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Numerical assessment of the reduction of the entropy production rate caused by fin segmentation in heat exchangers

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ABSTRACT

A numerical comparison of the entropy production rates caused by plain and segmented fins is presented. These fins evolve as helical surfaces around their respective tubes, which are themselves arranged according to a standard layout in heat exchanger applications. A finite volume, two-layered, Reynolds Averaged Navier-Stokes (RANS) model was implemented to calculate the properties of a turbulent stream of hot air flowing through the array of tubes. This approach enabled an appropriate evaluation of the mean and the fluctuating contributions to the thermal and viscous entropy production terms. It was found that fin segmentation reduced the production of entropy nearly 16% with respect to the plain fin design. For this particular setup it was also shown that the thermal contribution to the global production of entropy is one-order-of-magnitude larger than its viscous counterpart. The numerical results agree with the experimental observations previously reported by other researchers. Some design recommendations are given at the end of the conclusions section.

1. Introduction

The rational use of energy demands a continuous search for efficient heat exchangers. It is for this reason that compact heat exchangers are engineered to maximize the amount of heat transferred, while preventing large pressure drops [1]. Apart from the obvious economic benefits, savings in the expenditure of the energy required to operate the heat exchangers also have a strong environmental repercussion. These requirements reflect on the specification of the geometrical configurations, the materials, the fluid properties, and the operating conditions [2]. For instance, the performance is found to be largely determined by the pattern of tubes in the array (e.g., staggered vs. in-line), the types of fluid involved (e.g., gas vs. liquid), and the particular flow regime (e.g., laminar vs. turbulent).

Naturally, the pitch and thickness of the fins also have a strong bearing on the performance of this kind of device [3]. Understanding the influence of a particular design constitutes, as a matter of fact, the primary motivation of the present study. Previous investigations have shown that the fins contribute to increasing the efficiency by making a larger surface available to the heat transfer process [4–7]. A side benefit in applications where gas is one of the working fluids, is that the global convective coefficient is also enhanced.

In the special case of helical fins, several authors have investigated the effects associated with the variations to the elementary plain geometry (constituted by a simple surface). A series of useful correlations have resulted from those investigations, which allow an adequate prediction of the pressure drop and the convective heat transfer coefficient [6–15]. The advantages of certain modifications to the basic plain geometry (e.g., such as segmentation) have also been demonstrated for different internal layouts of the tubes.

Papa [11] and Kawaguchi et al. [12–15] conducted some of the most detailed experimental studies with these geometries. The results obtained by Papa [11] showed that, although the total amount of heat transferred through plain fins is slightly higher than with segmented fins, the global convective coefficient is larger in the latter case. Besides the evaluation of these coefficients, the velocity and the temperature profiles were also reported for both fin types. Kawaguchi et al. [12,13], on the other hand, measured and compared the pressure drop and the amount of heat transferred in arrays where the pitch of the fins were modified. The effects related with the length of the segments were considered in their posterior

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set of experiments [14,15]. It was found that the segmentation of the fins increased the convective coefficient, but also the pressure drop, owing to the induced turbulence. Others relevant studies concerning segmented fins were carried out by Martínez et al. [16,17], who compared the available correlations for the pressure and the convective coefficient, against experimental data obtained from an industrial compact heat exchanger. Their results indicated that the correlation proposed by Weierman for the pressure drop [8], and by Kawaguchi-Gnielinski for the overall heat transfer coefficient [13,18], were more appropriate for industrial compact heat recovery systems.

Interestingly, the assessment of compact heat exchangers has been conducted mostly from a conservation of energy point of view. Some authors, however, have considered an entropy based approach, because it enables an adequate evaluation of the (adverse) effects associated with the imperfections in the system [19–22]. The production of entropy provides a measure of such effects which, ultimately, hinder the overall efficiency of the device. In view of this possibility, the present investigation focuses on the simultaneous contributions of the thermal and the flow fields to the production of entropy.

Some of the first numerical studies concerned with the production of entropy of thermal and viscous origin, involved the interactions of laminar flows with simple geometries [23–26]. Since the two types of contributions to the production of entropy are relevant in many applications, other investigators developed correlations to produce their corresponding global estimates in the presence of turbulent flows interacting with simple geometries [27,28].

