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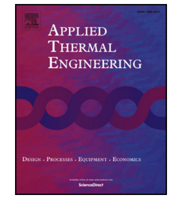

Research Paper

Model-based analysis of thermal energy storage for multiple temperature level heat supply

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HIGHLIGHTS

- Reduced model based on the logistic CDF for the thermocline of hot water TES.
- Correlation between the thermocline thickness and Reynolds and Fourier numbers.
- Comparison three different numerical models: 1D, 2D and reduced model.
- Validation on test data of two TES at different temperatures in a mCHP + HP system.

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ABSTRACT

Thermal Energy Storages (TES) are widely used in many energy systems and improving their performance has become increasingly important. Various CFD models are currently available, both one-dimensional and multi-dimensional, with different level of accuracy, computational cost and capability to be generalised. This work is aimed at analising the relevant phases, i.e. charge, discharge and low inertial discharge, of a couple of hot water TES characterized by different inlet temperatures and flow rates, with three numerical approaches: 1D, 2D, and a reduced model. In particular, the latter approach provides a simple analytical function for the evaluation of the temperature profile inside the tanks. The numerical models are validated on experimental data obtained from a test bench with two hot water tanks, in which one tank is connected to a micro-CHP while the other is connected to a heat pump, and operated at different temperature levels.

The results of the 2D and the reduced models are in good agreement with experiments showing a maximum error lower than 1.2 K during the discharge cycles; nevertheless, the reduced model has a much lower computational cost and the dimensionless nature of the implemented function allows generalising the validity of the results to storage tanks operating at different conditions.

1. Introduction

Thermal energy storages (TES) are widely used in energy systems regardless of their size, i.e. from small domestic solar thermal systems to large district heating networks, in order to store energy and to act as a buffer between the heat source and the user. In particular, TES play a relevant role in combination with renewables, since the latter are generally not programmable and the energy production generally does not match the user demand. Therefore, TES can contribute to optimise the performance and to improve the energy efficiency of the overall energy system. In such a context, an accurate and reliable analysis of TES is required, since an efficient operation of TES strictly depends both on its characteristics, i.e. geometry, presence of inlet diffusers, insulation, and on operative parameters, e.g. flow rate and temperatures of the thermal fluid. These characteristics affect the temperature distribution inside the tank, which can be either uniform (i.e. fully mixed) or stratified. In the latter case, TES can be divided into three zones

a hot zone, a cold zone, and a region with a temperature gradient, also known as thermocline. Previous studies proved that stratified storage tanks are more efficient than fully mixed ones [1]. These findings increase the interest in accurate modeling of the temperature distribution inside thermal tanks.

Many authors have investigated the topic, and proposed numerical models for the temperature distribution inside storage tanks, based on analytical, numerical or empirical approaches, with different results in

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Nomenclature

A	cross section, m^2
c	specific heat of water, $J\,kg^{-1}\,K^{-1}$
Fo	Fourier number
g	gravitational acceleration, $m\,s^{-2}$
h	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
H	height of the tank, m
k	thermal conductivity, $W\,m^{-1}\,K^{-1}$
Pe	Peclet number
Re	Reynolds number
Ri	Richardson number
S	quasi-variance
T	temperature, °C (K)
TC^*	thermocline thickness
v	velocity, $m\,s^{-1}$
$\dot{V}$	flow rate
Z	mixing coefficient
z_c	center of the thermocline

Greek symbols

α	thermal diffusivity, $m^2\,s^{-1}$
β	thermal expansion coefficient, K^{-1}
ε	turbulent kinetic energy of dissipation, $J\,kg^{-1}\,s^{-1}$
κ	turbulent kinetic energy, $J\,kg^{-1}$
μ	dynamic viscosity, $kg\,m^{-1}\,s^{-1}$
ρ	density, $kg\,m^{-3}$
τ	time, s

Subscripts

w	wall
f	fluid (water)
I	internal
n	nominal
0	ambient
r	return
s	supply
z	axial coordinate

Acronyms

CDF	cumulative distribution function
MAE	mean average error
SD	standard deviation
TES	thermal energy storage

terms of accuracy and computational cost. Numerical modeling has attracted considerable attention because of relevant progress in term of advancements in hardware and software resources, time saving and improved accuracy, if compared to experimental tests. Consequently, numerical analysis and commercial software are widely used to optimize the operation of existing TES and to design new installations [2].

