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# Thermo-hydraulic Responses of Unsaturated Sand Around a Model Energy Pile

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**Abstract**

This paper examines the effects of monotonic and cyclic temperature changes of a model energy pile (diameter = 25 mm and length = 264 mm) on the variations in temperature and volumetric water content of surrounding unsaturated sand. Water flowed away from the pile during heating to 36°C and towards the pile during cooling to 5°C, causing soil drying and wetting near the pile, respectively. The change in volumetric water content was time-dependent, non-linear and slower than the change in soil temperature and continued to evolve after the soil temperature changes stabilized. Cyclic heating/cooling induced lower thermo-hydraulic changes in the soil than monotonic heating and cooling. The most significant changes in soil temperatures and volumetric water content were closest to the pile at a radial distance of 20 mm from the edge of the pile and reduced with increasing radial distance for all cases. The largest change in the degree of saturation was near the pile and was up to 6% for monotonic heating. Cyclic heating/cooling induced irreversible cyclic hydraulic responses near the pile with consecutive thermal cycles and caused a permanent reduction in the soil volumetric water content. However, these irreversible cyclic effects were dominant at a radius of 20 mm and reduced with increasing radial distance from the energy pile. The change in volumetric water content was time-dependent, indicating that the ratio of heating to cooling times during cyclic heating/cooling will have a significant effect on the reversibility of hydraulic responses under temperature cycles.

***Keywords****: Energy pile; temperature cycles; unsaturated soil; thermo-hydraulic response.*

## Introduction

The temperatures of energy piles and surrounding soils vary according to the heating and cooling cycles of ground source heat pumps (GSHPs). Any changes in the soil's temperatures caused by the cyclic or monotonic operation of the GSHPs will induce water movement within the soil's pores, particularly for unsaturated soils which are multi-phase porous media. Thermally-induced water flow in unsaturated soils occurs due to the influence of temperature on the changes in properties of the pore water (e.g. density, viscosity, surface tension) and due to evaporation and condensation of pore water (Philip and DeVries 1957; Smits et al. 2013; Başer et al. 2018). The thermo-hydraulic variations of unsaturated soils could potentially affect the piles' thermal and geotechnical performance.

The thermal performance of the pile is affected due to an increase or reduction in the soil thermal conductivity when the soil gains or loses water, respectively, which affects the heat transfer between the pile and the ground (e.g. Akrouch et al. 2016; Coccia and McCartney 2016; Wang et al. 2016; Başer et al. 2018; Hedayati-Dezfooli and Leong 2019; Sani and Singh 2020). The mechanism of heat transfer between the energy pile and the soil (very often unsaturated) is, therefore, a combination of conduction and convection rather than the commonly assumed conduction being the primary mechanism (Wang and Qi 2011; Moradi et al. 2015; Moradi et al. 2016; Başer et al. 2018). Thomas and Rees (2009), Choi et al. (2011) and Akrouch et al. (2016) indicated that the thermal efficiency of energy piles tended to reduce when the soil degree of saturation reduces due to drying.

Temperature variations of unsaturated soils affect their thermo-hydro-mechanical behaviour (Uchaipichat and Khalili 2009; McCartney et al. 2014; Coccia and McCartney 2016). Changes in the soil thermo-hydro-mechanical behaviour would also affect the coupling between the energy pile and the soil, hence the pile's long-term geotechnical performance. Wang et al. (2015) investigated the shaft capacity of a field-scale energy pile installed in unsaturated sand using Osterberg cells for static load testing. They found that the pile shaft capacity increased after heating. An early centrifuge modelling study by McCartney and Rosenberg (2011) also observed an increase in the ultimate axial capacity of semi-floating energy piles in unsaturated silt with increasing temperature and hypothesised that this was due to an increase in radial stresses due to differential expansion of the pile and soil. However, later centrifuge modelling studies on semi-floating energy piles in unsaturated silt and dry sand by Goode and McCartney (2015) found an increase in ultimate axial capacity was only observed in unsaturated silt. They hypothesised that the increases in axial capacity of energy piles with increasing temperature were caused by an increase in soil effective stress due to drying triggered by the heating process. Behbehani and McCartney (2020) recently analysed unreported dielectric sensor measurements from Goode and McCartney (2015). They found that thermally-induced drying was the cause of the observed increase in axial capacity, confirming the importance of considering the impacts of coupled heat transfer and water flow on energy pile behaviour.

Several physical and numerical studies have generally shown that drying occurs in unsaturated soils in the vicinity close to an underground heat source during heating (e.g. Thomas et al. 2001; Wang and Qi 2011; Wang et al. 2012; Goode 2013; Chen et al. 2014; Moradi et al. 2015; Wang et al. 2015; Başer et al. 2016; Coccia and McCartney 2016; Chen et al. 2018; Başer et al. 2018; Jahangir et al. 2018; Cherati and Ghasemi-Fare 2019; Hedayati-Dezfooli and Leong 2019; Başer and McCartney 2020; Gao et al. 2020). Studies conducted on thermo-hydraulic responses of unsaturated soils during monotonic cooling are scarce. A preliminary study conducted on monotonic cooling of a model energy pile in loose unsaturated sand has shown evidence of an increase in volumetric water content near the pile (Cameron et al. 2016).

Cyclic temperature variations result from seasonal or daily intermittent operations of the GSHP with either natural or forced ground thermal recoveries (Brandl 2006; Yi et al. 2008; Wood et al. 2010; Dai et al. 2015; Faizal et al. 2016; Murphy and McCartney 2015; McCartney and Murphy 2017; Faizal et al. 2018, 2019a, 2019b). Cyclic temperature changes, particularly for systems with daily forced recharging using solar energy or cooling towers, induce frequent temperature reversals of the pile and the soil (Faizal et al. 2016; Faizal and Bouazza 2018). This would ideally cause frequent hydraulic reversals, and hence, repetitive drying/wetting cycles of the soil which could lead to a complex response of stresses in the soil. The frequent cyclic thermo-hydraulic responses of unsaturated soils around energy piles are not well understood yet. A few physical model studies on cyclic temperature changes of energy piles in unsaturated soils have shown that the changes in the degree of saturation in one thermal cycle tend to recover in the following cycle, but the recovery of the degree of saturation is much lower than the restoration of soil temperatures (Moya et al. 1999; Goode 2013; Stewart and McCartney 2014; Cameron et al. 2016). This was confirmed through simulations of coupled heat transfer and water flow surrounding a geothermal heat exchanger in an unsaturated soil layer by Baser et al. (2018), albeit for relatively high temperatures representative of a heat storage system. Therefore, cyclic heating/cooling has the potential to cause irreversible changes in soil water content and permanent drying or wetting of the soil near the pile. Further studies are required to investigate cyclic thermo-hydraulic responses of unsaturated soils around energy piles under cyclic temperature changes.

