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Fin design for conjugate heat transfer optimization in double pipe

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ABSTRACT

Optimal design of longitudinal fins augmented to the outer surface of the inner pipe in a double pipe, is investigated for maximizing conjugate heat transfer coefficient. Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) has been used for fin-surface representation at each step of the optimization process with control points as the design variables. Genetic algorithm has been employed as the optimizer together with the Discontinuous Galarkin Finite Element Method (DG-FEM) as the solver of the governing equations. The results show that the optimal fin design is greatly influenced by the characteristic length, the number of fins, the conductivity of the material of heated surface and the number of control points. Optimal designs based on the equivalent diameter give upto 289% improvement in the heat transfer coefficient and those based on the hydraulic diameter render such improvement upto 70%. Optimal fin shape has also out-performed the conventional fin shapes present in the literature and shown upto 203%, 263% and 227% increase in the heat transfer coefficient relative to the equivalent diameter for trapezoidal, triangular and parabolic fins respectively. For the case of hydraulic diameter, these figures are respectively 482%, 70% and 117%. The optimal designs based on the equivalent diameter corresponding to $\Omega = 500$ have proven to be the best in view of cost, frictional loss and heat transfer coefficient. These give upto 39% higher heat transfer coefficient than the corresponding increase in frictional loss due to augmentation of the fins to the double pipe. The validity and accuracy of the present results has been shown by comparison with the available literature results.

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1. Introduction

Finned ducts are extensively used in heat exchangers in various industrial applications. The design of finned ducts for improving heat transfer coefficient is an important problem in various engineering disciplines. The use of extended surfaces in spite of its sole advantage of promoting heat transfer rate has many demerits in terms of requiring high pumping power, and increasing the weight and cost of the heat exchange system. Therefore, it is very crucial to use the extended surfaces judiciously. It is natural to be interested in minimizing the weight, cost and pressure loss while maximizing the heat transfer coefficient. This becomes a multi-objective optimization problem whose solution may optimize these quantities. Refs. [1,2] gives a good critical review of the work on optimization of finned surfaces.

Generally, for conventional convective heat transfer problems specified temperature or heat flux or their combination may be applied as a boundary condition on the heated surface. However, in conjugate heat transfer problems, the thermal conditions at the solid fluid interfaces are governed by both the conduction and convection phenomenon and are characterised by the continuity of temperature and heat flux along the normal to the interfaces of the solid and fluid media. This, in turn, requires to solve the energy equation in both the media simultaneously.

Here we present a brief review of the work done on conjugate heat problems. Mori et al. [3], studied wall conduction effects on heat transfer in the circular tube geometry and concluded that the ratio of conductivity of the wall and the fluid, and the wall thickness significantly affect the heat transfer characteristics. For the case of thin wall, the effects of heat conduction in the wall are not significant and may be neglected. Faghri and Sparrow [4] discussed the problem of simultaneous axial heat conduction in both the fluid and the wall in a pipe and assuming very thin wall ignored the radial temperature gradient. They concluded that the axial heat

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Nomenclature

A	free flow area, m^2
C_p	specific heat capacity, j/kg K
D	diameter, m
dp/dz	pressure gradient in finned geometry, pa/m
f	Fanning friction factor, dimensionless
H	fin height relative to the annulus, m
(j/f)	surface flow area goodness factor, dimensionless
l	actual fin height, m
M	number of fins
Nu	Nusselt number, dimensionless
Pr	Prandtl number, dimensionless
PW	wetted perimeter, m
Ph	heated perimeter, m
R	radial coordinate, dimensionless
Re	Reynolds number, dimensionless
r, ϕ, z	cylindrical coordinates
$\dot{Q}'$	heat transfer rate per unit axial length of the pipe, W/m
U	axial velocity component, m/s
α	half-angle between successive fins, rad
β	fin half angle, rad
θ	temperature, °C
λ	thermal conductivity, W/m K
δ	wall thickness of the inner pipe, dimensionless
ρ	density
Ω	ratio of conductivities of the fin-pipe material and fluid, dimensionless

