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On the Curzon–Ahlborn efficiency and its lack of connection to power producing processes

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Abstract

Because some physicists continue to defend the nonexistent theory of finite time thermodynamics, additional incontrovertible experimental and theoretical evidence is provided about its irrationality and nonreality. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Response to a charge

Several esteemed colleagues claim that I misinterpret and misrepresent the ideas of finite time (irreversible) thermodynamics (FTT) [1]. I plead not guilty to the claim and amiably request a thorough review and study of all the experimental and theoretical evidence.

I have given many reasons, which prove beyond a shadow of a doubt, that FTT is not a valid theory [2]. It is a collection of homework problems that tests the ability of sophomores to apply the energy and entropy balances to specially concocted processes. These processes admit exact and analytically explicit numerical results. The rationale behind the results, however, ignores the foundations of thermodynamics and contradicts the overwhelming empirical evidence. In what follows, I provide both experimental and fundamental theoretical evidence in addition to the arguments discussed in Ref. [2].

To make the ideas specific, it is helpful to discuss in some detail the cause of the latest dispute. One of the homework problems specified by FTT is a heat engine affected only by the

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irreversibility of finite rate interactions with two reservoirs at T_H and T_L. It consists of two thermal resistances and a cyclic engine that is reversible. For such a plant, a fascinating aura surrounds its attractiveness because, according to FTT, reversible thermodynamics yields a thermal efficiency at maximum power

$$\eta_C = 1 - \frac{T_L}{T_H} \tag{1}$$

but the maximum power is zero, whereas the corresponding result of FTT is equally explicit, that is

$$\eta_{CA} = 1 - \sqrt{\frac{T_L}{T_H}} \tag{2}$$

but the maximum power is greater than zero. The subscript "C" of η_C stands for Carnot, and the subscript "CA" of η_{CA} for Curzon and Ahlborn [3], two authors who derived Eq. (2) independently of the first derivation by Novikov [4].

Upon deriving Eq. (2), Curzon and Ahlborn emphasized, without any restrictions, that "Eq. (2) has the interesting property that it serves as quite an accurate guide to the best observed performance of real heat engines". In support of this conclusion, a graph of $(1 - \eta_{CA})$ versus T_L/T_H was made (Fig. 1) on which experimental values of the thermal efficiencies of ten fossil fueled and nuclear power plants were superimposed, and relatively good agreement between the FTT results and experiments was found.

In my essay [2], I admiringly referred to the announcement by General Electric (GE) about the design and manufacture of gas turbine, combined cycle power plants with thermal efficiencies exceeding 60%. Because the comparisons between η_{CA} versus T_L/T_H and experimental thermal efficiencies were made without any restrictions, and Curzon and Ahlborn emphasized that "η_{CA} is quite an accurate guide to the best performance of heat engines", I placed on the graph the high thermal efficiency reported by GE and estimated the value of T_L/T_H. Next, I used the estimated value of T_L/T_H and calculated the available energy (exergy) of the energy from the high temperature reservoir with respect to the low temperature reservoir. Thus, I found that the calculated available energy is much larger than that either calculated or measured for the products of

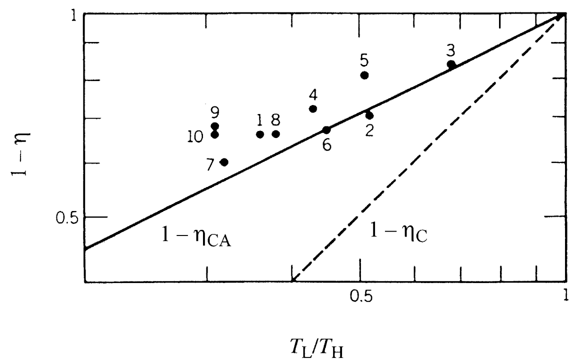

Fig. 1. Comparison of $1-\eta_{CA}$ and thermal efficiencies of 10 fossil fueled and nuclear power plants [5]. The specific power plants are listed in Ref. [5].

combustion of any hydrocarbon and concluded that the GE experimental results provide one more contradiction to the claims of FTT.

