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EXPERIMENTAL INVESTIGATION OF WATER TO AIR HEAT EXCHANGER PERFORMANCE AS PASSIVE COOLING STRATEGY ON VENTILATION SYSTEM IN TROPICAL REGION

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Abstract

This experimental study aims to investigate and analyze the performance of a Water-Air Heat Exchanger that functions as passive cooling in a building ventilation system in the tropics. Before being blown into the room, the high-temperature outdoor air will be passively cooled by the lower-temperature water. Air driven by an Inline Duct Fan with a constant mass flow rate of 4.68 cubic meters per minute flows through a PVC hose as a heat exchanger inserted into a full water reservoir with a diameter of 100 cm and a height of 110 cm. A heat exchanger hose with a diameter of 6.35 cm and a length of 4130 cm is installed in a spiral-circular manner with a total of 16 coils with a diameter of 80 cm to increase the heat transfer effectiveness between water and air. The passive cooling effectiveness is analyzed by decreasing the air temperature between the inlet and outlet of the ventilator after passing through the heat exchanger. The temperature, humidity, and daylight measurement data were carried out for 36 consecutive hours using a multichannel data logger at several locations; ventilator inlet, ventilator outlet, water in the tub, and outside air. The measurement results show that the designed water-to-air heat exchanger provides a significant passive cooling effect and can reduce air temperature to 6.88 °C. By utilizing the passive cooling effect, the cooling energy gain obtained during the measurement period in the ventilation system of this building is 8.3 kWh. The methodology and results of this research are expected to make a positive contribution to the development of the concept of energy-efficient buildings by using passive cooling techniques.

Keywords*:* water-air heat exchanger, passive cooling, ventilation system, cooling energy gain, tropical region.

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1. Introduction

Thermal comfort is one of the main aspects that need to be considered in a building design [1]. Thermal comfort is strongly affected by the air conditioning system and ventilation system [2–4]. To meet the thermal comfort of occupants in tropical climates, buildings are usually equipped with air conditioning and ventilation devices, often called by Heating, Ventilating, and Air Conditioning (HVAC) systems [5]. Unfortunately, the HVAC systems in buildings requires significant energy and potentially damage the environment [6, 7]. The energy consumption of buildings for HVAC systems is around 40 % of the building's total energy consumption [8–10]. The high growth of energy consumption in the building sector not supported by adequate production and energy reserves can disrupt the stability of national energy security. Therefore, it is necessary to make an intensive effort to increase energy consumption efficiency in all sectors. For energy security and environmental preservation, minimizing energy consumption and environmental impacts caused by HVAC systems in buildings is necessary. Although energy efficiency is very significant, the thermal comfort of occupants remains the primary requirement that must be considered in the design and construction process of buildings [11].

One effective strategy for energy efficiency of HVAC systems is passive cooling techniques [12]. This technique is a method of lowering the temperature of a building using two principles, namely minimizing heat gain from the environment and maximizing heat dissipation to the environment Several alternative passive cooling techniques that can be implemented in buildings include natural ventilation, sun protection, evaporative cooling, cooling by soil, materials, thermal stratification, etc. [13, 14]. Unfortunately, the current architectural design of buildings in Indonesia has not maximally adopted passive cooling techniques to increase the thermal comfort of the room [15]. Therefore, the development of passive cooling techniques in building design can be an effective solution to increasing occupant comfort and energy efficiency.

This study aims to design and analyze the thermal performance of a passive cooling engineering device in a ventilation system in the tropics called the Water-Air Heat Exchanger (WAHE). This WAHE device is a heat transfer device from air flowing in a heat exchanger pipe, which is immersed in a reservoir filled with water. The heat carried by air is then transferred into the water as it passes through the heat exchanger pipe submerged in the reservoir. The passive cooling effectiveness was analyzed by decreasing the air temperature between the inlet and outlet of the ventilator after passing through the heat exchanger. Temperature data measurements were carried out for 36 consecutive hours using a data logger at several points in the device. This research is expected to contribute to the concept of energy-efficient buildings development by using passive cooling techniques, especially in the tropics.

For air quality and comfort, buildings need to be equipped with a cooling and ventilation system both naturally and mechanically. Air circulation can evacuate various particles that interfere with the health of residents, such as dust, smoke, and CO_2 gas trapped in the room into the environment. Thermally, in the tropics, air circulation through ventilation can remove excess heat in the room. The air movement from the room to the environment or vice versa is caused by pressure differences that are generated naturally (wind or thermal stack effect) or mechanically (fans, air conditioning). In buildings, air conditioners are often found integrated into a ventilation system. Air conditioning and ventilation are essential equipment in buildings for tropical areas that are unavoidable to ensure the thermal comfort of occupants. In Indonesia, cooling and ventilation systems consume a large amount of energy, up to 40 % of the total energy consumption of buildings [16, 17]. Besides the large energy consumption, the air conditioning and ventilation system have several other disadvantages, such as not being environmentally friendly and high investment and maintenance costs. One way to increase energy efficiency in the HVAC system is to take advantage of the passive cooling effect by using water at a lower temperature than air as a heat release medium.

