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Comparison of energy, exergy and entropy generation-based criteria for evaluating stratified thermal store performances

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ABSTRACT

It is well established that stratification improves the performance of stratified sensible thermal energy stores (SSTES). A detailed review is presented of studies in which the contribution of stratification to the performance SSTES is assessed on the basis of energy and exergy analyses, and lately, entropy generation analysis. To obtain clear and useful distinctions between stratified and non-stratified stores, and for stores at different states of stratification, analyses that incorporate second law considerations (i.e. exergy/entropy generation) are required. Also, based on outcomes of computational fluid dynamics (CFD) simulations of SSTES, we present results of energy efficiency, η_e, normalized exergy efficiency, $\overline{\eta}_x$, and entropy generation number, N_s, assessments of SSTES, corresponding to three possible approaches. Energy efficiencies, are shown to be limited in their ability to quantifying these improvements, while $\overline{\eta}_x$ is introduced as an improved exergy-based performance measure. Comparing $\overline{\eta}_x$ with N_s it is found that $\overline{\eta}_x$ is effective for assessing store performances prior to the exit of the thermocline from the store, while N_s offers useful assessments for the full duration of store operation. The parametric dependence of $\overline{\eta}_x$ and N_s on some significant dimensionless variables (Peclet number, Pe_D, Richardson number, Ri, and aspect ratio, AR) is such that as Pe_D, Ri and AR increase $\overline{\eta}_x$ increases. N_s decreases with increasing Pe_D and AR but the effect of Ri on it depends on the value of Ri.

1. Introduction

Stratified sensible thermal energy stores (SSTES) are liquid based sensible thermal stores that are operated in such a way as to minimize mixing between incoming thermal storage fluid and exiting resident fluid in the store. When charging/discharging the stores, two quasi-uniform temperature fluid regions exist within such stores – a hot region at the top and a cold one at the bottom of the store. The two regions are separated by a mixing fluid layer – the thermocline, within which temperature gradients are largely confined. A simplified representation of the typical temperature profile in SSTES is presented in Fig. 1. The double layer temperature stratification in the SSTES is occasioned by gravity induced buoyancy forces, developed as a result of the difference in the densities of the hot incoming fluid and cold fluid it is displacing from the store.

Experimental and analytical studies on temperature and fluid flow phenomena in SSTES, energy and exergy accumulation characteristics, design and operation characteristics, etc., are abundant in the literature (e.g. [1–6]). These studies have generally established that the presence of stratification is to be desired for the enhanced performance of liquid based sensible thermal storage systems [7–11]. And in this regard, a number of measures have been devised for assessing and characterizing the performances of SSTES, especially during the dynamic phase of operation, i.e. during either charging or discharging.

2. Background

Energy and exergy efficiencies are the most prevalent measures used for assessing SSTES. An efficiency measure is generally the ratio of the products to the inputs of a system. Rosen [12] has summarized the various possible energy and exergy efficiency expressions for energy storage systems and determined that the system inputs could be considered to be either the energy (exergy) input or the sum of the energy (exergy) input and the initial energy (exergy) already in the store, while the products could be either the energy (exergy) recovered from the store or the sum of the energy

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Nomenclature

A_{in}	inlet cross-sectional area (m^2)
AR	aspect ratio (= H/D)
c_p	constant pressure specific heat ($J\,kg^{-1}\,K^{-1}$)
D	tank diameter (m)
En	energy (J)
Ex	exergy (J)
g	gravitational acceleration ($m\,s^{-2}$)
H	tank height (m)
m	mass of tank contents (kg)
$\dot{m}$	inlet mass flow rate (m)
N_s	entropy generation number
P	pressure ($N\,m^{-2}$)
Pe_D	Peclet number (= $U_\infty D/\alpha$)
r	radial distance (m)
Re_D	Reynolds number (= $U_\infty D/\nu$)
Ri	Richardson number ($= g\beta H(T - T_{ini})/U_\infty^2$)
S_{gen}	total entropy generation (J)
$\dot{S}_{gen}$	entropy generation rate (W)
$\dot{S}'''_{gen}$	volumetric entropy generation rate (W/m^3)
t	time (s)
T	temperature (K)
$\overline{T}$	equivalent energy temperature (K)
T^*	equivalent exergy temperature (K)
U_∞	free stream velocity ($= \dot{m}/\rho A_{in}$ $m\,s^{-1}$)
v	velocity ($m\,s^{-1}$)
V	tank volume (m^3)
z	axial distance (m)

