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Research Paper

Thermal and friction characteristics of a circular tube fitted with perforated hollow circular cylinder inserts

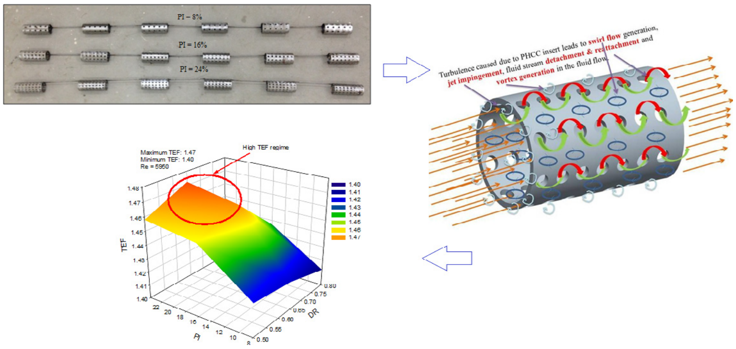
Sumit Kumar Singh [a], Manoj Kumar [a], Alok Kumar [a], Abhishek Gautam [b], Sunil Chamoli [a,*]

[a] Department of Mechanical Engineering, DIT University, Dehradun 248009, India
[b] Departmentof Mechanical Engineering, Tula's Institute, Dehradun 248011, India

HIGHLIGHTS

- Perforated hollow circular cylinder offers superior thermal performance.
- Heat transfer rate increases with decreasing perforation index ratio.
- Perforated hollow circular cylinder gives the thermal performance of up to 1.47.
- Statistical correlations developed for the Nusselt number and friction factor.

GRAPHICAL ABSTRACT



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ABSTRACT

The objective of the present work is to measure the heat transfer and pressure drop in a circular tube integrated with the perforated hollow circular cylinder (PHCC) inserts with air as the working medium. The experiments are performed with PHCC inserts of three different diameter ratios ($DR = 0.5$, 0.65, and 0.8) and three perforation index ($PI = 8\%$, 16%, and 24%) in a circular tube turbulent flow regime, where the Reynolds number is varied from 6000 to 27,000. A fixed value of pitch ratio ($PR = 2$) is considered in all the experiments. The experimental results demonstrated that the Nusselt number (Nu) and friction factor (f) are increased with the decrease of pitch ratio. The results also reveal that the heat transfer rate in the tube fitted with PHCC inserts is significantly increased with the corresponding marginal increase in pressure drop. In the range of the present work, heat transfer rate and friction factor are obtained to be around 150–230% and 160–450% higher than those of the plain tube values, respectively. Thermal enhancement factor (TEF) in the present study is in the range of 1.21–1.47 with a maximum value for $DR = 0.65$ and $PI = 8\%$, respectively. In addition, the empirical correlations for the Nusselt number and friction factor are also developed, based on the experimental data.

1. Introduction

Heat exchangers are the most commonly used devices in most of the thermo-mechanical systems. The thermal performance improvement of a heat exchanger is one of the most challenging tasks in any heat transfer process. To save more energy and cost, the technology of heat exchangers needs to be improved. Several methods are used for performance improvement in heat transfer applications including passive, active and conjugate methods. The passive methodology of heat transfer enhancement [1], has received major attention in the last decade. The enhancement of

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* Corresponding author.
E-mail address: mech.chamoli@gmail.com (S. Chamoli).

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Nomenclature

A	surface area of test section, m^2
C_d	coefficient of discharge
D	tube inner diameter, m
d	internal diameter of insert, m
DR	diameter ratio
f	friction factor
h	convective heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
K	thermal conductivity of air, $W\,m^{-1}\,K^{-1}$
l	length of PHCC, m
L	length of test section, m
$\dot{m}$	mass flow rate of fluid, $kg\,s^{-1}$
Nu	Nusselt number
P_A	perforated area of insert, m^2
P_{atm}	atmospheric pressure, Pa
ΔP	pressure drop across test section, Pa
Nu_s	Nusselt number of smooth tube
ΔP_O	pressure drop across orifice plate, Pa
PR	Pitch ratio
Pr	Prandtl number
PI	perforation index
PHCC	perforated hollow circular cylinder
q	heat flux, $W\,m^{-2}$
Re	Reynolds number
T_w	local wall temperature, K
T_b	bulk mean temperature, K
T_{wm}	mean wall temperature, K
T_i	fluid inlet temperature, K
T_o	fluid exit temperature, K
T_A	total area of insert, m^2
TEF	thermal enhancement factor
d_h	diameter of insert hole, m
PR	pitch ratio
f_s	friction factor in smooth tube

