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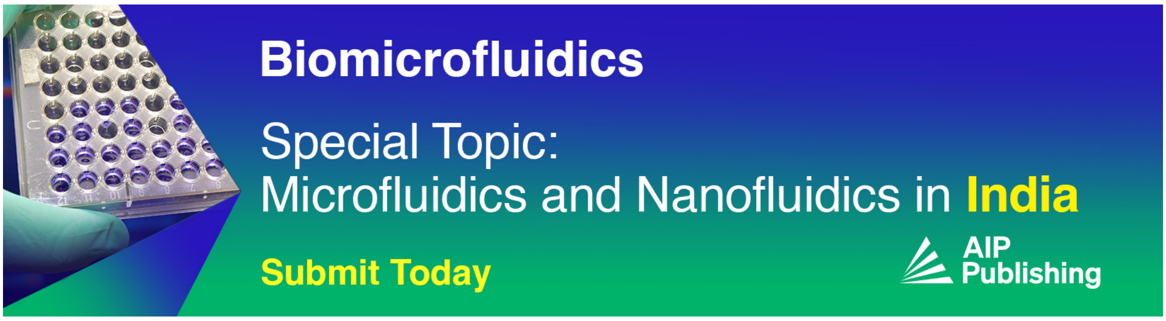

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Comment on "A fallacious argument in the finite time thermodynamic concept of endoreversibility" [J. Appl. Phys. 83, 4561 (1998)]

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In his paper D. P. Sekulic [J. Appl. Phys. **83**, 4561 (1998)] advances a number of arguments about finite-time thermodynamics which call for refutation as well as comment. It provides an opportunity to put into print a clarification of just what finite-time thermodynamics is, what it is not, and how it is related to some of the other, parallel efforts in the treatment of irreversible systems and their performance. The two major points of the present comment are (i) finite-time thermodynamics is a general theory independent of the concept of endoreversibility, which was originally introduced only to generate simple examples, and (ii) the strict division between the system to be optimized and the given fixed surroundings is essential to a correct interpretation of the results. I will refrain from commenting on details in D. P. Sekulic [J. Appl. Phys. **83**, 4561 (1998)] in order not to obscure these main points. [DOI: 10.1063/1.1415752]

Finite-time thermodynamics (FTT) is a completely general extension of classical thermodynamics with the specific added constraint that the process under consideration must go to completion in a finite time (or alternatively at a nonvanishing rate).[1–6] Subsequent research has shown that the ideas and methods of FTT apply equally well to limitations on other resources like size or reservoirs.[8]. This single requirement which takes the subject beyond reversible operation opens up a wealth of new results and considerations, some of which are extensions of well established concepts while others are altogether new. Proofs of the existence of analogs of thermodynamic potentials and availability/exergy as well as algorithms for their evaluation were among the first results that established the subject.[8,9] Entirely new ideas include the concept of thermodynamic distance and its physical significance as a measure of dissipation[10,11] and the importance of specifying objective functions and constraints.[12,13] Thus FTT is not a part of entropy generation minimization,[14] quite the opposite. Entropy generation is but one of countless possible objective functions for which a finite-time extremum may be found. Power, efficiency, amount of chemical product, and profit are other examples.

Likewise, a concept that needs much clarification here is that of ''endoreversibility.'' This term, introduced by Rubin,[15] refers specifically to a process which is reversible in its interior while all irreversibilities are located at its boundaries, in its couplings to the surroundings. For heat engines or heat pumps this would mean heat resistance and friction, for chemical reactors it would be finite diffusion rates. The concept was introduced to describe one class of processes that are particularly amenable to exact analysis and which therefore offer simple illustrative examples of the general FTT theories. Endoreversibility has never been intended to be a general assumption inherent to FTT. Real life engineering systems are much more complicated than models like this. In fact, there are numerous FTT examples where an assumption of endoreversibility is quite inadequate.[16]

FTT is criticized for equating ''infinite process time'' with ''reversible operation.'' No question about it, those two statements are in the most general situations different. An example of such intrinsically irreversible processes, which do not become reversible in the limit of infinite time, was already given along with the definition of finite-time availability.[9] Other examples are certain processes which completely disappear in the limit of infinite time like acoustic heat engines.[17] However, for most everyday processes such as heat conduction, friction, simple chemical reactions, etc., infinite time is equivalent to reversible operation because the dissipative gradients vanish in that limit. If one enlarges one's view from the process under consideration to the full plant, including furnace, piping, reactor insulation, etc., extraneous standby losses like heat leak or evaporation will almost always mitigate against infinite duration, but that is qualitatively different from those processes where the entire desired effect disappears at vanishing speed.