An assessment of the thermally induced hydraulic responses of unsaturated soils around energy piles under typical monotonic or cyclic temperatures is needed to improve our understanding of this complex coupled heat and mass transfer problem. This paper sheds some light on the above issue; particularly, it examines the thermo-hydraulic responses of an unsaturated soil layer surrounding a model energy pile when subjected to temperature changes typically encountered in practice. The variations in soil temperatures and volumetric water content are physically assessed at different radial distances from the edge of the pile for monotonic heating, monotonic cooling, and cyclic heating/cooling of the energy pile. Although the laboratory-scale tests in this study are not intended to represent a field-scale energy pile, the heat transfer and water flow processes occurring in the laboratory-scale test are the same as those occurring at the field scale, so this study helps understand the range of transient processes that may occur in unsaturated soils close to energy piles. This is particularly important as the soil closest to the energy pile may have the greatest effect on the pile's mechanical response.

## Experimental Setup and Procedure

The experiments were conducted on a concrete model energy pile embedded in compacted, unsaturated sand. A schematic of the experimental setup is shown in Figure 1. The diameter and length of the energy pile were 25 mm and 264 mm, respectively. The concrete used consisted of 4.5 mm aggregates and water-to-cement ratio of 0.42. The average uniaxial compressive strength of unreinforced cylindrical concrete samples was 45.4 MPa after 35 days of curing. The concrete's thermal conductivity was 2.2 W/mK and was measured using a divided bar apparatus (Barry-Macaulay et al. 2013; Ali et al. 2016). The model pile was not reinforced since this study focused on the soil's thermo-hydraulic response only and not on the thermo-mechanical performance of the pile. The thermo-hydraulic variations of the sand depend on the heat transfer between the energy pile and the sand. A single U-loop heat exchanger made of copper tubing with an outer diameter of 4 mm and a thickness of 0.5 mm was cast in the concrete. The sand was compacted in a container made of 15 mm-thick Perspex and had dimensions of 560 mm (length) x 560 mm (width) x 300 mm (height). The top, bottom and sides of the container were insulated with earthen wool with a thermal resistance of 2

$m^2K/W$ to prevent the sand from interacting with local environmental conditions (Figure 1c and Figure 1d).

The sand was compacted to a dry density of 1300 kg/$m^3$ to allow an easier installation of the sensors. The soil-water retention curve (SWRC) and the sand's grain size distribution are shown in Figure 2. The SWRC was estimated using the grain size distribution, the sand specific gravity of 2.65, and a porosity of 0.51 (e.g. Aubertin et al. 2003). The sand used had a uniformity coefficient of 2.4 and a gradation coefficient of 1.0 and was classified as poorly graded. The sand was hand-mixed at a target initial gravimetric moisture content of 5% and a total mass of 77.05 kg of wet soil. Losses of water due to evaporation during mixing resulted in an average initial gravimetric water content of 4.4% (corresponding to an initial degree of saturation, $S_r$, of approximately 11.2%) for the monotonic cooling experiment and 4.7% (corresponding to $S_r$ = 12%) for the monotonic heating and cyclic heating/cooling experiments. The initial temperature and volumetric water content of the compacted sand, recorded from the 5TM sensors, were approximately 21°C and 0.08 $m^3/m^3$, respectively. The compacted sand's thermal conductivity was 1.0 W/mK and was measured using the KD2 Pro thermal needle probe (Barry-Macaulay et al. 2013).

The toe of the energy pile was placed on the container’s base. The moist sand was compacted around the energy pile in four 45 mm layers using a hand-held mechanical compactor. The embedded depth of the energy pile was thus 180 mm. Each layer of sand was hand-spread evenly in the box and compacted to the desired 45 mm thickness, which was marked on the container’s internal walls, ensuring that all the four layers were compacted to the same thickness and density. Each soil layer's gravimetric water content was verified before compaction to ensure consistency between all the layers. The upper surface of each layer of compacted sand was roughened using sandpaper before compacting the next layer to improve contact between the layers. A plastic sheet was placed on the fourth sand layer to prevent direct interaction between the sand and the insulation and minimise moisture losses from the sand.

Four 5TM dielectric sensors (Decagon Inc. of Pullman, WA) were installed approximately at mid-height of the soil column to monitor volumetric water content (VWC) and temperatures simultaneously at radial distances, *R*, of 20 mm, 50 mm, 80 mm, and 110 mm from the edge of the pile (i.e. $R = R_{sensor} - R_{pile}$ from the center of the pile) . The sensors were located on planes 90° from each other to minimize interference on the heat transfer and water flow process during the experiments (Figure 1b). The sensors were pushed vertically in the sand after compacting the third sand layer, followed by the fourth layer's compaction to prevent the influence of room environmental conditions on the sensors' responses during experiments. A Decagon EM50 data logger recorded the VWC and temperature continuously from the sensors at 2-minute intervals.

The VWC sensors were calibrated against different gravimetric water contents of the sand (i.e. approximately 3%, 5%, 7%, and 9%) at a dry density of 1300 kg/m$^3$. The calibration slopes of the four sensors are shown in Figure 3. The moist sand was compacted in a Polyvinyl chloride cylindrical container with an external diameter of 250 mm, a wall thickness of 7 mm and a height of 255 mm. The sand was hand spread evenly in the container and compacted in three 45 mm layers using a hand-held mechanical compactor. The contact between the compacted layers was improved by roughening each layer's upper surface with sandpaper. The sensors were pushed vertically in the sand after compacting the third layer, and the soil temperature and the VWC were recorded using the Decagon EM50 data logger. The average temperature of the compacted sand was approximately 22°C. Similar to the study of Moradi et al. (2016), it was assumed that temperature did not affect the inferred volumetric water content from the dielectric sensors.

