Study on the Heat Transfer of Capillary Heat Exchanger for Heat Pump in Coastal Areas at Different Times of Diary Operation

Zhenpeng Bai, Xiaohan Zhao, Jin Zhang

Abstract— **This paper studies the optimization design of capillary heat exchangers and their innovative engineering applications in buildings. The purpose of this study is to use a capillary heat exchanger as the front-end device of the heat pump in coastal areas to extract energy to facilitate the application of renewable energy in buildings. Firstly, in this paper, the main factors of capillary heat transfer efficiency were explored in areas near the coast. Secondly, for the sake of improve the heat transfer efficiency of the capillary heat exchanger, numerical calculations were carried out on the heat transfer of the capillary in the case of inconsistent operating patterns in the summer and winter months, respectively. The results showed that when the daily working time of the capillary heat exchanger was 8 hours, the temperature difference of the capillary inlet and outlet was 2.1 ℃. And the heat transfer rate was 87.1 W/m^2. In summer, the temperature difference of the capillary inlet and outlet was 2.6 ℃. And the heat transfer rate was 107.8 W/m^2. This article helps to promote innovative and sustainable technologies in coastland development, such as capillary heat exchangers and heat pumps, which could used in renewable energy extraction and building utilization in near coastal areas.**

Index Terms—**Heat pump; Diary operation; Capillary heat exchanger; Coastland**

I. INTRODUCTION

Previous research has focused on the development of renewable energy sources [1][2]. For a long time, research on the heat transfer mechanism of ground source heat pump buried pipe heat exchangers has mainly been applied to deterministic heat transfer theory. Due to the fact that the working environment near the coast involves heat exchange in geotechnical media, there are still few reports on the mechanism of capillary heat transfer in coastal areas, especially research on intermittent heat transfer phenomena. In practical engineering, the factors that affect the normal operation of capillary heat exchanger systems are extremely complex and diverse, and many factors themselves have significant uncertainties, or existing theories and technologies cannot obtain complete data. The deterministic stock theory and methods currently used cannot explain the heat transfer phenomenon of intermittent operation of ground source heat pumps well. Due to the lack of appropriate theoretical guidance, there are often significant deviations in the design and construction of capillary heat exchangers for ground source heat pumps, leading to problems such as excessive initial investment or insufficient heat exchange function in the project.

Heat pump technology in improving building energy efficiency has been highly regarded. Farshi et al. [3] evaluated the heat economy of the heat pump by using the exergy cost method. Shu et al. [4] made a field measurement and analysis of the energy efficiency of the actual seawater source heat pump regional heating system. The heating performance coefficient (COP) of the seawater source heat pump unit was 2.43. Marrasso et al [5] analyzed a coupled heat exchange system composed of ground source heat pump, low temperature heat grid and electric heat pump. There are several forms of buried heat exchange tubes in conventional ground source heat pump systems [6]. Some scholars have carried out some research work [7-15]. At present, research on capillary tubes in China mainly focused on radiant cooling and heating at the end of air conditioning systems. Theoretical research is becoming more mature, and capillary tubes are being applied to the front-end heat exchanger system. There is not much research on the application of capillaries as front-end heat exchangers to extract energy in seawater source heat pumps. There is a fundamental difference in the application of capillary heat exchangers between front-end and back-end systems. There are significant differences in heat transfer patterns and performance between capillary front-end heat exchangers and end radiation heat exchangers. The theory of capillary radiation heat transfer system cannot be directly applied to the front-end heat transfer system of capillaries.

Previous scholars have used capillary heat exchangers as the end-radiant system for air conditioning. Lazarus [16] suggested placing a capillary heat exchanger underground in a greenhouse to keep the indoor temperature at night at 12 ℃. Attar et al [17] used numerical simulation methods to study the effects of length and water flow rate of capillary heat

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exchangers on heat transfer efficiency. And energy consumption was reduced by 25% under heating conditions in December and 51.08% under cooling conditions in April. Water was used as the cold source. Capillary heat exchangers were used to extract energy at a depth of 30 m underground. It was concluded that the thermal efficiency of the Salamabo Museum and Aquarium in Tunisia was approximately 80%. Hazami et al [18][19] described a device for solar energy storage combined with capillary tubes.

