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Multi-Node Thermal Modelling and Performance Analysis of Stratified Chilled-Water Thermal Energy Storage Tanks

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Abstract

Thermal energy storage (TES) in a stratified water tank allows cooling or heating capacity to be stored when it is cheap and delivered when it is needed. This paper evaluates such a tank in terms of energy efficiency, storage capacity and discharge behaviour. A small-capacity storage unit for a refrigeration system was designed, developed and fabricated to study thermal stratification at different flow rates, using the thermocline thickness, the figure of merit and the equivalent lost tank height as indicators. A multi-node energy balance, a fully mixed tank model and capacity-based performance equations are presented to describe the tank. The work shows that stratification stores thermal energy with high efficiency and capacity. Tank design, flow rate and inlet temperature are the key factors, and a low inlet velocity, a large temperature difference and wide port spacing limit mixing. Therefore, the paper strongly emphasized the multi-node model, eddy diffusivity, and Froude/Reynolds number relationships as the novel contributions of this paper.

1. Introduction

Storing heat or cold for later use is one of the more practical ways of managing energy

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efficiently, lowering operating costs and improving sustainability. In buildings in particular, thermal energy storage (TES) can cut both energy consumption and expense. Among the available approaches, stratified storage keeps hot and cold water apart inside a single tank, and it is this separation that allows the tank to deliver energy at useful temperatures. The present work models and examines the behaviour of a stratified TES tank. Because of growing pressure to reduce carbon emissions and shift towards renewable sources, holding energy in the form of heat is attractive: it helps to match supply with demand, lessens the dependence on fossil-fuel power plants and limits wasted energy.

1.1 Thermal energy storage

A TES system retains thermal energy in a material or medium so that heating or cooling can be supplied at a later time. Three broad categories are recognised: sensible heat storage, latent heat storage and thermochemical storage. In sensible storage the temperature of a medium such as water or rock is raised or lowered. Latent storage makes use of a phase change, for example the melting of ice or the evaporation of water. Thermochemical storage relies on a chemical reaction that absorbs or releases heat. The stratified water tank studied here is a sensible-heat store.

1.2 Importance of stratification

Stratification is the arrangement of water in layers of different temperature, with the warmest water at the top and the coldest at the bottom. Denser cold water settles beneath lighter warm water, so the layers stay separate, heat passes between them only slowly and energy losses remain small. Once the layering is lost, the stored energy is spread through the whole volume and quickly becomes unusable. Building applications illustrate the point: surplus heat collected during the day can be released at night, easing the load on heating equipment, but only if the stored heat does not mix with cooler surroundings and dissipate. Preserving stratification is therefore central to effective storage. The main benefits of thermal energy storage can be summarised as follows:

- Peak demand is reduced and the load is levelled, because energy is stored while demand is low and released when demand is high.
- CO₂ emissions and costs fall, because energy can be used when it is cheaper and when the supply contains more renewable generation.
- The overall efficiency of the energy system increases.
- TES is a key element of peak-shaving schemes, in which off-peak electricity drives heat pumps that produce heat or cold for later use.

1.3 Literature Survey

Stratified storage has been studied from several directions. Chilled-water tanks in district cooling plants have been examined through case studies and performance assessments [1, 2], and sensor data from such a plant have been used to train machine-learning models that predict tank performance [3]. Overviews of stratified thermal storage and its energy- and exergy-based

evaluation [4, 5], together with a review of the methods available for quantifying stratification efficiency [6], provide the analytical background for the present work. A further review deals with seasonal storage technologies [7]; the charging performance of different sensible-heat storage systems has been compared [8], and water pit storage systems have been assessed using energy, exergy and stratification indicators [9]. Thermodynamic analyses have also been carried out for stores integrated into cogeneration systems [10]. Modelling techniques for stratified thermal storage have been surveyed [11], and numerical modelling of large-scale storage has been discussed in the context of renewable district heating [12]. Seasonal storage with heat pumps and low temperatures in buildings has been reviewed comparatively [13], and a contrastive experiment has been used to improve the thermal performance of storage systems [14]. The sustainability of district cooling has been addressed by adjusting cold storage and chiller operation [15]. Multi-node dynamic models for simulating stratified storage [16], exergy analysis of seasonal stratified storage [17] and the behaviour of a real industrial thermocline tank used for cogeneration [18] complete the picture.

