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A new method of characterization for stratified thermal energy stores

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Abstract

A new method for characterization of stratified thermal energy stores (TES) that integrates both the first law and the second law concerns is presented here. The first law concern is incorporated into a quantity called energy response factor and the second law concern into an entropy generation ratio. A product of these two quantities is at the heart of the TES efficiency definitions. This approach removes the overemphasis of the existing methods either on the first or the second law of thermodynamics which often biases the characterization results. The information about the evolution of the temperature field of the system in time is the prerequisite of the new method. It may be obtained from experiments or from suitable numerical simulations. The current method can be easily integrated into computational fluid dynamic (CFD) simulations and thus facilitate CFD-based design analysis. As an example of such CFD-integrated analysis, a large-scale hot water seasonal heat store is numerically studied to identify the effects of aspect ratio, containment shape, internal structures, and containment size on their efficiency. The results suggest the effectiveness of the new method in deriving useful design insights.

Keywords: Hot water seasonal heat store; Computational fluid dynamics (CFD) model; First law of thermodynamics; Second law of thermodynamics; Stratified thermal energy store (TES) characterization; Entropy generation ratio; Energy response factor; Aspect ratio; Containment shape; Internal structures; Containment size

1. Introduction

The effort to develop proper efficiency definitions for different thermal energy storage (TES) processes and to characterize the TES has a long history. Introducing one of their latest versions of exergy analysis of TES, Rosen et al. (2004) state that: "at present, no valid and generally accepted standards have been established for comparison of the performance of stratified thermal storage systems". The methods currently used to characterize a TES may be broadly categorized as (1) those based on the general dimensionless numbers of heat transfer and fluid dynamics, (2) those based on the first law of thermodynamics (energy-based characterizations) and (3) those based on the second law of thermodynamics (entropy/exergy-based characterizations).

The important dimensionless numbers used to correlate the efficiency of a TES are Reynolds number, Grashof number, Richardson number, Froude number, Peclet number, Biot number and Fourier number. Only general definitions of these numbers are given here. Since each author takes freedom in defining length, velocity, temperature and turbulence scales one has to refer to the cited works for their exact definitions. The effects of inertial and viscous forces on a fluid element in convective motion are compared by Reynolds number (Re) and that in buoyant motion is accounted for by the Grashof number (Gr). Lavan and Thompson (1977) in their premier attempt to characterize a TES, have correlated the extraction

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Nomenclature

c	specific heat (J/kg K)
E_R	energy response factor defined in Eq. (9)
g	acceleration due to gravity (m/s^2)
H	total height of the heat store (m)
h	specific enthalpy (J/kg)
h	depth of the ring structure from top of HWSHS (m)
m	mass (kg)
p	pressure (bar)
r	radial width of the rings, radius of discs (m)
R	radius of HWSHS (m)
R_{EG}	entropy generation ratio defined in Eq. (7)
s	specific entropy (J/kg K)
S	total entropy (J/K)
T	absolute temperature (K)

Greek symbols

ΔE	change in energy of a system (J)
$\Delta s/\Delta S$	change in specific/total entropy (J/kg K)
η	efficiency (%)
ρ	density (kg/m^3)
θ	angle defined in Figs. 6 and 10 (°)

Indices

12	change from state 1 to state 2
c	charging–discharging process
s	storing process
ext	external
ideal	resulting from a perfectly reversible and adiabatic process
int	internal
mixed	resulting from a perfectly mixed re-ordering
real	real storage process
SEN1	corresponding to SEN analysis for charging–discharging process
SEN2	corresponding to SEN analysis for storing process
stratified	resulting from a stratified re-ordering
$t1$	at a point of time $t1$
$t2$	at a point of time $t2$

Abbreviations

CFD	computational fluid dynamics
HWHS	hot water heat store
HWSHS	hot water seasonal heat store
SEN	storage evaluation number
TES	thermal energy store

efficiency of a TES with *Re* and *Gr*. The Richardson number may be viewed as a mixed convection parameter and it compares buoyancy forces and inertial forces acting on a fluid element entering or leaving the TES. It has also found application in many correlations for TES efficiency (Cabelli, 1977; Hyun, 1984; Hahne and Chen, 1998). The Froude number (*Fr*) is defined as the inverse square root of the Richardson number and may be alternatively used in place of *Ri* (Yoo et al., 1986). The Peclet number (*Pe*) compares the effects of convection and diffusion of fluid elements especially at the interface between the cold and hot fluid regions (thermocline) within a TES. It is often used to characterize the deviation of charging and discharging processes of a TES from the ideal adiabatic piston flow scenario (Baines et al., 1983; Mavros et al., 1994; Nelson et al., 1999a). Biot number compares the relative importance of convection and conduction modes of heat transfer and Fourier number, a dimensionless time, describes the transient behavior of heat transfer. Modified forms of the Biot number (*Bi*) have found application in the study of the wall conduction of TES and its influence on thermal stratification, and the Fourier number (*Fo*) in the study of temporal evolution of thermal stratification (Nelson et al., 1999b).

Efficiency definitions for TES process based on dimensionless numbers provide useful design insights. However, it is highly probable that one loses the total view of different storage processes in this effort. A typical TES process may involve a multitude of length, velocity, temperature and turbulence scales. In the absence of comprehensive efficiency definitions, it is difficult to keep perspective of the influence of one or the other design parameter on the global behavior of the TES. Hence it is useful to correlate TES efficiency based on changes in the global properties of the system caused by localized parameter variations.

The first law based characterization methods generally account for the heat losses due to the heat transfer interactions between TES and its surrounding. Some of these methods neglect the effects of internal thermal mixing completely (Wildin and Truman, 1989). Some others consider both the heat losses to the surroundings and the enhanced enthalpy outflow of the TES due to excessive thermal mixing (Hahne and Chen, 1998; Chan et al., 1983; Yoo and Pak, 1993; Ismail and Carrocci, 1988). However the actual loss of usefulness of the stored energy in the face of internal thermal mixing is often overlooked. The first law of thermodynamics provides rules for the estimation of the quantity of energy and its transformations due to the interaction of a system and its surroundings. However, it describes the level of thermal mixing of a TES only partially through its effects registered at the inlets/outlets of the system. The information about the real exergy levels