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Research Paper

Transient local entropy generation analysis for the design improvement of a thermocline thermal energy storage

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HIGHLIGHTS

- A methodology for local entropy generation analysis of unsteady processes is needed.
- We propose three indicators to locate irreversibilities in both space and time.
- We apply these novel tools for the design improvement of a thermocline TES.
- The total entropy generation during the discharging is reduced by more than 60%.

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ABSTRACT

Second-law methodologies for the design improvement of thermal energy storage (TES) systems are complicated by the fact that TES charging and discharging are highly dynamic (i.e. unsteady) in nature and most of the works done in the field consist of black-box parametric studies, where no information at the local level can be obtained by the analyst.

In the present paper, we aim at filling this gap by the introduction of three novel indicators, namely the cumulated local exergy destruction, the characteristic time and the lifespan of entropy generation. These figures of merit provide the designer with a powerful tool that facilitates the identification of the temporal and spatial location of criticalities and the development of design improvements. To test the effectiveness of this innovative methodology, we focused on the design improvement of a molten salts thermocline TES tank for concentrated solar power applications.

We found that analyzing the cumulated exergy destruction only is a blind way to proceed because very limited insights can be obtained on the physical phenomenon. In this case, the total irreversibilities can be reduced only by 7% and 12% with the help of a porous and a solid baffle respectively. On the other hand, the simultaneous examination of the three parameters allows to generate a far better design by using a compounded baffle able to reduce the total entropy generation of more than 60% compared to the initial configuration.

1. Introduction

Entropy generation driven design methodologies for the performance improvement of engineering systems have met broad acceptance among the scientific community. However, their application to the analysis of strongly unsteady processes, such as TES charging and discharging, is quite complicated: the optimization of the design involves the search for an optimal time history, i.e. the one that minimizes the global entropy produced during a finite time interval. As a consequence, according to Sciacovelli et al. [1], very few researchers are dedicated to the study of the thermodynamic performances of a TES system under unsteady conditions. The majority of them adopted a lumped parameter (i.e. 0D or black-box) approach, where no or little information is gathered on local phenomena. For instance, in one of the earliest study of this type, Bejan [2] developed a simplified black box model considering the heat capacity of the storage element and the global heat transfer coefficient between heat transfer fluid and storage medium, demonstrating the existence, from a second-law perspective, of an optimal charging and discharging time.

The application of second-law analysis to thermal storage has been particularly focused on phase change material as discussed in the recent review of Jegadheeswaran et al. [3]. In this field, a good number of studies were performed where more detailed black-box models have been implemented [4–6]. As far as high temperature molten salts storage is concerned, Yang et al. [7] proposed to use

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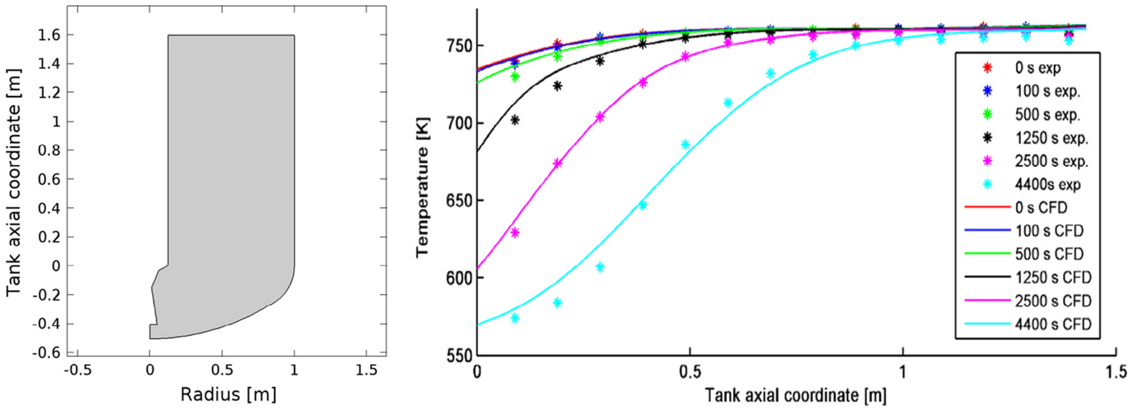

Fig. 1. Left: Geometry considered. Right: Validation of the CFD model with experimental data.

the global entropy generation as a useful criterion for the selection of a suitable filler material. A more refined model to investigate how the granule diameter of the filler in a thermocline molten salts TES influences the heat transfer and the thermodynamic efficiency was made by Flueckiger and Garimella [8]. However, despite having adopted a CFD model for the solution of the thermo-fluid dynamics problem, their second-law analysis was performed only at the global level and local information was not exploited to propose improved designs.

