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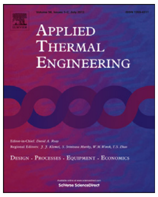

Assessing long-term performance of centralized thermal energy storage system

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HIGHLIGHTS

- Integration of ventilation system and centralized LHTES to shave peak demand.
- Development artificial neural network to predict the long-term performance of the system.
- Performing a parametric study using developed and an experimentally verified 3D numerical model.
- Assessing the reduction of ventilation load for typical days of summer season in Montreal city.

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ABSTRACT

A validated computational fluid dynamics simulation tool is used to study the long-term performance of a centralized latent heat thermal energy storage system (LHTES). The LHTES system is integrated with a building mechanical ventilation system. Paraffin RT20 was used as a phase change material (PCM) and fins are used to enhance its performance.

To reduce the computational time, artificial neural networks (ANN) was used to relate the relationships between the LHTES inputs and output parameters. Extensive CFD simulations were carried out to identify all the influential parameters for the development of ANN. They include phase change temperature range, air flow rate, the geometrical configuration of a LHTES system, fin size, and the unit's length. Further CFD simulations were carried out to provide sufficient data for proper training and testing of the ANN. The ANN model was used to predict the LHTES's outlet air-temperature. There was a good agreement between the ANN prediction and CFD model's prediction.

The ANN model then was used to study the annual performance of a LHTES for application in Montreal. We found that the potential of use the centralized LHTES system to reduce the cooling load is high with a wider phase change temperature range. The centralized LHTES system contributes to reducing the cooling load from 21% to 36% when the length of the centralized LHTES system is increased from 500 to 650 mm at a flow rate of 1.5 m/s.

1. Introduction

Evidence from a variety of research suggests that the built environment contributes substantially to global energy consumption and to the production of greenhouse gases (GHG) that impact climate change: buildings use about 40% of the world-wide total energy and contribute up-to 35% of GHG. These facts highlight the importance of targeting building energy use as a way to decrease the energy consumption and GHG emission simultaneously. The contribution of building energy use to the climate change has been acknowledged by the intergovernmental panel on climate change (IPCC) [1]. The IPCC has prepared documents that assist policy makers to design programs for reducing energy use in buildings. Hence, net-zero energy buildings (NZEB) have been suggested as an approach to achieving this goal. NZEB, are defined as buildings that produce as much energy as they use over the course of a year. There are a number of challenges in the design, construction and operation of NZEB.

Presently, designers use guidelines developed for passive solar buildings to design NZEB where the focus is on the design of a well-insulated-and airtight-building envelope. Then, the building is connected with an on-site renewable energy sources (RES). The main drawback of RES is the variability and intermittence in their availability; significant mismatches between energy demand time and energy production time can occur. Thus to make the NZEB a viable solution, it must be integrated with thermal energy storage [2].

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Nomenclature

A	porosity function
a	convection coefficient, W/m^2 K
c	specific heat at constant pressure, J/kg K
c_{eff}	effective specific heat, J/kg K
ΔH	latent heat content
h	sensible enthalpy, J/kg
k	thermal conductivity, W/m K
f	liquid fraction
g	gravity, m/s^2
L	latent heat of phase change, J/kg
$Q_{C,Air}$	conventional ventilation load, kJ
$Q_{C,LHTES}$	ventilation load of LHTES system, kJ
$Q_{cooling}$	potential cooling load, kJ
P	effective pressure, Pa
q''	mean heat flux, W/m^2
Ra	Rayleigh number
S_b	buoyancy source term
S_h	latent heat source term
T_C	control temperature, K
T_m	mean melting temperature of the PCM, K
T	temperature, K
T_i	indoor air temperature, K
T_a	ambient air temperature, K
T_{out}	LHTES outlet air temperature, K
t	time, s
$\underline{u}$	velocity, (u,v,w), (m/s)
$\dot{V}$	air flow rate, m^3/s

Greek symbols

β	thermal expansion coefficient, 1/K
μ	viscosity, kg/m s
λ	porosity
ω	A constant used to calculate porosity function (Eq. (7))