The colleagues of Ref. [1] argue that the conclusion just cited is not well founded because I make the irrational assumption that the GE plant operates at maximum power. Instead, they say, I must assume that the plant operates at abated power, less than half the maximum computed by the FTT model, and then, the efficiency is greater than η_{CA} and close to η_C.

This is an amazing and totally erroneous line of argumentation because it overlooks the overwhelming experimental evidence about the performance characteristics of power plants. Part of this evidence is the measured thermal efficiencies versus power graphs shown in Figs. 2–5. Without exception, the experimental results show that higher power is always accompanied by higher thermal efficiency, and conversely, higher thermal efficiency is always accompanied by higher power. No plant contradicts these observations.

The cause for the sharp difference of views between the proponents of FTT and those that question its validity is that in no power plant does the largest irreversibility occur as a result of finite rate heat interactions between the engine and the reservoirs. The design of an engine begins with the specification of a desired power output. Over the past century, designers use thorough understanding of thermodynamics and their ingenuity and creativity, and invent processes that

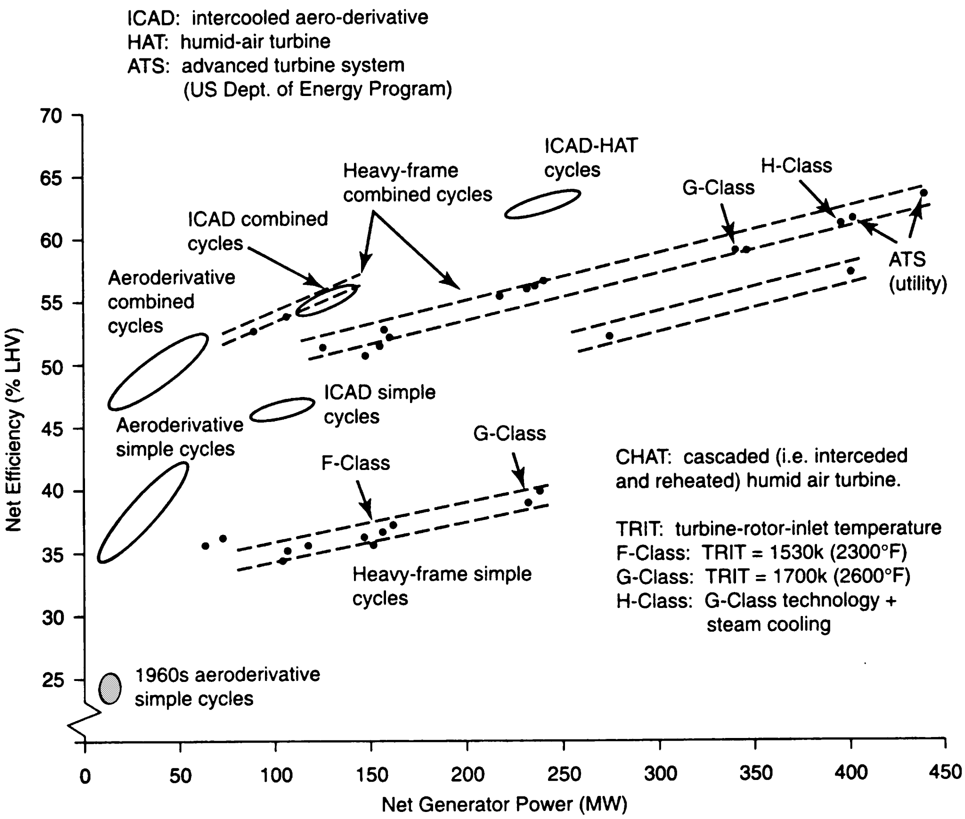

Fig. 2. Thermal efficiency versus power and type of different power plants [6].

