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Numerical study of an innovative design of a finned double-pipe heat exchanger with variable fin-tip thickness

K.S. Syed [a], Muhammad Ishaq [b,*], Zafar Iqbal [c], Ahmad Hassan [d]

[a] Centre for Advanced Studies in Pure and Applied Mathematics (CASPAM), Bahauddin Zakariya University, Multan 68000, Pakistan
[b] Department of Computer Science, COMSATS Institute of Information Technology, Vehari Campus, Mailsi Road, Off Multan Road, Vehari, Pakistan
[c] Department of Mathematics, Government Emerson College, Multan 60700, Pakistan
[d] Department of Basic Sciences and Humanities, University College of Engineering & Technology, Bahauddin Zakariya University, Multan 68000, Pakistan

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ABSTRACT

The analysis of fully developed laminar convective heat transfer in an innovate design of a finned double-pipe heat exchanger (DPHE) with longitudinal fins of variable thickness of the tip subjected to the constant heat transfer rate boundary conditions is investigated here. The tip thickness is controlled by the ratio of tip to base angles as a parameter whose values varying from 0 to 1 correspond to the fin shapes varying from the triangular to the rectangular cross-section. Upto the knowledge of the authors, this parameter is being introduced for the first time in the literature. Discontinuous Galerkin finite element method (DG-FEM) has been employed in the present work. The overall performance of the proposed DPHE has been investigated by considering the friction factor, the Nusselt number and the *j*-factor. Upto 178% gain in the Nusselt number and 89% gain in the *j*-factor have been achieved relative to the rectangular cross-section. Such gains relative to the triangular cross-section are respectively 9.5% and 19%. The results indicate that the newly introduced parameter the ratio of tip to base angles has proved to play significant role in the design of a double-pipe heat exchanger in reducing the cost, weight and frictional loss, in improving the heat transfer rate and making the exchanger energy-efficient. Therefore, it must be considered as an important design parameter for heat exchanger design.

1. Introduction

With the advancement of technology, the importance of heat transfer engineering has increased and there is always a need to meet new design challenges in this field for high performance heat transfer particularly due to energy concern. Usually, heat exchangers are widely used for this purpose. There are many techniques, which are employed to enhance the heat transfer rate in the heat exchanger but the most effective one among them is using mounted fins. The design of a heat exchanger depends upon many features namely sizing, compactness, heat transfer, performance estimation, economic aspect and pressure drop analysis. Present investigation depicts the numerical study of an innovate design of a finned double-pipe heat exchanger with variable fin-tip thickness. The relevant literature is presented in the next few paragraphs of this section.

Through augmentation of fins in a single pipe, significant enhancement in heat transfer rate has been achieved [1–6]. A simple double-pipe heat exchanger (DPHE) made up of two concentric tubes is a well-probed geometry. In this heat exchanger, one fluid (hot) flows in the inner pipe and the other (cold) through the annulus between the two pipes, both moving in either opposite or the same direction. Lorenzo and Anderson [7] presented the data on longitudinal finned double-pipe in graphical form. Kraus [8] independently developed an expression for the overall efficiency of the annular region (obtained by connecting the fin-tips to the outer pipe) of a DPHE. Prata and Sparrow [9] presented the analysis of heat transfer characteristics in the annulus of periodically varying cross-section. Taborek [10] provided a comprehensive review of plain and longitudinal finned double-pipes and multi-tubes. He outlined the areas, conditions, calculation methods and turbulence parameter with "cut-and-twist" for double and multi-tube heat exchangers. Agrawal and Sengupta [11] reported increase in heat transfer rate in the finned annulus with periodic circular fins. Suryanarayana and Apparao [12] investigated experimentally the heat transfer analysis and pumping power in the DPHE. Li et al. [13] presented the significant gain in heat transfer in the annular sector. They numerically performed the investigation of the fully-developed turbulent flow. Goldstein et al. [14,15] presented a broad review of heat transfer related to different heat exchangers

* Corresponding author. Cell: +92 3007345759.

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A_c	free flow area, m^2
D	diameter of finned annulus, m
$\frac{dp}{dz}$	pressure gradient, Pa/m
j	Colburn j-factor, dimensionless
Nu	Nusselt number, dimensionless
P_h	length of heated perimeter, m
Pr	Prandtl number, dimensionless
$\dot{Q}'$	uniform heat transfer per unit axial length, W/m
r	radial coordinate, m
R	dimensionless radial coordinate, dimensionless
$\hat{R}$	ratio of radii of inner and outer pipes, dimensionless
r_1	radial coordinate of the fin-tip, m
R_1	dimensionless radial coordinate of the fin-tip, dimensionless
r, ϕ, z	cylindrical coordinates
T	temperature, °C
U	axial velocity component, m/s
U_{max}	maximum axial fluid speed at a cross-section, m/s
α	angle between the flanks of two adjacent fins, rad
β_1	fin-tip, half angle, rad
β_2	fin-base, half angle, rad
γ	angle between the centre line of two adjacent fins, rad
κ	thermal diffusivity, m^2/s
λ_f	thermal conductivity of fluid, W/m K
μ	fluid dynamic viscosity, Pa s

