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DG-FEM based simulation of laminar convection in an annulus with triangular fins of different heights

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ABSTRACT

This work presents numerical simulation of laminar forced convection in the fully developed flow through the finned annulus of a double-pipe with triangular fins of different heights. The flow is subjected to the boundary condition of constant heat transfer rate per unit axial length with uniform peripheral temperature distribution. The aim is to investigate the effects of employing fins in two groups of unequal heights for different values of other parameters determining the configuration of the finned annulus, on the thermal performance of the finned duct. The governing partial differential equations of the convection problem are numerically solved by employing the discontinuous Galerkin finite element method (DG-FEM). The hydraulic and thermal characteristics like the friction factor, the Nusselt number and the *j*-factor are studied against various geometric design parameters. It has been observed that using the fins in two groups of different heights, the velocity and temperature distributions can be significantly altered to have more favourable flow and thermal characteristics. The maximum values of the coefficients of friction and heat transfer, and the *j*-factor do not necessarily lie on equal heights of the two fin groups. An arrangement of one group of fins being at its maximum height and the other one at its minimum height, has shown very fascinating performance in comparison with all the fins being at their maximum equal height. Upto 63 times more gain in the Nusselt number and 61 times more gain in the *j*-factor than the corresponding increase in the friction factor has been achieved by such an arrangement. The present study recommends the use of the fins with unequal heights for reducing the cost, weight and pressure loss with their thermal performance being better or at least comparable with that of the equal fins.

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1. Introduction

To enhance the heat transfer rate in the circular duct, the idea of augmented fins is widely employed. This idea of extended fins has been successfully employed for promoting heat transfer in many engineering applications like chemical processing, environment control, power generation, space heating, etc. The flow and heat transfer characteristics investigations have been carried out for several finned geometries under various physical and operating conditions. Nandakumar and Masliyah [1] studied fully developed laminar flow in a straight circular tube with internal triangular fins and employed the finite element method for their numerical investigation. They computed flow characteristics for a wide range of values of the length, thickness and number of fins and proposed some empirical relations for the friction factor. Later, Masliyah and Nandakumar [2] considered the same problem and presented heat transfer analysis subjected to axially uniform heat flux with peripherally uniform temperature (the so-called H1 boundary condition). Their findings include enhancement in the Nusselt number and the existence of optimum number of fins of a specified configuration. Soliman et al. [3] studied this problem with tapered longitudinal fins subjected to the uniform outside wall temperature condition (the so-called T1 boundary condition) and reported significant improvement in heat transfer over a pipe without fins. They also considered one-dimensional temperature profile in the radial direction of the fins and reported that the fin conductance parameter has very less effect when the shorter fins are employed. In all of these studies the pressure drop increase is so large that the performance of the finned tube is no more better than that of the finless tube. In other words the ratio of the overall Nusselt number

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Nomenclature

A	flow cross-sectional area, m^2
D_e	equivalent diameter of finned geometry, m
D_H	hydraulic diameter of finned geometry, m
$\mathrm{d}p/\mathrm{d}z$	pressure gradient in finned geometry, pa/m
f	Fanning friction factor, dimensionless
fRe	product of the Fanning friction factor and the Reynolds number, dimensionless
h_T	average heat transfer coefficient, W m^{-2} K^{-1}
H_1^*	dimensionless fin height of one group of fins
H_2^*	dimensionless fin height of other group of fins
j	Colburn j-factor, dimensionless
l_1^*	dimensionless length of fin lateral surface of one group
l_2^*	dimensionless length of fin lateral surface of other group
M	number of fins
N	degree of local polynomial
N_p	number of grid points in kth element
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
$\widehat{R}$	ratio of radii of inner and outer pipes, dimensionless
r_i	double-pipe : outer radius of inner pipe, m
r_m	radial position of the point of maximum velocity, m
R_m	dimensionless radial position of the point of maximum velocity, dimensionless
r_o	double-pipe: inner radius of outer pipe, m
r_1	radial coordinate of the tip of one fin group, m
R_1	dimensionless radial coordinate of the tip of one fin group, dimensionless
r_2	radial coordinate of the tip of other fin group, m
R_2	dimensionless radial coordinate of the tip of other fin group, dimensionless
r, ϕ, z	cylindrical coordinates
Re	Reynolds number, dimensionless
T	temperature, °C
T_b	bulk mean fluid temperature, °C
T_w	wall or fluid temperature at the solid–fluid interface, °C
U	axial velocity component, m/s
U^*	dimensionless axial velocity component, dimensionless
U_max	maximum axial fluid speed at a cross-section, m/s
2α	angle between the flanks of two adjacent fins, rad
β	fin 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
τ	dimensionless temperature, dimensionless
Ω^d	numerical domain
Ω_k^d	kth triangular element of numerical domain
$\partial\Omega_k^\mathrm{d}$	boundary of the kth element

