge et al. [1,2] investigated experimentally and numerically the turbulent convection heat transfer in a square duct inserted diagonally with 30° angle-finned tapes. They indicated that the finned tapes with smaller fin pitch yielded the highest heat transfer and friction factor and the thermal performance for the finned-tape insert was much higher than that of the wire-coil/twisted-tape acting alone. Eiamsa-ard et al. [3] studied the influence of using the tandem wire-coil element inserts on thermal behaviors in a square duct and reported that the heat transfer and friction factor characteristics for the full-length wire-coil were higher than those for the tandem wire-coil elements. Promvonge et al. [4] examined numerically the heat transfer enhancement of turbulent flow through a square duct fitted with inline 60° discrete V-ribs on two opposite duct walls. Chompookham et al. [5] reported the application of combined ribs and winglet vortex generators (WVGs) to increase the heat transfer rate in a channel. They found that the heat transfer and flow friction behaviors for using the ribs in common with the WVGs were much higher than those for the ribs or the WVGs alone. Sri Harsha et al. [6] and Gupta et al. [7] investigated the local Nusselt number distribution and friction loss in a square duct fitted with various ribs and reported that the heat transfer augmentation by the 60° V-discrete ribs was higher than that by the 90° continuous and profiled ribs. Tanda [8] studied the heat transfer and flow friction characteristics in a rectangular duct by using the transverse, discrete ribs; angled, angled discrete ribs; V-shaped, V-shaped discrete ribs and parallel discrete ribs. Chandra et al. [9] conducted an experiment on the heat transfer rate and friction loss in a square channel fitted with continuous ribs placed on four channel walls and found the heat transfer augmentation rose with the increase in the number of ribbed walls. Murata and Mochizuki [10] examined the laminar and turbulent heat transfer distribution in a square duct with transverse or angled rib turbulators. Han et al. [11,12] carried out experiments on the heat transfer augmentation in a square channel with parallel, crossed, and V-shaped angled ribs on two opposite walls. Lau et al. [13] proposed the use of V-shaped rib arrays to increase the

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Nomenclature

A	convection heat transfer area of duct, m^2
A_c	cross-sectional area, m^2
C_p	specific heat capacity of air, J/kgK
D_h	hydraulic diameter of duct (=H), m
e	winglet height, m
f	friction factor
H	duct height, m
h	average heat transfer coefficient, W/m^2K
k	thermal conductivity of air, W/mK
L	length of test duct, m
$\dot{m}$	mass flow rate of air, kg/s
Nu	Nusselt number
P	winglet pitch spacing, m
P_w	wetted perimeter of cross-section, m
ΔP	pressure drop, Pa
Pr	Prandtl number
R_B	winglet blockage ratio, e/H
Re	Reynolds number
R_P	winglet pitch ratio, P/w
Q	heat transfer, W
T	temperature, K
TT	twisted tape
t	thickness of winglet, m
U	mean velocity, m/s
w	tape width, m
Y	twist ratio, y/w
y	pitch length of twisted tape (180° rotation), m

Greek letters

α	attack angle of winglet, °
η	thermal enhancement factor, $(Nu/Nu_0)/(f/f_0)^{1/3}$
ν	kinematics viscosity, m^2/s
ρ	density of air, kg/m^3

Subscripts

b	bulk
0	smooth duct
conv	convection
i	inlet
o	outlet
bp	blowing power
s	duct surface

heat transfer rate of fully turbulent developed flow through a square channel.

