Optimizing Air Ventilation Cooling With Earth-Water Heat Exchangers in Residential Buildings

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***Abstract* – This study investigated the cooling effect of an Earth Water-Air Heat Exchanger (EWAHE) device for ventilation applications. To address the lack of data on EWAHE performance in moderate climates, we measured temperature parameters (inlet-outlet, indoor-outdoor, water, and soil) continuously for three days. Air temperatures, air flowrate, light intensity are measured using a multi-channel data logger with several sensors. Results showed that the EWAHE effectively reduced indoor air temperature by an average of 7.5°C with a maximum reduction of 9.3°C, offering a promising passive cooling solution for buildings. The primary limitation of this study is that it requires open space around the building to place the device, so this method is inappropriate for building in a dense urban area. Future studies could investigate the association between ground-water cooling effect and natural ventilation without using energy for air circulation.**

***Keywords* – Heat exchanger, cooling effect, passive cooling, ventilation, tropical region.**

DOI: 10.18421/TEM131-50
https://doi.org/10.18421/TEM131-50

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Received: 05 September 2023.
Revised: 16 December 2023.
Accepted: 05 January 2024.
Published: 27 February 2024.

1. Introduction

The residential, commercial, and tertiary building sector is among the largest consumers of national energy in Indonesia [1], [2]. Energy consumption in this building sector is used to maintain comfort conditions for occupants in the building [3], [4]. In tropical climates with hot and humid conditions like Indonesia, buildings are often equipped with air conditioning systems [5], [6]. However, the use of an air conditioning system causes a significant increase in energy consumption and potentially causes environmental damage and pollution through the greenhouse gas emissions effect [7], [8].

Indonesia, as a country with a tropical climate's characteristics, has high humidity and temperature, intensity of solar radiation, and high rainfall. This condition often causes thermal comfort in buildings that do not meet the specified minimum comfort criteria. The high thermal gain obtained inside the building has the potential to cause overheating and can raise the indoor air temperature. This condition is getting even worse by the effects of global warming due to increased CO_2 emissions. Besides, in terms of microclimate, the lack of greenery around the building will reduce the thermal comfort of the building. Therefore, it is recommended to find alternative solutions to increase the building's thermal comfort without the urge to consume large amounts of energy for the air conditioning system. One alternative solution for increasing the thermal comfort of the building in the tropical area is the development of passive cooling techniques by using the cooling effect of the ground, which has a lower temperature all along the day compared to the outdoor [9], [10].

Based on researches conducted by Kusuda *et al.* [11], [12], at a certain depth (usually 10 m below the surface), the temperature of the ground will be the same as the annual mean temperature of the outside air at the location. During the day, the ground surface absorbs solar radiation and transfers it to a point at depth. With a high thermal capacity soil can act as a large reservoir storing heat from the sun [13]. Heat transfer and changes in ground temperature depend on the intensity of solar radiation absorbed by the ground surface, the thermo-physical characteristics of the ground (thermal capacity, thermal conductivity, diffusivity), and the condition of the soil surface (open, covered with grass, etc.). When the temperature of outdoor air is high (during daytime), the temperature of the ground will be lower than the outdoor. Thus, it can be used as a cooling medium. This passive cooling technique with a ground cooling effect has the advantage of being environmentally friendly and low energy consumption to cool the room temperature within comfortable limits [14], [15].

Another significant aspect of a healthy and comfortable building design is the availability of an adequate ventilation system. In buildings, ventilation functions for circulation and air conditioning to keep the rooms fresher, healthier, and more comfortable [16], [17]. The stale and warm air inside the room must be vented outside to replace it with cooler and cleaner air. Improving the air quality and thermal comfort of buildings by applying passive cooling techniques integrated with ventilation systems is a promising challenge in research in the building field [18], [19], [20], [21].

The aim of this research is to design and evaluate the performance of a heat exchanger (HE) device from earth to air called the Earth–Water to Air Heat Exchanger. This device is integrated into a mechanical ventilation system for buildings. In this device, the cooling effect of groundwater is used to reduce the outside air temperature before being distributed into the room. The experimental data from measurements of changes in temperature (air, water in soil, and soil) were analyzed to figure out the effectiveness of the passive cooling from the device. It is hoped that this EWAHE device can be used effectively to increase the thermal comfort of buildings without a significant increase in energy consumption for the air conditioning system.

