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Normalized charging exergy performance of stratified sensible thermal stores

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ABSTRACT

This paper presents the performance assessment of stratified sensible thermal energy stores (SSTES) on the basis of the normalized exergy efficiency, $\overline{\eta}_x$. Assessments based on $\overline{\eta}_x$ provide comparisons with performances of both the perfectly stratified and the fully mixed stores, which offer the best and worst performances, respectively. This is in contrast with energy and exergy efficiencies, which compare SSTES with only the perfectly stratified store. A dimensionless unsteady axisymmetric model of vertical cylindrical SSTES was implemented using a finite volume numerical scheme. The effect of some significant parameters on SSTES performance were considered by performing computations for aspect ratios (AR) between 1 and 4, Peclet number (Pe_D) varying from 5×10^3 to 100×10^3, Richardson number (Ri) varying from 10 to 10^4, and overall heat loss coefficients (U) varying from 0 to 100 W m^{-2} K^{-1}. $\overline{\eta}_x$ increases with Pe_D, Ri and AR, with the most significant increases occurring at low values of these parameters, and appreciable increases are no longer obtained beyond $\mathrm{Pe}_D \approx 30 \times 10^3$, Ri $\approx 10^3$ and AR ≈ 3. $\overline{\eta}_x$ also falls monotonically as the U values increase.

1. Introduction

During the charging and discharging of a stratified thermal energy store, different regions are at different temperatures due to the action of buoyancy forces. When charging a stratified hot water storage tank, for example, hot water flows into the tank as the water in the tank is simultaneously withdrawn for heating. The difference in the densities of the incoming hot water and the cooler water already in the tank causes the hot water to rise to the top and the cooler water to fall to the bottom of the storage tank, creating a transition layer, known as the thermocline, which separates the hot upper zone from the cold lower zone. The same situation obtains, albeit in the reverse, during the discharging of the tank, when hot water is withdrawn from the tank to service a load while cooler water is simultaneously let into the tank from the mains. An illustration of the typical temperature profile existing in a stratified thermal storage tank is presented in Fig. 1.

Compared to a situation in which the liquid storage media (water, in this case) is fully mixed during the charging process, the storage tank's performance is improved by the presence of temperature stratification in several ways. If the storage tank is connected in closed circuit to a heat source and stratification maintained during charging, a shorter charging period will be required to extract an equal amount of heat in comparison with a fully mixed tank. This is so because the return storage fluid stream from the stratified tank is at a quasi-constant low temperature as it passes through the heat source, thus creating a higher heat transfer gradient at the heat source. For a solar collector heat source, for example, this will translate to higher mean collector heat output and thus higher efficiencies (Abu-Hamdan et al., 1992; Cristofari et al., 2003; Hollands and Lightstone, 1989). During discharge also, more heat will be available for supply to the load because of the quasi-constant high temperature at which the storage fluid is withdrawn from the storage tank to service the load.

2. Background

In order to quantify the extent of improvements obtainable in sensible thermal energy stores (STES) due to the presence of stratification, objective and rational performance assessment criteria are needed. Several of such criteria have been proposed in the literature, including familiar dimensionless numbers, efficiency measures, and other miscellaneous parameters. Some are solely based on first law (energy) considerations, others on second law (entropy) considerations, while the rest result from a combination

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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)
ΔE	energy accumulation (J)
g	gravitational acceleration ($m\,s^{-2}$)
H	tank height (m)
m	mass of tank content (kg)
$\dot{m}$	inlet mass flow rate (m)
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 ($= g\beta H(T - T_{ini})/U_\infty^2$)
t	time (s)
T	temperature (K)
$\overline{T}$	equivalent energy temperature (K)
T^*	equivalent exergy temperature (K)
U	overall heat loss coefficient ($W\,m^{-2}\,K^{-1}$)
U_∞	free stream velocity ($= \dot{m}/\rho A_{in}$ $m\,s^{-1}$)
v	velocity ($m\,s^{-1}$)
V	tank volume (m^3)
V_d	discharge volume fraction
z	axial distance (m)

