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Comparing meshless local Petrov–Galerkin and artificial neural networks methods for modeling heat transfer in cisterns

M. Razavi [a], A.R. Dehghani-sanij [a], M.R. Khani [b,*], M.R. Dehghani [c]

[a] Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's, NL, Canada A1B 3X5
[b] Department of Environmental Health Engineering, Faculty of Health, Islamic Azad University, Medical Sciences Branch, Tehran, Iran
[c] Department of Architectural Engineering, Science and Arts University, Yazd Branch, Yazd, Iran

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ABSTRACT

Long-term underground cold-water cisterns had been used in old days in the hot and arid regions of Iran. These cisterns provide cold drinking water during warm seasons for local communities. In this paper, the thermal performance of an underground cold-water cistern during the withdrawal cycles in warm seasons is modeled. The cistern is located in the central region of Iran in the city of Yazd. Two approaches are used to model the heat transfer in the mentioned cistern. The first approach is meshless local Petrov–Galerkin (MLPG) method with unity test function and the second approach is artificial neural networks (ANN). For the ANN method, the multi layers perceptron (MLP) feed-forward neural network training by back propagation algorithm is used. Both methods are compared and a good agreement is observed between the MLPG and ANN results. The results show a stable thermal stratification in the cistern throughout the withdrawal cycle. The thermal stratification is linear in lower areas and exponential in upper areas. The exponential trend in the upper area is because of several factors such as: thermal exchange among the upper layers of water and the domed roof, transfer of mass and evaporation due to entry air from the wind towers.

Contents

1. Introduction

Climate conditions have always influenced the life of human beings. Cities and villages in hot and arid regions have special architectures to tolerate the climate conditions. Hot and arid regions are known by the following specifications: hot and sunny days, cold nights even in the summer time, low rain and fast evaporation because of the sun and wind, large temperature difference between shade and sun and the problem of low available water [1]. People of these regions had invented special architectural passive cooling systems to contradict these weather conditions [2,3] and these systems were widely investigated during the recent decades [4–13].

One of the passive cooling systems is the cold thermal energy storage system (CTES). This system employs numerous methods to store cold thermal energy. For instance, long-term cold thermal storage systems take advantages of seasonal climate variation in

* Corresponding author.
E-mail addresses: m.razavi@mun.ca (M. Razavi), ads485@mun.ca (A.R. Dehghani-sanij), mkhani@iautmu.ac.ir (M.R. Khani).

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Nomenclature

B	length (m)
C_{Pa}	air specific heat (kJ/kg °C)
h_a	heat transfer coefficient (W/m^2 °C)
h_{fg}	latent heat of vaporization of water (kJ/kg)
h_m	mass transfer coefficient (W/m^2 °C)
H	height (m)
k_w	thermal conductivity of water (W/m °C)
k_s	thermal conductivity of soil (W/m °C)
$\dot{m}_v$	evaporation rate (kg/m^2 s)
r	radius axis
t	time
T	temperature (°C)
T_a	ambient air temperature (°C)
T_H	domed roof temperature (°C)
w	weight matrix of each layer, humidity ratio of air (kg/kg)
z	vertical axis

Greek symbols

α	thermal diffusivity (m^2/s)
ε	emissivity
Ω	domain
Γ	domain boundary
ϕ	interpolation function
σ	Stefan–Boltzmann constant

order to store cold energy during the winter time for using in the summer time. A comprehensive review on the concept of CTES, application of different types, and their advantages and disadvantages had been conducted by Dincer et al. [14] and Saito [15].

CTES mostly use water as the storage medium. They store cold water in cold seasons for using during the warm seasons. For this purpose, a thermal stratification should develop in the water; therefore, the influence of various design parameters on the thermal stratification is the most important factor investigated by numerous researchers. Nelson et al. [16] investigated experimentally the effects of storage tank dimensions, the physical properties of walls and mixing effects of fluid flow during charging and discharging cycles on the thermal stratification of water in a vertical cylinder storage tank. Their results show that by increasing the length to the diameter ratio of the tank, the degradation of the thermal stratification is minimized. However, this effect is negligible for the aspect ratios more than three. They reported that the fluid flow during charging and discharging cycles reduce the stability of the established thermal stratification inside of the storage tank. Also, they mentioned that using insulation around the tank improves the stability of the thermal stratification.