Parametric performance modelling of stratified water tanks [19] and CFD-based second-law analysis of a large storage vessel [20] have been reported, as have experimental and CFD comparisons of latent- and sensible-heat storage [21] and numerical studies of solar hot-water tanks [22]. Energy-, exergy- and entropy-generation-based criteria for rating stratified stores have been compared [23], and stratification in domestic hot-water tanks under dynamic operation has been analysed with CFD [24]. Other work addresses air-based thermocline storage with low-cost filler material [25], entropy generation in stratified stores [26], the effect of a baffle plate on stratification [27] and the assessment of stratified storage by energy and exergy methods [28].

Against this background, the present work aims to design, build and test a small-capacity stratified storage unit for a refrigeration system and to examine how the thermocline thicknesses, the figure of merit and the equivalent lost tank height vary with the flow rate.

2. Material and Methods

2.1 System layout

The arrangement used for thermal energy storage by stratification is shown in Fig. 1. A chiller, a chilled-water tank held at 7 °C and a hot-water tank at 30 °C are connected by two pumps and a network of eleven valves (V1–V11) to the stratification tank, and a mass flow meter (MFM) records the flow. A temperature indicator-controller (TIC) is attached to the hot tank. Inside the stratification tank the hot water occupies the upper zone and the cold water the lower zone, with the thermocline forming between them. The present work expands upon this by introducing a multi-node dynamic model and investigating flow-rate-dependent eddy diffusivity in the thermal stratification storage.

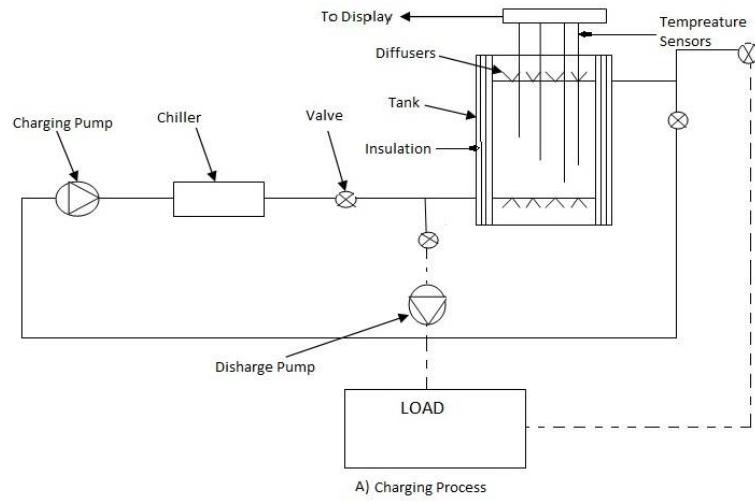


Figure 1. Schematic diagram of thermal energy storage by stratification

2.2 Multi-node mathematical model

To describe the stratified tank mathematically, the water volume is divided into a number of horizontal layers, or nodes, stacked along the height of the tank (Fig. 2) [16]. An energy balance written for every node forms the core of the model. It equates the change in internal energy of the water in that layer to the heat exchanged with the neighbouring layers, the energy carried by fluid entering and leaving, and the loss to the environment, as expressed in Eq. (1).

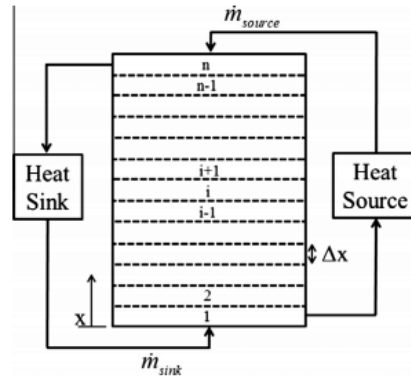


Figure 2. Multi-node representation of the stratified TES tank

$$(\rho C_p V)_i \frac{dT_i}{dt} = Q_{i-1,i} - Q_{i,i+1} + Q_{in\ flow} - Q_{out\ flow} + Q_{loss,i} \quad (1)$$

where $(\rho C_p V)_i$ is the thermal capacity of the water in node i , with ρ the density, C_p the specific heat and V the volume of the node; $\frac{dT_i}{dt}$ is the rate of temperature change of node i ; $Q_{i-1,i}$ and $Q_{i,i+1}$ are the conductive heat-transfer rates between adjacent nodes; $Q_{in\ flow}$ and $Q_{out\ flow}$ are the energy-transfer rates associated with fluid entering and leaving the node; and $Q_{loss,i}$ is the heat loss from the node to the environment.

