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Thermal and flow characteristics of a single-row circular-finned tube heat exchanger under elevated free-stream turbulence

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ABSTRACT

The thermal performance of *single-row* heat exchangers is generally considered to be inferior to *multi-row* heat exchangers. It is therefore desirable to optimize the former; especially for those cases which cannot accommodate an alternative. In this study, the heat transfer performance of a single-row circular-finned tube heat exchanger was investigated experimentally under elevated disturbance levels. Specifically, grid-generated turbulence (GGT)—the characteristics of which had been measured beforehand with a hot-wire anemometer—was applied to a clean-flow benchmark case and measurements taken at the heat exchanger outlet. It was shown that when the grid is positioned appropriately, a mean enhancement (in global Nusselt number) of up to 11% can be achieved. Flow visualizations revealed the flow structures responsible for the increase in heat transfer.

1. Introduction

The deployment of Concentrated Solar Power (CSP) plants in suitable worldwide locations requires more efficient dry cooling solutions (SunShot-Vision-Study, 2012, Carter and Campbell, 2009, Turchi et al., 2010). This paper is therefore focused towards the development of next-generation dry-cooling technology for these facilities, the details of which were reported in (Moore et al., 2014). It was concluded from that study that shallow circular-finned tube designs were an attractive option in terms of the cost-efficiency plant performance. The reduction in material costs and fan power requirements in these designs offset the poorer thermal characteristics and can potentially provide an overall performance similar to deeper, more conventional heat exchangers. A survey of literature in the area highlighted that potential heat transfer enhancements were possible for shallow tube bundles in turbulent and fan-generated flows. This paper focuses on the air-side performance of a single-row circular-finned tube bank subjected to various levels of grid generated free-stream turbulence.

The thermal performance of a single-row helically finned tube bundle was firstly investigated under uniform and low free-stream turbulence air-flow conditions in a wind tunnel facility. In comparison to conventional finned tube bundle research, where $n_r > 4$–6, relatively few authors have published results on shallow tube bundles. Some authors have presented correction factors for existing correlations for heat transfer and pressure drop predictions. Huisseune et al. (2010) reported that the use of data from multiple row heat exchangers for prediction of single-row heat exchangers is always speculative as many of these correction factors are a constant value over the entire Reynolds number range. Eckels and Rabas (1985) also reported that the influence of the number of rows depends on the Reynolds number. Huisseune et al. (2010) presented a heat transfer correlation for a single-row tube bundle. The measurements were compared to published correlations and they showed that the Mirkovic (1974) correlation over predicts the Nusselt number for a single-row tube bundle. Sparrow and Samie (1985) performed measurements on a single-row and a two-row tube bundle. For the one row array they found that the heat transfer coefficient increased as the transverse pitch decreased. The Nusselt number increased by about 35% as (S_t/d_{ex}) was decreased from 1.52 to 1.07. Kearney and Jacobi (1996) also studied the performance of a single-row tube bundle by measuring local mass transfer over the finned surface and using these measurements to infer local heat transfer coefficients. Through an integration process the average mass transfer was computed and hence the average Nusselt number was determined.

In the present study, the effect of elevated free-stream turbulence (i.e. that above the background level of the test facility) was investigated by placing a grid upstream of the tube bundle. At the outset it was therefore necessary to measure and characterize the GGT behind the grid of interest.

Roach (1987) gives a comprehensive survey of GGT for wind tunnel facilities. He provides several guidelines for grid geometry and scalings, and includes relevant correlations for the attendant downstream evolution of both RMS turbulence intensity and length scales.