Two water baths (model: LAUDA ECO RE 620) were used to circulate warm and cold water in the U-loop of the energy pile at set-point temperatures, simulating monotonic heating and cooling, respectively. The cyclic heating/cooling experiment was conducted by heating the energy pile for 24 hours, followed by cooling for 24 hours. The warm and cold water was circulated at approximately 0.6 liters/min through the heat exchange tubing, which corresponded to a Reynolds number of 2957 during cooling to 5°C and 6070 during heating to 36°C. These correspond to turbulent flow conditions in the heat exchanger, which is desirable for optimal heat exchange. The inlet and outlet water temperatures at the pile head were recorded using two thermocouples. Two thermocouples were placed on the container's inner edges to monitor boundary thermal effects. The data from the thermocouples were continuously logged using a Pico Technology's USB-TC08 data logger at 5-minute intervals. The heating, cooling, and cyclic heating/cooling experiments were conducted independently of each other by repeating the experimental procedure for each test.

Although the experiments were conducted in a temperature-controlled room, there were instances where the temperature was not constant due to technical issues with the room temperature controller. An XC0424 USB Temperature and Humidity Datalogger was used to record the room temperature and humidity during all the experiments. The room air temperatures and the humidity during the experiments are shown in Figure 4. The room temperatures generally remained around 20°C for all experiments, apart from the days where the room temperature controller was unstable. Variations in room humidity were not expected to affect the experimental results since the setup was insulated and the top of the soil column in the container was covered with a plastic sheet.

## Results and Discussions

The inlet/outlet water and boundary temperatures are shown in Figure 5. The inlet water temperatures were 5°C during cooling (Figure 5a) and 36°C during heating (Figure 5b) and cycled between 5°C and 36°C during the cyclic heating/cooling test (Figure 5c). The outlet water temperatures were approximately 1.5°C higher and lower than inlet temperatures during cooling and heating, respectively. The average soil temperatures at the container boundary changed by 6°C during monotonic cooling (Figure 5a) and by 3°C during monotonic heating and cyclic heating/cooling (Figure 5b and Figure 5c, respectively). However, these boundary temperature changes remained constant for the duration of the experiments. Hence any boundary effects on the results were also constant. The difference in room temperatures slightly affected the boundary soil temperatures on Day 4 of the cooling test and Day 9 of the heating test. There were instances of some data logging issues during the experiments; hence the temperature monitoring on Day 4 of the cyclic experiments was affected for a few hours (Figure 5c). The transient temperature changes of the sand, $\Delta T_{Soil}$, the change in volumetric water content of the sand, $\Delta\theta$, and the change in the sand degree of saturation, $\Delta Sr$, at different radial distances from the edge of the model energy pile are shown in Figure 6. The soil temperatures at Day 4 and Day 9 increased by around 1°C for monotonic cooling (Figure 6a) and monotonic heating (Figure 6d), respectively, due to an increase in room temperatures on these two days. The soil temperatures closely followed the trends of the inlet fluid temperatures and reached thermal equilibrium with operating time and remained stable for all experiments. The cyclic temperature changes returned to similar peak values at the end of heating and cooling for a given radial distance (Figure 6g). Cyclic heating/cooling induced slightly lower soil temperature changes than monotonic heating and monotonic cooling due to the frequent temperature reversals of the energy pile. The largest $\Delta T_{Soil}$ for all experiments was close to the pile and reduced with increasing radial distance from the pile's edge.

Monotonic cooling reduced the ground temperature below the initial conditions temperature and induced negative soil thermal gradients (Figure 6a). Thus, water moved towards the pile during monotonic cooling, causing an increase in $\Delta\theta$ and $\Delta Sr$ due to wetting of the soil (Figure 6b and Figure 6c). On the other hand, monotonic heating induced positive temperature changes (Figure 6d). Thus, water moved away from the pile and $\Delta\theta$, and $\Delta Sr$ reduced due to soil drying during monotonic heating (Figure 6e and Figure 6f). The cyclic heating/cooling induced a repetitive drying and wetting process during heating and cooling cycles, respectively, where $\Delta\theta$ and $\Delta Sr$ shows a cyclic response due to the cyclic nature of soil temperature changes (Figure 6g, Figure 6h and Figure 6i).

Unlike $\Delta T_{Soil}$, $\Delta\theta$ and $\Delta Sr$ varies with operating time for a given experiment and is not stable, i.e. the VWC does not directly follow the trends of inlet fluid temperatures and continues to change when the soil temperatures had stabilized. There is also a time lag in $\Delta\theta$ and $\Delta Sr$ between different radial distances with the soil closest to the pile at R = 20 mm undergoing an earlier change in volumetric water content, followed by R = 50 mm, R = 80 mm and R = 110 mm. It is important to note that the VWC changed eventually with time due to the sustainable application of a constant $\Delta T_{Soil}$, even though the change in VWC was slower than soil temperature change. This indicates that the moisture movement at any given radial location depends on the magnitude of the soil temperature change and the duration that temperature change is maintained; longer time with a fixed $\Delta T_{Soil}$ will eventually lead to water movement in unsaturated soils.

The largest magnitudes of $\Delta\theta$ and $\Delta Sr$ are closer to the pile at R = 20 mm (i.e. closer to the heat source) for all experiments and reduces with increasing radial distance from the edge of the energy pile. The amplitude of $\Delta\theta$ and $\Delta Sr$ for cyclic heating/cooling also decreases with increasing radial distance from the heat source (Figure 6h and Figure 6i). The $\Delta\theta$ and $\Delta Sr$ at R = 20 mm for cyclic heating/cooling (Figure 6h and Figure 6i ) undergoes a progressive reduction with time since heating was the first cycle and the subsequent cooling time was insufficient to return $\Delta\theta$ and $\Delta Sr$ to initial conditions, even though $\Delta T_{Soil}$ was reversed beyond initial conditions temperatures (Figure 6g). This confirms that the hydraulic response is much slower than temperature response and that the ratio of heating to cooling times has a significant effect on the water movement. Compared to the initial degree of saturation, the $\Delta Sr$ increased by approximately 5% for monotonic cooling (Figure 6c), decreased by about 6% for monotonic heating (Figure 6f) and decreased by around 4% for cyclic heating/cooling (Figure 6i) at R = 20 mm. There are slight differences in $\Delta\theta$ and $\Delta Sr$ between monotonic heating and monotonic cooling, particularly at R = 80 mm and R = 100 mm. This could have occurred due to the differences in temperature-induced properties of the water in the pores, which could have affected convection in the sand. For example, heating could have increased convection due to a larger influence on water density and viscosity compared to cooling. However, further studies on flow visualisation using numerical studies are required to explain this observation.