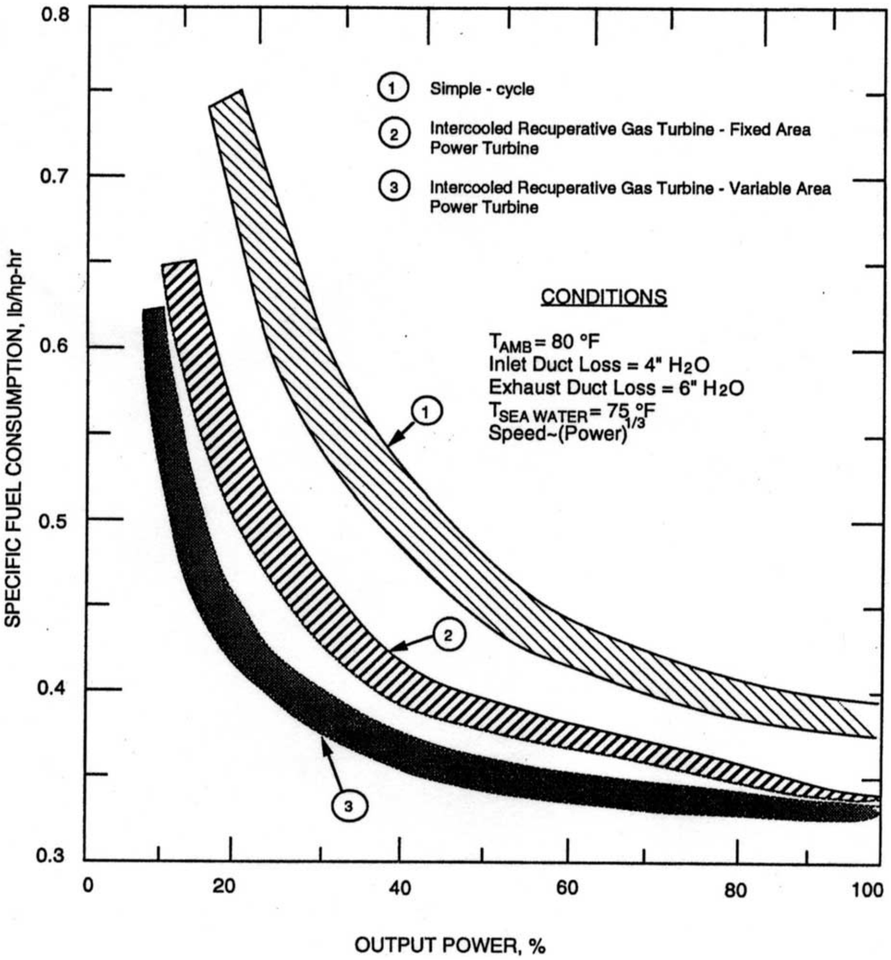

Fig. 3. Part load fuel consumption characteristics of different turbine cycles [7]. The specific fuel consumption is inversely proportional to the thermal efficiency. It is clear that the highest efficiency coincides with the largest power output.

deliver the desired power at an affordable cost, and at the highest possible thermal efficiency. Their accomplishments are really outstanding. They started with an engine that had a thermal efficiency equal to a small fraction of one percent, and today they design and manufacture engines that have thermal efficiencies over 60%. In fact, if we do not charge the irreversibility of combustion to the engine per se, the thermodynamic efficiencies (ratio of power output to rate of available energy input) are close to 90%(!), that is, almost at the 100% limit of the reversible Carnot engine.

2. More scientific evidence against the validity of finite time thermodynamics

In my essay [2], I introduce the foundations of thermodynamics with the following assertion. The laws and theorems of thermodynamics are valid for any system (both microscopic and

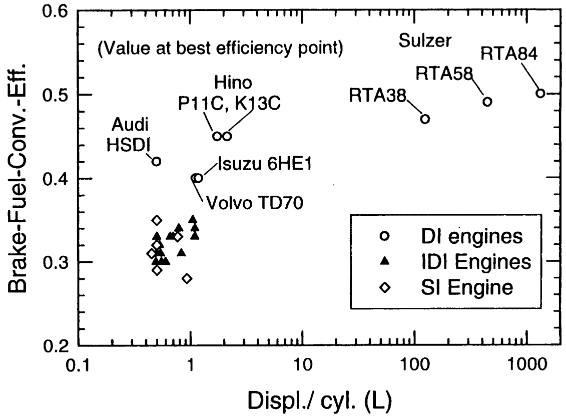

Fig. 4. Thermal efficiencies versus displacement per cylinder of diesel engines [8]. The displacement is proportional to the power rating; DI = direct injection; IDI = indirect injection; SI = spark ignition.

