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Experimental and numerical heat transfer investigation in turbulent square-duct flow through oblique horseshoe baffles

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ABSTRACT

An experimental and numerical work has been carried out to study the heat transfer enhancement in a heat exchanger square-duct fitted with 30° oblique horseshoe baffles (HB). In the current work, air is passed through the HB-inserted duct having a constant surface heat-flux. The air flow and heat transfer behaviors are presented for turbulent flow region, Reynolds number ranging from 4000 to 25,000. The pertinent parameters of the 30° HB elements include three relative baffle-pitches ($P_R = P/H = 0.5$, 1 and 2) and five relative baffle heights ($B_R = b/H = 0.05$, 0.1, 0.15, 0.2 and 0.25). Influences of those parameters on heat transfer and energy loss due to friction in terms of Nusselt number and friction factor, respectively are studied. The experimental result shows that at a given B_R, the smallest pitch spacing ($P_R = 0.5$) provides the highest heat transfer and friction factor. The HB at $B_R = 0.25$ and $P_R = 0.5$ yields the highest heat transfer and friction factor but the one at $B_R = 0.2$ and $P_R = 1$ gives the maximum thermal performance. In addition, the thermal performance of using the HB is much higher than that of the wire coil insert, in comparison with other turbulators. To understand the heat transfer mechanism, a numerical inserted-duct flow simulation is also conducted and the obtained numerical results are in good agreement with measurements. Numerical flow and heat transfer behaviors such as streamlines, temperature and Nusselt number contours of the duct flow model are also reported.

1. Introduction

In fluid flow over a heated surface of heat exchanger systems, the heat transfer coefficient is quite low especially for air/gas flow due to the development of thermal boundary layer. To obtain higher heat transfer coefficient the boundary layer near the wall must be thinner or destroyed and this can be achieved by using a vortex-flow device. In general, vortex/swirl flow is widely applied in cooling/heating systems in many industrial/engineering applications such as drying or curing of agricultural/industrial products, cooling of the gas turbine blades, chemical process plants, cooling of thermal load or heating process from duct airflow through the attic space of a house and so on. The aim of enhancing heat transfer is to make the heat exchangers more compact leading to reducing overall sizes of heat exchangers, possibly their cost or reducing the pumping power required for a given heat transfer target. The vortex flows can be divided into two types: decaying vortex and continuous vortex flows. The former includes the tangential flow injection to induce a vortex motion along the tube [1,2] and the guide vanes swirl generator [3,4]. The latter is twisted tape [5–9], coiled wire [10,11], nozzle and snail [12], groove/dimple [13,14], baffle/winglet/fin/rib [15–24]. The application of baffles/winglets fins/ribs is to create longitudinal vortices that help increase turbulence intensities resulting in improving thermal performance and reducing thermal boundary layer in the heated tube/duct. The employ of vortex-flow devices such as baffle/winglet/fin/rib is one of the commonly used passive heat transfer enhancement technique in single-phase flows since periodically positioned baffle/winglet/fin/rib in duct/tubes can interrupt thermal boundary layer and induce recirculation flows. Several researches on passive heat transfer enhancements in tube/duct/channel heat exchangers can be found in Ref. [25–27].

The utilization of vortex generator (VG) does not only enhance the heat transfer but also yield a considerable increase in pressure drop. Promvonge et al. [28] presented the heat transfer augmentation in a circular tube with inclined vortex ring and provided the condition that the vortex ring yields the best thermal performance.

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Nomenclature

A_s	surface area of duct (m^2)
A_c	cross-sectional area (m^2)
b	baffle height (m)
B_R	baffle blockage ratio or relative baffle height (b/H)
C_p	specific heat capacity of air (J/kg K)
D	hydraulic diameter of square duct, (= H) (m)
f	friction factor, (dimensionless)
h	average heat transfer coefficient ($W/m^2 K$)
H	duct height (m)
HB	horseshoe baffle
I	current (A)
k	turbulent kinetic energy; thermal conductivity of air (W/m K)
L	length of test duct (m)
$\dot{m}$	mass flow rate of air (kg/s)
Nu	Nusselt number, (=hD/k), (dimensionless)
Nu_x	local Nusselt number, (=h_xD/k), (dimensionless)
P	baffle pitch spacing (axial length of spacing) or cyclic length of one module (m)
ΔP	pressure drop (Pa)
P_R	baffle pitch to duct height ratio or relative baffle pitch, (P/H)
P_w	wetted perimeter
Pr	Prandtl number, (dimensionless)
q''	heat flux (W/m^2)
Q	heat transfer (W)
Re	Reynolds number, (UD/ν), (dimensionless)
t	thickness of baffle (m)
T	temperature (K)
U	mean velocity (m/s)
V	voltage (volt)
$\dot{V}$	volumetric flow rate (m^3/s)