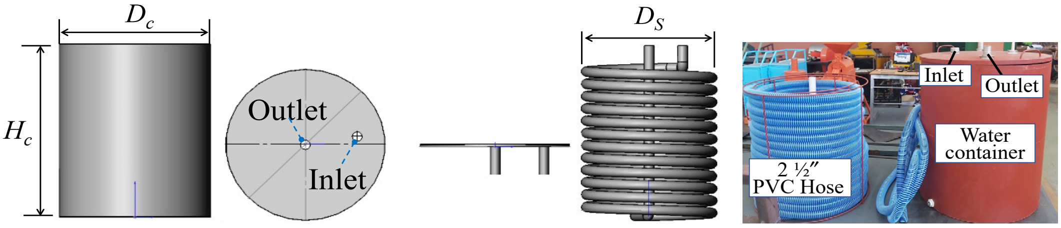
Water has a greater heat capacity ($4.18\ kJ{\cdot}Kg^{-1}{\cdot}K^{-1}$) than air ($1.005\ kJ{\cdot}kg^{-1}{\cdot}K^{-1}$) [18, 19]. With a high heat capacity, water can maintain its initial temperature longer when heat changes from the environment occur. In a place with a high heat gain (solar radiation, thermal radiation, lighting system, other heat gains), the outside air temperature will be higher than the water temperature in the atmosphere. It happens due to the faster response to temperature changes made by the air due to environmental heat disturbances compared to water. In addition, the fluctuations in outside air temperature between day and night appear to be greater than that of water [20]. A study showed a significant temperature difference of 15 °C between the ambient air and the water in a pond [21]. Other studies showed that the air temperature during the day around the water pond was 2.6 °C lower than the air in other positions around it [22, 23]. Another study confirms that due to high thermal inertia, the water temperature during the day is lower than the air temperature. On the contrary, the water temperature at the night could probably higher than overlying air [24–26]. In addition, other studies have shown that the presence of artificial water facilities (such as shallow pools, swimming pools, fountains, etc.) can reduce the temperature of the surrounding air [27, 28]. Vice versa, if there is a significant decrease in temperature in the environment, the water will maintain its temperature longer than the air so that the water temperature feels hotter than the air temperature. In locations with no significant heat source for a long time, the water temperature is almost the same as the air temperature. Under these conditions, water is one alternative media that can be used as a passive coolant for air containing higher heat.

In addition to the Earth-to-Air Heat Exchanger (EAHE), another widely used passive cooling method is the Water-Air Heat Exchanger (WAHE). The WAHE system was firstly designed and patented by Bourne and Springer [29]. The WAHE was the modified by other researcher by combining them in an insulated roof pond [30]. WAHE aims to transfer heat between water and air as a cooling medium. Studies on passive cooling techniques using the cooling effect of water and soil can be found in various literature studies [31, 32]. Compared to EAHE, WAHE shows better performance in reducing air temperature because the heat dissipation process is easier due to the high heat capacity of water compared to soil. A study on a roof pond integrated with WAHE showed significant results in decreasing air temperature up to 10 °C [33]. A roof pond is a passive cooling technique that uses water in the cooling process that has the potential to be developed [34]. Another study [21] showed that the cooling process using a 3.5 m Water to Air Heat Exchanger in ventilation system can maintain room temperature at 27 °C even though the outdoor temperature is around 36 °C. This study also shows that the temperature of the water in the tank increase 3 °C due to the absorption of heat from the air passing through the ventilation pipe [21]. In work [33] evaluate the benefits of adopting different roof pond configurations combined with a WAHE System. The heat from the building is transferred by convection to the 4″ underwater pipe, which then exchanges this heat by conduction to the water. The cooled air in the ventilation pipe is then introduced into the room to reduce overheating. However, although WAHE shows several advantages, research on WAHE is less than Earth to Air heat Exchanger (EAHE) [33].

