Success versus failure: Efficient heat devices in thermodynamics

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Classical equilibrium thermodynamics provides, in a general way, upper Carnot bounds for the performance of energy converters. Nevertheless, to suggest lower bounds is a much more subtle issue, especially when they are related to a definition of *convenience*. Here, this issue is investigated in a unified way for heat engines, refrigerators, and heat pumps. First, irreversibilities are weighted in the context of heat reservoir stability for irreversible engines by using the thermodynamic distance between minimum energy and maximum entropy steady states. Some stability coefficients can be related to a majorization process and the obtention of Pareto fronts, linking stability and optimization by means of efficiency and entropy due to correlations between system and reservoirs. Second, these findings are interpreted in a very simple context. A region where the heat device is efficient is defined in a general scheme and, below this zone, the heat device is inefficient in the sense that irreversibilities somehow dominate its behavior. These findings allow for a clearer understanding of the role played by some well-known figures of merit in the scope of finite-time and -size optimization. Comparison with experimental results is provided.

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I. INTRODUCTION

As noted by Seifert [1], "From its very beginnings, thermodynamics has fascinated scientists by posing deep conceptual issues that needed to be resolved for understanding and optimizing quite practical matters such as the design of heat engines." Since the seminal work by Carnot [2] to the stochastic thermodynamics framework, spectacular experimental and theoretical advances have encouraged the thermodynamic coverage of heat devices. It includes systems ranging from macroscopic dimensions to nanoscales including biomolecular devices [3–8].

As a straightforward consequence, the thermodynamic optimization of heat devices is receiving nowadays great attention heightened by the contemporary growing importance of saving energy resources in any energy conversion process for heat engines (HE), refrigerators (RE), and heat pumps (HP) [9–11]. Common features of optimization criteria are their inherent dependence on the elected model in each case (classical, mesoscopic, or quantum) and that the objective function should be dependent on the stated optimization problem [12–14]. Accordingly, appropriate theoretical frameworks have been used and, in all of them, important efforts have been devoted to the derivation of specific trade-offs and upper bounds [15–19] to guide more efficient designs.

One of the main goals of this paper is to focus on the opposite side. It is shown that the interplay between reversibility and irreversibilities (losses) could be used to define a threshold in regards to the efficiency of energy conversion processes in the landscape of heat reservoir stability for irreversible engines. After all, the contact surface between the system and the reservoirs is irretrievably affected by heat transfers and the departure from equilibrium in reservoirs could offer valuable information regarding the heat engine performance. The resulting thresholds (*lower bounds*) of these singular states are obtained by leveling reversibility and losses. All the results are general and apply without resorting to any particular model or explicit optimization criterion based on usual trade-off functions. However, the above findings allow for a clearer interpretation of the meaning of some figures of merit used in studies of heat device optimization. In between these thresholds and the corresponding maximum Carnot values, a fairly good agreement with experimental results for both HE and RE is found. Lately, the role of stability in optimization processes has been addressed, first, with a compromise between fluctuations and operation regimes in small systems for cyclic and steady-state processes [15,16,20] and, later on, addressing a possible role of stability of operation regimes in an optimization mechanism, which could favor evolution and adaptation [21], with possible applications under more realistic energetic demands [22,23]. Recently, it has also been discussed that in a variety of natural phenomena the time evolution of nonequilibrium states follows entropy demands [24]. This, ultimately, should be related to the heat transport mechanisms between systems and reservoirs. Thus it is expected that some constraints should be imposed by heat reservoirs.

The paper is structured as follows. In Sec. II two stability coefficients that measure the nearness to equilibrium states for the reservoirs are proposed. In Sec. III these coefficients are linked to a departure from reversibility and the degree of irreversibility of an energy converter; this allows one to define a success region. A comparison with experimental results is presented. Finally, in Sec. IV some remarks and conclusions are outlined.