The model must represent the following features.

Charging and discharging. Two operating modes are considered. During charging, cold water from the chiller is pumped into the bottom of the tank through a diffuser. Being denser, it displaces the warmer water upwards, and the region of steep temperature gradient, the thermocline, travels up the tank. During discharging, warm return water from the district cooling loop enters at the top and pushes the colder water out through the bottom to meet the cooling demand.

Diffuser modelling. The design of the diffusers at the top and bottom of the tank strongly influences how well stratification is maintained. The model assumes that the entering water has low momentum so that mixing is minimal, a condition usually expressed through the Froude number, $Fr < 1$.

Boundary conditions. Thermal and hydrodynamic conditions must be specified at the tank boundaries: the inlet and outlet temperatures, the ambient temperature, the mass flow rate and the heat-loss coefficients of the tank walls.

Heat-transfer terms. Conduction across the thermocline and through the tank insulation is included, together with convection, both forced convection due to the water flow and natural convection caused by temperature-dependent density differences.

Performance indicators. The model is used to evaluate the thermocline thickness, the figure of merit and the equivalent lost tank height, which are summarised in Table 1 and illustrated in Fig. 3.

Table 1 Performance indicators used to assess stratification

Indicator	Symbol	What it measures
Thermocline thickness	h_t	Mixing intensity in the tank; a narrower thermocline indicates higher stratification efficiency
Figure of merit	FOM	Ratio of the useful energy stored to the theoretical maximum, quantifying losses due to mixing and heat exchange
Equivalent lost tank height	ELH	Part of the tank height (volume) lost to poor stratification or heat transfer

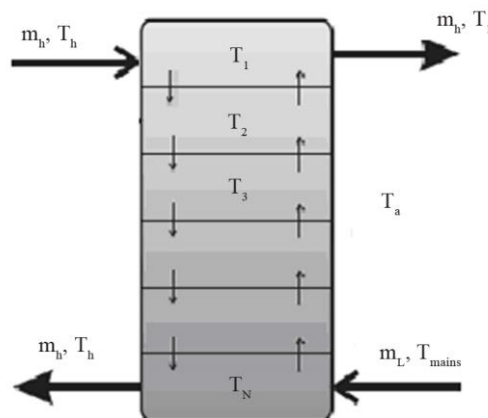


Figure 3. Analysis of the stratified TES tank

2.3 Fully mixed tank model

Because of its simplicity, the fully mixed tank model is often used for rapid, preliminary calculations, even though real tanks are neither fully mixed nor perfectly stratified [17]. The heat loss from the tank, Q_l [kWh], follows from Eq. (2), where U is the overall heat-loss coefficient, S the tank surface area, t_w the water temperature, t_g the temperature of the surroundings and $\Delta\tau$ the time step.

$$Q_l = U \cdot S \cdot (t_w - t_g) \cdot \Delta\tau \quad (2)$$

The accumulated heat, Q_a [kWh or kJ], is obtained from Eq. (3), in which m is the mass of water, c_w its specific heat and Δt the temperature change.

$$Q_a = m \cdot c_w \cdot \Delta t \quad (3)$$

When the demand Q_d is smaller than the heat supplied Q_s and the water temperature in the tank is below its maximum ($t_w < t_{\max}$), the heat stored, Q_{st} , is:

$$Q_{st} = Q_s - Q_d \quad (4)$$

If the heating load exceeds the heat provided by the solar collectors ($Q_d > Q_s$) and the water temperature is above its minimum ($t_w > t_{\min}$), heat is extracted from the tank, Q_{ss} :

$$Q_{ss} = Q_d - Q_s \quad (5)$$

The thermal balance of the seasonal storage tank is then:

$$Q_a = Q_{st} - Q_{ss} - Q_l \quad (6)$$

and the water temperature in the tank is updated at each step as:

$$\begin{aligned} T_w &= T_{w,\tau-1} + \Delta T_w \\ &= T_{w,\tau-1} + \frac{\Delta T}{m \cdot c_w} \cdot Q_a \\ &= T_{w,\tau-1} + \frac{\Delta T}{m \cdot c_w} \cdot (Q_{st} - Q_{ss} - Q_l) \end{aligned} \quad (7)$$

