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Numerical simulation of natural convection heat transfer for annular elliptical finned tube heat exchanger with experimental data

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ABSTRACT

This study presents a hybrid method of three-dimensional computational fluid dynamics (CFD) commercial software and inverse method along with experimental data and various flow models to study the natural convection heat transfer and fluid flow characteristics of vertical annular elliptical finned tube heat exchangers for various fin spacings. The inverse method of the finite difference method along with the experimental temperature data is first applied to estimate the heat transfer coefficient on the fins. After that, CFD along with various flow models and estimated heat transfer coefficients are used to determine air temperature and air velocity profiles, fin surface temperature and heat transfer coefficient on the fins. More accurate numerical results, appropriate flow model and number of grid points, number of iterations and relative convergence criteria can be obtained when the resulting heat transfer coefficient and fin temperature are as close as possible to the inverse results and experimental temperature measurements, respectively. The results show that the zero-equation turbulence model is more suitable for this study than other flow models. The choice of relative convergence criteria, number of iterations and grid points are important for obtaining more accurate results. The commercial software version, the relative convergence criteria for momentum and energy equations, the number of iterations and the N_t value vary with the fin spacing. The effect of the round-off error on the numerical results obtained needs to be considered. The heat transfer coefficient increases with increasing fin spacing and approaches a constant. The best fin spacing is about 18 mm. The fin efficiency of the annular elliptical fins is higher than that of the annular circular fins. The proposed correlations between Nusselt number and Rayleigh number is in good agreement with the numerical and inverse results obtained.

1. Introduction

Many experimental and numerical methods have been proposed to obtain the natural convection heat transfer and fluid flow characteristics of the plate fin and tube heat exchanger. The air is heated at the tube and moves upward due to the density difference caused by the heating. The upward-moving natural convection boundary layer flow is induced by two adjacent fins. The boundary layer begins to develop upward from the bottom of the heating horizontal tube. Its thickness increases along the circumference of the tube. After that, the cold air is again heated by the heated tube. A plume of heated air over a heating tube can form a low velocity wake region. It is seen from Refs. [1,2] that two large natural circulations are formed outside the fins above the tube in the upper left corner and upper right corner of the box with an upper opening. This strong circulation helps to transfer heat from the adjacent fin surface to ambient air. This means that there are very complex three-dimensional (3D) heat transfer and fluid flow characteristics in plate fin and tube heat exchangers due to the plume of hot air over the heated horizontal tube in natural convection. Thus, this complex flow pattern can be interesting to study for heat transfer enhancement mechanisms.

Various inverse methods along with the measured temperature in the test material have been developed to analyze the inverse heat conduction problem [3,4]. However, the traditional inverse method cannot determine the heat transfer and fluid flow characteristics of the problem under investigation. Due to the lack of reliable experimental temperature data and heat transfer coefficient estimates, computational fluid dynamics (CFD) commercial software is not easy to obtain more reliable numerical results. Therefore, Chen et al. [1,2,5–7] used a hybrid method of inverse

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Nomenclature

a_i	major axis of the elliptical tube, mm
a_o	major axis of the elliptical fin, mm
b_i	minor axis of the elliptical tube, mm
b_o	minor axis of the elliptical fin, mm
A_f	lateral surface area of the fin, m^2
c_p	specific heat of air, kJ/(kg K)
d_{eff}	effective diameter of elliptical tube, $\sqrt{a_i b_i}$
D_{eff}	effective diameter of the fins, $\sqrt{a_o b_o}$
g_i	gravitational acceleration component, m/s^2
h	local heat transfer coefficient on the fins, $W/(m^2\ K)$
$\bar{h}$	average heat transfer coefficient on the fins, $W/(m^2\ K)$
$\bar{h}_b$	heat transfer coefficient under the situation of T_0, $W/(m^2\ K)$
$\bar{h}_k$	heat transfer coefficient in the kth sub-fin region, $W/(m^2\ K)$
k_a	thermal conductivity of the air, W/(m K)
k_f	thermal conductivity of the fins, W/(m K)
N	number of sub-fin regions
N_x, N_y, N_z	number of grid points on the fins in the x, y and z directions
N_t	total number of grid points
Nu	Nusselt number, $Nu = \bar{h}_b S/k_a$
Nu_s	Nusselt number, $Nu_s = \bar{h} S/k_a$
N_{za}	number of grid points between two adjacent fins in the z direction
Pr_t	turbulent Prandtl number
Q	total heat rate dissipated from the entire fin, W
Ra	Rayleigh number, $Ra = \frac{g\beta(T_0 - T_\infty)S^3}{\nu\alpha}\left(\frac{S}{D_{eff}}\right)$
S	fin spacing, mm
T	fin temperature, K
T_a	air temperature, K
T_k	measured fin temperature at the kth measurement location, K
T_0	fin base temperature
T_∞	ambient air temperature, K
t	fin thickness, m
u_i	air velocity in the i direction, m/s
x, y, z	Cartesian coordinates, m
Greek symbols	
β	volumetric thermal expansion coefficient
ε_f	emissivity of the fins
η_f	fin efficiency
ν	laminar kinematic viscosity, m^2/s
ν_{eff}	effective kinematic viscosity, m^2/s
ν_t	turbulent kinematic viscosity, m^2/s
ρ	density of the air, kg/m^3

