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Research Paper

Numerical study on flow structure and heat transfer in a circular tube integrated with novel anchor shaped inserts

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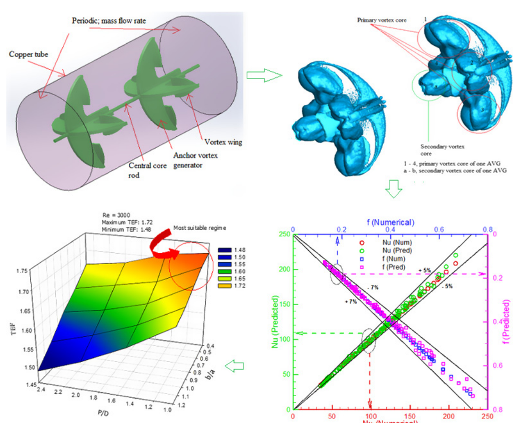
HIGHLIGHTS

- AVGs used generate vortex flow to promote efficient fluid mixing.
- High heat transfer and pressure drop occurs at the higher aspect ratio.
- AVG inserts shows good thermal enhancement factor with a maximum value of 1.72.
- Statistical correlations for Nusselt number and friction factor are also developed.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper reports a numerical study of the thermal performance enhancement of a circular tube embedded with novel anchor-shaped vortex generators. The three-dimensional turbulent periodic flow in the tube subject to a constant heat-flux wall boundary condition is investigated. The fluid flow and heat transfer characteristics are presented for Reynolds number (*Re*) ranging from 3000 to 18,000. The influences of pitch ratios ($PR = P/D = 1$, 1.5, 2, and 2.5) and the anchor vortex wing aspect ratios ($\sigma = b/a = 0.4$, 0.6, 0.8, 1, and 1.2) on Nusselt Number (*Nu*), friction factor (*f*), and the thermal enhancement factor (TEF) are reported. The vortex flow induced by the anchor vortex generator (AVG) inserts leads to a better fluid mixing, thereby accompanied a high heat transfer rate. The results indicate that the presence of AVG inserts elicits a considerable enhancement of Nusselt number and friction factor, which are about 2.24–4.56 and 4.01–23.23 times of those in the corresponding smooth tube, respectively. The maximum TEF of 1.72 is obtained for $b/a = 0.4$ and $P/D = 1$ at $Re = 3000$. These results provide evidence that the AVG insert is a promising device for turbulent convection heat transfer enhancement in a heat exchanger tube.

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Nomenclature

a	height of anchor vortex wing (m)
b/di	circumferential contact length to tube
b	height of anchor vortex wing (m)
BR	blockage ratio
$C_{1\varepsilon}$	constant (1.44)
$C_{2\varepsilon}$	constant (1.92)
C_p	specific heat of fluid (J/kg K)
D	tube diameter (m)
DR	diameter ratio
f	friction factor
$\frac{f}{f_s}$	friction factor ratio
G_k	generation of turbulence kinetic energy due to the mean velocity gradients
h	heat transfer coefficient (W/m^2 K)
k	turbulent kinetic energy (m^2/s^2)
L	length of tube (m)
Nu	Nusselt number
$\frac{Nu}{Nu_s}$	Nusselt number ratio
P	distance between two AVG (m)
PI	perforation index
p/p_a	relative pitch length
p/pl	pitch to projected length ratio
ΔP	pressure drop across duct (Pa)
Pr	Prandlt number
q	heat flux (W/m^2)
R_1, R_2	radius of arc of anchor wings (m)
Re	Reynolds number
PR	pitch ratio (*P/D*)
T_w	wall fluid temperature (K)
T_f	mean fluid temperature (K)
u_i	velocity component in x_i-direction (m/s)
V	mean fluid velocity in the duct (m/s)
X_1	anchor transverse edge to edge distance (m)
y+	dimensionless length scale