For twisted-tapes (TT), several modified twisted tapes were presented with different types by targeting the increase in the heat transfer rate rather than the decrease of pressure loss due to low flow resistance of itself, for example, the perforated/serrated/jagged/broken twisted tapes and so on. Nanan et al. [14] and Eiamsa-ard et al. [15] reported the application of helical twisted-tapes can help increase the thermal performance in a circular tube at around 10–15% higher than that of twisted-tapes alone. Thianpong et al. [16] studied experimentally the use of twisted-rings to promote the heat transfer rate in a round tube and found that the heat transfer and friction factor tend to increase with increasing width ratio but with decreasing pitch ratio. Eiamsa-ard and Seemawute [17] examined experimentally and numerically the local heat transfer and friction behaviors in a circular tube inserted with short-length twisted tapes. Wongcharee and Eiamsa-ard [18] investigated thermal characteristics in a round tube with the insertion of twisted tapes with alternate-axes and triangular, rectangular and trapezoidal wings. Eiamsa-ard [19] carried out a measurement to examine the influence of multiple TT vortex generators on the heat transfer and fluid friction characteristics in turbulent channel flow. Eiamsa-ard et al. [20–22] studied the thermal performance enhancement in a round tube with short-length twisted tape, delta-winglet-cut twisted tape and peripherally-cut twisted tape inserts and indicated that the winglet-cut twisted tape provided higher thermal performance and the peripherally-cut twisted tape produced more turbulence around the tube wall than the typical one. Rahimi et al. [23] experimentally and numerically investigated on heat transfer and friction factor characteristics in a tube with modified twisted tapes and concluded that the jagged twisted tape insert provides the highest thermal performance. Chang et al. [24,25] examined the turbulent heat transfer and pressure drop in a tube with serrated and broken twisted tapes. Eiamsa-ard and Promvonge [26] found that the heat transfer rate in a tube can be increased by serrated twisted tape inserts.

For twisted tapes in conjunction with other vortex generators, Promvonge et al. [27] investigated the turbulent convective heat transfer characteristics in a helical-ribbed tube fitted with twin twisted tapes and found that the co-swirling inserted tube performs much better than the ribbed/smooth tube alone. Eiamsa-ard et al. [28] examined thermal performance behaviors in a tube fitted with the combined devices between the twisted tape and constant/periodically varying wire coil pitch ratio. Promvonge and Eiamsa-ard [29] investigated experimentally the heat transfer and friction factor characteristics in a circular tube fitted with conical-ring and twisted-tape swirl generator. Bharadwaj et al. [30] studied experimentally the friction factor and heat transfer characteristics of water flow in a 75-start spirally grooved tube with twisted-tape inserts. Ray and Date [31] presented numerical prediction of characteristics of laminar and turbulent flow and heat transfer in a square duct with twisted tape inserts.

Most of the literature review above reveal that typical or modified twisted-tape vortex generators are often used in circular tubes to intensify fluid mixing between the central-core and the wall regions while fin/baffle/rib/winglet vortex generators are always employed in ducts/channels or flat surfaces to increase the degree of turbulence intensity. The combined twisted-tape and V-winglet has never been reported in the literature. In general, the twisted-tape vortex generator has low flow resistance and ease in manufacturing but lower vortex strength leading to lower thermal performance while the winglet vortex generator is superior to thermal performance due to the lowest penalty of pressure drop. Therefore, with consideration of the merits of both the vortex generators, a newly designed enhancement device by integrating the V-winglet into the twisted-tape is proposed and expected to provide higher swirl/vortex strength or turbulence intensity at the near-wall region from the V-winglet and stronger fluid mixing by transporting the fluid in the central-core to the near-wall regimes from using the twisted-tape and thus, improve heat transfer rate in the duct surface.

2. Experimental setup

2.1. Apparatus and vortex generator characteristics

A schematic diagram of the experimental apparatus is presented in Fig. 1 whereas the vortex generator types and the detail of combined twisted tape and rectangular V-winglet in a square duct are shown in Figs. 2 and 3, respectively. In Fig. 1, a circular pipe was connected between a high-pressure blower and a settling tank while an orifice flow meter was placed in this pipeline. The square duct connected to the other side of the settling tank had overall length of 3000 mm and was divided into two sections: calm section and test section. The test section duct made of 3 mm thick aluminum sheets having a cross section of 45×45 mm^2 was 1000 mm long (L). In Fig. 2a, the twisted tape was made of aluminum sheet with its dimension of $42 \times 1200 \times 0.8$ mm^3.