Subscripts

b	bulk
c	cross-sectional
h	heated parameter
H	hydraulic diameter
i	outer surface of inner pipe
m	point of maximum velocity
$\circ$	outer surface of outer pipe
w	solid wall

Superscripts

$*$	dimensionless quantity
overbar	$\bar{()}$ mean value

geometries. Targui and Kahalerras [16] used porous baffles and pulsating flow in their numerical investigation to enhance heat transfer rate in the DPHE. Hadidi et al. [17] proposed a new design approach based on imperialist competitive algorithm to minimize the cost of shell and tube heat exchanger.

Syed [18] numerically studied the heat transfer analysis in the rectangular finned annulus of a DPHE by employing finite difference method. In his study, he considered two types of boundary conditions namely, the constant heat flux (H1) and the uniform wall temperature (T1). His investigation showed that the fin height and the number of fins are the most influential parameters to the overall Nusselt number. Mazhar [19], Syed et al. [20] and Iqbal and Syed [21] extended the problem considered in [18] for thermally developed/developing and hydrodynamically developed flow. They considered H1 and T1 type boundary conditions. They employed finite difference method for their numerical investigations. They showed that the axially local and circumferentially averaged heat transfer coefficient and the thermal entrance length are significantly sensitive to the configuration of the finned annulus. Syed et al. [22] considered the previous problem [18] and used triangular fins of equal height instead of rectangular fins with H1 boundary condition. Triangular fins have narrow top and wider base, and thus have low cost and weight compared to rectangular fins. They performed their numerical simulation by employing the finite element method instead of the finite difference method. Their investigation reported that by mounting the triangular fins to a DPHE, gain in heat transfer could be achieved up to 177 times that of the finless double-pipe while the corresponding increase in the product of fanning friction factor and the Reynolds number reached up to 40 times that of the finless DPHE. In this way, enhancement in the relative heat transfer rate could be attained more than four times larger than the corresponding increase in the relative friction loss. Syed et al. [23] reported many optimal configurations of the finned annulus with rectangular fins, depending on the practical and industrial interest. Iqbal et al. [24] numerically investigated the optimal configuration of finned annulus with parabolic fins. They used trust-region method and genetic algorithm as optimizing methods. Ishaq et al. [25] performed numerical simulation of the laminar forced convection in the fully developed flow through the annulus of a double-pipe heat exchanger with triangular fins of different fin heights subject to the constant heat transfer rate boundary condition. They employed the discontinuous Galerkin finite element method (DG-FEM) for their investigation. They reported many cases of practical interest for specified values of the number of fins and the size of the inner pipe for which combinations of unequal heights of the two fin groups render maximum heat transfer coefficient. They achieved up to 63 and 61 times more gain, respectively in the Nusselt number and the j-factor, than the corresponding increase in the friction factor.

The tapered longitudinal fins used in the investigations [18,19] may be regarded as rectangular in shape as the sides of the fin are parallel to the coordinate curves of the polar coordinate system and its opposite sides are represented by equal differences of the coordinate variables. Although these fins have equal fin-base and fin-tip angles, yet the thickness of the base and tip determined by their arc lengths may significantly be different particularly for fins of larger height. Therefore, the rectangular fins in polar coordinates may have narrow base and considerably wider tip. Such a shape with wider top on a narrow base may not be fully exploited as the wider top will receive only a portion of the heat conducted through the narrow base. This shape may be disadvantageous in many respects like cost, weight and pressure loss. Particularly when there are higher and thinner fins attached to the inner pipe of small radius, the structural integrity may also be at risk. Another extreme is the triangular fin with wider base and pointed top. In view of these concerns, in the present work, longitudinal fins with variable base and top thicknesses are considered, as to be controlled by two fin angles, the base-angle and the tip-angle. Taking the ratio of tip to base angles as a parameter, it may have its values varying from 0 to 1, where 0 will correspond to the triangular fin, 1 to the above referred tapered rectangular fin and the values between 0 and 1 correspond to the trapezoidal fins. Upto the knowledge of the authors, this parameter is being introduced for the first time in the literature. This is the motivation for the present work in which, the ratio of the fin-tip and base angles is investigated as an important parameter in designing the longitudinal fins for DPHE.

2. Problem statement and mathematical formulation

Laminar, steady and, hydrodynamically and thermally fully developed flow is considered in the double-pipe heat exchanger with longitudinal fins, mounted at to the outer surface of the inner