Abbreviations

CL	characteristic length
CP	control points
DG-FEM	discontinuous Galarkin finite element method
FDM	finite difference method
FEM	finite element method
GA	genetic algorithm
IP	improvement
max	maximum
PCHIP	Piecewise Cubic Hermite Interpolating Polynomial
Par	parabolic
Trap	trapezoidal
Tri	triangular

Subscripts

0	un-finned double pipe
1	radial position of the tip of the fin
ˆ	for ratio of radii of inner and outer pipes
b	bulk
B	base shape
c	cross-section
f	fluid
e	equivalent diameter
h	hydraulic diameter
i	inner-pipe
m	radial position of the point of maximum velocity in the annulus without fins
opt	optimal value
o	outer-pipe
s	solid
W	solid wall
w	with-out pipe thickness

Superscripts

*	dimensionless quantity
$(\bar{\ })$	over bar, average value

conduction in the wall can carry substantial amount of heat upstream. Soliman [5] investigated the effects of heat conductance on the heat transfer characteristics in the internally tapered longitudinal finned tubes. He found that the fin conductance parameter greatly affects the heat transfer characteristics which mainly depend on the tube geometry. Krishen [6] studied conjugate heat transfer in the fully developed flow through a circular pipe. Barrozi and Pagliarini [7] developed a numerical method for the study of conjugate heat transfer in fully developed laminar flow through a pipe. They discussed the effects of axial heat conduction along the wall on the heat flux, the bulk temperature of the fluid and the Nusselt number. Skakibara et al. [8] analytically investigated the conjugate heat transfer problem in the annulus region and concluded that the effect of the wall heat conduction is significant. Tao [9] has solved conjugate problem for the double pipe heat exchanger in which the tube is internally finned and showed that the ratio of the heat capacities of the fluids has significant effect on the finned tube heat transfer. Pagliarini [10] investigated conjugate heat transfer problem in a long circular tube and concluded that for the thin wall, the wall resistance may be neglected and for low values of the wall conductivity and Pecelet number, the effect of the axial heat conduction in the fluid is significant. Kettener et al. [11] numerically simulated laminar heat transfer in internally finned tubes. They concluded that the ratio of thermal conductivities of the solid and fluid has no significant effect on shorter fins; however, when the fin height is taken more than 40% relative to the tube radius, this conductivity ratio has significant effect on the heat transfer results. The conjugate heat transfer in the finned tube element was also investigated by Fiebig et al. [12,13]. They concluded that the fin efficiency parameter has strong influence on the fin heat flux, and the Nusselt number. Conjugate heat transfer problems have been investigated for various geometric configurations in Refs. [14,15].

The optimization of such finned ducts has been carried out in the literature by finding either the optimal values of the parameters determining the fin dimensions for a given fin shape [16–21] or by optimizing the fin shape (lateral profile) for specified fin dimensions [22–28]. The detail of categorization of the problems and relevant literature review can be found in Ref. [2]. Colle and Maliska [25] performed optimization of finned double tubes under laminar flow conditions for heat transfer enhancement. By using analytical approach, they investigated the relationship of the configurations parameters (the fin spacing, the fin height and the fin radius) with the friction factor, the Nusselt number and the Reynolds number. Fabbri [22] used genetic algorithm for the optimization polynomial fin profile under the constraint of minimum and maximum specified fin thickness. The fin profile was represented by nth degree polynomial function. He optimized the coefficients of nth degree polynomial passing through $n + 1$ interpolating points for rendering maximum fin effectiveness. Then he optimized the laminar heat convection in internally finned tubes [23]. Later on, he [24] optimized the heat transfer of finned annular ducts subject to the laminar flow assumptions. For the solution of the momentum, energy and heat equations he used finite element method. He found the higher degree polynomial with wavy fin shapes performing the best in comparison to the simple fin shapes. Cheng and Wu [26,27] performed the fin shape optimization of conduction problems by using body-fitted curvilinear grid along with the

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