It should be noted at this point that a wise post-processing of the results of CFD simulations allows to calculate the local distribution of entropy generation, providing the designer with the so-called entropy generation maps. This approach has been often coupled to a heuristic pseudo-optimization methodology [9–12] in which the analyst identifies the most critical regions of the device and proposes effective improvements.

To the knowledge of the authors, the unique application of the local approach for the design improvement of a transient process is the work of Guelpa et al. [13], who proposed a modification of the fin arrangement in a latent heat TES suggested by the analysis of local entropy generation at different instants of time. The final configuration was selected as the one enhancing heat transfer and boosting the second law performances of the device during the whole duration of the process.

Despite this last example, we feel that there is a considerable gap in the literature addressing the thermodynamic optimization of transient processes and systems. Hence, the aim of this paper is to provide the analyst/designer with innovative tools for the study of this type of phenomena and to help to clarify not only the spatial but also the temporal location of irreversibilities.

In order to show the effectiveness of the methodology proposed, we focused on the design improvement of the 1.3 $\mathrm{MWh_t}$ thermocline (i.e. single-tank) TES system located at the ENEA research centre La Casaccia (Rome). In the first part of the paper, we present the 2D CFD model, accounting for fluid-flow and heat transfer, which we used for the investigation of the thermo-fluid dynamic behaviour of the tank. Then, the CFD model is used to perform a first entropy generation analysis (EGA) where two possible improvements are identified. Finally, with the help of two innovative figures of merit that keep into account the temporal evolution of the process, a final design is proposed and evaluated.

2. System description and numerical model

The thermocline TES system at the research centre La Casaccia consists of a single tank with diameter D = 2 m and height H = 2.2 m. The storage medium is molten salt (60% $NaNO_3$ and 40% KNO_3 on mass basis) with operating temperatures ranging from 280 °C to 550 °C and the steam generator is fully integrated in the TES, as detailed in Ref. 14. A bi-dimensional axial-symmetric representation of the system is given on the left side of Fig. 1. The internal cavity represents the external envelope of the integrated steam generator, whose radius measures 0.125 m. From a careful examination of its shape, it is possible to notice a Venturi tube at the bottom, which has the aim of slowing down the fluid during the discharge of the tank and avoid mixing due to inlet effects.

Due to the high velocity in the inlet region, we have chosen to adopt a turbulent model in which, assuming negligible fluctuations in density, viscosity and thermal conductivity, the continuity, momentum and energy equations can be written as follows:

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u_j}{\partial x_j}=0 \tag{1}$$

$$\frac{\partial \rho u_i}{\partial t}+\frac{\partial(\rho u_i u_j)}{\partial x_j}=-\frac{\partial P}{\partial x_i}+\frac{\partial \sigma_{ij}}{\partial x_j}+F_i \tag{2}$$

$$\frac{\partial \rho E}{\partial t}+\frac{\partial(\rho u_j H)}{\partial x_j}=\frac{\partial(u_i \sigma_{ij})}{\partial x_j}-\frac{\partial}{\partial x_j}\left(\left(\frac{\mu}{\mathrm{Pr}}+\frac{\mu_T}{\mathrm{Pr}_T}\right)\left(\frac{\partial T}{\partial x_j}\right)\right) \tag{3}$$

where

- σ_{ij} is the tensor of viscous stresses defined as:

$$\sigma_{ij}=2(\mu+\mu_T)\left(S_{ij}-\frac{1}{3}S_{kk}\delta_{ij}\right) \tag{4}$$

- S_{ij} is the tensor of shear stresses defined as:

$$S_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \tag{5}$$

- H is the total enthalpy:

$$H=E+\frac{P}{\rho} \tag{6}$$

For the closure of the equation set, the two-equation $k-\omega$ model has been implemented, which consists of solving for two additional variables: k, the turbulent kinetic energy, and ω, the specific rate of dissipation of kinetic energy.

The governing equations are converted to algebraic equations using the finite-element technique in COMSOL. The discretization

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