2. Material and Methods

In the experimental study, Earth-Water to Air Heat Exchanger device has been designed and tested for its performance in passively cooling air integrated with a mechanical ventilation system for applications in buildings. The function of this device is to passively reduce the temperature of the air flowing through the heat exchanger pipe through the cooling effect of lower-temperature water.

2.1. Design of EWAHE for Ventilation

The EWAHE device consists of two main components. The components are a water tank (Figure 1. c) and a PVC pipe as a HE from air to water in the water container (Figure 1. b). The water tank is made of iron plate with 2-mm thick, 100 cm diameter (D_{tank}), and 120 cm height. The container is filled with water and then immersed to a depth where the bottom of the container is 150 cm from the ground surface. The inner and the outer surfaces of the tank are coated with antirust paint to avoid corrosion. The HE is made of a polyvinyl-chloride hose that has an inner diameter (D_{pipe}) of 6.35 cm (2.5 inc) and a length of 4,130 cm, wound in the form of a single helical coil and inserted vertically into the water tank. The diameter of PVC-coil (D_{coil}) is 80 cm, with 16 coils (Figure 1. a). The more turns the pipe has, the longer the air interacts thermally with the water then the greater the cooling effect obtained. The container cover is made from the same material with two holes for the ventilation inlet/outlet (Figure 1. c). As a motor that drives air movement, a 4 inch-diameter blower is used with a constant debit of 4.68 m^3 per minute. The air that has the temperature lowered is then circulated throughout the room.

b. c.

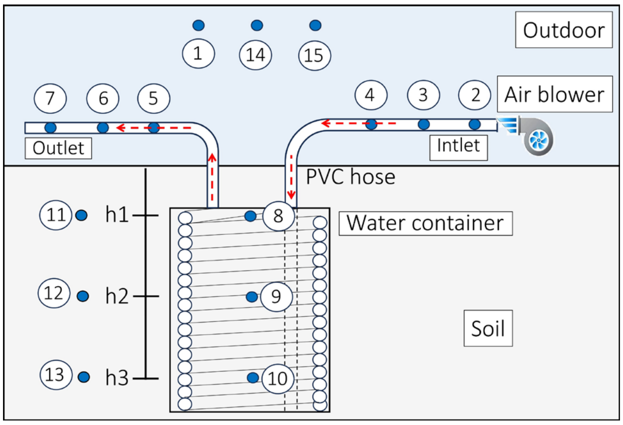
a.

Figure 1. Design of EWAHE; a. Design of heat-exchanger, b. PVC hose and water tube before disassembly, c. the process of immersing water tubes into the ground to a depth of 30 cm below the surface of ground

2.2. Experimental Protocol and Setup

This study uses: 13 temperature sensors, one humidity sensor, and one lighting sensor (see detailed sensor position in Figure 2). To measure the outdoor air temperature, one sensor is located in a free open space outside the building protected from direct solar radiation (sensor 1). To determine the air temperature at the inlet point, three sensors are placed on the inlet pipe with a distance of 10cm (sensor no 2), 20cm (sensor no 3), and 30cm (sensor no 4) measured from the outer end of the inlet pipe.

Likewise, for the outlet side, three temperature sensors are placed at the same distance, namely 10cm, 20cm, and 30cm from the outer end of the outlet pipe (sensors 7, 6, and sensor 5). Furthermore, to measure the water temperature, three temperature sensors are placed in a holding container full of water. The three sensors are placed at different depth positions measured from the ground surface, namely a depth of 40 cm (sensor 8), a depth of 80-cm (sensor 9), and a depth of 120-cm (sensor 10). To measure variations in soil temperature, three temperature sensors are placed at three different points but with the same depth as the three temperature sensors in the water tank (sensor 11, sensor 12, and sensor 13).