Subscripts

b	bulk
c	cross-sectional
e	equivalent diameter
h	heated parameter
H	hydraulic diameter
i	outer surface of inner pipe
o	outer surface of outer pipe
w	solid wall

Superscripts

*	Dimensionless quantity
overbar	$(\overline{})$ mean value

to the product of friction factor and Reynolds number for finned ducts is smaller than that for the corresponding finless one. The analysis of laminar convection in the entrance region of a circular tube with longitudinal fins of zero thickness was carried out by Prakash and Liu [4] for both types of above stated thermal boundary conditions (H1 & T1). Sparrow and Charmchi [5] determined the numerical solution of laminar heat transfer in a circular tube fitted with regularly spaced array of annular external fins and found substantial increase in the heat transfer rate. Nasiruddin and Kamran [6] introduced baffles in a smooth circular tube for vortex generation and numerically investigated the enhancement in heat transfer due to the mixing carried out by vortex motion. Convective heat transfer in the annulus region of a double-pipe has also been investigated for various configurations of fins and pipes [7–11]. Zeitoun and Hegazy [12] carried out analysis of fully developed convective heat transfer in the internally finned tube with uniform outside wall temperature. The fins were of different fin heights. They reported that substantial amount of heat transfer occurs through the surfaces of the fins, especially when the fins are very high and the contribution of the pipe surface is very small when compared with that of the fin surface. Suryanarayana [13] reported experimental results in the double-pipe heat exchanger related to the heat augmentation and pumping power. Hu and Chang [14] studied the laminar forced convection problem subject to uniform axial and peripheral heat fluxes in finned tubes and reported an optimum configuration for the heat transfer enhancement. Li et al. [15] performed simulation of the fully developed turbulent flow in an annulus sector duct and reported significant heat transfer enhancement. Qingling et al. [16] performed heat transfer analysis in a tube with elliptic pin fins in the cross flow of air. Chen et al. [17] investigated convective heat transfer and pressure loss in the rectangular ducts with drop-shaped pin fins. Wang [18] analytically investigated the heat transfer characteristics in parallel plates with longitudinal fins. He reported that the use of fins whether sufficient pumping power is under consideration or not, has significant advantage in heat transfer enhancement. Sparrow et al. [19] investigated heat transfer characteristics of the shrouded fin array. They reported that the surface of the fin is more efficient than that of the base. Prata and Sparrow [20] studied fluid flow and heat transfer characteristics in an annulus of periodically varying cross-section. They demonstrated increase in the heat transfer rate and a relatively smaller increase in the pressure drop. Yu et al. [21] experimentally determined the heat transfer characteristics in the developing and fully developed regions of a double-pipe with internal wave-like longitudinal fins. The conjugate heat transfer in a double-pipe with longitudinal fins attached to the inner tube was discussed by Tao [22]. Emin and Erdem [23] investigated the effects of the duct shapes on the heat transfer characteristics. They reported that the Nusselt number has its dependence on the shape of the duct like circular, semicircular, rectangular and parallel plate ducts. Goldstein et al. [24,25] gave a comprehensive review of the work done on convective heat transfer in different geometries

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