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Nomenclature

A	Area m^2
b_1, b_2, b_3	King's-law constants-
C	Constant-
C_{min}	minimum capacity rate W/K
c_p	specific heat capacity J/kg K
d	Diameter m
h	heat transfer coefficient W/m^2 K
I	Constant
k	thermal conductivity W/m K
L	Length m
$\dot{m}$	mass flow rate kg/s
M	grid mesh-length m
N_f	fins per unit length 1/m
N_t	number of tubes per row
n_r	number of tube rows
Nu	Nusselt number
p	Pressure Pa
Q	heat power W
Re	Reynolds number
R_{uu}	autocorrelation function
S_t	transverse tube spacing m
T	turbulence intensity
t	temperature K
u	velocity component m/s
U	mean velocity m/s
U_t	overall thermal conductance W/m^2 K
u'	velocity fluctuation m/s
v	velocity component m/s
v'	velocity fluctuation m/s
w	velocity component m/s
w'	velocity fluctuation m/s
x	distance in flow direction m
α	correction factor
β	expansibility factor
δ	thickness m
Δ	differential
Λ_x	integral length scale m
ε	effectiveness
η	efficiency
μ	dynamic viscosity kg/m s
ρ	density kg/m^3
τ	time constant

Subscripts

a	air
atm	atmospheric
c	condensate
ex	external
f	fin
gd	grid
ht	heat transfer
i	inlet
o	outlet
pst	Pitot-static tube
ws	working section
∞	ambient

Abbreviations

CF	Circular finned
GGT	Grid-Generated Turbulence
SBG	Square-Bar Grid

Of particular interest, though, is the suggested location at which GGT becomes statistically symmetrical or *isotropic*—indeed, for this study the tube bundle is quite close to the grid ($\leq$ 10 mesh-lengths) and in this region GGT is notoriously *anisotropic*.

There are many different opinions on the emergence of isotropy behind grids. Groth and Johansson (1988) measured the ratio of streamwise and lateral intensities behind several rod-type grids and suggested that the flow was practically isotropic after 20 mesh-lengths (although the indicated trend may tentatively suggest 10—the value also put forth by Roach). Yet other studies (Comte-Bellot and Corrsin (1966), in particular) suggest that anisotropy may persist for many *hundreds* of mesh-lengths behind the grid in some cases. In many facilities and real-world setups, however, a settling region of more than a few mesh-lengths is simply impractical and a small degree of anisotropy must often be tolerated. This underscores the need to measure—and also to understand the nature of—the turbulence generated by a grid in a specific setup. In this study, a grid of 50% solidity (the blockage area-ratio) was used and its characteristics measured with a hot-wire anemometer. The thermal performance of the heat exchanger was then evaluated with the grid 100 mm (3.7 M) and 270 mm (10 M) upstream.

Fourie and Kroger (1987) and Zozulya and Khavin (1973) both performed thermal measurements on circular-finned tube heat exchangers with grids installed upstream. Fourie and Kröger reported enhancements of 12–17% in the first tube row of a three-row exchanger and Zozulya et al., for a turbulence intensity of 25%, enhancements of up to 35%. The suggested reasons for the enhancement were that: (i) due to the effected delay in separation (and therefore shrinkage of the tube wake) the finned region downstream of the tube provided better heat transfer; and (ii) vortices in the free-stream perturbed the fin-tube boundary layers, thereby introducing colder masses of flow to the heat transfer surfaces (much like the streaky structures generated by free-stream turbulence in, for example, a plate boundary layer) and increasing the mean temperature gradients there. Brauer (1964) and Hu and Jacobi (1993) have also found evidence to support this result. Mon and Gross (2004), however, suggest that such local flow interactions are heavily dependent on the fin-pitch.

All experiments in this study were conducted in a subsonic wind tunnel facility. The specific objectives are thus:

- To measure the thermal performance of a single-row heat exchanger and assess the accuracy of existing correlations in predicting the thermal characteristics.
- To investigate the thermal performance of the heat exchanger under various levels of free-stream GGT.

2. Theory

This section presents the theoretical relationships required characterize the air-side heat transfer from finned-tube heat exchangers. Correlations for grid turbulence are also presented.

2.1. Heat transfer

The thermal performance of a heat exchanger is expressed in terms of the dimensionless flow rate, Reynolds number, and a dimensionless heat transfer coefficient (in this case the Nusselt number). These relationships are provided in Eqs. (1) and (2), respectively.

$$Re = \frac{\rho u d}{\mu} = \frac{d_{ex}\dot{m}_a}{\mu A_{min}} \quad (1)$$

$$Nu = \frac{h d_{ex}}{k} \quad (2)$$