This paper considers coupling seawater and ground source heat pumps together, fully utilizing the thermal energy of seawater and seabed sand, and proposes a new method of burying capillaries in shallow coastal areas as the front heat exchanger of seawater source heat pump systems to extract heat and cold. This method will not cause seawater corrosion to the equipment and pipelines. It does not require additional filtering and other auxiliary equipment. It is not affected by geology, and it does not occupy public areas. It can better improve the energy extraction ability of capillary heat exchangers. The soil temperature in the seabed sand layer is higher in winter and lower in summer, which is more conducive to achieving energy-saving operation of heat pump units. This is more conducive to the energy-saving operation of the heat pump unit and may bring the underwater buried pipes closer to the coast.

This article placed a capillary heat exchanger as an energy extraction device in the soil beneath seawater in coastal areas. It used capillaries as a device for extracting underground energy. During the process of energy extraction, the temperature of seawater and the intermittent working time of the capillary had a significant impact on the heat transfer of the capillary. Therefore, this article focuses on four different daily working time modes and investigates the heat transfer performance of capillary heat exchangers under different daily operating times. The objectives of this study focus on three aspects, namely the temperature difference of the capillary tube inlet and outlet, the heat transfer of capillaries, and the soil temperature around the capillary tube.

II. METHOD

A. Capillary heat exchanger system

According to heat transfer theory, thermal energy is calculated by Equation (1). It is based on the heat exchange of the heat transfer medium in a capillary heat exchanger.

$$Q = \mathrm{m}c_p\Delta t = k\mathrm{A}T_m \quad (1)$$

where, Q is the basic heat rate, W. m is the total number of parallel capillaries required. c_p is the heat transfer coefficient, W/(m^2▪℃). Δt is the temperature of the fluid difference between the inlet and outlet in a capillary tube, ℃. K is the heat transfer coefficient. A is the cross-sectional area of the heat exchanger, m^2. T_m is capillary inlet and outlet temperature difference, ℃.

The heat exchanger consists of capillary tube with an outer diameter of 4.3 mm, an inner diameter of 2.8 mm and a wall thicknessof 0.75 mm. The spacing between the plastic capillary tubes is 20 mm as shown in Fig. 1. The medium in the capillary is ethylene glycol [9].

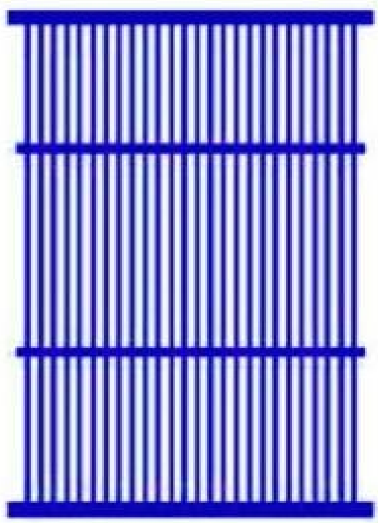

Fig. 1. Capillary network with a spacing of 20mm.

B. Capillary application of numerical simulation

As shown in Table 1, it defines the relative physical parameters for the capillary heat exchanger design in coastal areas. The average seawater temperature is 3.7 ℃ in winter. The average seawater temperature is 24.6 ℃ in summer. At a depth of 10 meters below the ground, the soil temperature is 13.8 ℃.

TABLE 1 CAPILLARY HEAT EXCHANGER SYSTEM PARAMETERS

Parameter	Glycol	Capillar y	Seawater	Soil
Coefficient of thermal conductivity （W/(m▪K)）	0.53	0.24	0.56	1.6
The density（kg/m^3）	1015	900	1025	1600
The specific heat at constant pressure （J/(kg▪K)）	3980	2000	4217	2530
Pr	0.53			

The energy collection of capillary heat exchangers is centered around the capillary and collected from the surrounding sand. If the capillary heat exchanger system is shut down, the heat transfer performance of the capillary will be restored. Therefore, it is necessary to study the intermittent operation of capillary heat exchangers. Capillary heat exchangers that operates intermittently during the day. When it stops the capillary operation, it is considered that the soil temperature around the buried pipe is still higher than (in summer) or lower than (in winter) the capillary wall temperature and continuing heat transfer. The capillary performance will not fully recover to the situation at the beginning of capillary operation. And there is heat accumulation. If the daily running time of capillaries is short, the soil thermal recovery is good.

The length of the capillary was 3.0 m. The distance between the capillary supports was 160 m, and the spacing between the capillaries was 20 mm. Five capillary grids were shallowly buried in soil 1.0 m above ground level. The daily working time of capillaries is less than 24 hours. The daytime intermittent operation of capillary tubes refers to the operation within 24 hours per day. This article focuses on analyzing the daytime intermittent operation of capillary heat exchangers. A model was established. And then it was simulated by using CFD. The capillary was run for one week of operation for 8, 10, 12 and 14 hours per day. It was simulated to calculate the operating conditions in winter and summer. It was prepared as a UDF file and set up in FLUENT software.