Borst and Aghamir [17] considered a water storage tank with the approximate volume of 35 m^3 that conserved cold water for half of the year. They compared two methods for cooling the water. The first method was blowing the cold ambient air in winter over the surface of the water and the second method was using a solar collector at night in summer. They showed the first method is more efficient.

The other approach that used in the CTES is cooling the water in storage tanks using the electrical power in the low demand period for using as a cooling system in the time of high-demand for electrical power. Truman et al. [18] were studied one of these water storage tanks using the finite difference method (FDM). Bahadori et al. [19] investigated the thermal characterization of a long-term chilled water cistern in hot and arid regions by the finite difference method assuming a simplified thermal boundary condition at the water surface. Their results show a developed thermal stratification in the cistern. Also, the temperatures of the upper layers of water were a function of the surrounding air temperature and the temperature of the lower layers in the bottom of the cistern remained lower than the ambient temperature.

Aghanajafi et al. [20] used the computational fluid dynamics (CFD) to model the thermal behavior of a lake. They showed the temperature and density distributions of water are not stable in the layer of water close to the water surface. Al-Marafie [21] experimentally studied the thermal stratification of a chilled water storage tank with the volume of 7.5 m^3. For cooling the water, an air-conditioning system is used during the off-peak periods. The chilled water was used throughout the peak time. He showed the efficiency of the system is almost 90 %.

Moreover, the thermal stratification in a long-term underground cold-water cistern was studied experimentally by Dehghan and Dehghani [22,23]. They concluded that the radiation heat exchange between the water surface and ceiling and the convective heat and mass transfer from the water surface induced by the airflow have the most impact on the thermal stratification of the cistern.

Hooshmand Aini [24] numerically studied the effect of the domed roof and wind towers in the structure of traditional cisterns of Iran for cooling the water. They studied the water cooling process of cistern in different conditions including different wind velocities and modeled the air flow pattern in the cistern using FLUENT commercial software package. Also, Najafi et al. [25] numerically investigated the fluid flow inside and around the cisterns using the FLUENT commercial software package. They investigated the effect of different parameters including the diameter of the domed roof, wind velocity, inlet and outlet geometry of wind tower and its elevation. They obtained the best geometry for having the best performance of cisterns. Khani et al. [26] experimentally studied the performance of a long term cold water cistern. They considered its effect in the reduction of fuel consumption and environmental pollutants.

Moreover, the history, architecture and functionality of cisterns in different regions of Iran were studied by some researchers [27–39]. The architecture of cisterns in different areas represents the architectural identity of the area. Masarrat and Dehghani [40]

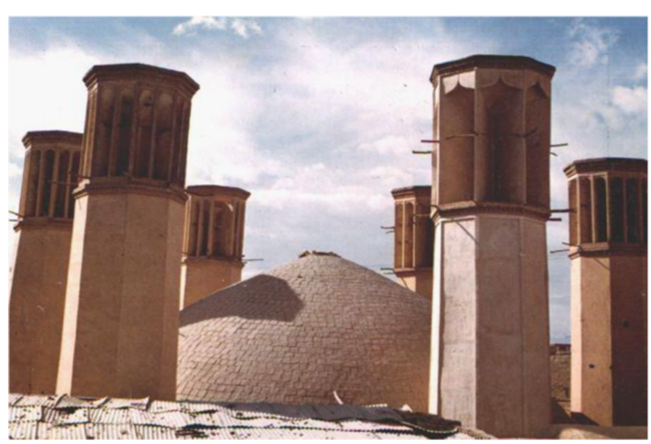

Fig. 1. A city cistern in Yazd with six wind towers.