Sensor Position	Parameter
1	Outdoor temperature
2, 3, 4	Inlet air temperature
5, 6, 7	Outlet air temperature
8, 9, 10	Water temperature
11, 12, 13	Soil temperature
14	Outdoor air humidity
15	Outdoor day lighting

Figure 2. Experimental setup, instrumentation, and sensors position

Outside air flows in the heat exchanger pipe driven by a blower fan with a constant flowrate of 4.68 CMM or the equivalent of 5.63 $kg{\cdot}min^{-1}$. The thermal capacity (C_{Air}) and air density (ρ_{air}) during the measurement period are assumed to be constant at 1.005 $kJ \cdot kg^{-1}. K^{-1}$, and 1.204 $kg \cdot m^{-3}$.

2.3. EWAHE Performance Indicators

In analysing the performance of the EWAHE device, several indicators were used to calculate the cooling effect and heat transfer effectiveness of the device. These indicators can be explained as follows:

a. The decrease in air temperature between the inlet -outlet points (ΔT_{AIR}) can be analyzed using the expression Eq. 1. The higher the ΔT_{AIR}, the better the cooling effect generated.
b. Energy saving (E_{S}) is obtained from the passive cooling effect through heat transfer from ventilation air to water as a cooling medium. This energy-saving value can be calculated using the Eq. 2.
c. The other indicator is the effectiveness of heat transfer in the HE. This indicator shows the ability of the HE device to reduce the air temperature through a cooling effect.

Two parameters can be performed to measure the effectiveness of heat transfer, namely: HE effectiveness (η_{HE}) [22] and the logarithmic average temperature difference (ΔT_{lm}) [23]. Values of η_{HE} and ΔT_{lm}, can be calculated using Eq. 3 and Eq. 4.

$$\Delta T_{\text{AIR}} = T_{\text{Outlet}} - T_{\text{Inlet}} \quad \text{Eq. 1}$$

$$E_S = \dot{m}\,.\,C_{\text{AIR}}.\,(T_{\text{Outlet}} - T_{\text{Inlet}}) \quad \text{Eq. 2}$$

$$\eta_{\text{HE}} = \frac{T_{\text{Inlet}} - T_{\text{Outlet}}}{T_{\text{Inlet}} - T_{\text{Water}}} \quad \text{Eq. 3}$$

$$\Delta T_{\text{lm}} = \frac{T_{\text{Inlet}} - T_{\text{Outlet}}}{\ln\left[\frac{T_{\text{Inlet}} - T_{\text{Water}}}{T_{\text{Outlet}} - T_{\text{Water}}}\right]} \quad \text{Eq. 4}$$

Where ΔT_{AIR} is the temperature difference that occurs before and after passing through the heat exchanger (°C), T_{Outlet} and $T_{\text{Inlet}}$are the air temperatures on the outlet-inlet sides of pipe (°C), $\dot{m}$ is the debit of air flowing in the pipe (kg/min), C_{AIR} is the thermal capacity of air at room temperature conditions equivalent to a value of 1.005 $kJ{\cdot} kg^{-1}{\cdot} K^{-1}$ [24], T_{Water} (°C) is the average temperature of the water in HE device immersed in the soil. Because the air duct is submerged in water, the temperature of the pipe material is assumed to be close to the water temperature in the tube.

3. Results and Discussion

To analyse the thermal performance of the EWAHE device, several indicators will be discussed in more depth in this section, including: presentation of outdoor conditions at the research location, air and underground water temperature profiles, passive cooling effect obtained by air in the heat exchanger, and energy efficiency in ventilation systems.

3.1. Outdoor Conditions of a Measurement Site

Figure 3 shows changes in outdoor air temperature and natural lighting intensity during the measurement period. During the two consecutive days of experimental data collection, the outdoor air temperature varies from 25.8 °C to 33.3 °C. The lowest temperature occurs in the early morning between 5 and 6 a.m.

Meanwhile, the hottest temperature occurs between 12 to 2 p.m. Daily fluctuations in outdoor air temperature occur quite significantly up to 7.6 °C. On the other hand, outdoor day lighting levels are present from 6 a.m. at sunrise until 6 p.m. when the sun began to set. Compared to other days, the natural outdoor lighting value on 29th August 2023 increased drastically from 2 to 3 p.m. with a maximum of 27.03 klux. On other days, the maximum natural lighting value ranges between 5-10 klux. The high daylighting value on the second day was caused by the clear sky, with no clouds covering the sky. In general, the increase in air temperature, solar radiation intensity, and lighting occur from 6 a.m. For the night, the air temperature gradually decreases after 6 p.m. due to the gradual release of heat stored in the air to the atmosphere.