Greek symbols

α	thermal diffusivity ($m^2\,s^{-1}$)
β	compressibility coefficient (K^{-1})
$\Delta\Xi$	exergy accumulation (J)
$\overline{\eta}_x(t)$	normalized exergy efficiency
$\overline{\eta}_{x,max}$	maximum 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	dimensionless temperature ratio ($= T/(T_h - T_{ini})$)
τ	dimensionless time ($= U_\infty t/D$)
Ξ	exergy (J)

Subscripts and superscripts

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

of first and second law considerations (exergy analysis). Reviews of these assessment criteria are well discussed in the literature (Zurigat and Ghajar, 2007; Haller et al., 2009; Castell et al., 2010; Njoku et al., 2014). The incorporation of second law considerations, (e.g., in the form of exergy analysis,) into the assessment of stratified sensible thermal energy stores (SSTES) has however been shown to be more rational and illuminating than assessments based only on energy analysis (Rosen, 2001; Rosen and Dincer, 2003; Rosen et al., 2004). Therefore, in addition to energy efficiencies, exergy efficiencies, which incorporate second law considerations, have been applied to the assessment of SSTES (e.g., Rosen, 2001; Solé et al., 2008).

The analysis of SSTES is best undertaken using computer aided multi-dimensional numerical models (otherwise known as computational fluid dynamics (CFD)), as these better account for the inherently multi-dimensional temperature and flow regimes developed within the SSTES during its operation. Also, the number of simplifying assumptions made are limited, unlike what obtains with analytical models. The use of multi-dimensional numerical models in the study of SSTES, however, has traditionally focused on the simulation of temporal evolution of temperature and velocity profiles within the storage units (Eames and Norton, 1998; Yee and Lai, 2001; Zachar et al., 2003; Shin et al., 2004), the determination thereby, of thermal energy accumulation in the units, and the computation of energy based efficiencies (Abdoly and Rapp, 1982; Ismail et al., 1997; Hahne and Chen, 1998; Shah et al., 2005). In such studies therefore, the influence of such factors as inlet flow rate and temperature, tank aspect ratio, and the presence of various stratifier mechanisms, on the efficiency of energy accumulation in SSTES have been investigated. Ismail et al. (1997) developed a 2D CFD model which was used to simulate temperature profiles within a SSTES during charging and discharging and obtained temperature profiles which showed close agreement with experimental results. Using a 3D CFD model, Shah et al. (2005) investigated the effectiveness of a thermal stratifier within a SSTES. Their model results compared well with experimental PIV and temperature measurements. They computed *stratifier efficiencies*, (ratios of actual energy supplied to the tank to the maximum possible energy supplied to the tank in the absence of mixing,) and indicated that a range of optimal flow rates – 5–8 l/min existed for the SSTES configurations they studied.

Results of multi-dimensional numerical simulation studies have also led to better insights into the processes that lead to both the enhancement of and the breakdown of stratification in SSTES. Such studies have shown that placing obstacles close to the entrances or exits invariably enhances temperature stratification in SSTES (Zachar et al., 2003; Altuntop et al., 2005). 2D CFD simulation studies of Van Berkel (1996) and Van Berkel et al. (1999) have shown that destratification caused by mixing in SSTES thermocline regions can be approximated by a two stage process of fluid withdrawal from the thermocline by drag, and subsequent mixing due to the stretching and folding of fluid particles.

A limited number of studies in which exergy methods and multi-dimensional numerical models were simultaneous used, have been reported. Time varying temperature profiles in a horizontal SSTES tank were obtained by Cónsul et al. (2004) using 3D numerical simulations. The performances of the tank when assessed using a "non-dimensional thermocline thickness", the "MIX number" and the "non-dimensional exergy" were determined and compared, leading to the conclusion that the non-dimensional exergy gave the best assessment of the tank's performance. Farmahini-Farahani (2012) performed a 2D CFD study of the effect of tank aspect ratios (AR), inlet/outlet geometries (diameter, vertical position and inclination) on stratification in SSTES tanks. Stratification was measured using a dimensionless exergy parameter and was found to improve with higher AR, smaller