International Communications in Heat and Mass Transfer 81 (2017) 1–7

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Forced convection on grey cast iron plate-fins: Prediction of the heat transfer coefficient

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ARTICLE INFO

Available online xxxx

Keywords:
Plate-fins
Experimental analysis
Forced convection
Direct/inverse numerical techniques

ABSTRACT

The main goal of the present work is to evaluate the convective heat transfer coefficient at the surface of grey cast iron plate-fins. A hybrid numerical/experimental approach was adopted, i.e., temperature was measured at selected points at the fin surface and an inverse problem technique based on optimization was used to obtain the heat transfer coefficients. The direct heat transfer problem was solved numerically using the finite volume method, whilst the optimization problem was resolved based on particle swarm optimization (PSO). Firstly, the temperature dependence is investigated by comparing uniform, linear and parabolic equations for the heat transfer coefficient. The hybrid approach was validated through an energy balance applied to the finned surface. The parametric study was performed by assessing the influence of the fin spacing and flow velocity on the convective heat transfer coefficient: the results indicate that the convective coefficient is enhanced with increasing Reynolds number and fin spacing. Finally, the experimental results for the Nusselt number in the parametric study were condensed into a single new empirical correlation with good accuracy.

1. Introduction

The convection/radiation heat transfer in extended surfaces (commonly known as fins) occurs in many practical engineering problems. Application of fins ranges from simple heat sinks for cooling electronic packaging to complex thermal systems in nuclear energy generation power plants. Moreover, it is important to emphasize that one of the most widely used fin geometry is the plate-fin heat exchanger [1–3], which is the object of the present work.

The works reported in the literature dealing with this topic are rapidly growing in recent years. The main objective of the investigations has been to examine the effects of the flow parameters on heat transfer at finned surfaces and to estimate the convective heat transfer coefficient [1–9]. Within this framework, focusing on both numerical and experimental works with practical applications, one finds the following studies: (*i*) Chen and Hsu [1] and Chen et al. [2] present two similar works proposing an hybrid methodology to obtain the heat transfer coefficient on fins of annular-finned tube heat exchanger in natural/forced convection; The authors applied the finite difference method in conjunction with the least-squares scheme and temperature measurements to predict the average heat transfer coefficient; Finally, a parametric study was performed and the main results indicate that the average heat coefficient increases with increasing fin spacing. (*ii*) In other study, Chen et al. [3] investigate the convective heat transfer coefficient in a plate-fin heat sink. The authors apply the inverse method in conjunction with experimental temperature data to determine the average heat transfer coefficient. The commercial CFD software Fluent® is also used to solve the governing equations in order to obtain the heat transfer and fluid flow characteristics. The results obtained by the authors indicate good agreement between the experimental data and the Fluent® commercial code. (*iii*) Diani et al. [4] study both numerically and experimentally the forced convection on extended surfaces (fins). The thermal and hydraulic behaviour of a reference trapezoidal finned surface was experimentally evaluated by the authors and compared against numerical simulations using the commercial software COMSOL®; The authors assessed the effects of the fin thickness, fin pitch and fin height on the thermo-hydraulic behaviour of the extended surface. The main results are collapsed in a new empirical correlation for the average heat transfer coefficient. (*iv*) Lee et al. [5] investigate experimentally the effects of perforated circular finned-tube on the convective heat transfer performance of heat exchangers; the results indicated that the convective heat transfer coefficient increases around 4% when using two holes in the fin surface. According to the authors, the increase in the convective heat transfer coefficient was related to the reduction of the recirculation region by introducing perforations on the finned tube. (*v*) Elshafei [6] performs theoretical and experimental studies to investigate the effects of duct velocity and fin density on thermal performance and pressure drop across a longitudinal aluminium fin array.

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2016.11.007
0735-1933/

Nomenclature

D_h	characteristic length, $D_h = \frac{4SL}{2L+S}$
g	objective function
$\bar{h}_c$	average convective heat transfer coefficient (W/m^{2}K)
H	fin height (m)
k	fin thermal conductivity (W/mK)
k_f	thermal conductivity of the air (W/mK)
L	finned plate length (m)
Nu_{D_h}	Nusselt number, $\mathrm{Nu}_{D_h} = \frac{\bar{h}_c D_h}{k_f}$
$\mathbf{p}$	design variables
q	heat flux per unit length (W/m)
Q_E	electric power input (W)
Re_{D_h}	Reynolds number, $\mathrm{Re}_{Dh} = \frac{U_\infty D_h}{\nu_f}$
S	fin spacing (m)
t	half of the fin thickness (m)
T	temperature (K)
U_∞	free-stream velocity in the wind tunnel (m/s)

Greek letters

ε^T_{RMS}	RMS temperature difference (K)
ν_f	kinematic viscosity (m^2/s)

The author's results show that flow bypass increases with increasing fin density and the calculated total pressure drop is greatly affected by fin density.