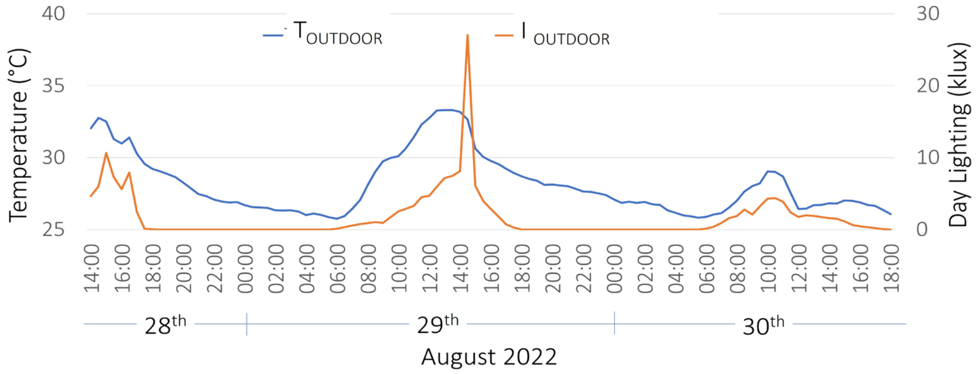


Figure 3. The variation of outdoor temperature and outdoor illuminance on experiment site.

3.2. Air Temperature and Soil-Water Temperature Profiles Underground

Changes in outdoor air temperature, soil temperature, and water temperature at a certain depth can be seen in Figure 4. The curve line in Figure 4 shows temperature changes in the three parameters measured during the data collection. They are outside air, ground and water temperature in the container at a depth of 120 cm below the ground surface. The graph presents that the ground and the water temperature in the container are almost identical.

Both temperatures are stable in the interval of 27 °C to 28 °C. This temperature is close to average outdoor air temperature for one year in the Padang area [25], [26]. Small changes in water temperature and soil temperature show that thermal fluctuations in outdoor air between day and night do not significantly affect the thermal conditions of soil and water at a depth of 120 cm. This condition follows the theory, which states that the ground temperature at a certain depth is close to the annual average temperature of the outdoor air in that area [27], [28].

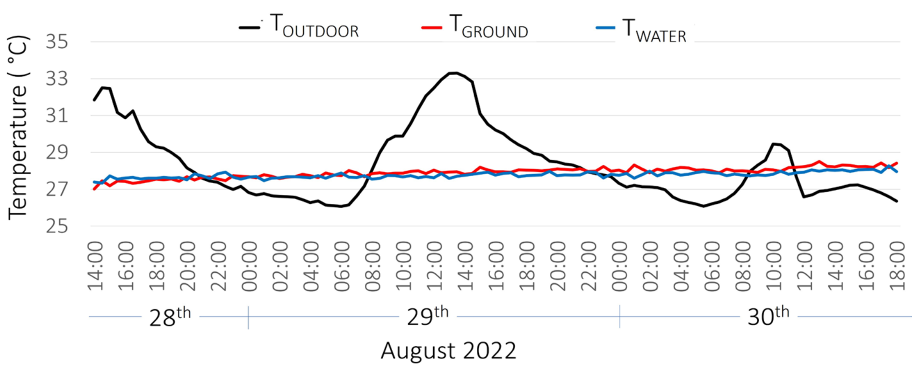


Figure 4. The variation of temperatures for outdoor, water-underground, and soil during the measurement period

In Figure 4, it can be observed that there are several intersections that occured between the outdoor air temperature (black line), the ground (red line) and water temperatures (blue line). During the daytime, between 08.00 and 20.00, the outdoor air temperature was higher than the ground and water temperatures. In the day, when the solar thermal gain is significant, the temperature of the air will rapidly and significantly change due to its low thermal capacity.