Subscripts

i	initial
ref	Reference
l	Liquid
s	Solid
PCM	phase change material
ANN	artificial neural network
CFD	computational fluid dynamics
DSC	differential scanning calorimeter
HTF	heat transfer fluid
TES	thermal energy storage
RES	renewable energy sources
GHG	greenhouse gases
IPCC	intergovernmental panel on climate change
NZEB	net-zero energy buildings
LHTES	latent heat thermal energy storage
TRNSYS	transient system simulation program
GMDH	group method of data handling

Arkar et al. [3] studied the free cooling of a low-energy building using an integrated LHTES system with a mechanical ventilation system. Spherical capsules of RT20 paraffin (PCM) were filled into the LHTES system. A periodic variation of the inlet ambient-air temperature was considered in a developed numerical packed-bed model in order to obtain the optimum phase-change temperature. The distributions of the air axial velocity and the bed porosity were considered uniform and applied into coupled energy equations for the air and PCM. The outlet-air temperature of LHTES system was approximated as Fourier functions and then integrated into the TRNSYS building thermal model. The selected building has a floor area of 191 m^2. The simulation results showed that a PCM with a melting temperature between 20 and 22 °C has a significant potential to be implemented for free cooling for continental climate, characterized by hot summers and cold winters. They reported that the LHTES with 6.4 kg of PCM per m^2 of floor area can afford suitable thermal comfort conditions inside the selected building.

Arkar et al. [4] also investigated the potential efficiency of using free cooling principles in a heavyweight and lightweight low-energy building equipped with a mechanical ventilation system. The storage system had two cylindrical LHTES systems: one for cooling the fresh supply air and the other for cooling the re-circulated indoor air. LHTES system contained spherical capsules filled with paraffin RT20. A numerical model was used to describe heat transfer for the air and the PCM. The output temperatures of the LHTES model were given to TRNSYS to calculate the building thermal response. The temperature response functions considered the heat storage size, the air flow rates, and the PCM's thermal properties. They showed that the free cooling technique has a potential to minimize the size of the mechanical ventilation system when both LHTES1 and LHTES2 were filled with 6.75 kg/m^2 of PCM for the floor area of the studied heavyweight building.

The potential of a ventilation system containing a direct heat exchange between ventilation air and PCM packed bed granules was experimentally investigated [5,6]. The system was consisted of rectangular parallel piped and PCM granules (RUBITHERM GmbH, 2003) which were packed at its center in the vicinity of insulation. The granules constituted of 65% ceramic materials and 35% paraffinic hydrocarbon by weight and having a particle diameter of 1–3 mm. The measured outlet air temperature was uniform in the range of the PCM temperature phase change when the inlet air temperature was periodically changed. The simulation was conducted for cooling season for eight cites in Japan. The results showed that the ventilation load reduction depended on the city daily temperature variation. The maximum reduction of ventilation load was found for Kyoto by 63% of total required ventilation.

Dincer et al. [7] applied a feed-forward back-propagation artificial neural network (ANN) algorithm to analyze heat transfer through annularly finned tube with a PCM, concluding that ANN approach is a promising method for analyzing thermal energy storage systems within a maximum discrepancy of about 5% compared to a numerical solution. Sanchez et al. [8] applied ANN to study the performance of microencapsulation containing a PCM. They investigated the effect of the ratios of paraffin wax to styrene mass, of poly-vinylpyrrolidone to styrene mass, and of water to styrene mass on the micro particles. The average of the particle size was empirically correlated based on the latent heat of microcapsules using a neural network with a single neuron. It was concluded that the developed neural network can predict the latent heat with less than 7% error and the average of particle size with less than 20% error. To the authors' knowledge, no effort has been made to investigate the performance of LHTES system integrated with a building under realistic conditions.

This paper reports the outcome of an extensive CFD simulation to study the long-term performance of a centralized LHTES system. A validate CFD simulation tool is integrated with a building's mechanical ventilation system. Paraffin RT20 was used as a PCM and fins are used to enhance its performance.

To reduce the computational time, ANN was used to relate the relationships between the LHTES inputs and output parameters. To