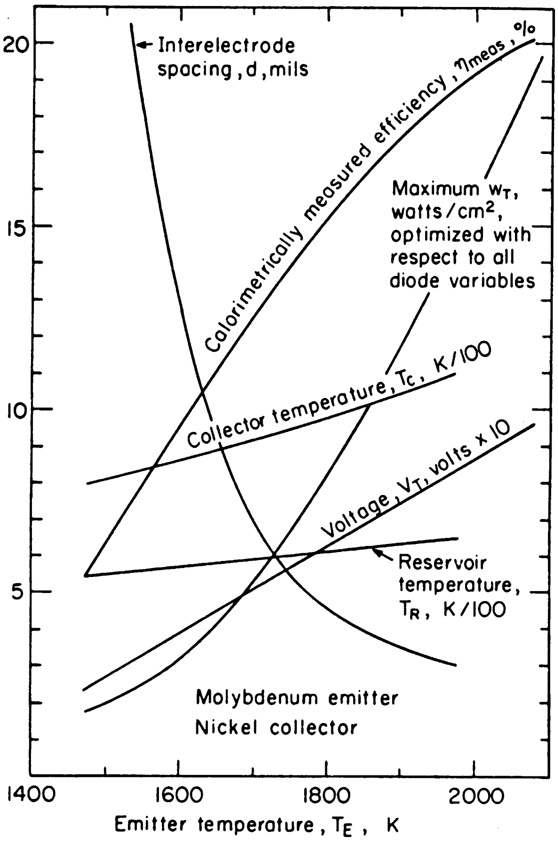

Fig. 5. Measured thermal efficiency versus emitter temperature of a thermionic converter at terminal output power density maximized with respect to cesium reservoir temperature, interelectrode spacing, and collector temperature [9].

macroscopic), for any state (both thermodynamic equilibrium and not thermodynamic equilibrium) and for any interval in time (both infinite and finite).

In contrast, FTT claims that thermodynamics is restricted to reversible phenomena that occur over infinite intervals in time and at infinitesimally small rates, whereas FTT covers irreversible phenomena that occur over finite intervals in time and at finite rates. This distinction is false and leads to unreal conclusions about physical phenomena.

As an illustration of the last remark, recall two important and universally accepted theorems of thermodynamics: (i) IF an adiabatic process is reversible, the entropy of the system remains invariant; and (ii) IF an adiabatic process is irreversible, the entropy of the system increases. The key word in each of these two statements is "IF" because it clearly indicates that thermodynamics does not require that processes be either reversible or irreversible. It simply asserts one of the consequences of either reversibility or irreversibility. This conclusion is analogous to one in classical mechanics about free fall in a gravity field. If a body falls freely, its kinetic energy increases and its potential energy decreases. However, this fact does not require that all bodies need engage in free fall.

To illustrate the validity and importance of the two theorems just cited, we can recall the following results of the thermodynamics defined at the beginning of this section.

Zero entropy physics: All processes obeying either the laws of classical mechanics or the laws of conventional quantum mechanics are reversible; they can be either fast or slow; they represent the limiting case of zero entropy physics.

Nonzero entropy physics: (i) all processes involving unitary changes of state are reversible; they can be either fast or slow; (ii) all adiabatic processes involving nonunitary but isentropic changes of state are reversible; they can be either fast or slow; (iii) all limit cycles in isolated systems are reversible, and each has its own period, short or long; (iv) all adiabatic nonisentropic processes are irreversible; they can be fast or slow; and (v) all spontaneous changes of state that are not limit cycles can be either fast or slow, and all are shown to be irreversible.

In view of these general results, it is hard to accept the premise of FTT.

3. Concluding remark

In closing, I urge all my esteemed colleagues in both science and engineering to study and think about thermodynamics more carefully than has been the case over the past century and a half. Then and only then, they will recognize the generality, beauty and breadth of applicability of the theory and the opportunities for additional theoretical and applied work at the frontiers of science and engineering.

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