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Methods to determine stratification efficiency of thermal energy storage processes – Review and theoretical comparison

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Abstract

This paper reviews different methods that have been proposed to characterize thermal stratification in energy storages from a theoretical point of view. Specifically, this paper focuses on the methods that can be used to determine the ability of a storage to promote and maintain stratification during charging, storing and discharging, and represent this ability with a single numerical value in terms of a stratification efficiency for a given experiment or under given boundary conditions. Existing methods for calculating stratification efficiencies have been applied to hypothetical storage processes of charging, discharging and storing, and compared with the rate of entropy production caused by mixing calculated for the same experiments. The results depict that only one of the applied methods is in qualitative agreement with the rate of entropy production, however, none of the applied methods is in agreement with the rate of entropy production and also able to distinguish between the entropy production caused by mixing and the entropy changes due to heat losses.

Keywords: Thermal stratification; Thermal energy storage; Solar heating systems; Thermocline

1. Introduction

It has been shown that temperature stratification[1] (Fig. 1) in a thermal energy storage (TES) of a solar heating system may considerably increase system performance, especially for low flow solar heating systems (e.g., Lavan and Thompson, 1977; Phillips and Dave, 1982; Hollands and Lightstone, 1989; Cristofari et al., 2003).

Stratification of a water-based TES may be destroyed by different physical processes (Hollands and Lightstone, 1989):

- Plume entrainment is caused by mixing of water due to natural convection inside the tank driven by an adverse temperature gradient, typically caused by heat supplied to the bottom of the TES or by heat loss from the top. In these cases, a thermal plume can be observed that entrains surrounding water.
- Inlet jet mixing caused by the kinetic energy of water entering the storage tank.
- Thermal conduction and diffusion within the water and within other materials in the TES including the storage tank wall, reducing temperature differences within the TES.

A TES with no stratification corresponds to a fully mixed TES.

For the development of TES components and processes (e.g., stratification enhancers and inlet mass

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[1] The existence of a temperature gradient in the storage that allows the separation of fluid at different temperatures.

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Nomenclature

c	specific heat capacity (J/kg K)
E	energy contained in node/volume of a thermal energy storage (TES) (J)
H	storage height (m)
M_E	moment of energy (Jm)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
R_{EG}	entropy generation ratio (–)
S	entropy (J/K)
ΔS^{irr}	entropy generation (J/K)
ST_{Wu}	stratification coefficient of Wu and Bannerot (1987)
T	absolute temperature (K)
t	time (s)
y	vertical coordinate inside the tank that corresponds to the distance of the center of a node (or the center of a volume element) from the bottom of the tank (m)
η	efficiency (–)
ξ	exergy contained in a node or volume of a TES (J)
$\Delta\xi^L$	exergy loss (J)

Superscripts

*	non-dimensional value
irr	specifies irreversible part of entropy change (=entropy production)

Subscripts

0	thermodynamic dead state (i.e., state with no exergy content), or start of the experiment in the case of t_0
And	referring to Andersen et al. (2007)
avg	mass weighted average of storage
Ch	referring to Chan et al. (1983)
Dav	referring to Davidson et al. (1994)
d	specifies time at which the temperature of the fluid leaving the TES reaches the limit of usefulness
del	"useful" temperature limit of delivery
exp	experimentally determined "real case" (generally includes heat losses and mixing)
flow	value attributed to the flow of fluid into and out of the TES
hl	calculated including heat losses assuming the same heat loss coefficients as for the experimental storage
Hu	referring to Huhn (2007)
i	index for the vertical position of a horizontal layer in the tank
ini	initial, e.g., at the beginning of a charging/discharging or standby experiment
inlet	fluid entering the TES
m	counter for simulation (or calculation) timestep
min	minimum
max	maximum
MIX	based on the MIX number
mix0	perfectly mixed from the beginning of the experiment by constantly mixing the inlet fluid with the tank fluid. The temperature of the outlet fluid is the same as the temperature of the mixed tank fluid, which is gradually approaching the temperature of the inlet fluid. Energy content is thus not the same as in the experimental storage
mix1	perfectly mixed by mixing the volume of the experimental storage at any moment of evaluation. Energy content is thus always the same as in the experimental storage
out	fluid leaving the TES
REG	based on the entropy generation ratio
Rg	referring to Rosengarten (1999)
store	value for total storage
Sh	referring to Shah and Furbo (2003)
str0	perfectly stratified from the beginning of the experiment assuming adiabatic, isentropic plug flow. Energy content is not the same as in the experimental storage
str0d	perfectly stratified plug flow from the beginning of the experiment including diffusion and conduction within the fluid (i.e., anisentropic)
str1	perfectly stratified by rearranging the energy content of the storage at any moment of evaluation into two zones with uniform temperature that correspond to the maximum and minimum temperature of the experimental storage (str1a) or of the entire experiment (str1b)
VB	referring to van Berkel (1997)
ZG	referring to Zurigat and Ghajar (2002)

flows), as well as for the comparison of different TES on the market, it is desirable to have an index or "measure" to determine the ability of a TES to promote and maintain stratification during charging, storing and discharging. Ideally, this measure is given in terms of a stratification efficiency that will range from 0% to 100%, with 0% corresponding to a fully mixed TES that shows no stratification and 100% corresponding to a "best case" TES with perfect stratification. Alternatively, the degree of mixing may be defined ranging from 0% for perfect stratification to 100% for fully mixed (Davidson et al., 1994).