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Non-local entropy evolution in heat exchangers with elliptical and circular tube geometries

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ABSTRACT

Numerical simulations of the entropy transportation process inside a plate and tube heat exchanger are presented. Entropy levels around tubes with circular and elliptical cross sections are analyzed and compared. The purpose of the comparison is to determine how the entropy flux contributes to increase, or decrease, the value of the entropy in certain regions of the flow field. This is accomplished by numerically integrating the Reynolds averaged transport equations for the mass, momentum, energy and entropy, in a three dimensional domain. A k-ε-2L model is used to account for the fluctuations appearing in the laminar-to-turbulent transitional regime of the flow. The importance of entropy convection, relative to the generation of entropy, is underlined by means of a direct comparison through a series of visualization maps. This approach allows some useful insights about the evolution of the entropy field in complex geometries. For example, in this case certain troublesome regions where the entropy field reaches high values can be identified and, therefore, design recommendations can be stated in order to increase the thermal efficiencies of the devices under consideration.

1. Introduction

Understanding the entropy transportation process inside heat exchangers becomes a matter of practical importance when optimal efficiencies are sought. The traditional approach has been that of assessing the location of the sources of irreversibility (e.g. [1–4]). However, a transport point of view may provide additional insights, because the evolution of the entropy field is non-local in nature [5,6]. In this paper we, therefore, seek to consider the evolution of the entropy field from a macroscopic transportation perspective.

The relevance of the processes by which entropy is transferred from one point to another in a flow system, was previously pointed out by other researchers [e.g. Refs. [5,7–10]]. For example, Shuja et al. [8] anticipated a relationship between the entropy produced downstream from the bodies and the formation of wakes. Then Simo Tala et al. [9] stressed the interrelation between the global characteristics of the flow structures and the local values of the quantities involved in the generation of entropy (global and local behavior were related via non-local operators). More recently Hernández-Arrieta et al. [10] reported the appearance of secondary entropy generation spots at particular locations in a heat exchanger, and suggested that these spots were strongly dependent on the development of large-scale flow structures.

Precedents of such observations may be traced back to the work by Moore J. and Moore J. G [11]. These authors developed an entropy equation for turbulent flows from an earlier formulation for laminar flows [12]. Following these first steps, Kramer-Bevan J. S [13]. Developed and applied an averaged entropy transport equation to various flow problems. In that context the entropy generation counterbalance effects, caused by the convective-diffusive and transient mechanisms, were amply discussed. In a subsequent study, Jansen K. E [14]. Further advanced the technique by symmetrizing the Reynolds-averaged entropy transport equation, through a generalized function that satisfied the Clausius-Duhem inequality. It is important to note that ad hoc transport equations for the entropy have produced results that differed from those obtained by post-processing thermal and velocity field values [15].

The fundamental development of “second law” methodologies is based on the generation of entropy, while its application to diverse types of systems has produced a wide variety of important results [e.g. 16 to 20]. One of the most influential points of view concerns the systematic approach to the entropy generation minimization problem in thermal systems, which is embodied in the practical methods advanced by Bejan [16]. From that point of view, a variety of irreversible processes may be analyzed with the ultimate goal of optimizing the system under the given time and space constraints. At the heart of the method lay the minimization of the entropy generation rate and the Gouy-

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Stodola theorem [17]. Augmentation techniques for heat exchangers emphasizes the interplay between the viscous and the thermal contributions to the entropy generation rate [e.g. Ref. [18]]. In the interesting case of microchannel flows subjected to the combined action of conjugate heat transfer and magneto-hydrodynamic effects, Ibañez and Cuevas showed that the minimization of the generation entropy could be effected in various meaningful ways to suit specific design needs [19]. Other interesting optimizations regarding counterflow heat exchangers are discussed by Ordóñez and Bejan [20].

More recently, processes related with the flow of nanofluids have deserved much attention. For a comprehensive review on entropy generation in nanofluid flows the reader is referred to Mahian et al. [21]. In particular, the use of Cu-water nanofluids to enhance the convective heat transfer in heat exchangers is shown to have noticeable effects. Another review concerning the generation of entropy in enclosures and porous media is provided by H. F. Oztop and K. Al-Salem [22].

Entropy generation has been the subject matter of various convection processes, flows in cavities, around cylinders and in porous media, as well as in the presence of external fields and with nanofluids [e.g. 23 to 25]. Articles along these lines involve analytical, numerical and experimental research. For instance, the magneto-hydrodynamic flow of non-Newtonian nanofluids in enclosures was numerically shown to enhance the thermal efficiency when the Hartmann number increases [23]. Mahian et al. [24] presented an analytical solution for a nanofluid flow in a cylindrical annulus subjected to a heat transfer process. These authors also found that an increase of the Hartmann number entails a reduction of the generation of entropy. Bianco's et al. parametric study showed that for turbulent convection in tubes the thermal efficiency may be increased with rather low concentrations of nanoparticles [25].