Greek letters

α	attack angle of baffle (degree)
ρ	density of air (kg/m^3)
η	thermal enhancement factor, (dimensionless)
ν	kinematics viscosity (m^2/s)

Subscripts

b	bulk
0	smooth duct
conv	convection
i	inlet
o	out
pp	pumping power
s	duct surface

Yakut and co-workers [29,30] studied the effect of conical-ring insertion on Nusselt number, friction factor and enhancement efficiency in a tubular heat exchanger and indicated that the merit of the conical-ring as energy saving device was at lower Reynolds number. The influences of using converging, diverging, and converging–diverging conical rings on heat transfer and fluid friction in a heat exchanger tube were investigated by Promvonge [31]. Gunes et al. [32] examined experimentally the pressure loss and heat transfer in a round tube inserted with loose-fitted coiled-wire at three pitch ratios and two different distances in turbulent flow regime and the best overall enhancement efficiency was reported. Eiamsa-ard et al. [33] studied thermal characteristics in a square duct fitted with various wire-coils (1D, 2D length coil elements and full-length coil) and pointed out that the full-length coil performs higher heat transfer and flow resistance than the tandem coil elements.

For numerical work, several studies on heat transfer augmentation using vortex flow devices were also reported [34,35]. A numerical investigation on turbulent flow and thermal characteristics in a square channel with oblique discrete ribs (placed on one wall) was presented by Tatsumi et al. [36]. They suggested that the higher heat transfer was achieved because of stronger secondary flow induced. Yadav and Bhagoria [37,38] proposed a numerical study on turbulent duct flow in a solar air heater equipped with equilateral triangular sectioned ribs and transverse square ribs and found that the triangular and square ribs have the best thermo-hydraulic performance at different rib height and pitch values. Chu et al. [39] performed numerical work on a fin-and-oval-tube heat exchanger with LVG (longitudinal vortex generator) and indicated that the LVG with downstream placement, angle of attack, $\alpha = 30°$ and minimum tube-row number provided the best thermal performance. A 3D numerical simulation on laminar flow and heat transfer of the fin-and-tube surface with delta-winglet longitudinal vortex generator (DWLVG) was performed by Wu and Tao [40]. They found that when the reduction of the synergy angle always leads to the heat transfer enhancement by DWLVG. Effects of vortex-induced impingement on thermal performance augmentation in a square duct/channel with inclined baffles were numerically examined by Kwankaomeng and Promvonge [41] and Promvonge et al. [42] for laminar flow, and by Promvonge et al. [43] for turbulent flow. The application of finned-tape inserts in a square-duct heat exchanger [19,43] was seen to obtain higher thermal performance than that of wire coils [33].

Most of the investigations cited above have focused on thermal performance improvement in many heat exchanger systems by means of ribs/baffles with different heights, pitches and arrangements: angled, transverse, continuous or discrete, V-shaped, square-ribs. The investigation on turbulent flow through tandem oblique horseshoe-baffles in a square duct by experimental and numerical work has rarely been reported. The past study suggested that the thermal performance for using ribs/fins/baffles/winglets was higher than that for typical twisted-tape/wire-coil [44]. The work in Refs. [21,41,42] triggered the present work to incorporate the inline rib/baffles placed on two opposite walls for ease of insertion and therefore, those baffles were modified by joining one end of an inline baffle pair together to become a horseshoe baffle (HB). In the present study, an experimental and numerical work of turbulent periodic flow through the 30° oblique HB elements in a square duct was carried out to investigate the flow and heat transfer characteristics. The HB were inserted on the test duct with three relative baffle-pitches ($P_R = P/H = 0.5$, 1 and 2) and five relative baffle heights ($B_R = b/H = 0.05$, 0.1, 0.15, 0.2 and 0.25). The work was conducted using air as the test fluid for a turbulent flow regime, in the Reynolds number range from about 4000 to 25,000.

2. Experimental program and procedure

2.1. Equipment and VG characteristics

In the experimental setup, a 3 mm thick aluminum square duct was used as the test duct and the overall length of the duct was 3500 mm that includes three sections, namely, entry or calm section (2000 mm), test section (1000 mm) and exit section (500 mm). More details of the experimental apparatus can be found in Ref. [19]. The detail of 30° HB inserts into the test section is depicted in Fig. 1a and b. The duct was characterized by the inner duct width (W) of 45 mm, height (H) of 45 mm with overall length of 3500 mm, including the test section (L) of 1000 mm. The HB elements made of a 0.5 mm thick aluminum strip were placed