A comparison of the effect of cyclic heating/cooling against monotonic cooling and monotonic heating at a given radial distance is shown in Figure 7. As discussed earlier, heating and cooling induce moisture movement in opposite directions to each other, and $\Delta\theta$ reduces with increasing radial distance. Cyclic heating/cooling causes lower magnitudes of $\Delta\theta$ than monotonic temperature changes. The $\Delta\theta$ during cyclic heating/cooling after R = 50 mm are closer to zero, indicating that variations in the VWC remain near initial conditions compared to monotonic heating and monotonic cooling. Therefore, cyclic temperature operations of GSHPs would be useful for long-term operation of energy piles due to lower impacts on the thermo-hydraulic conditions of the surrounding soil. Long-term physical tests with different heating to cooling ratios are needed to confirm this observation since variations in $\Delta\theta$ depend on the period the change in soil temperatures is maintained.

It can be also be observed from Figure 7 that the VWC changed earlier at R = 20 mm while there was a time lag at other radial distances. An initial increase in $\Delta\theta$ is observed at R = 80 mm and R = 110 mm before reducing during monotonic heating (Figure 7f and Figure 7h). Similarly, there is an initial reduction in $\Delta\theta$ before increasing during monotonic cooling at R = 80 mm and R = 110 mm. This could be attributed to mass balance as water moves between different radial distances in unsaturated soils under temperature gradients (Chen et al. 2014; Chen et al. 2018; Cherati and Ghasemi-Fare 2019). For example, as VWC reduces and moves away from near the pile during heating, there is an initial increase in VWC at other radial distances. This initial increase in VWC is why there is a time lag in VWC reduction during heating at farther radial distances. Similarly, opposite movement of water and mass balance occurs during cooling as water moves from farther radial distances towards the energy pile. This hydraulic balance between different radial distances could also be why $\Delta\theta$ is slightly lower at R = 80 mm than R = 110 mm during cyclic heating/cooling.

The thermal and hydraulic radial thermal influence zones are further assessed in Figure 8 by plotting $\Delta T_{Soil}$ and $\Delta\theta$ against different radial distances and at different days of operation. Average magnitudes of $\Delta T_{Soil}$ and $\Delta\theta$ are shown for cyclic heating/cooling. For a given experiment, the $\Delta T_{Soil}$ magnitudes were similar for all the days at a given radial distance (Figure 8a) since the temperatures had stabilized with operating time. The $\Delta T_{Soil}$ magnitudes reduced with increasing radial distance for monotonic heating and monotonic cooling, while the average soil temperature changes remained almost constant and close to zero for cyclic heating/cooling. The $\Delta\theta$ magnitudes shown in Figure 8b also reduce with increasing radial distance from the energy pile and has a similar radial influence zone as $\Delta T_{Soil}$. However, the $\Delta\theta$ magnitudes for a given experiment increase with the increasing number of days for any given radial distance, and as discussed earlier, occur due to the prolonged time $\Delta T_{Soil}$ is maintained.

The $\Delta\theta$ magnitudes versus $\Delta T_{Soil}$ are plotted in Figure 9 to better assess the temperature-dependent response of $\Delta\theta$. For monotonic heating and monotonic cooling, $\Delta\theta$ reduced and increased, respectively, approximately between $\Delta T_{Soil}$ = 6°C to 11°C at all radial distances, confirming that $\Delta\theta$ can increase/decrease at a constant $\Delta T_{Soil}$, and that $\Delta\theta$ does not have a linear relationship with $\Delta T_{Soil}$. The $\Delta\theta$ magnitudes during cyclic heating/cooling showed different responses at different radial distances. The $\Delta\theta$ magnitudes at R = 20 mm showed a cyclic hysteresis with irreversible responses against a stable range of $\Delta T_{Soil}$ (Figure 9a), indicating that permanent reduction in volumetric water content occurred. As discussed for Figure 6, heating was the first cycle and the subsequent cooling time was insufficient to return $\Delta\theta$ to initial conditions at R = 20 mm in the cyclic heating/cooling test, hence $\Delta\theta$ reduced with consecutive thermal cycles leading to an irreversible response against $\Delta T_{Soil}$. It is also likely that soil drying during heating could have reduced the hydraulic conductivity of the soil which prevented a return of water during cooling (Coccia and McCartney 2016; Başer et al. 2018); this, however, cannot be confirmed from the current results and requires further physical and numerical studies. The $\Delta\theta$ magnitudes during cyclic heating/cooling at other radial distances (Figure 9b, Figure 9c, and Figure 9d) showed insignificant changes with consecutive thermal cycles, indicating that the zone of influence of permanent increase/decrease of $\Delta\theta$ is closer to the pile at R = 20 mm and reduces with increasing radial distance.

## Conclusions

This paper examined the variations in temperatures and volumetric water content of unsaturated sand around a model energy pile (diameter = 25 mm and length = 264 mm) when the pile was subjected to monotonic heating, monotonic cooling, and frequent cyclic heating/cooling. Water moved away from the pile during heating and towards the pile during cooling, causing drying and wetting of the soil, respectively. Cyclic responses of change in the volumetric water content were observed near the pile during cyclic heating/cooling. The change in volumetric water content was non-linear and slower with respect to soil temperature changes. This resulted in permanent drying of the soil closest to the energy pile after several cycles of heating and cooling. Cyclic heating/cooling induced lower changes in soil temperatures and volumetric water content than monotonic heating/cooling and would, therefore, be useful for long-term energy piles operations. The largest changes in soil temperatures and volumetric water content were closer to the energy pile at a radial distance of 20 mm and reduced with increasing radial distance for all cases. The change in volumetric water content did not stabilize with operating time. It continued to evolve even though soil temperatures had stabilized, indicating that soil moisture variations depend on the magnitudes of change in soil temperatures and the duration the temperature change is maintained. The zone of radial thermal influence of temperature changes and change in volumetric water content was similar.

