ON THE SECOND LAW EFFICIENCY OF THERMAL ENERGY STORAGE

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Thermal energy storage (TES) is required when the supply of and the demand for thermal energy do not coincide in time. In particular, TES is an essential ingredient of many solar power generation systems. In such systems the purpose of TES is to store exergy, so that the Second Law efficiency is the main figure of merit of TES system. Therefore, the major goal of TES design for power-generating systems is the reduction of irreversibilities associated with the exergy storage and release. This approach, pioneered by Bejan [2-4], became an active subfield of the TES research [1-14] during the last decade.

Early works developed within this approach [2,5] have treated the storage units as "lumped" elements and addressed the exergy storage and release separately. Recent advance in this area is focused primarily on accounting for internal irreversibilities of the storage units treating the latter as distributed systems and addressing the complete cycle of exergy storage (charging) followed be the exergy release (discharge) [1,9-11,14]. The aim of the present paper is to review the recent studies of the Second Law efficiency of TES systems.

The first part of the paper addresses the general principles under- lying the Second Law analysis of TES. A typical TES consisting of a distributed storage element interacting with a heat transfer fluid (HTF) is considered. The balance equations for energy, entropy and exergy of the storage element and of the HTF are formulated and the second law efficiency is defined for the full storage-discharge cycle. This quantity measures the ratio of the exergy, extracted from the TES system during the discharge stage, to the overall exergy input during the full cycle. The irreversibilities associated with the heat transfer and pressure drop of convecting fluid, as well as the internal irreversibilities of the heat storage element are clarified. In particular, we present expressions for entropy production associated with the sencible and the latent heat storage. The quasi-steady approximation, often used in the analysis of latent heat storage, is clarified within the context of the entropy production in the PCM.

We next consider storage and release in a shell-and-tube heat exchanger with phase-change material [7-10]. An analytic solution [7, 13], describing a two-dimensional axisymmetric conduction-controlled melting/solidification in the PCM, coupled to a forced convection in the tube, and valid for small Stefan and Stanton numbers is discussed. It is used in order to formulate the cyclic operation conditions at each cross-section. These conditions relate the main characteristics of the charging stage to those of the discharge part of the cycle. We then proceed with a detailed analysis of entropy generation in the system considered. It is shown how the overall entropy generation number splits into a sum of two contributions reflecting the heat transfer and the pressure drop irreversibilities. Explicit expressions for these quantities are derived. In particular we show that the pressure drop irreversibility during the discharge stage depends on the ratio of the freezing temperature to that of the "dead" state.

In the sequel we address the optimization of the second law efficiency of this system. Considering the freezing point of the PCM as a control parameter we analyze optimal selection of this temperature both for a storage stage, treated separately, and for the entire cycle. It is shown that typically the optimal value of the freezing point is bounded from below by the geometric mean of

the highest and lowest temperatures, while from above the optimal freezing point is bounded by the arithmetic mean of these temperatures. As a particular example, which enables one to use a closed form analytic solution, we consider a heat exchanger with a negligibly small pressure drop irreversibility and with a thin PCM shell. For such a system we study the variation of the second law efficiency with the number of the heat transfer units, and with the inlet temperature of the HTF at the storage stage.

The last section of the paper discusses the main results of the Second Law analysis of several sensible [14] and latent heat [1] TES systems and formulates some problems to be addressed in the future.

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