The simplest models are one-dimensional, which calculate the temperature distribution along the tank axis. They are useful for energy-related studies and for long-term (e.g. annual) simulations of the overall plant. These models follow two main approaches

multinode and plug-flow [3,4]. According to the former approach, Rahman et al. [5], Baeten et al. [6], Nash et al. [7], Duffie and Beckman [8] and Angrisani et al. [9] divided the tank into N equal elements governed by energy and mass conservation laws. These models account for the various contributions to heat transfer in a different way: heat losses to the environment, thermal diffusion and mixing between adjacent nodes (i.e. node-mixing model or temperature inversion correction). Hoffman et al. [10] developed a one-dimensional model for a two-phase TES with first law equations and fixed inlet and outlet points. Further, Bejarano et al. [11] compared a multinode model with an analytical one for the analysis of the thermal charge and discharge of a latent heat thermal storage, in order to find the number of layers for the best approximation of the analytical solution. As regards the approach plug-flow, the 1D convection-diffusion equation has been used for the heat transfer in the control volumes. Nelson et al. [12] developed a plug-flow model, which is at the basis of the 1D model implemented in our work, in order to study the effects of geometry and wall material on the formation of the thermocline. They found that the most relevant phenomenon for stratification was the thermal mixing; moreover, they obtained a correlation for the estimation of the thermal mixing in the inlet and outlet nodes based on the Reynolds and Richardson numbers [13]. Instead, Cole and Bellinger [14] proposed experimental coefficients in order to account for the mixing, the fluid-wall interaction and the contribution to stratification due to the heat transfer along the wall. Alizadeh [15] developed different models in order to evaluate the effects of the thermal conductivity of water and the heat losses to the environment. Zurigat and Ghajar [16] studied the combined contributions of mixing and heat losses. Moreover, Yoo and Pak [17] found 1D analytical solutions for a finite domain, and Cabelli [18] addressed to a semi-infinite domain using Laplace transforms.

Two and three-dimensional models can perform accurate analyses of the thermal-fluid-dynamics inside a tank, especially with high inlet flows and in presence of diffusers, because mixing and turbulence strongly affect stratification [19]. Lightstone [20] and Zurigat [21] solved the equations in the primitive variables using a finite volume method. Guo and Wu [22], and Hahne and Chen [23] solved the vorticity-stream function in dimensionless equations through finite differences methods. Commercial CFD softwares like Comsol® and Fluent® have been extensively used to model storage tanks [24], to analyze the influence of the inlet layout [25], and to study the effect of tank insulation on stratification [26]. Yaici et al. [27] used Comsol to design a novel inner equalizer in a hot water storage tank aimed at investigating the influence of several parameters on stratification, i.e. aspect ratio, inlet and outlet positions and operating conditions. Instead, Nandi et al. [28] evaluated the influence of geometrical and thermodynamic parameters on a packed-bed thermocline TES through a transient 3D model. Cascetta et al. [29] studied a packed-bed TES with a 2D axisymmetric geometry and a two-phase transient model equation. Tinaikar et al. investigated the effects of flow disturbances [30] and laminar vortexes [31] on stratification, finding a correlation between thermocline and Richardson number. Moncho-Esteve et al. [32] studied the effects of different inlet devices on thermal stratification in a storage tank similar to those investigated in our work, by using Star-CCM commercial code. Further, from a geometrical point of view, Yang et al. [33] evaluated the effects of the shape of the tank on thermal energy storage capacity and thermal stratification.

All these works have clearly demonstrated that multidimensional CFD models are effective tools in describing the performances and the thermocline formation in thermal energy storages. However, the main issue associated with CFD models is the high computational cost. In this regard, the adoption of reduced models can be a useful alternative, since they rely on simple correlations. A lot of literature, which was collected by Bayon and Rojas [34], shows that the temperature distribution inside a thermally stratified storage tank is similar to a sigmoid. From a mathematical point of view, they suggested both a normal and a logistic cumulative distribution function, while Chung [35] proposed the Fermi-Dirac distribution function. Bonanos and Votyakov used the normal-CDF to identify which governing parameters have the