In their work, Adeyinka and Naterer [29] determined the general form of the averaged thermal and viscous entropy production terms with turbulent flows. Meanwhile, Herwig and Kock [30] performed an integral analysis based on a finite volume, Reynolds Averaged Navier-Stokes (or RANS) methodology, for a flow in a pipe with twisted tape inserts. Furthermore, these authors proposed expressions for the thermal and viscous entropy production terms in the κ-ε turbulence model. It is important to remark that Herwig and Koch concluded that the numerical computation is more accurate than the analytical one, because the turbulent diffusive term is usually neglected in the later approach [30]. Another closely related study was carried out by Simo Tala et al. [31]. Their numerical investigation concerned the use of a RANS code coupled to a finite volume method. The aim of the study was to evaluate the effect of the tube's ellipticity on the production of entropy, when the tubes are subjected to a cross-flow. One of the significant findings in Simo Tala's work is the localized appearance of entropy production spikes in certain regions of the flow. Moreover, it was demonstrated that an increase of the ellipticity improved the thermo-hydraulic performance of the device as a result of a lower produced entropy.

To the best our knowledge, there are no previous numerical studies concerned with the production of entropy in compact heat exchangers, which are built around arrays of tubes with helical fins. Consequently, the performance of two fin geometries is analyzed in this work: a) a plain helical fin, and b) a segmented helical fin. The general configuration of the device and the operating conditions are the same as those reported by Papa [11] and by Martínez et al. [32]. In contrast with the research previously conducted with

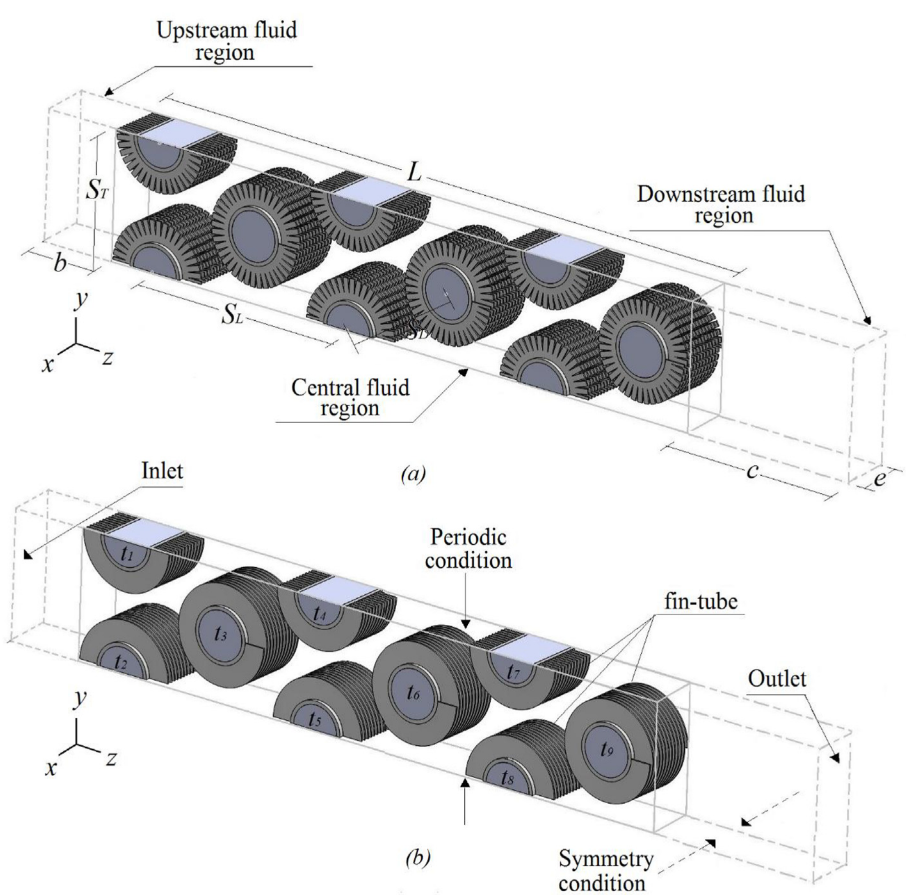

Fig. 1. Segmented and plain finned tubes arrays under analysis: *(a)* domain lengths, *(b)* Boundary conditions.