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Editorial

Second-Law Analysis: A Powerful Tool for Analyzing Computational Fluid Dynamics (CFD) Results

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Second-law analysis (SLA) is an important concept in thermodynamics, which basically assesses energy by its value in terms of its convertibility from one form to another. Highly-valued forms of energy in this context are called exergy, defined as those energies from which the maximum theoretical work is obtainable when the energy is interacting with the environment to equilibrium (see Moran et al. [1], for example).

The counterpart of exergy, also called available work, is anergy, so that with this concept energy can generally be regarded as the sum of exergy and anergy. As a consequence of the second law of thermodynamics, exergy can be lost but cannot be created. Therefore, in a reversible process, exergy is preserved, whereas irreversibility (like losses in a flow field) leads to a loss of exergy (in favor of the corresponding increasing anergy).

Losses in flow and heat transfer fields can, thus, be determined by their impact on the exergy, i.e., by determining the exergy losses. These losses of exergy are thermodynamically linked to the generation of entropy by the so-called Gouy Stodola theorem. It states that the lost exergy corresponds to the product of entropy generation and the environmental temperature (see, again, Moran et al. [1]).

From a thermodynamic point of view, the quality of a flow or heat transfer process can be assessed by the entropy generation rate in this process (see Herwig [2]). However, entropy almost never appears in the textbooks of fluid dynamics and heat transfer (see, e.g., Batchelor, et al. [3] and Incropera, et al. [4]). This concept is widely ignored perhaps because the irreversibility effect is often fundamentally important in these two disciplines.

After Bejan [5,6] laid the foundation with respect to analyzing and optimizing thermal systems with the SLA approach, the SLA of flow and heat transfer problems received more and more attention. Applying the SLA in computational fluid dynamics (CFD), Kock and Herwig [7] extended this concept to an in-depth analysis of turbulent flows and identified four different mechanisms of entropy generation: dissipation in a mean and fluctuating velocity field and heat flux in a mean and fluctuating temperature field. They also suggested how to calculate the entropy generation rates with the Reynolds Averaged Navier–Stokes (RANS) results. Herwig [2] stated that, with the help of the SLA, one may answer four important questions regarding a momentum and/or heat transfer process:

- Which is the ideal process (no entropy generation)?
- Where does entropy generation occur in a non-ideal process?
- Why does entropy generation occur at a certain location and with certain strength?
- How can entropy generation be reduced overall or locally?

The purpose of this special issue is to demonstrate how the CFD results can be better interpreted by the SLA. We collected 12 papers in this special issue, covering both engineering applications [8–12] and fundamental studies [13–19] with respect to CFD of flow and heat transfer problems and interpretation of the CFD results with the SLA.

An important engineering application of the SLA is evaluating irreversibility in gas turbines. Three papers [8–10] in this special issue belong to this topic. Jin et al. [8] derived the entropy and exergy equations for compressible/incompressible flows in rotating/stationary frames. These equations can not only be applied to assessing gas turbines, but can also be used for analyzing general CFD results. They also proposed the concepts of energy transformation efficiency and number, which can be used to assess the contribution of a gas turbine or a single process in it to exergy transformation. In more detail, Lin et al. [9] investigated the local entropy generation through a high-pressure turbine cascade, while Wang et al. [10] analyzed the irreversible losses in a compressor cascade.

Laskowski et al. [11] applied the SLA to an optimization of a condenser in a steam power plant. An economic optimization method was introduced to assess the performance of a condenser. Eger et al. [12] employed the SLA in an electric machine to enhance heat transfer sinks. They found that the design obtained by the SLA optimization is noticeably better than those obtained with a classical analysis.

The SLA was also intensively applied to fundamental studies, such as convective heat transfer problems [13–18]. Four papers among these studies are about forced convection: Ji et al. [13] analyzed the entropy generation of fully-turbulent convective heat transfer of nano-fluids in a circular tube according to their RANS results. The Soret effect on entropy generation in a porous medium was studied by Torabi et al. [14]. Based on the numerical results, they argued that the SLA can be helpful for the design of micro-reactors and micro-combustor systems. Isaacson [15] studied the entropy generation rates in helium boundary layer flows. The influences of temperature and pressure were considered. The transition from laminar to fully-turbulent flow was also discussed in the study. Adesanya and Fakoya [16] calculated the entropy generation due to the flow and heat transfer through an infinite inclined channel filled with porous media.

Two papers [17,18] are about natural or mixed convection. Adesanya et al. [17] studied the entropy generation due to mixed convection in an inclined channel filled with porous media. They argued that the coupled stresses and porous medium may reduce the entropy generation rate. Wei et al. [18] studied entropy generation of two-dimensional Rayleigh-Bénard convection. The effects of the Prandtl number were investigated.

Zhou et al. [19] employed the concepts of entropy in turbulence model development. They proposed a shear stress transport (SST) based delayed detached-eddy simulation (DDES) model, which uses the entropy function to shield the turbulent boundary layer. The turbulence model was validated through a test case with large-scale vortex shedding.

The papers in this special issue show the potential of using the SLA to analyze CFD results. In addition to the traditional fields, such as gas and steam turbines, it is interesting to see that the SLA is also becoming popular in some emerging subjects, such as the heat transfer of nano-fluids [12,16] and micro-fluid flows in porous media [14,16].

In addition to this progress, some barriers still have to be overcome to obtain more benefits from the SLA. One of the barriers is due to the accuracy of the CFD results. In the papers of this special issue, the turbulent flow and temperature fields were generally calculated with RANS methods [8,12,13,15] or DDES methods [9,10,19]. However, the accuracy of the entropy generation rates are very sensitive to the turbulence model. The often-used RANS models may introduce considerable model errors (see Jin and Herwig [20]). Large eddy simulation (LES) and direct numerical simulation (DNS) are more accurate, whereas their computational cost is too high to be used in industrial problems. More accurate models with acceptable computational cost should be developed in the future to evaluate the irreversible losses accurately.

In addition, the concepts of the SLA were traditionally developed in the discipline of thermodynamics for assessing thermal systems. Their interrelation with other disciplines, particularly the emerging disciplines, should be further studied. For example, in fluid mechanics, the loss often refers to the loss of kinetic energy in the flow field, which can be quantified by the dissipation rate. According to the SLA, however, only a part of the loss of kinetic energy is the irreversible loss if the fluid temperature is higher than the environmental temperature. More efforts are still required to interrelate the concepts of the SLA in different disciplines.

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