The first explicit aim of FTT is to derive more realistic bounds on performance than the traditional Carnot efficiency for generic processes, and next, wherever possible, the paths that achieve those bounds. Detailed specific modeling is not a primary objective, although it may be useful to illustrate specific examples. Identification of dominant causes of dissipative losses, particularly rate-dependent losses, and characterization of differences in the behavior of systems with different dominant loss mechanisms are important objectives of FTT. This approach provides estimates of the potential for improvement of a process that are more realistic than traditional thermodynamics with its reversible models as limits. The FTT bounds, on the other hand, are likely to be less precise than one would obtain from full exergy analyses, but are generally much faster and cheaper to obtain, have greater generality, and therefore offer guides to where further efforts may best be directed. Thermoeconomics is a tangentially re-

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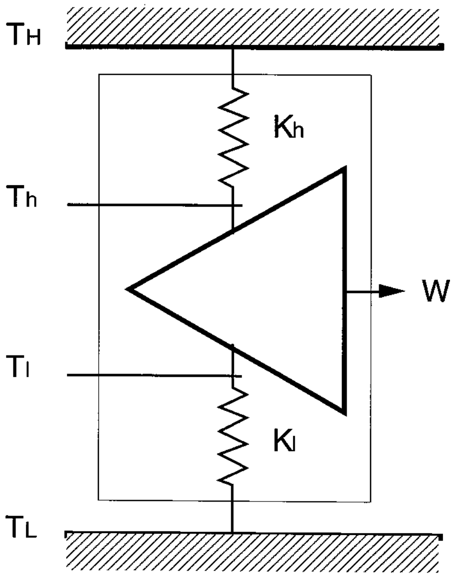

FIG. 1. An endoreversible engine has all its losses associated with its coupling to the environment, there are no internal irreversibilities. This is illustrated here as resistances in the flows of heat to and from the working device indicated by a triangle. These unavoidable resistances cause the engine proper to work across a smaller temperature interval, $[T_h;T_l]$ than that between the reservoirs, $[T_H;T_L]$, one which depends on the rate of operation. The components enclosed in the light rectangle are considered the "system" while the reservoirs are the "environment."

lated field which may also benefit from some of the ideas behind FTT.[18]

Almost by definition the Carnot efficiency of any process is greater than its actual efficiency as well as greater than the FTT efficiency. However, one cannot make the corresponding statement that the FTT efficiency is always greater than the actual efficiency. The opposite may occur if the actual process is not operated to maximize the same objective as the one chosen for the FTT analysis, or if the generic description of the actual process used in the FTT analysis is inadequate. One example is the well known Curzon–Ahlborn efficiency[19] $\eta_{\mathrm{CA}}=1-\sqrt{T_L/T_H}$ which is a consequence of operation at maximum power but not itself a limit. Thus while it is impossible to make an endoreversible heat engine deliver more power than that calculated by Curzon and Ahlborn, its efficiency may easily be greater than η_{CA}, e.g., if the heat engine is run more slowly. This was earlier pointed out in Ref. 20. Note that it is not an empirical observation but a mathematical consequence.

As stated above, an endoreversible process is simply defined as one which is reversible on the inside while all irreversibilities are located in the couplings to the surroundings.[15] The archetypal example is the endoreversible engine shown in Fig. 1. The triangular conversion process between heat and work is by definition reversible, while the only irreversibilities in this model are the heat conductances K_h and K_l to the fixed temperature reservoirs at T_H and T_L. In its generic form this endoreversible engine does not specify the type of reversible conversion process employed (Carnot, Otto, Stirling cycle, or whatever). Nor does the engine specify the physical type of thermal connections, only that they are isothermal (that may be achieved, e.g., by simple heat conduction).

Slightly modifying that model into Fig. 1 of the Sekulic[21] article with explicit flow-type heat exchangers in which the fluid temperatures naturally vary is a self-inflicted complication. For certain engineering applications one may of course argue that the Sekulic engine is a more realistic model than the endoreversible engine, but it is a breach of logic to try to disprove one model based on criticism of another model. Personal opinions (Refs. 7, 10, and 11 in Ref. 21) also do not constitute a proof.

The distinction between what is defined as the system and the environment is a central issue in optimization theory and a frequent cause of misinterpretation of FTT.[13] In the endoreversible FTT engine the system contains the reversible conversion (the triangle) and the two heat conductances (all enclosed in the light rectangle in Fig. 1), whereas the two constant temperature reservoirs comprise the surroundings. All combined, that is our universe. The heat reservoirs are usually taken to be of constant temperature for two reasons: it is by far the simplest and it gives the closest resemblance to Carnot's analysis. Considerations about how these reservoirs are maintained at their constant temperatures or what the ultimate source of the heat is are thus irrelevant for the analysis. As a model of a steam power plant, this means that the steam source is considered to be the reservoir, whereas the flames producing the steam or the flue gasses are outside consideration. Those are of course also interesting problems, but they confuse the endoreversible analysis. It is thus clear that Sekulic's use of flow heat exchangers violates the assumption of constant temperature reservoirs in that the source fluid leaves the heat exchanger at temperature $T_{H,\mathrm{out}}$ which is less than the inlet temperature T_H.

The losses in the FTT universe spelled out above may be described in terms of the total entropy production. The triangular conversion process is by definition lossless, and constant temperature reservoirs cannot produce entropy either, so the only sources of created entropy are the two heat conductances. Certainly there are also flows of entropy connected with the heat flows in and out of the reversible triangular process, but they balance.

In the preceding I have argued two points: (1) Endoreversibility is not an integral part of finite-time thermodynamics, but rather was originally a convenient assumption for illustrative purposes. (2) A precise division between the system to be optimized and the given surroundings is essential in optimization theory.

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