III. Results And Discussions

There are some differences in the load changes of different buildings. According to the different functions of buildings, such as libraries, office buildings, shopping malls, hotels, etc., the daily operating hours of typical buildings vary. For office buildings, including office buildings, equipment operates during the day and shuts down at night. For shopping malls, the capillary heat exchanger is in operation from 10:00 am to 22:00 pm. For hotels, due to the fact that the daily equipment is mostly in operation, the underground capillary heat exchanger has been in continuous operation. This determines the intermittent operation mode of the capillary based on analysis. Capillary tubes run for 14 hours a day in the office building. Capillary tubes run for 12 hours a day in shopping malls. The capillary tube runs for 8 hours daily in the library. Capillary tubes run continuously daily in hotels. Due to the different functions of buildings, the daily running time of capillaries varies.

A. Temperature difference between capillary inlet and outlet

The capillary flow rate was 0.1 m/s. According to engineering applications, the length of each capillary was selected as 3m. It is recommended that buildings use closed-loop capillary heat transfer systems.

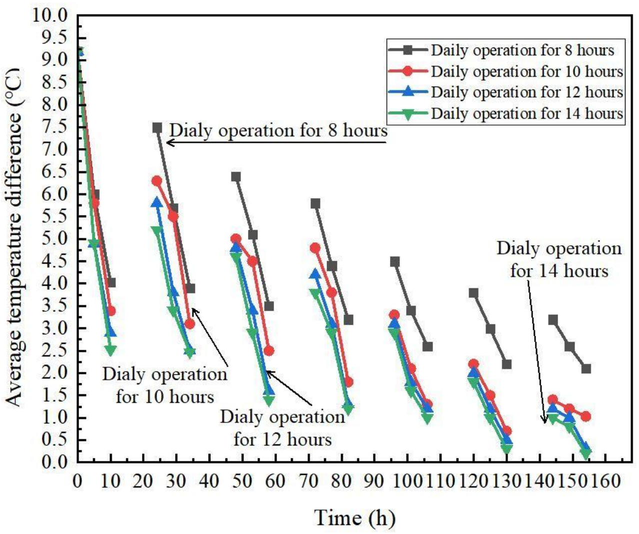

Fig. 2. Temperature difference between capillary inlet and outlet in winter.

As shown in Fig. 2, the temperature difference of the capillary inlet and outlet in winter was 2.1 ℃, 1.03 ℃, 0.31 ℃, and 0.2 ℃ when the capillary was operated for 8, 10, 12, and 14 hours per day, respectively. The reason is that the operating time of these four modes gradually increases, and the time for soil temperature recovery gradually decreases, resulting in a gradual decrease for the temperature difference of the capillary tube.

As shown in Fig. 3, when the capillary heat exchanger was operated for 14, 12, 10 and 8 hours per day. the temperature difference of the capillary inlet and outlet was 1 ℃, 1.7 ℃, 2.1 ℃ and 2.6 ℃ in summer, respectively. The reason is that the operating time of these four modes gradually decreases, and the soil recovery period time gradually increases.

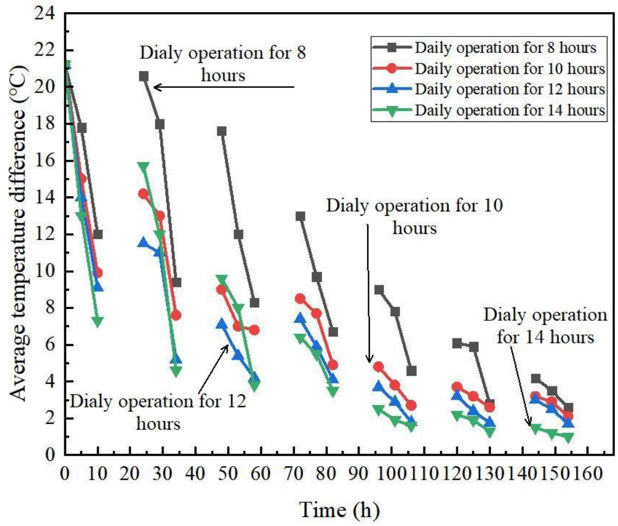

Fig. 3. Temperature difference between capillary inlet and outlet in summer.