2.4 Mixing and dimensionless numbers

The influence of parameters such as the inlet water velocity on mixing can be assessed through the dimensionless Reynolds and Richardson numbers. Nelson et al. reported that thermocline decay is closely related to a mixing coefficient, Z , which depends on the ratio of these two numbers and was proposed in the form of Eq. (8).

$$Z = 1.688 \times 10^4 \left(\frac{Re}{Ri} \right)^{0.67} \quad (8)$$

The Reynolds and Richardson numbers are defined as

$$\text{Re} = \frac{\rho v d}{\mu}$$

$$\text{Ri} = \frac{g \beta \Delta T h}{v^2}$$

where ρ is the water density, v the inlet velocity, d and h characteristic lengths of the inlet, μ the dynamic viscosity, g the gravitational acceleration, β the thermal expansion coefficient and ΔT the temperature difference between the hot and cold water. A mixing coefficient of one corresponds to a perfectly stratified system without mixing, and mixing decreases as the ratio Re/Ri decreases. This ratio can be written as

$$\frac{\text{Re}}{\text{Ri}} = \frac{\rho v^3 d}{\mu \beta g \Delta T h} \quad (9)$$

Equation (9) shows that the flow velocity has a strong influence on mixing in the store. Since the density, viscosity and thermal expansion coefficient of water all depend on temperature, mixing can be reduced by:

- (i) lowering the inflow velocity;
- (ii) increasing the temperature difference; and
- (iii) increasing the distance between the ports (that is, increasing the aspect ratio).

2.5 Basic thermal relations

The heat energy exchanged by a mass of water is calculated from

$$Q = m \times C_p \times (T_1 - T_2) \quad (10)$$

where Q is the energy, m the mass, C_p the specific heat capacity and T_1 , T_2 the temperatures. For water, C_p is about 4.18 kJ/kg·K at 20 °C. The corresponding heat-transfer relation is

$$Q = mc\Delta T \quad (11)$$

The cooling of a body is described by Newton's law of cooling,

$$\frac{dT}{dt} = k(M - T) \quad (12)$$

in which k is a proportionality constant and M the temperature of the surrounding medium. The thermal efficiency of a process is the ratio of the work done W to the heat received Q , $\eta = W/Q$.

The thermocline thickness, h_t , is evaluated from a dimensionless temperature θ and a chosen cut-off value, where

$$\theta = \frac{T(y, t) - T_c}{T_h - T_c} \quad (13)$$

Here $T(y, t)$ is the temperature measured by the sensor at position y at time t [°C], T_c is the cold-water (final) temperature [°C] and T_h is the warm-water (initial) temperature [°C].

2.6 Capacity-based performance indicators

The indicators below follow the capacity-based approach commonly used for stratified chilled-water storage [1, 2]. The thermal capacity is the quantity of heat removed from, or added to, a mass of storage medium as its temperature falls or rises over a period of time:

$$C_t = \dot{m}c\Delta T\Delta t \quad (14)$$

where C_t is the thermal capacity [kJ], $\dot{m}$ the mass flow rate [kg/s], c the specific heat [kJ/kg·K], ΔT the temperature difference [°C] and Δt the time interval [s]. For the storage medium held in one tank volume, the thermal capacity is

$$C_t = \rho AHc\Delta T \quad (15)$$

where ρ is the water density [kg/m³], A the tank cross-sectional area and H the tank height. For one tank volume three measures of capacity can be combined in a single relation:

$$C_{\max} = C_{\text{int}} + C_{\text{lost}} \quad (16)$$

The **theoretical capacity** is

$$C_{\max} = \rho AHc(T_h - T_{\text{in}}) \quad (17)$$

where $C_{\max}$ is the maximum capacity [kJ] and T_{in} the average inlet temperature [°C]. The **integrated capacity** is

$$C_{\text{int}} = \rho AHc(T_{\text{ini}} - T_f) \quad (18)$$

where T_f is the average final temperature [°C]. The lost capacity is

$$C_{\text{lost}} = \sum \dot{m}c(T - T_{\text{in}})\Delta t \quad (19)$$

where C_{lost} is the lost capacity [kJ] and $T_{\text{in}} + \varepsilon < T < T_{\text{limit}}$, with ε an arbitrarily small temperature tolerance used to define the extent of the thermocline.