Solar heat gain obtained by the ground surface will be transferred to the ground depth. However, due to the large thermal capacity, the change in soil temperature is less significant, especially at a deep underground.

Under these conditions, the underground soil potentially become a cooling medium for the air flowing in the EWAHE device in the ventilation system.

The second intersection between the air temperature and soil temperature curves occurs around 8 p.m. (Figure 4). During this time, the outdoor temperature is cooler than the ground or water temperature. It happened due to the capacity of the air to easily release heat when the solar thermal gain is absent. Meanwhile, soil with a high thermal inertia can maintain its temperature longer when the surrounding temperature drops drastically. In this condition, the heat stored in the soil underground will be distributed towards the environment with a lower temperature.

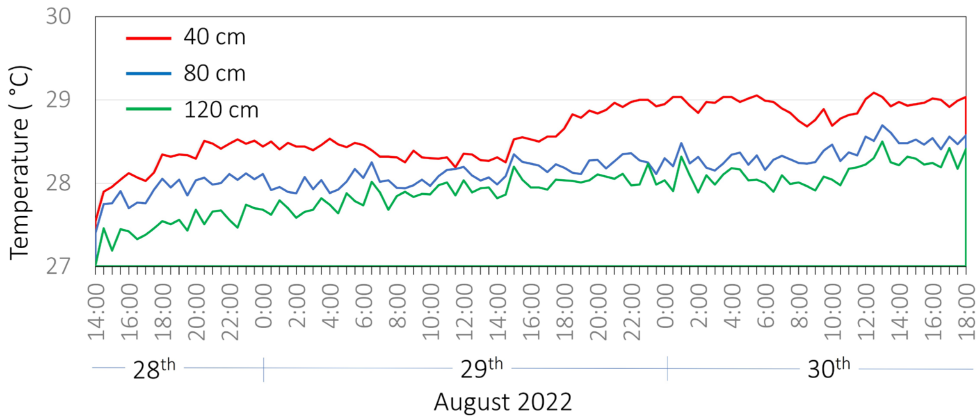


Figure 5. Soil temperature profile based on its depth measured from the ground surface

In determining changes in soil temperature based on depth, three sensors were installed at different depth positions; 40 cm, 80 cm, and 120 cm from the surface. The soil temperature profile based on depth during the measurement period is presented in Figure 5. The measurement results show that the soil temperature has decreased depending on the position of the sensor. These results support the Kusuda expression [11], [12], who states that soil temperature is strongly influenced by position depth. Soil temperature will be constant to a depth of 10 m, from the surface [11], [12], [27]. This study only measured to a depth of 1.5 meters, so changes in soil temperature were only recorded in the range of 1°C - 1.5 °C (Figure 5).

3.3. Passive Cooling Effect Received by Ventilated Air

Figure 6 shows the cooling effect generated by the EWAHE device. In general, this EWAHE device can provide a cooling effect on the air in the ventilation ducts.

It can be observed from the decrease in air temperature on the outlet side (blue line) compared to the inlet side (red line) in Figure 6. The lowest cooling in air temperature during the measurement period occurred on 29th August 2022 at 2 p.m. At that hour, the air at the inlet/outlet sides has a temperature of 38.8 °C and 29.5 °C, respectively (Figure 6). The temperature drop during the day was very significant, up to 9.3 °C due to the cooling effect from lower temperature of the ground during the daytime.

However, compared to the outdoor temperature, the air on the inlet side has increased significantly due to the influence of heat absorbed by the air when it passes through the fan blower motor at the inlet point. It pushes the air to move in the pipe. It shows that the inline duct fan is less suitable to be used as a driving motor for this ventilation model because it has an overheating effect on the air on the inlet. Meanwhile, on the outlet side, the outside temperature is almost similar to the water temperature in the ground (Figure 6). It proves that the thermal inertia of the ground provides important cooling effect on the air.