Greek letters

α	angle of attack (deg)
δ	diameter of the centre core rod
ε	dissipation rate (m^2/s^3)
σ	anchor vortex wing aspect ratio (*b/a*)
σ_k	turbulent Prandtl number for *k*
σ_ε	turbulent Prandtl number for *ε*
μ	dynamic viscosity (kg/s m)
μ_t	turbulent viscosity (kg/s m)
ρ	density of fluid (kg/m^3)
λ	thermal conductivity of fluid (W/m K)
i, j	Cartesian coordinates in x and y direction

Abbreviations

AVG	anchor vortex generator
CFD	computational fluid dynamics
CVG	curved vortex generator
DWT	delta wing tape
PVGs	perforated vortex generators
TEF	thermal enhancement factor
VG	vortex generator
WPT	winglet perforated tape

Subscripts

s	smooth tube
x	local values

1. Introduction

The heat exchangers are widely used in many industrial processes. Increasing energy demand and efficacious functioning of the thermal transport systems have led to the developments of efficient heat transport devices like compact heat exchangers. Many passive methodologies have been proposed to improve the thermal performance of heat exchangers [1–5]. The finned tube heat exchangers are widely used in the past years in single and two phase heat flow. Kim et al. [6] investigated the impact of different types of pin-fin on heat transfer and pressure drop of an air-oil heat exchanger. Ali and Abubaker [7,8] explored the effect of vapour velocity and circumferential pin thickness on condensate retention. Ali & Briggs [9] examined the effect of thermal conductivity and pin height on the thermal performance of pin-fin heat sink. Adding nano particles in the base fluid is also a promising technique to enhance heat transfer [10–12]. Sheikholeslami & Bhatti [13] investigated the forced convection of nanofluid subject to a uniform magnetic field. They found that Nusselt number reduces with the increment in Lorentz forces.

Another effective passive method to enhance the convective heat transfer is the turbulence promoters. The promoters tend to thin the thermal boundary layer near the tube wall, thus enhancing the heat transfer and miniaturizing heat exchanger systems. The turbulence promoters in the form of VGs [14–19], twisted tapes [20–23], vortex ring [24–27], compound inserts [28–30], and square wire [31] are utilized for producing the swirl and vortex flow inside the tubes. The insertion of passive heat transfer enhancement devices induces the swirl/vortex flow inside the tube and thus increases the fluid residing time, which accords a higher thermal performance.

The reported studies indicate that the turbulence promoters/VGs significantly enhance the thermal performance of a heat exchanger tube. The VGs such as baffles, fins, and vortex rods have been studied by many researchers. The baffles can escalate the convective rate of heat transfer, but the associated pumping power is also significant. The modifications in the shapes of VGs are implemented to achieve the high convective heat transfer at the reduced friction losses.

Guo et al. [32] investigated the heat transfer and flow characteristics experimentally of a circular tube fitted with louvered strip inserts. They reported the thermal enhancement factor (TEF) improvement with the louvered strip inserts over the conventional conical ring inserts. Deshmukh & Vedula [33] reported the use of curved vortex generator (CVG) inserts for heat transfer enhancement in a tube in the turbulent flow regime. The parameters considered were the pitch to projected length ratio from 1.4 to 7.9, the angle of attack from 15° to 45°, and the height to tube diameter ratio from 0.09 to 0.25. They reported the Nusselt number enhancement with CVG in the range from 1.3 to 5 times over that for the smooth tube. Tu et al. [34] carried out the numerical investigation to study the heat transfer and fluid flow behavior inside a tube fitted with novel pipe inserts for the Reynolds number range of 2892–28,915. They reported the TEF improvement with the novel pipe inserts in the range from 1.4 to 3.0 times of that for the smooth tube. Pourramezan & Ajam [35] numerically investigated the thermo-hydraulic characteristics of a circular tube fitted with twisted conical inserts. The study revealed that the maximum Nu_a/Nu_s, f_a/f_s with the inserts over the plain tube were 3.5 and 25, respectively. Skullong et al. [36] revealed that the highest *TEF* of 1.71 was achieved by utilizing the winglet perforated tape (WPT) with the blockage ratio of 0.15, the pitch ratio of 1.0 at *Re* of 4180. Deshmukh et al. [37] investigated the curved delta wing VG inserts and found the significant increase in both the heat transfer and pressure drop, compared with the