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Can CFD accurately predict the heat-transfer and pressure-drop performance of finned-tube bundles?

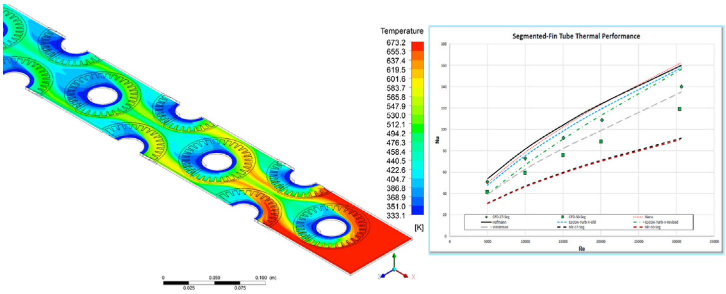
Cathal T. Ó Cléirigh*, William J. Smith

School of Mechanical & Materials Engineering, University College Dublin, Belfield, Dublin 4, Ireland

HIGHLIGHTS

- Finned-tube bundles in cross flow were modelled using Computational Fluid Dynamics (CFD).
- The model was used to predict heat-transfer and pressure-drop performance of the bundle.
- Solid; partially-serrated; and fully-serrated, helically-wound fins were investigated.
- Results were found to be within the range predicted by existing empirical correlations.
- Finned-tube performance is highly sensitive to the height/density of fin serrations.

GRAPHICAL ABSTRACT



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ABSTRACT

A Computational Fluid Dynamics (CFD) model capable of predicting heat-transfer and pressure-drop performance of finned-tube bundles in cross flow is presented. Three helically-wound fin geometries are investigated: solid (continuous); partially-serrated; and fully-serrated. A steady-state approach, with a two-equation turbulence model, is employed to examine Reynolds numbers in the range of 5000–30,000. The external Nusselt number and overall pressure drop predicted by the CFD model are compared with those predicted by published empirical correlations. The CFD results fall within the range of values predicted by the empirical correlations. The CFD results show that the Nusselt number increases by up to 23% between the partially- and fully-serrated fins; this sensitivity to serration geometry is not captured in any currently published empirical correlations.

1. Introduction

Tube bundles in cross flow are found in many industrial heat-transfer applications, from air conditioning and cooling, to boiling and heat-recovery operations. Commonly, wound fins are located on the external tube surface, improving the rate of heat transfer by increasing the surface area and improving convection at the surface. These fins may be continuous (solid) or serrated (segmented, as is the case in Fig. 1). In general, a serrated fin will have a higher average convection coefficient, but a reduced surface area, when compared to a solid fin of the same dimensions. The presence of serrations disturbs the formation of boundary layers in the fluid flow over the fin, increasing convection at the surface.

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* Corresponding author. Tel.: +353 1 716 1932, +353 86 395 5923 (mobile).
E-mail addresses: cathal.ocleirigh@ucdconnect.ie, cocleirigh@gmail.com (C.T. Ó Cléirigh).

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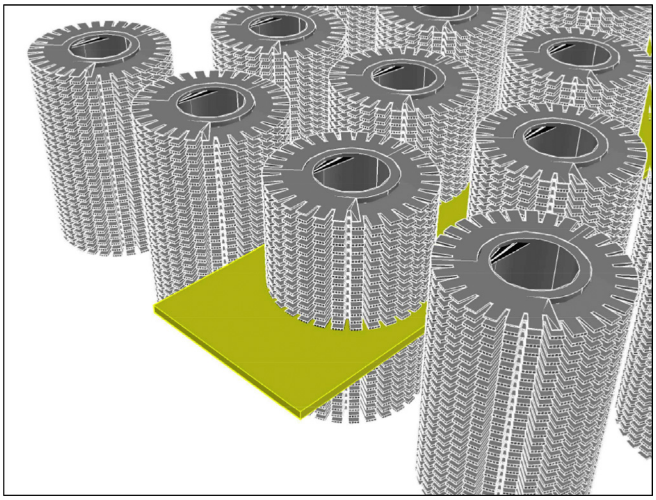

Fig. 1. Section of finned-tube bundle with computational region highlighted (yellow). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Of particular interest are helically wound, finned-tube bundles in cross flow, as are commonly used in Heat Recovery Steam Generators (HRSGs) of combined-cycle power generation plant. Where the external flow through the bundles is gaseous, and there is a high internal convection coefficient (e.g. liquid water flow), the gas-side convection resistance will constitute approximately 95% of the overall thermal resistance [1]. Therefore, optimisation of heat exchanger design and modelling requires high-quality gas-side performance data, for both the heat transfer and pressure drop calculations.