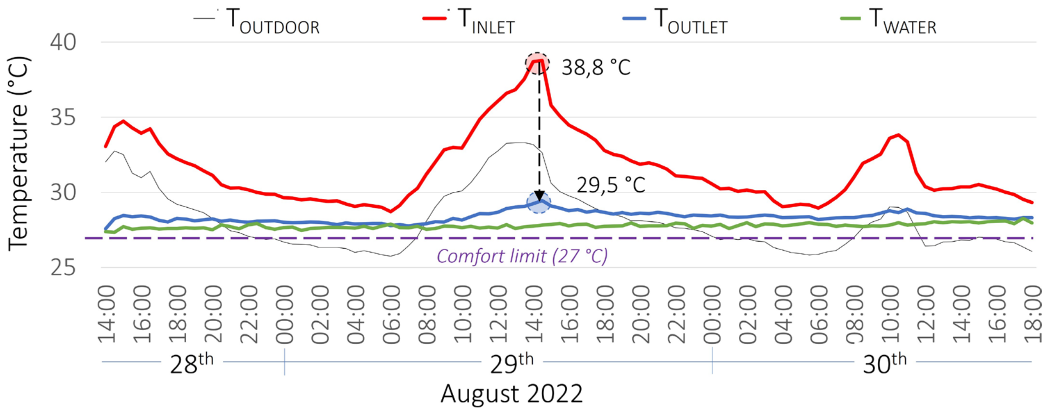


Figure 6. Changes in air temperature on the outlet side due to the cooling effect from a cooler-temperature water

The reduction in ventilation temperature due to the cooling effect provided by lower-temperature water is presented in Figure 7. With high thermal inertia, water in the ground can absorb the heat carried by the air when it flows across the heat exchanger pipe. The graph of Figure 7 shows that temperature changes on the inlet side present significant dampening on the outlet side. The low gradient of the trend line for the temperature comparison between the inlet-outlet side (R^2: 0.5077) shows that the cooling effect of water is very influential in reducing air temperature.

On the other side, the graph in Figure 7 presents that, although the passive cooling effect on the air generated by the water thermal inertia is quite significant. The air temperature at the outlet side could not be reduced below the specified comfort limit (27 °C). It shows that in tropical climates with hot and humid temperatures, if we want to ensure that the indoor temperature is always within comfortable limits, the passive cooling techniques implementation must be combined with active cooling devices (air conditioning, fans, etc.).

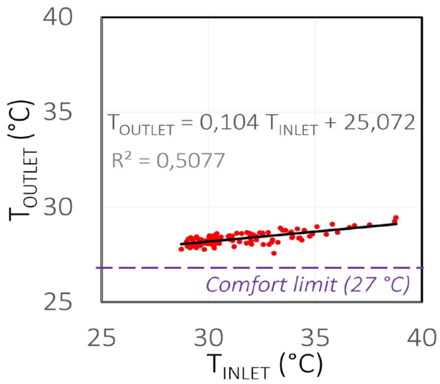


Figure 7. Comparison of air temperature on the inlet-outlet side

3.4. Thermal Analysis and Energy Efficiency

There are three substantial indicators in measuring the heat transfer performance of this EWAHE device. They are the logarithmic average temperature difference (ΔT_{lm}), heat transfer effectiveness (η_{HE}), and energy saving (E_S) obtained from passive cooling. These three performance parameters are presented in Figure 8. The logarithmic average temperature deviation (LATD) value shows the temperature difference between the outlet-inlet sides (red line).

This temperature difference will represent the amount of energy savings (black line) that will be obtained as a result of the passive cooling provided by the water. In Figure 8, the data shows that the maximum LATD occurred at 2 p.m. on 29th August 2022, which had a value of 4.9 °C. With this temperature gap, the energy that can be saved can reach 3.18 MJ/h. The savings obtained during the 52 hours of the experiment were 56.91 MJ/h. Energy savings due to passive cooling of ground water are more significant during the daytime when the outdoor temperature is very high. The value of heat transfer effectiveness is shown by the blue line on the graph. η_{HE} value varies from 57 % to 98.5 % depending on the time of day.