Further applications in relevant in engineering contexts may be inferred from the work by Siavashi and Jamali [26], who found that the generation of entropy in two-phase, turbulent flows in cylindrical annuli can be minimized by adding nanoparticles. Another interesting application concerns MHD pumps that operate with nanofluids in cooling channels for electronic devices [27]. Yousofvand's et al. results indicate that the entropy generation may be reduced by a subtle interplay between the fraction of nanoparticles and the strength of the external electromagnetic fields.

On the other hand, the emphasis placed on the sources of entropy stimulated the development of sophisticated models for the turbulent thermal and viscous effects. Along these lines Adeyinka and Naterer [28] developed closure relations for their entropy transport equation. These closures were modeled under the "small turbulent temperature assumption" (or STTA). Apparently, their validity was confirmed with a simplified model that resembles a laminar flow model, except for the appearance of an effective diffusivity. Afterwards, Stanciu and Marinescu [29] suggested that bulk based models might be insufficient to properly account for turbulent fluctuations. One of their main conclusions was that the contributions from the fluctuating field may be as important as those emerging from the mean field.

The theoretical groundwork eventually lead to a variety of computational fluid dynamics (or CFD) studies concerning entropy generation with more complex flows and geometries (e.g. Refs. [8,30–32]). In the present context, for example, Iandoli and Sciubba [8] applied Large Eddie Simulations (LES) to investigate the local generation of entropy in the vicinity of turbine blades. Important aspects, such as vortex dissipation (via the stretching mechanism), the limitations of two-dimensional flow models and the possibility entropy transportation, were discussed. Before that Kock and Herwig [33] approached the entropy generation problem in a practical way by post-processing the field variables calculated from the mass, momentum, and energy equations. The objective was to circumvent the limitations of commercial codes. Eventually, semi-empirical wall functions were devised for processes characterized by high Reynolds numbers, and were incorporated into their CFD codes [33]. Generally speaking, the results were comparable to the those obtained from direct numerical simulations for pipe flows, as well as for shear flows [34]. Finned oval tubes, with vortex generators punched in the fins, were also investigated from the local entropy generation point of view by Herpe et al. [35]. Strong gradient zones within the boundary layer, as well as the vortex structures, were found to greatly influence the generation of entropy.

Since the present interest is in plate and tube heat exchangers, we give further consideration to the work by Simo Tala et al. [9]. In their CFD study these authors analyzed the effect of the tube's ellipticity on the generation of entropy. A Reynolds Averaged Navier-Stokes (RANS) model, and a *k-ω* Shear Stress Transport Model (or *k-ω-SST*) for turbulent transport, were jointly solved by means of a finite volume method. Besides evaluating the generation of entropy, a series of characteristic flow features were shown to be relevant and were discussed accordingly. Other tube geometries with segmented helicoidal fins were subsequently investigated [10]. In this later work it was found that, although relatively small quantities of entropy were actually produced on the downstream sides of the tubes, the overall entropy budget was quite significant in those regions.

Finally, it is worthwhile remarking that heat lines and energy flux vector contours have been successfully used to depict the manner in which various interactions take place [e.g. Hussain [36], Hooman et al. [37]]. In particular, Hooman et al. concludes that, besides implying savings in the numerical computations, the technique moreover allows an appropriate visualization of the flow of energy near specific features (such as the walls).

In view of the foregoing antecedents, the purpose of this article is to describe the characteristic features of the entropy transportation process in the laminar-to-turbulent transitional regime. The process takes place in a three dimensional domain, inside a plate and tube heat exchanger.

It should be remarked that this paper is a continuation of the work by Hernández-Arrieta et al. [10]. The salient observation in the present investigation is that the entropy convected in the wake regions behind the tubes differs from the locally produced entropy. Therefore, in order to fully understand how the entropy is distributed throughout the domain, the flow structures evolving around the tubes should be considered. For instance, the focus could be placed on the evaluation of the convective, the diffusive and the generation mechanisms participating in the specific flow situation under consideration. In this sense the flow regime, the geometrical details of the device, and the properties of the materials and the substances involved, would jointly contribute to define the characteristics of the entropy distribution. It follows that understanding the relative importance of each contribution could prove to be useful during the design and optimization stages.

In the particular case at hand, the results are formatted such that the visualization of the flow structures is more clearly revealed. The color scales indicate the numerical value of the entropy in each location. Furthermore, if necessary, these results could be represented by level curves (with their corresponding numerical values), in a fashion similar to the results reported by Hussain [36].

To the best our knowledge, there are no previous numerical studies concerned with the entropy transportation in a plate and tube heat exchangers. Two types of staggered tubes (circular and elliptical) were analyzed. The purpose of this article is to determine the local distribution of the entropy transportation process in order to identify the main differences between the convective and the diffusive mechanisms comparing both arrays. The general configuration of the device and boundary conditions are the same as Simo Tala et al. [9].

2. Problem under consideration

Following Simo Tala et al. [9] we consider the plate and tube heat exchanger illustrated in Fig. 1. This is a three dimensional geometry, where solid tubes with circular and elliptic cross sections are investigated for comparison purposes. Both the longitudinal and the