B. Heat transfer per unit area for capillary heat exchange in the coastal area

As shown in Fig. 4, when the capillary heat exchanger was operated for 8, 10, 12, and 14 hours per day, and after 168 hours of operation, the winter heat transfer rate per unit area was 87.1 W/m^2, 42.7 W/m^2, 12.9 W/m^2, and 8.3 W/m^2. This is due to the fact that the operating time of these four modes gradually increases, and the recovery period time decreases, which results in the gradual heat transfer rate per unit area in winter decrease.

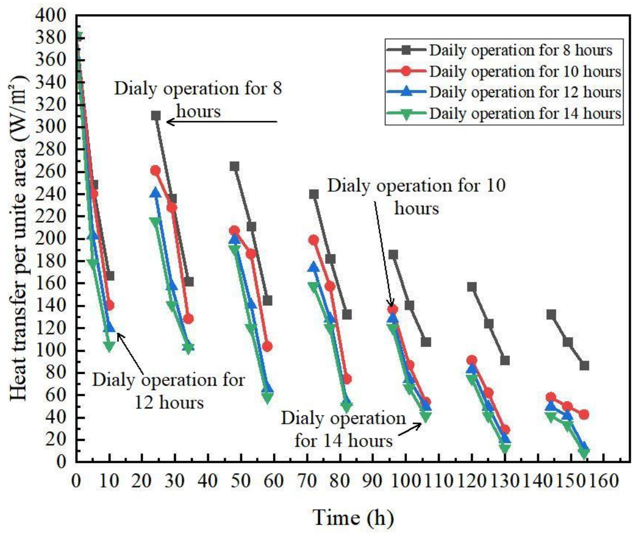

Fig. 4. Heat transfer per unit area for capillary heat exchange in winter.

As shown in Fig. 5, after running for 168 hours, when the capillary heat exchanger run for 8, 10, 12, and 14 hours per day, the heat transfer rates per unit area capacity in summer were 107.8 W/m^2 , 87.1 W/m^2 , 70.5 W/m^2 and 41.5 W/m^2, respectively. The reason is that the running time of the four models gradually increases, and the duration of the soil temperature recovery period decreases.

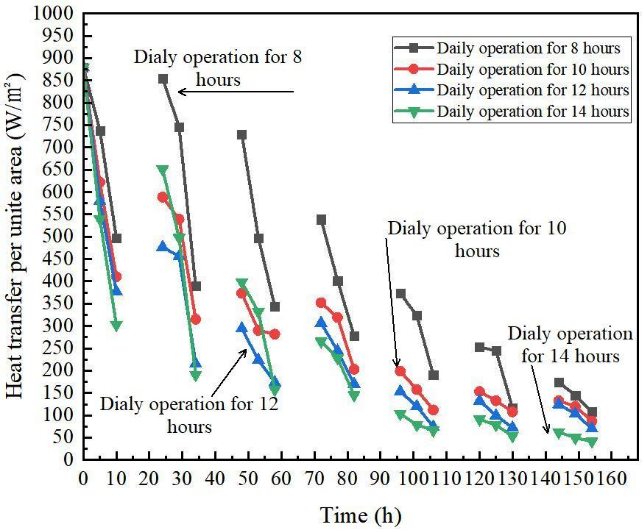

Fig. 5. Heat transfer per unit area for capillary heat exchange in summer.

C. Soil temperature around the buried capillary area

As shown in Fig. 6, the winter soil temperature rotated around the capillary heat exchange. In winter, the soil temperatures around the capillary corresponding to the four operation modes of 8, 10, 12, and 14 hours per day were 1.9 ℃, 0.83 ℃, 0.6 ℃, and 0.4 ℃, respectively. The reason is that the operating time of these four modes gradually increases and the capillary pipe absorbs more heat from the surrounding soil. As a result, the soil temperature around the buried pipe area gradually decreases.