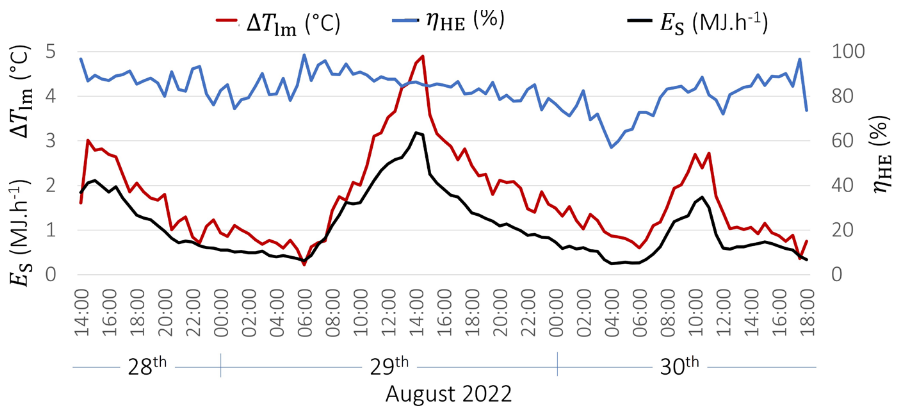


Figure 8. The logarithmic average temperature difference, heat transfer effectiveness and energy saving in EWAHE device

Comparison of the average heat transfer effectiveness that occurs in EWAHE devices between daytime and night can be seen in Figure 9. The red-line on the graph shows the effectiveness value for the daytime period between 6 a. m - 6 p. m. Meanwhile, the blue-line shows effectiveness in the nighttime period, from 6 p. m. to 6 a. m. The data shows that the device's effectiveness during the day is better than at night. During the day, the heat transfer effectiveness ranges from 79.87 % to 89.67 %, with an average value of 85.92 %. Whereas at night, this effectiveness value has decreased quite large with a minimum and maximum value of 69.06% and 89.26% with an average effectiveness of 79.45% (Figure 9). The high heat transfer effectiveness during the day happened due to the significant differentiation between the outdoor temperature and the ground or water. The more the disparity between the two temperatures, the greater the effectiveness obtained.

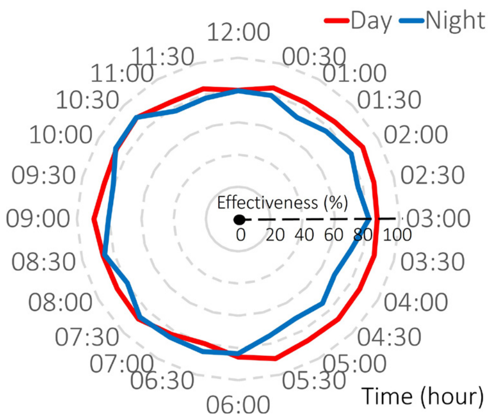


Figure 9. Hourly heat transfer effectiveness

4. Conclusion

One alternative solution worth considering in increasing thermal comfort and energy efficiency through building ventilation in hot and humid climates is the passive cooling effect of soil or water in the soil. This experimental study has shown the advantage of cooling effects obtained by reducing the air temperature in ventilation before it is diffused into the building. At a certain depth, the ground temperature approaches the annual average outdoor air temperature. It is produced due to the greater thermal inertia of the soil compared to air. Thus, the response of the soil to environmental thermal changes is slower than the air.

Therefore, the ground has a relatively cooler temperature to the outdoor air during the day. A significant temperature difference between air and ground-water and can be an effective cooling medium in reducing the outdoor temperature circulating in the HE. Thanks to the passive ground cooling effect, this EWAHE device can lower the air temperature in the ventilation ducts by up to 9.3 °C. In addition, the results show a more significant passive cooling effect is obtained during the day when the temperature dissimilarity, between the ground and the air is big. The research methods and results are expected to significantly contribute to the passive cooling strategies development, particularly in ventilation systems for tropical climates.

Acknowledgements

We would like to express our sincere gratitude to the Directorate of DRTPM, The Ministry of Education and Culture - Republic of Indonesia (MECRT-RI), and all members of CEPER UNP for their funding support and technical assistance. This research has been undertaken in the project of GWAHE in ventilation funded by The (MECRT-RI) under Grant No. 039 / E5 / PG.02. 00.PL / 2023 and the Contract No. 1045 / UN35.15 / LT /2023.

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