The **half-cycle figure of merit** is defined as the ratio of the integrated discharge capacity to the theoretical capacity over a complete charge–discharge cycle, both evaluated for one tank volume:

$$\text{FOM}_{1/2} = \frac{C_{\text{int}}}{C_{\max}}$$

where $\text{FOM}_{1/2}$ is the half-cycle figure of merit. The expression simplifies to

$$\text{FOM}_{1/2} = \frac{T_h - T_f}{T_h - T_{\text{in}}} \quad (20)$$

The **equivalent lost tank height**, in metres, expresses the lost capacity as a height of tank:

$$\text{ELH} = \frac{C_{\text{lost}}}{\rho c A (T_h - T_{\text{in}})} \quad (21)$$

Finally, the energy balance of the TES tank as a whole is

$$\frac{d(\rho V C_p T)}{dt} = Q_{\text{in}} - Q_{\text{out}} + Q_{\text{loss}} \quad (22)$$

This governing equation contains the density ρ , the specific heat C_p and the temperature T of the water. Heat is lost by conduction, convection and radiation, and stratification is handled by modelling the temperature gradient in the tank.

2.7 Performance metrics and investigation approaches

Analysis of the fluid dynamics inside the tank centres on the following quantities:

- **Thermocline thickness:** the dynamic thermal layer separating the hot fluid at the top from the cold fluid at the bottom. A thinner thermocline indicates less mixing and a better storage arrangement.
- **Richardson number (Ri):** a dimensionless parameter comparing buoyancy forces with the shear forces that cause mixing.
- **Péclet number (Pe):** the ratio of advective to diffusive thermal transport.
- **Stratification efficiency:** obtained from exergy analysis, it shows how much high-grade usable energy (availability) is preserved and how much is lost through mixing in dead volume.

Stratification can be investigated experimentally, numerically, or by combining both. Experimental verification typically considers tanks of different aspect ratio (height-to-diameter ratio, usually between 2.0 and 4.0) and mechanical inlet diffusers of different type, such as a slotted pipe, an octagonal ring or a radial disk, which lower the inlet velocity. Temperature is recorded with a vertical array of high-precision thermocouples spaced at short intervals (for example every 50 mm) along the central axis, so that the thermal boundary can be mapped continuously. In computational fluid dynamics (CFD) studies, ANSYS Fluent is a common platform. Standard laminar models are inadequate at high charging velocities, so the SST $k-\omega$ or RNG $k-\epsilon$ turbulence models are used to capture buoyancy-driven shear layers and the vortices generated near the inlets.

2.8 Test rig for flow-rate studies

Stratification raises the efficiency of hot- and chilled-water storage by maintaining separate temperature zones, which limits mixing and the associated energy loss over the storage cycle. This matters in solar thermal, HVAC and industrial applications, where accurate temperature control is required. A test rig was therefore conceived to study stratification across a range of flow rates. Its main components are:

- **Temperature monitoring:** a vertical cylindrical tank fitted with precision temperature sensors at several heights to record the full thermal profile.

- **Flow control:** an adjustable system that sets inlet velocities corresponding to flow rates of 0.5 to 3 GPM.
- **Inlet design:** specialized inlet diffusers or stratifiers that control the flow geometry and reduce turbulence at the entry point.
- **Data acquisition:** a system for real-time logging of temperature and flow with high precision.

Mixing in the tank is described by an eddy diffusivity that depends on the flow rate (Fig. 4). In laminar flow ($Re < 2100$) mixing is low and turbulence decays exponentially, so the stratified layers are preserved. In turbulent flow ($Re > 10\,000$) mixing is stronger and turbulence decays hyperbolically, which thickens the thermocline and degrades stratification. Including $K(Re)$ relationships noticeably improve the predicted temperature profiles across the different flow regimes.