The change in volumetric water content near the pile reduced with consecutive thermal cycles. It showed irreversible responses against change in soil temperatures during cyclic heating/cooling, indicating a permanent reduction in volumetric water content near the pile at a radius of 20 mm. However, these irreversible cyclic effects reduced with increasing radial distance from the pile. Since water movement depends on the magnitude and duration of soil temperature change, the ratio of heating to cooling times during cyclic heating/cooling significantly affects the reversibility of hydraulic responses under temperature cycles. This paper's results and conclusions are based on a small-scale model energy pile embedded in an idealised sand layer and controlled boundary conditions. Even though the results present useful insights into sand's thermo-hydraulic behaviour around energy piles, further in-situ tests are still warranted to understand the temperature dependant water movement in the soil under real boundary conditions. Finally, the results presented in this paper are for a single energy pile.

Further studies are required to assess the thermo-hydraulic responses of closely spaced energy piles operating in groups where soil temperature changes are expected to be higher.

## Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article.


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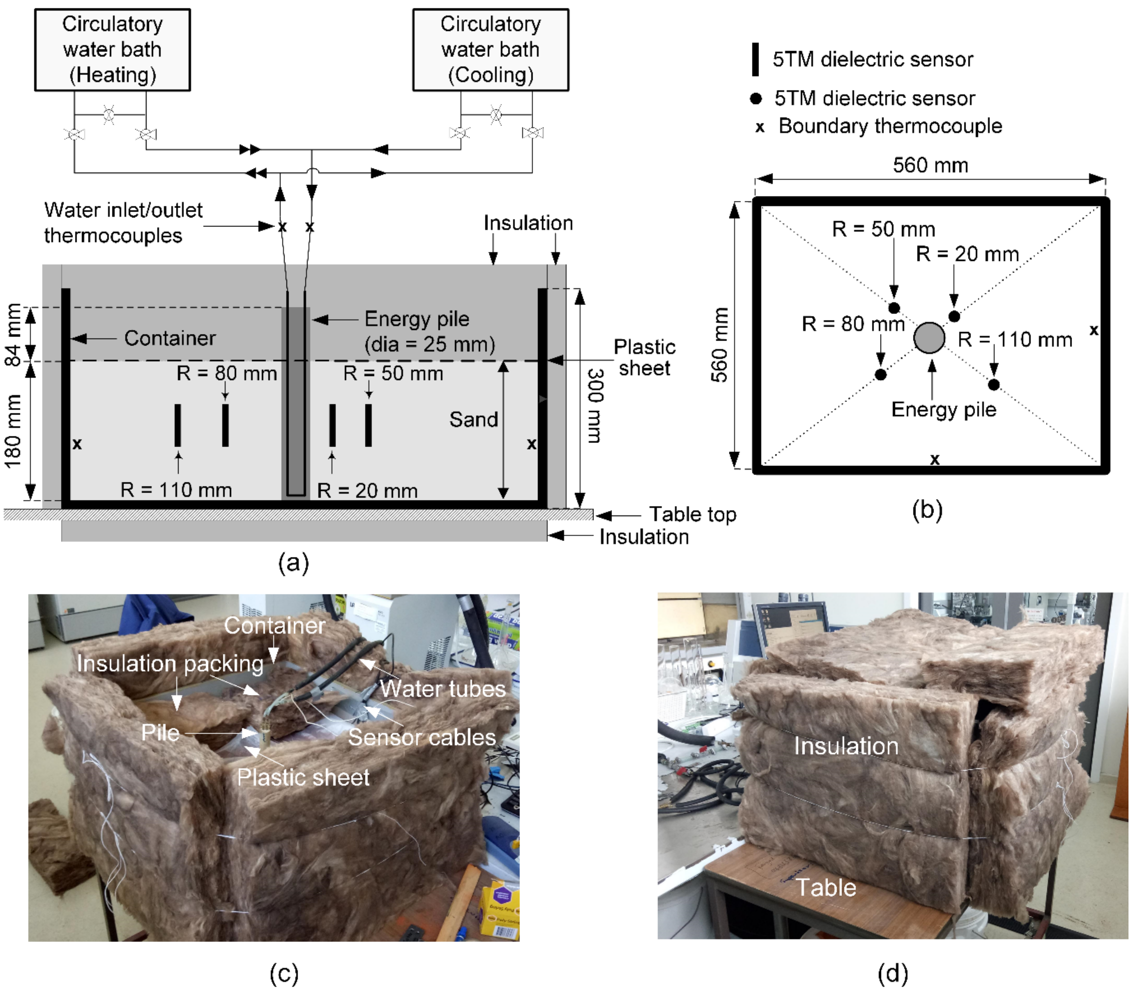
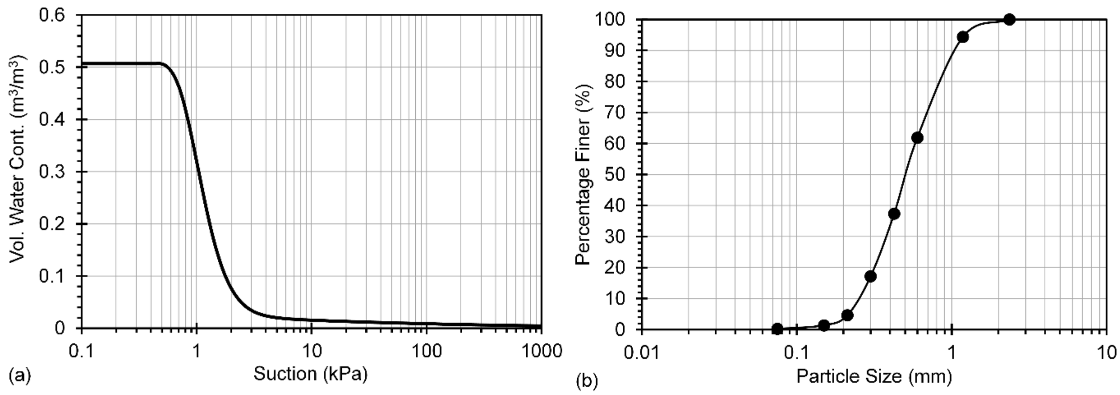



**Figure 1**. Experimental setup : (a) cross-sectional elevation view; (b) cross-sectional plan view; (c) partially insulated; and (d) fully insulated.