Although numerous semi-empirical correlations are available in the literature for estimating the convection coefficient of tube bundles with solid fins (both annular and helically wound), the values predicted by such correlations rarely agree with one another, and in some cases can differ by as much as 30%. In this study, convection coefficient estimates produced by a 3D CFD (computational fluid dynamics) model are compared to those obtained with some of the most widely-used empirical correlations: Kaunas [2], PFR [2], ESCOA [1,3], Weierman [4] and Nir [5]. Modelling of solid-fin tube geometry was included in this study for the sake of completeness; the primary focus of this study was on modelling of the serrated-fin tubes typically found in HRSGs.

There are a limited number of correlations available for serrated-fin tubes bundles, and with each correlation based on a finite range of experimental data, application is restricted to a limited range of geometric parameters and Reynolds number. The correlation developed by Næss 2010 [6], for example, was based on various serrated-fin tube geometries; however the relative fin pitch was limited to the range: $0.1333 \le S_f/d_o \le 0.2432$.

Heat exchanger designers and researchers would benefit immeasurably from a method to accurately predict the performance of a fin tube bundle, with geometric parameters outside those covered by existing correlations, without recourse to time consuming and expensive experimental work.

This paper presents a method to predict the Nusselt number and pressure drop in helically finned tube bundles, both solid and serrated, using finite-volume Computational Fluid Dynamics (CFD). The method uses a steady-state approach; and a two-equation, eddy-viscosity, turbulence model. Selection of appropriate boundary conditions enables accurate results to be obtained on a desktop PC within a reasonable timeframe. Three staggered, finned-tube geometries were modelled – one solid-fin, and two serrated-fin designs – in the Reynolds number range of 5000–30,000. The results of the CFD models are compared with those obtained using published correlations; to the best of the authors' knowledge, this is the first work to do so for multi-row, finned-tube bundles.

There are few semi-empirical correlations available for helically-wound, serrated-fin, tubular heat exchangers. Weierman 1976 [4] presented a set of correlations for both solid and serrated fins, based on selected data from published and proprietary sources. The ESCOA correlations [3] follow a similar format to Weierman's; however they were published as a manufacture's recommendation to designers and the source of experimental data is unclear. The correlation developed by Nir 1991 [5] was based on a large range of published data for both solid- and serrated-fin tube bundles. More recent work – such as Kawaguchi et al., 2005 [7]; Hofmann 2009 [8]; Hofmann and Walter 2012 [9]; and Næss 2010 [6] – has focused on developing correlations based on the authors' own, published, experimental data. Kawaguchi's correlation is based on two solid-, and two serrated-, fin tube geometries. Næss identified the geometric parameters affecting Nusselt number and pressure drop by investigating the performance of ten serrated-fin tube geometries. Hofmann's correlation is based on one solid-fin, and two serrated-fin, tube geometries. Hofmann also presents the results from the k-ε CFD analysis of a single, helically-wound, serrated-fin tube in cross flow. His CFD predictions compared favourably with his experimental results for the same, single-tube layout.

Currently, the use of empirical correlations is an essential element of heat-exchanger design and modelling. Walter and Hofmann modelled boiler dynamics [10], demonstrating the effect of different correlations for external Nusselt numbers on predicted boiler behaviour. Martinez et al. [11] investigated the optimum fin tube geometry, based on published correlations for Nusselt number and pressure drop. Prieto et al. [12,13] employed empirical correlations to predict temperature distribution in unfinned boiler tubes.

Two studies by Martinez et al. [14,15] compare the experimental performance of a helically-serrated, finned-tube, heat exchanger in industrial operation, with the performance predicted using the correlations by Weierman [4], ESCOA (revised) [1], Nir [5] and Kawaguchi et al. [7]. At Reynolds numbers of 6000–11,000, Martinez found that Kawaguchi's correlation provided the most accurate prediction of *U*-value, with an accuracy of 77.74–99.59%. Nir's correlation was found to be the least accurate for the specific geometry studied, with an accuracy of 66.77–73.87%.

CFD simulations of solid and serrated helical-fin tubes in cross flow were carried out by Lemouedda et al. [16], at low Reynolds numbers ($1320 \le \mathrm{Re} \le 5750$ when calculated using the method below). The authors employed a computationally-intensive, transient, Large Eddy Simulation (LES) technique, without a sub-mesh turbulence model. At the higher Reynolds numbers investigated in this paper ($5000 \le \mathrm{Re} \le 30{,}000$), flow is turbulent, and therefore a sub-mesh turbulence model is required. On the other hand, no transient-flow structures are generated at a macro-scale (there is no vortex shedding), and so a steady-state approach can be adopted. Lemouedda's work investigated the effect of segment-twist angle on heat transfer rate and fan pumping power. However, the results obtained from the LES model were neither compared to experimental data, nor to results obtained from other studies in the literature.

2. Computational model

2.1. Finned-tube bundle

A horizontal region of the finned-tube bundles was selected for the computational model. As can be seen in Figs. 1 and 2, the geometry enclosed in the computational region repeats periodically