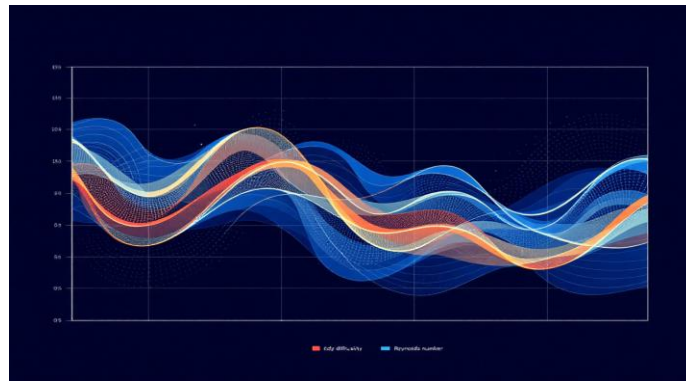


Figure 4. Flow-rate dependence of the stratified TES tank (illustrative)

The test programme varies the flow rate stepwise from 0.5 to 3.0 GPM to cover the whole operating range, measures the temperature stratification over time during both charging and discharging, and compares the experimental data with the one-dimensional model in order to refine the eddy-diffusivity correlations and improve accuracy.

3. Results and Discussion

The performance of the stratified thermal energy storage tank depends strongly on the interaction between the flow rate and the buoyancy-driven flow. The inlet flow has to be regulated so that a sharp thermocline is maintained and mixing is kept low, while the charging and discharging rates remain acceptable. Considering the temperature distribution, the thermocline thickness, the stored energy and the useful energy recovered together gives a complete picture of the thermal performance of the storage system. The literature indicates that inlet geometry has a marked effect on stratification quality: well-designed diffusers considerably reduce turbulence and unwanted mixing. Thermocline thickness and equivalent lost tank height serve as the main quantitative measures of stratification effectiveness, and higher flow velocities consistently thicken the thermocline, which directly lowers the stratification efficiency and the energy performance. At low flow rates a sharp thermocline forms, producing distinct temperature zones with little mixing between the layers. CFD

simulations reveal the complex flow patterns and mixing zones throughout the tank volume, and validation against experiments indicates that model predictions agree to within ± 2 °C over a range of operating conditions.

4. Conclusions

The study investigated the thermal stratification behaviour of a chilled-water thermal energy storage tank through experimental investigation and mathematical modelling. The results demonstrate that flow rate and inlet conditions have a significant influence on temperature distribution, thermocline development, mixing, and useful energy recovery.

The combined assessment of thermocline thickness, stored energy, useful energy recovery, and stratification characteristics provides a basis for evaluating the thermal performance of the storage tank. The multi-node energy-balance approach further provides a useful framework for predicting temperature variation within the tank under different operating conditions.

The analysis indicates that lower inlet velocity, an appropriate inlet temperature difference, and suitable inlet/outlet spacing can reduce undesirable mixing and improve thermal stratification. The consideration of flow and mixing characteristics through the proposed modelling framework provides useful guidance for the design and operation of stratified thermal energy storage systems.

Future work will focus on optimization of inlet configurations, improved control strategies, and validation of the mathematical model under a wider range of operating conditions.

Nomenclature

Symbol	Meaning	Symbol	Meaning
A	tank cross-sectional area [m ²]	Q	heat or energy [kJ]
c, c_w, C_p	specific heat [kJ/kg·K]	Q_l	heat loss from the tank [kWh]
C_t	thermal capacity [kJ]	Q_a	accumulated heat [kWh or kJ]
$C_{\max}$	maximum (theoretical) capacity [kJ]	Q_{st}, Q_{ss}	heat stored in, extracted from the tank
C_{int}	integrated capacity [kJ]	Q_d, Q_s	heating demand, heat supplied
C_{lost}	lost capacity [kJ]	S	tank surface area [m ²]
ELH	equivalent lost tank height [m]	T	temperature [°C]
FOM	figure of merit [–]	T_h, T_c	warm, cold-water temperature [°C]
Fr	Froude number [–]	T_{in}, T_f	average inlet, final temperature [°C]
g	gravitational acceleration [m/s ²]	U	overall heat-loss coefficient
H	tank height [m]	V	volume [m ³]
h_t	thermocline thickness [m]	Z	mixing coefficient [–]
$m, \dot{m}$	mass [kg], mass flow rate [kg/s]	β	thermal expansion coefficient [1/K]
Pe	Péclet number [–]	θ	dimensionless temperature [–]
Re, Ri	Reynolds, Richardson number [–]	μ, ρ	dynamic viscosity, density

Abbreviations: TES, thermal energy storage; CFD, computational fluid dynamics; FOM, figure of merit; ELH, equivalent lost tank height; GPM, US gallons per minute.

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