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Energy and exergy efficiencies assessment for a stratified cold thermal energy storage

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HIGHLIGHTS

- Energy and exergy analysis show the efficient operational conditions of a cold TES.
- The Richardson number shows the turbulence effect of on the stratification in TES.
- The Peclet and Fourier numbers predict the stratification profile of the TES.
- The Biot number shows the vertical temperature variation within the TES.
- The upper half of the TES is the most exergy efficient layers of the TES.

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ABSTRACT

Cold Thermal Energy storage systems (TES) present opportunities for offsetting peak demand from chillers. An assessment of the TES system at the University of Idaho was performed to quantify the current exergy efficiency of the single phase, water based, cold TES that typically operates under the full capacity. Internal temperatures within the TES vary from 7 °C and 15.5 °C throughout the summer months. Measurements were taken on internal temperatures and flow rates and were used to create a model in TRNSYS. Comparison of Richardson, Fourier Peclet, and Biot numbers show the influence of internal and external conditions on TES performance and stratification characteristics. The Richardson number indicates that the turbulence effect of the inlet geometry is very small and it has negligible effect on the stratification within the TES. The Peclet and Fourier numbers show that prediction of the stratification profile of a TES can be done with minimal measurements. The Biot number shows that the temperature variation only occurred vertically within the TES. Using the data obtained, as well as an analysis of the model, showed the TES is determined to have an overall energy efficiency of 75% and an exergy efficiency of 20%. The individual layers of the TES were evaluated to conclude that the upper half of the TES is the most exergy efficient layers of the TES and steps to maximize their usage should be taken without reducing the overall CAPACITY.

1. Introduction

Resource utilization with minimal environmental impacts is key to building sustainable systems [1]. While a completely sustainable system would require a fully reversible process, impacts on the environment can still be reduced. Approaching full sustainability benefits both the present and future environment [2]. Making use of resources in a responsible manner is important and it should always be considered when developing new technologies or analyzing current systems [3–6].

District energy (DE) systems offer opportunities for reductions in greenhouse gasses (GHGs) through the use of biomass fuels, or non-carbon energy sources [7]. Reductions in GHGs can also be accomplished by replacement of less efficient equipment with centralized heating and cooling systems often found in district energy plants [8]. Lake et al. reviewed district energy systems and showed trends and projections for future district energy systems. These policies, design and environmental considerations associated with heating and cooling technologies and their shift away from fossil fuels to more sustainable energy sources [9].

Szargut et al. suggested that exergy methods should be considered to better realize the impact on the environment [10]. Exergy is commonly considered to be the measure of potential work, maximum work that can be obtained from, or the quality of a heat source [11–14]. Exergy, unlike energy, is a non-conserved quantity, and exergy balances

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Nomenclature

DE	district energy
GHGs	greenhouse gasses
TES	thermal energy storage
UI	university of Idaho
A	cross sectional area (m^2)
α	thermal Diffusivity (m^2/s)
β	volumetric coefficient of thermal expansion (1/K)
Bi	Biot number
C	specific heat of a fluid (kJ/kg K)
D_i	diameter of tank
Δ	delta, difference between initial and final values
δ	wall thickness
E	thermal capacity
E_{max}	maximum thermal capacity
η	efficiency
Fo	Fourier number
g	gravity
Gr	Grashof number
h	specific enthalpy (kJ/kg)
H	height of the tank (m)
h_o	convective value ($W/m^2 K$)
k	conductivity (W/m K)
kw	conductivity of the wall (W/m K)
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
μ	viscosity (kg/m s)
P	pressure (kPa)
Pe	Peclet number
Pr	Prandtl number
Ψ	specific exergy (kJ/kg)
$\dot{Q}$	heat transfer rate (kW)
ρ	density
Re	Reynolds number
Ri	Richardson number
s	specific entropy (kJ/kg K)
T	temperature (°C or K)
t	time (s)
T_{max}	maximum return temperature (°C or K)
TES	thermal energy storage
V	velocity (m/s)
$\dot{X}$	exergy rate (kJ/kg)
Z	height (m)
η	Efficiency

Subscripts

0	reference property
b	boundary
C	charging
cw	chilled water
D	discharging
en	energy
f	flow
int	internal
Q	heat transfer
sys	system
w	work
x	exergy

account for inputs, losses, and wastes of a process [15]. Dincer and Rosen have shown links between energy, exergy and sustainable development and they have shown that exergy might allow for measuring impacts on the environment [16–19].

Often used in conjunction with district energy systems, thermal energy storage (TES) systems offer the ability to store thermal energy in a medium for later use. There are three types of TES systems, sensible, latent, and thermochemical. Sensible TES often utilizes water or rock, while latent utilizes phase changes (e.g. water/ice). Thermochemical storage makes use of inorganic substances as the storage medium. The medium used depends on the storage period, economic viability and operating conditions [20]. Liquid water is commonly used for the sensible system since it is non-toxic, easily obtainable, contains a high thermal capacity, and has a high range of temperature availability.

One common method for evaluation of sensible heat TES systems involves the stratification within the storage medium. Stratification occurs mostly in air or liquid mediums and most of the applications occur in water supply systems. Thermal stratification has been studied within tanks since the 1970s, showing that the stratification can improve the performance of the energy storage [21]. A fully stratified tank is shown to be better than a fully mixed water tank by up to 6% in storage efficiency and exhibits improvements in the whole system by up to 20% [22].

Stratification aspects including the influence of flow rate on the stratification degree, inlet geometry on mixing, and the effect of thermocline on the efficiency of the TES system have been studied [23]. During use, the heated water is discharged from the top inlet port of the TES and cold water is removed from the bottom outlet. This process results in a thermal stratification from the temperature variation. The temperature variation causes a density variation within the water, resulting in a separation of hot and cold water by gravitational effects. This region is called the thermocline. The efficiency of a TES increases as the temperature difference between the top and bottom increase and performance is improved by maintaining the stratification of the fluid [21,23–28].

Several energy and exergy studies have been performed for TES systems. Li has shown evaluations of sensible heat TES systems and he was able to conclude that these systems are one of the most efficient ways to store thermal energy. Li also addressed the major influencing factors in TES performance such as flow rate and geometry [29]. TES technology to capture industrial waste heat has been investigated by Miró et al. They identified a potential for the industrial sector to use TES to capture heat energy where conventional equipment would be impractical due to intermittent heat generation rates or physical location [30]. Cui et al. demonstrated the cost savings potential when integrating cold TES with HVAC systems in commercial buildings [31]. Rosen et al. analyzed the effect of stratification on energy and exergy capacities in thermal storage. They showed that an increase in exergy storage capacity is attained in thermal storage stratification. They concluded that the use of stratification in TES design should be considered as it increases exergy storage capacity [32–36].

Exergy analysis has been advocated by Rosen and Dincer for the study of thermal systems. They emphasize that an exergy analysis is necessary to assess performance improvements and for optimization of processes [37]. Rosen et al. also indicate that exergy analysis approaches provide intuitive advantages for cold TES systems [38]. Rismanchi et al. reviewed much of the work in energy, exergy, and environmental aspects in 2012, showing that cold TES systems often reach efficiencies of 90%. They also noted that exergy efficiencies were below 20% and provide a more realistic evaluation of the irreversibilities within TES systems [39].

This paper provides a detailed analysis of the cold TES system at the University of Idaho (UI), the Moscow campus, and reports on the data acquisition, modeling process, and exergy analysis. The data acquisition describes the measurements taken and procedures necessary to create a model representative of the current TES system. TRNSYS is used for