method and CFD commercial software to determine the heat transfer and fluid flow characteristics of a vertical plate finned tube heat exchanger. In order to verify the applicability and accuracy of this hybrid method, the heat transfer and fluid flow characteristics of the heat sink and a horizontal fin on a hot sidewall in a heated cavity are also studied [8,9]. It can be seen from Refs. [1,2,5–9] that this hybrid method can overcome the above drawbacks. Chen and Chou [10] and Chen and Hsu [11] used the inverse method of finite difference method along with experimental data to predict the heat transfer coefficient on fins for single-tube plate fin and tube heat exchangers. Recently, Chen et al. [1,2,5–7] proposed a hybrid method of 3D CFD commercial software and inverse method along with experimental data to estimate the heat transfer and fluid flow characteristics of single-tube plate fin and tube heat exchanger. It is found in Refs. [1,2,5–7] that the numerical results obtained are close to the inverse results and experimental temperature data or match the correlation [12]. The zero-equation and RNG k-ε turbulence models are more suitable for annular and square plate finned tube heat exchangers than other flow models, respectively. The number of grid points may vary with fin spacing in order to get more accurate results. This means that the grid independence assumption may be inappropriate.

Yildiz and Yuncu [13] experimentally explored the performance of annular fins mounted on a horizontal cylinder in free convection with various fin spacings and diameters at low temperature differences. For scale analysis, the flow is assumed to be laminar and the thickness of the fins is considered negligible. Tolpadi and Kuehn [14] numerically studied the steady 3D laminar natural convection heat transfer from a horizontal isothermal cylinder with infinitely large transverse non-isothermal fins. Kayansayan [15] studied the natural convection of air over an annular finned tube and observed the effects of the fin spacing, fin diameter to tube diameter ratio and Rayleigh number on the heat transfer. It is seen in Ref. [15] that the heat transfer coefficient increases with an increase in the fin to tube diameter ratio due to enhancement in the buoyant force by larger fins. The increase in the fin diameter increases the air temperature reaching the tubes. Sajedi et al. [16] used experimental and numerical study on the optimal fin numbering in an external extended finned tube heat exchanger. Couple heat transfer between the water flow, the fins and the external air flow field is solved using FLUENT along with the assumption of laminar flow. Qiu et al. [17] applied FLUENT along with the assumption of laminar flow to determine the 3D fluid flow and heat transfer outside the tube. The effects of the fin surface emissivity, fin angle and tube wall temperature on heat transfer enhancement are investigated for longitudinal external-finned tube placed vertically in the small chamber. The numerical model is validated by comparison with experimental measurements and the appropriateness of the general boundary condition is examined. The results show that both convection and radiation heat transfer modes are important. Dogan et al. [18] numerically investigated the 3D laminar natural convection heat transfer from a horizontal annular-finned tube. An optimum fin spacing of 8.7 mm is obtained for the fin diameter ranging from 35 mm to 160 mm. Yaghoubi and Mahdavi [19] applied the control volume scheme to investigate natural convection heat transfer from a horizontal cooled finned tube. Three different grid sizes of 80-40-8, 120-80-16 and 170-130-20 are tested in radial, tangential and axial directions, respectively. The results in terms of average convection heat transfer show that a grid distribution of 120-80-16 is more appropriate in order to ensure a grid-independent solution with a difference of less than 3% compared to the lowest grid size. Kumar et al. [20] used 3D CFD to investigate the transient natural convection of air around a circular cylinder enclosed in a box of 1000 mm × 600 mm × 1200 mm for a Rayleigh number of 1.3×10^6. Kumar et al. [21] also used the software OpenFOAM-2.2 based on the finite volume approach to investigate the natural convective transient 3D numerical simulations of the air around a circular finned tube with annular plain fins kept in a small chimney. An elliptical tube with a smaller cross section has a minimum wake region and a stronger flow behind the tube. This phenomenon leads to a higher heat transfer coefficient. Kumar et al. [21] investigated only a plain elliptical tube without studying