In order to conclude the present literature review, it is important to emphasize that some recent works have applied optimization procedures to determine technical parameters of finned heat exchangers [7–9]; along this route, (*vi*) Kotcioglu et al. [7] describe an experimental investigation for determination of optimum values of the design parameters in a plate-fin heat exchanger by using Taguchi method. The authors present experimental results which validate the suitability of the proposed approach. (*vii*) Salviano et al. [8] use genetic algorithms for optimization of position and angles of vortex generators in a plate-fin compact heat exchanger. The simulation using the Fluent® commercial code is applied to study the flow characteristics. The results indicate that the configurations of optimized vortex generators led to heat transfer enhancement rates higher than those reported in the literature. In other recent work, (*viii*) Dezan et al. [9] adopt the surrogate-based optimization procedure to maximize heat transfer for two basic geometries of multilouvered fin compact heat exchangers with delta-winglet vortex generators. According to the authors, when comparing with the respective baseline geometry (louvered fin without vortex generators), the results show that optimized solutions increase the heat transfer a minimum of 13.48% with associated pressure loss increasing around 20%.

Finally, in order to conclude the introduction section, it is worth mentioning that devising more efficient thermal systems is one of the research areas of the present authors. In recent works, Zdanski et al. [10,11] studied numerically/experimentally applications of turbulence promoters to thermal systems aiming at developing expressions for heat transfer/pressure drop predictions. In the present work a hybrid numerical/experimental approach is proposed to assess the convective heat transfer coefficient in a plate-fin heat exchanger. Distinctly from the aforementioned references [1–9] that address stainless steel and aluminium fins, the present study is applied to cast iron plate-fins which are typically used in cooling electric motors. In order to ensure velocity uniformity, the experimental tests were performed in a wind tunnel. In addition, bearing in mind the target application, the velocities tested in the wind tunnel are higher than the aforementioned works, leading to turbulent flow regime. Within this framework, the present assesses the influences of the flow velocity (Reynolds number) and fin spacing on the convective heat transfer coefficient at the finned surface. Furthermore, the results obtained for the Nusselt number are also condensed in a new empirical correlation with good accuracy.

2. Experimental setup

The experimental setup used in the present work is depicted in Figs. 1 and 2. An open circuit wind tunnel of suction type (range of velocities 4.0–15.0 m/s) was used to perform the experiments. The wind tunnel contraction ratio is 1:6 with a test section 0.25 m × 0.25 m, being the turbulence intensity of the oncoming flow in the empty test section less than 1% [11].

The plate-fin was manufactured of grey cast iron, typically used for cooling electric motors. The test fin has a height $H = 0.040$ m, length $L = 0.2$ m and thickness $2t = 0.005$ m. The fin surface temperature (T_s) was measured by twelve T-type thermocouples symmetrically positioned in three sections along the fin width (see Fig. 2). The limit of error of the T-type thermocouple is ±0.75% for the range 0–300 °C [12]. Aiming at supplying a constant heat flux, an electric resistance is attached to the fin base. A glasswool fiber thermal insulator is placed around the fin base aiming at minimize heat losses. Moreover, in order to study the effects of the fin spacing on the convection heat transfer coefficient, two acrylic fins are symmetrically placed with a variable spacing S parameter, illustrated in Fig. 2. The fins and corresponding gap dimensions were measured by an analog caliper. In addition, aiming at studying the effects of flow velocity on the heat transfer coefficient, the free-stream temperature (T_∞) and flow velocity (U_∞) were

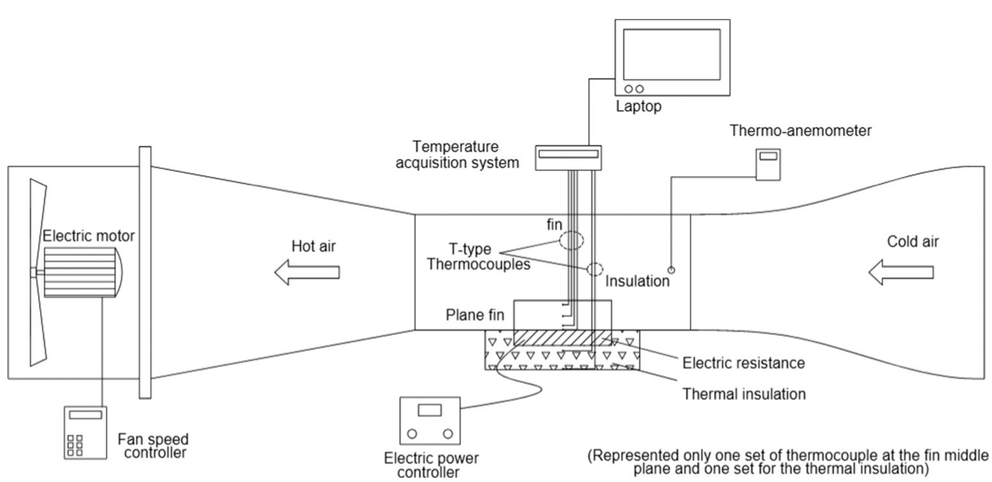

Fig. 1. Illustration of the experimental apparatus.