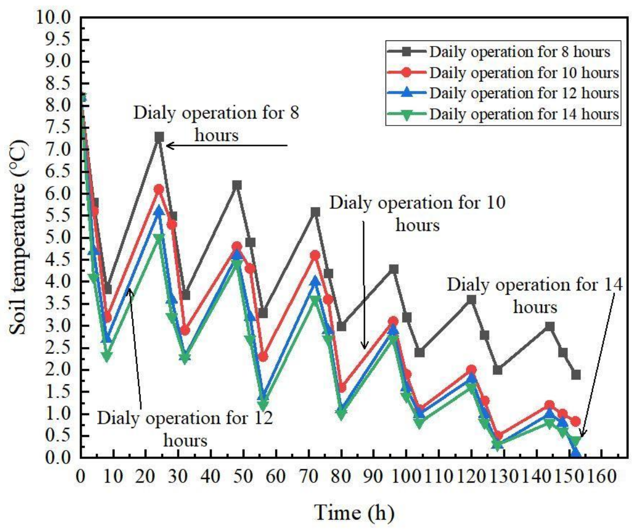

Fig. 6. Soil temperature around capillary heat exchange in winter.

As shown in Fig. 7, it is the temperature around the capillary heat transfer of soil in summer. The soil temperature around the capillary corresponding to the four operating modes of 8, 10, 12, and 14 hours per day was 35.2 ℃, 35.7 ℃, 36.1 ℃, and 36.8 ℃, respectively. The reason is that the operating time of these four modes gradually increases, and the capillary releases more heat into the surrounding soil. Therefore, the soil temperature around the buried pipeline area gradually increases.

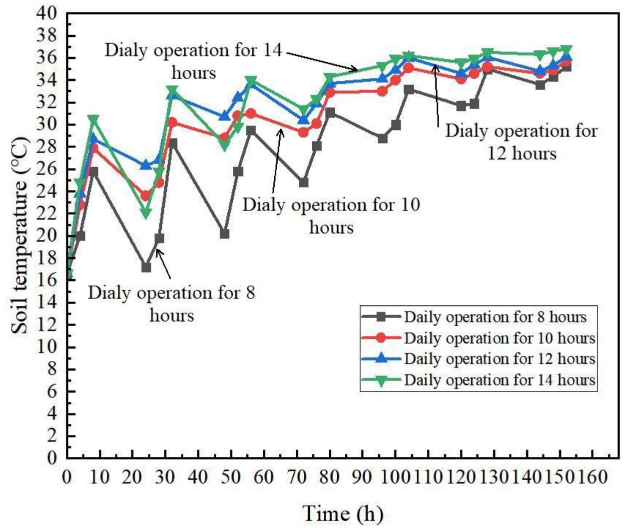

Fig. 7. Soil temperature around capillary heat exchange in summer.

In the future, further research will be conducted in this field, such as tidal induced water level changes, durability, algae growth, and economic analysis, to increase practical value to users.

IV. Conclusions

This paper describes a new capillary heat exchanger as an energy extraction device to provide the cooling and heating sources needed for buildings. The capillary tubes extract energy from the soil in near coastal areas. The heat transfer from the capillary tubes is calculated using different daily operating intervals in winter and summer, depending on the type of building. The main conclusions of this paper are as follows:

(1) If the daily working time of the capillary heat exchanger is well organized, the temperature difference between the inlet and outlet of the capillary heat exchanger could be increased. When the daily operating time of the capillary heat exchanger is 14 hours, 12 hours, 10 hours, and 8 hours, the inlet and outlet temperature differences of the capillary heat exchanger in winter are 2.1 ℃, 1.03 ℃, 0.31 ℃, and 0.2 ℃, respectively. When the daily operating time of the capillary heat exchanger is 14 hours, 12 hours, 10 hours, and 8 hours, the temperature difference of the capillary inlet and outlet in summer is 1 ℃, 1.7 ℃, 2.1 ℃, and 2.6 ℃, respectively.

(2) The daily operating time of the capillary is reasonably arranged to improve the heat transfer efficiency of the unit seat area of the capillary heat exchanger. For the capillary installed in the coastal areas, the winter seawater temperature is 3.7 ℃. After running for 168 hours, the heat transfer rates per unit area capacity were 87.1 W/m^2, 42.7 W/m^2, 12.9 W/m^2, and 8.3 W/m^2, respectively. The capillary was installed in the coastal areas, the temperature of seawater in summer was 24.6 ℃, and the heat transfer rates per unit area capacity was 107.8 W/m^2, 87.1 W/m^2, 70.5 W/m^2 and 41.5 W/m^2.

(3) The recovery of soil temperature around the capillary during the interval is related to the duration of the interval.

The longer the interval, the better the soil temperature recovery.

REFERENCES

[1] A. Inayat, and M. Raza. “District cooling system via renewable energy sources: A review”. *Renewable and Sustainable Energy Reviews*, vol. 107, pp. 360-373, 2019.