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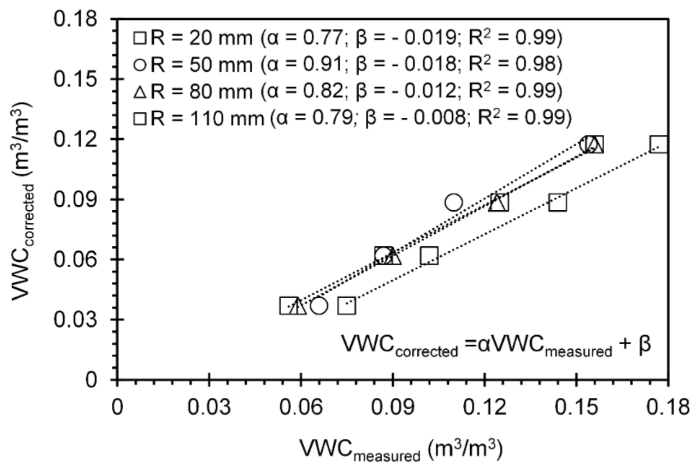


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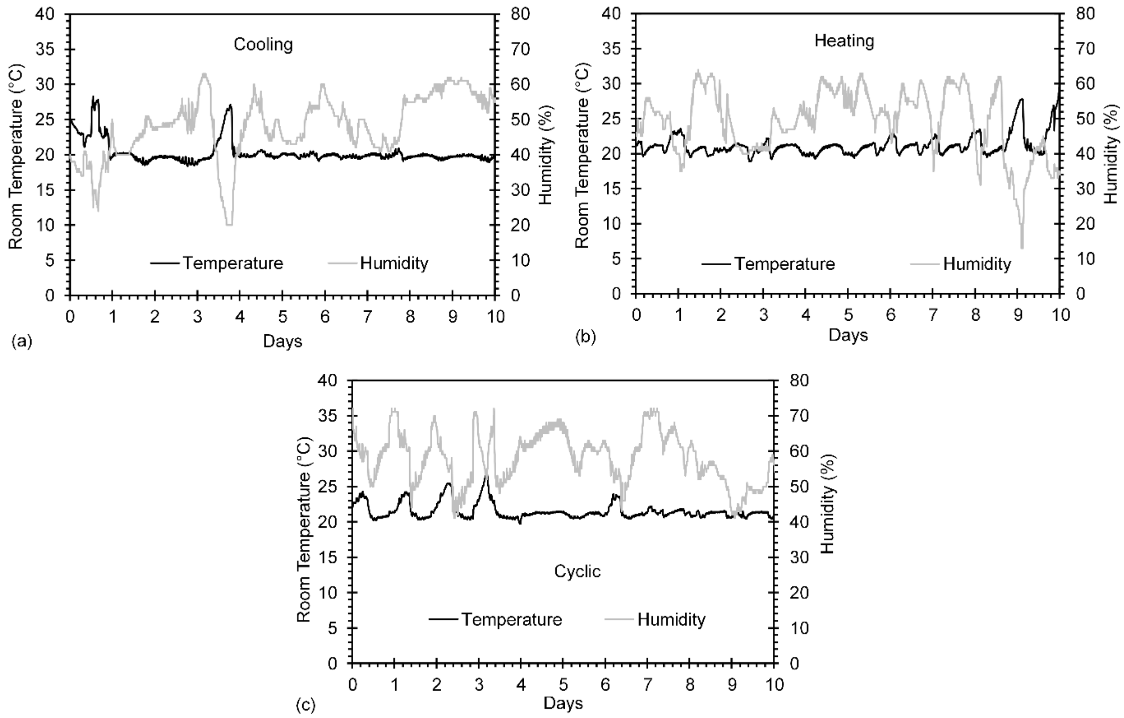


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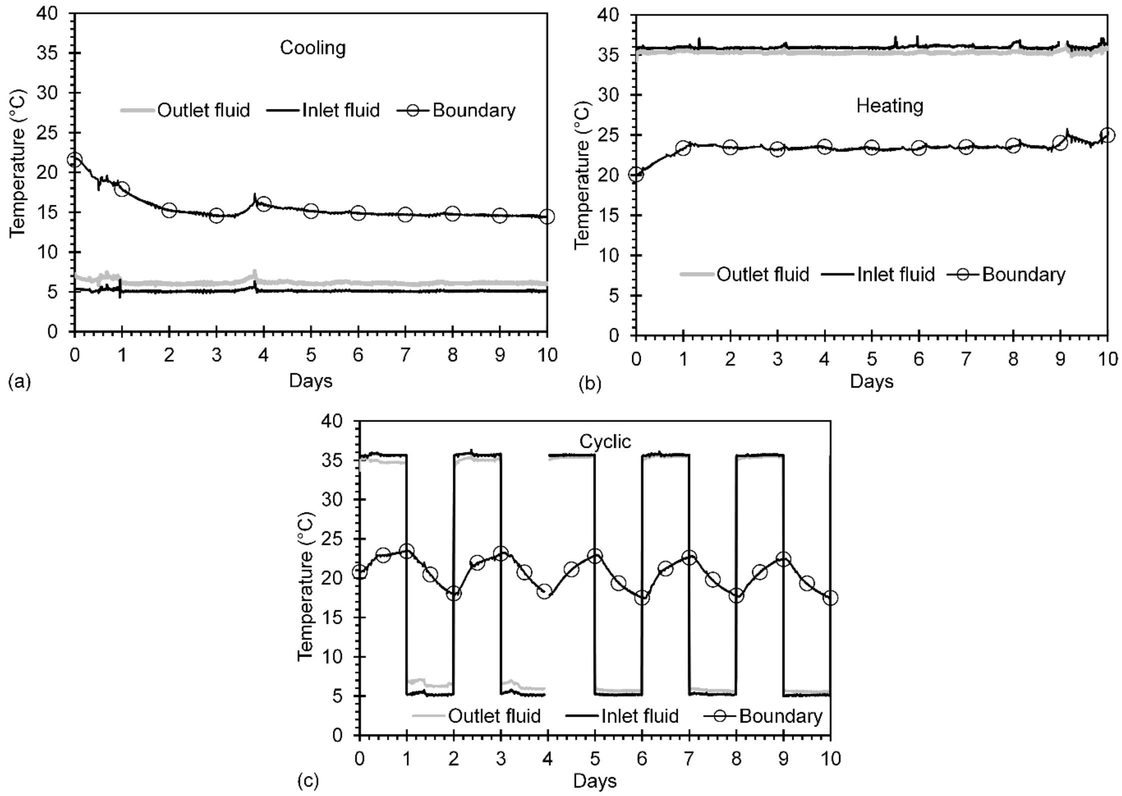