Subscript

A	area
atm	atmospheric
h	hole
b	bulk
C	cross-section
i	inlet
O	orifice
o	exit
s	smooth tube
wm	wall mean
w	local wall

heat transfer by disturbing the flow field using turbulence promoters is the basic criteria of this method. Several insert geometries with different flow and geometrical parameters were reported by numerous investigators. Twisted tapes are the most common inserts used by many investigators for heat transfer enhancement. The short length twisted tapes, serrated twisted tapes, double sided delta wing tapes and twisted tapes with a wire coil, respectively, were explored by Eiamsa-ard et al. [2–5]. They worked on the different length of twisted tapes and compared its performance with full length twisted tapes. They reported that the full length twisted tapes gave the best result for heat transfer. They also mentioned that the serration on the twisted tapes associates the significant decrease in pressure drop across the test section. The study also reported the maximum convective heat transfer rate at the minimum twist ratio. Singh et al. [6] explored the circular rings with multiple twisted tapes and found the significant improvement in thermal performance factor for the low pitch ratios and quadruple twisted tapes. The use of broken twisted tapes for the heat transfer enhancement of tubular heat exchanger was reported by Chang et al. [7]. They reported the maximum value of *Nu* for full length twisted tapes at the low twist ratio (*TR*). The perforation in the twisted tapes was explored by Nanan et al. [8]. They reported the significant decrease in the values of pressure drop with perforated twisted tapes. Moreover, in contrast to the low pressure drop due to perforations, the low *Nu* values were also accounted.

Similarly, Bhuiya et al. [9–11] introduced the double twisted tapes, perforated twisted tapes, and triple twisted tapes, respectively as insert geometries for the heat transfer enhancement. They observed the significant increase in heat transfer with the increase of number of twisted tapes and showed the superiority of triple twisted tapes over the single and double twisted tapes. Promvonge and Eiamsa-ard [12] used the conical ring with twisted tapes with the different values of diameter ratios (*DR*), pitch ratios (*PR*) and twist ratios (*TR*). The study revealed the maximum *Nu* for the lowest *PR*. The performance comparison of different insert geometries was studied by Kumar et al. [13] and they proposed the importance of perforation in controlling the friction factor to enhance the overall system performance. In another research papers, Kumar et al. [14–16] investigated the heat transfer and fluid behavior of the circular tubes fitted with protruded surface, circular disk and perforated circular disk, respectively. They also reported the superiority of surface protrusions over the smooth tube. Moreover, apart from the *PR*, *DR*, which are the common parameters for most of the studies, they explored the perforation index (*PI*) ranges from 0% to 24% in their work. They reported that the perforation in the geometries is a promising methodology for improving overall system performance. Similarly, Promvonge and Eiamsa-ard [17–19] explored the conical nozzle with free spacing and V- nozzle, respectively, as the insert geometries in tube heat exchangers. The study revealed the high pressure drop along the tube flow, which consecutively reduced the overall system thermal performance factor. In a similar way, other geometries were also reported like inclined vortex ring by Promvonge et al. [20], twisted ring by Thianpong et al. [21] and perforated conical ring by Kongkaitpaiboon et al. [22]. Recently, Chamoli et al. [23] reported the superiority of perforated vortex inserts over solid inserts. They reported the significant TEF improvement with perforated vortex inserts and promoted the aspect of perforations in the solid geometries.

The above literature survey shows that the heat transfer can be enhanced by modifying the insert geometries, which provides an efficient fluid mixing. It is also noted that the perforated geometries provide higher thermal performance than the conventional solid geometries. It is thus obvious that the utilization of perforation in the solid geometries is the most effective method for enhancing the convective heat transfer. The pressure drops associated with the perforated geometries are also very less, which in turn reduces the pumping cost. The impinging jet transformed very thin boundary layer over the heated surface and thus accounted high convective heat transfer rate. These research outcomes were also implemented in some practical and optimization applications by some researchers. Hatmi et al. [27–30] used the vortex generator