[2] N. Zhou, J. Zhang, N. Khanna, D. Fridley, S. Jiang, and X. Liu. “Intertwined impacts of water, energy development, and carbon emissions in China”. *Applied Energy*, vol. 238, pp. 78-91, 2019.

[3] L. Farshi, and S. Khalili. “Thermoeconomic analysis of a new ejector boosted hybrid heat pump (EBHP) and comparison with three conventional types of heat pumps”. *Energy*, vol. 170, pp. 619-635, 2019.

[4] H. Shu, L. Duanmu, J. Shi, X. Jia, Z. Ren, and H. Xu. “Field measurement and energy efficiency enhancement potential of a seawater source heat pump district heating system”. *Energy and Buildings*, vol. 105, pp. 352-357, 2015.

[5] E. Marrasso, C. Roselli, M. Sasso, and F. Tariello. “Global and local environmental and energy advantages of a geothermal heat pump interacting with a low temperature thermal micro grid”. *Energy conversion and management*, vol. 172, pp. 540-553, 2018.

[6] C. Hermes, C. Melo, and F. Knabben. “Algebraic solution of capillary tube flows Part I: Adiabatic capillary tubes”. *Applied Thermal Engineering*, vol. 30, no. 5, pp. 449-457, 2010.

[7] Z. Bai, H. Yao, and H. Zhang. “Experimental study on fire characteristics of cable compartment in utility tunnel with fire source at shaft side”. *Engineering Letters*, vol. 30, no. 2, pp. 806-810, 2022.

[8] Z. Bai, Y. Yu, K. Lv, H. Qin, H. Yao and C. Yang. “Experimental study on influence of natural ventilation on near wall fire in cable Tunnel”. *Engineering Letters*, vol. 31, no. 2, pp. 689-694, 2023.

[9] Z. Bai, Y. Li, J. Zhang, A. Fewkes, and H. Zhong. “Research on the design and application of capillary heat exchangers for heat pumps in coastal areas”. *Building Services Engineering Research and Technology*, vol. 42, no. 3, pp. 333-348, 2021.

[10] Z. Bai, H. Yao, and H. Zhang. “Experimental study on fire characteristics in cable compartment of utility tunnel with natural ventilation”. *Plos One*, vol. 17, no. 4, pp. e0266773, 2022.

[11] Z. Bai. "Burning characteristics of power cables with cone calorimeter." *Heliyon*, vol. 10, no. 3, pp. e25103, 2024.

[12] R. Fan, Y. Jiang, Y. Yao, S. Deng, and Z. Ma . “A study on the performance of a geothermal heat exchanger under coupled heat conduction and groundwater advection”. *Energy,* vol. 32, no. 11, pp. 2199-2209, 2007.

[13] A. Hobbi. “Design of solar water heating systems for cold climate and study of heat transfer enhancement devices in flat-plate solar collectors”. *Masters Abstracts International,* vol. 46-01, pp. 0502, 2007.

[14] Z. Bai, and H. Wang. “Study on characteristics of capillary heat exchanger buried in shallow beach area”. *Qingdao University of Technology*, vol.38, no. 03, pp. 70-73, 2017.

[15] H. Benli. “A performance comparison between a horizontal source and vertical source heat pump systems for a greenhouse heating in the mild climate Elaziğ, Turkey”. *Applied Thermal Engineering,* vol. 50, no. 1, pp. 197-206, 2013.

[16] M. Lazaar, S. Bouadila, S. Kooli, and A. Farhat. “Comparative study of conventional and solar heating systems under tunnel Tunisian greenhouses: Thermal performance and economic analysis”, *Solar Energy*, vol. 120, pp. 620-635, 2015.

[17] I. Attar, N. Naili, N. Khalifa, M. Hazami, and A. Farhat. “Parametric and numerical study of a solar system for heating a greenhouse equipped with a buried exchanger”, *Energy Conversion and Management*, vol. 70, pp. 163-173, 2013.

[18] M. Hazami, S. Kooli, M. Lazaar, A. Farhat, C. Kerkani, and A. Belguith. “Capillary polypropylene exchangers for conditioning of museum aquariums (Tunisia)”, *Desalination*, vol. 166, pp. 443-448, 2004.

[19] M. Hazami, S. Kooli, N. Naili, F. Mehdaoui, and A. Guizani. “Energy, exergy and economic viability of a heat storage system used for domestic hot water supply in urban and isolated households”. *Applied Thermal Engineering,* vol. 124, pp. 442-453, 2017.