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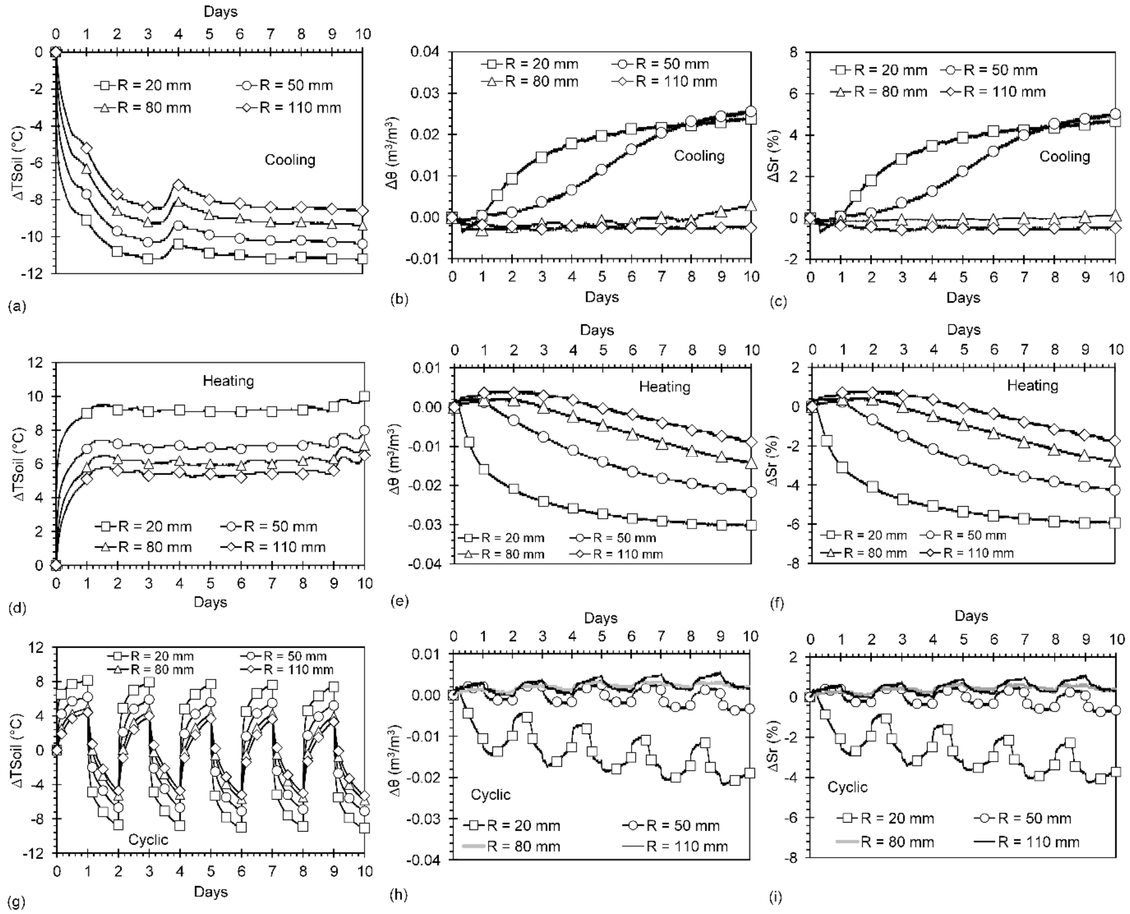


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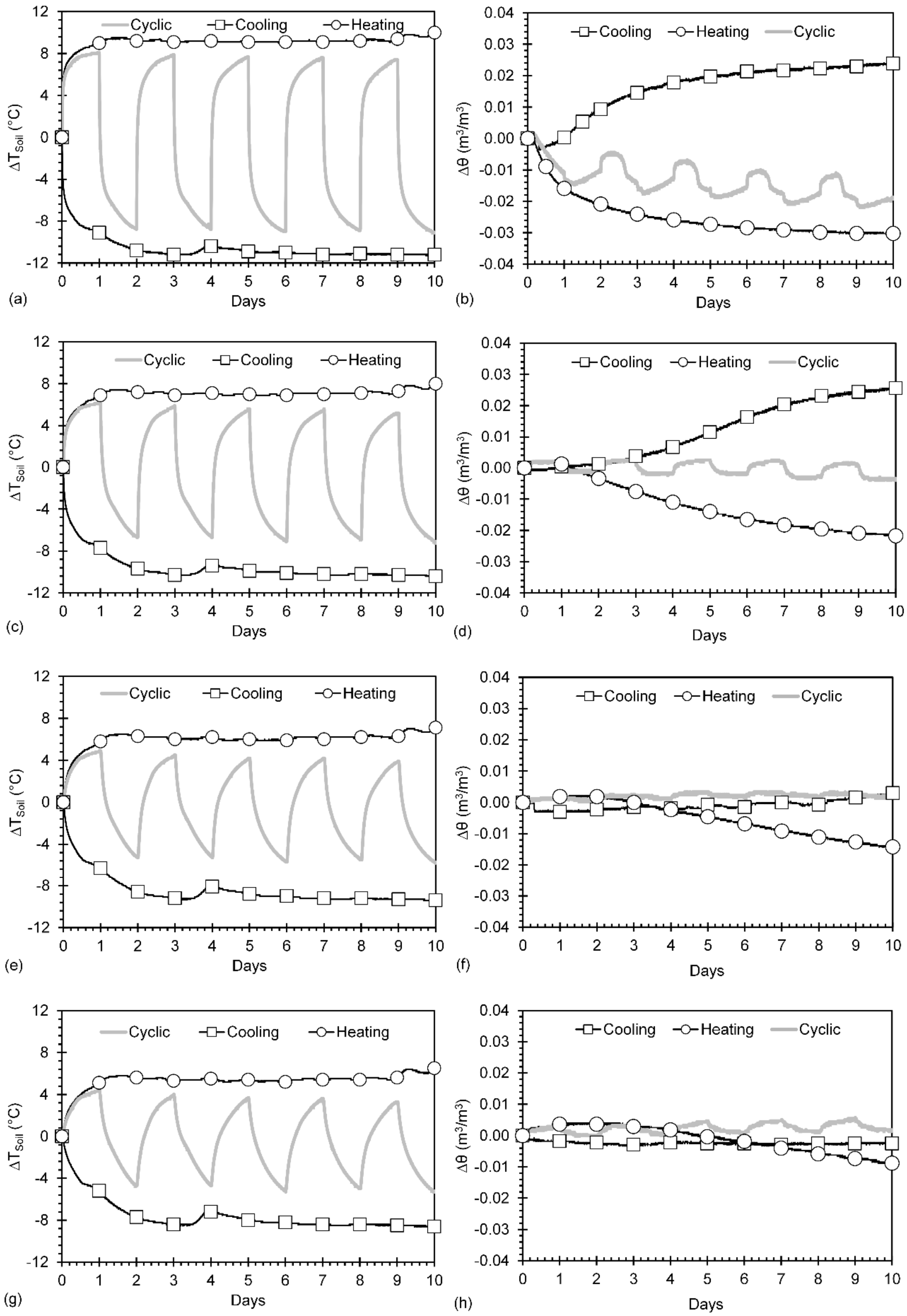