Greek symbols

α	thermal diffusivity ($m^2\,s^{-1}$)
β	compressibility coefficient (K^{-1})
$\Delta\Xi$	exergy accumulation (J)
η_e	energy efficiency
$\overline{\eta}_x$	normalized exergy efficiency
φ	volume change fraction ($= \dot{m}t/m$)
ν	kinematic viscosity ($m^2\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)
θ	dimensionless temperature (= $(T - T_{ini})/(T_h - T_{ini})$)
$\overline{\theta}$	dimensionless equivalent energy temperature
θ^*	dimensionless equivalent exergy temperature
ϑ	exergetic temperature factor (= $T/(T_h - T_{ini})$)
τ	dimensionless time (= $U_\infty t/D$)
ξ^*	non-dimensional exergy parameter
Ξ	exergy (J)

Subscripts and superscripts

a	referring to actual store
h	hot
in	inlet
ini	initial
m	referring to fully mixed store
max	maximum
min	minimum
0	reference state
r	radial
s	referring to perfectly stratified store
z	axial
*	dimensionless quantities

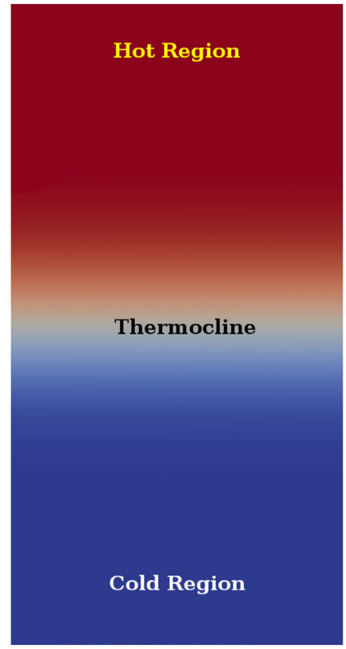

Fig. 1. Typical temperature profile in a stratified thermal storage tank.

(exergy) recovered and the final energy (exergy) remaining in the store. Energy efficiencies and exergy efficiencies were both utilized by Solé et al. [4] to investigate the enhancement of stratification in a domestic hot water storage tank caused by the inclusion of phase change material (PCM) tubes. The values of both efficiencies obtained for the SSTES with embedded PCMs were slightly higher than the values for the tanks without. However, Rosen and Dincer [13] have made a compelling case for exergy efficiencies over energy efficiencies for the assessment of energy storage, arguing that "the use of exergy analysis . . .is important because it clearly takes into account the loss of availability and temperature of heat in storage operations, and hence it more correctly reflects the thermodynamic and economic value of . . .storage operation(s)." Accordingly, outcomes of exergy analysis provide the basis for more rational assessments and comparisons of the performances of energy storage systems. The ratio of the exergy in a stratified store to that in fully mixed store, Ξ/Ξ_m, was used by Rosen et al. [11] to assess the influence of stratification on the storage capacities of liquid based sensible TES. Relying on a number of temperature models that approximate the vertical temperature stratification obtainable in SSTES, the stored energy and exergy values in stratified stores at different states of stratification were computed to show that, whereas the energy storage capacities of the stores were unaffected by the presence/extent of stratification, the presence of stratification invariably led to increased exergy storage in the stores. With a 2D computational fluid dynamics (CFD) SSTES model, Farmahini-Farahani [14] investigated the effect of tank aspect ratios (AR) and inlet/outlet geometries (diameter, vertical position and inclination) on stratification in SSTES. A dimensionless exergy parameter, ζ, was used to characterize the stratification in the SSTES. The value of ζ increased as AR increased, as inlet and outlet diameters decreased, and as the inlets(outlets) were inclined away from the top(bottom) of the stores.

In addition to efficiencies, several other measures, such as thermocline thickness, entropy generation numbers, percentage cold recoverable, stratification evaluation numbers, stratification numbers, MIX number, etc., have been proposed and utilized to study the behaviour of SSTES. Comprehensive reviews of these measures and their applications have been presented in Zurigat and Ghajar [15], Haller et al. [16], Han et al. [17], Castell et al. [18], Njoku