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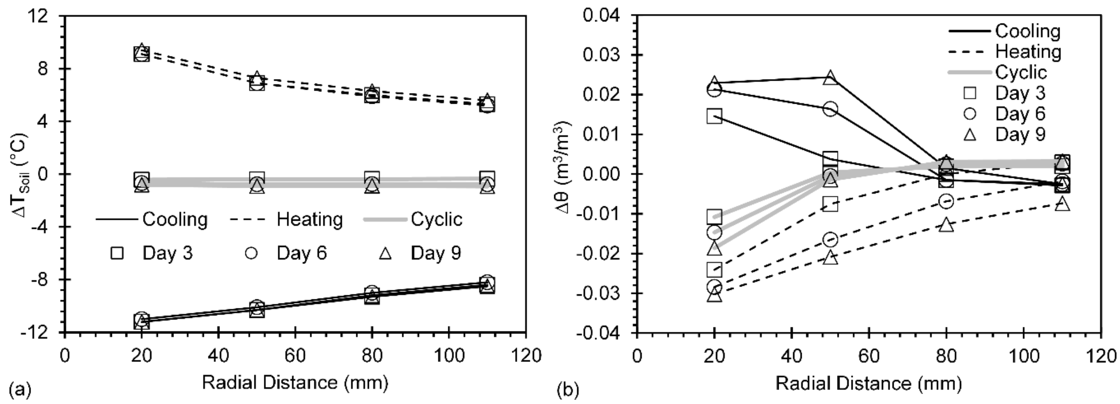


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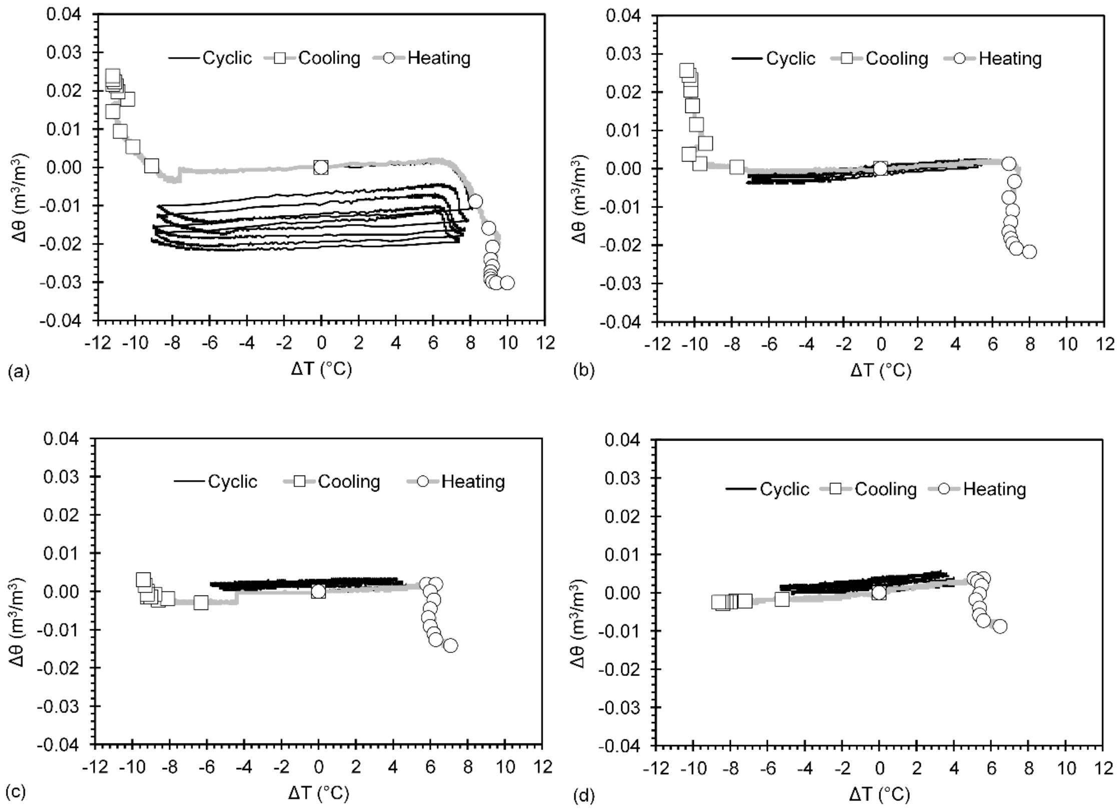


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