2. Materials and methods

2. 1. Design of water-air heat exchanger

In this experimental study, a Water-Air Heat Exchanger (WAHE) device was designed and analyzed for its performance on the effect of passive cooling in a mechanical ventilation system for buildings. This device aims to lower the air temperature before being distributed into the room and reduce energy consumption for the cooling system. This device consists of two main components; a water storage container (**Fig. 1, *a***) and a PVC hose as a heat exchanger for ventilation (**Fig. 1, *c***). The water storage container is made of a 2 mm thick iron plate, 100 cm in diameter (D_C) and 110 cm in height (H_C) (**Fig. 1, *a***). To avoid corrosion, the outer and inner surfaces of the container are coated with anti-rust paint. The heat exchanger is made of Polyvinyl Chloride (PVC) hose with an inner diameter of (din) 6.35 cm (2.5 inches) and a length of 4130 cm, coiled in a vertical spiral in a water container. The diameter of the spiral PVC hose (D_S) coil is 80 cm, with a total of 16 turns (**Fig. 1, *c***). The more the number of turns of the hose, the longer the hose is submerged in water. Thus, the better the cooling effect is obtained. The top cover of the holding container is made of the same material as the container walls and is equipped with two holes for the inlet (blower) and outlet (blown into the chamber) (**Fig. 1, *b***). As a driving motor that encourages air circulation, an inline duct fan with a 4-inch diameter is used with a constant flow rate of 4.68 cubic meters per minute. Air that has experienced a temperature decrease is then distributed into the building to meet the air circulation needed.



a *b* *c* *d*

Fig. 1. The design of the WAHE device to be developed: *a* – water storage container; *b* – water container cover; *c* – PVC hose as a heat exchanger; *d* – the prototype

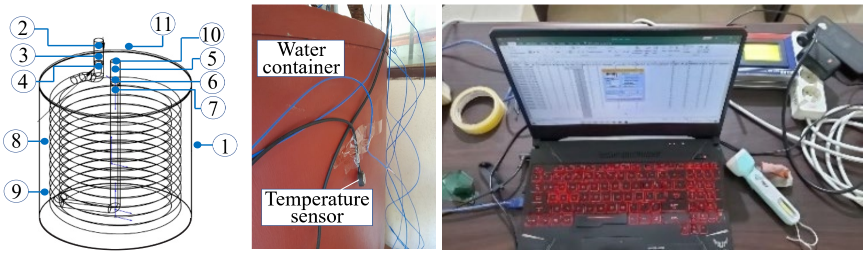
2. 2. Climate characteristics of experiment location

The experimental study was conducted in an open space on the terrace of a workshop at the Department of Mechanical Engineering, Padang State University, Padang city. The experiment location is protected from direct solar radiation, and it is assumed that there is no significant heat gain around the device. Padang City is a city on the west coast of the Sumatera Island, located at –0.898 South Latitude and 100.35 East Longitude (**Fig. 2**). The minimum, maximum, and average annual outdoor temperatures in Padang were 22.5 °C, 33.7 °C and 27.5 °C, consecutively [35]. Because of located in a coastal area in the tropics, the humidity and average annual rainfall in the city of Padang is high at 80.25 % and 343.7 $mm^3 \cdot year^{-1}$ [35]. With weather conditions like this, the thermal comfort of buildings in Padang is a crucial matter that needs consideration. The research location condition is shown in **Fig. 2**.

Fig. 2. Experiment location; the Padang City on the map

2. 3. The protocol of experiment and instrumentation

Air temperature measurement in the heat exchanger hose and water temperature in the container is done using a thermocouple data logger. The sensor is a Type K Thermocouple with a measurement interval of –200–1300 °C, a resolution of 0.25 °C, and an error of ±2 %. Data measurement was carried out for 36 consecutive hours day and night with 1-minute data storage intervals. One thermocouple sensor is outside the container (**Fig. 3, *b***) to measure the outside air temperature.



a *b* *c*

Fig. 3. Experimental study of WAHE devices:
a – sensor locations (**Table 1** for sensor description); *b* – temperature sensor; *c* – data logger monitoring

Three temperature sensors are installed at the inlet and outlet of the ventilator to monitor air temperature changes in the ventilation duct. In the water container, two sensors are in the middle and bottom (30 cm from the bottom of the container) of the water reservoir. One air humidity sensor is at the outlet with a resolution of 0.1 % and an error of ±3 %. A light intensity sensor with a resolution of 1 lux and an error of ±5 % is installed to measure the level of natural lighting around the device. Airflow in ventilation ducts was measured using a Lutron AM-4234 SD digital hot wire anemometer with a measurement interval of 0.2 to 35.0 $m \cdot s^{-1}$. The detailed sensor position on the WAHE device is shown in **Fig. 3, *a*** and **Table 1**.

Table 1
Sensor measurement and position parameters (**Fig. 3, *a***, for sensor location)

No.	Notation	Parameters	Sensors	No.	Notation	Parameters	Sensors
1	$T_{Outdoor}$	Temperature (°C)	Outdoor air	7	$T_{out,3}$	Temperature (°C)	Outlet 3
2	$T_{in,1}$		Inlet 1	8	$T_{W,1}$		Water, middle
3	$T_{in,2}$		Inlet 2	9	$T_{W,2}$		Water, bottom
4	$T_{in,3}$		Inlet 3	10	Hum	Humidity (%)	Air duct outlet
5	$T_{out,1}$		Outlet 1	11	Light	Daylighting (lux)	Horizontal plane
6	$T_{out,2}$		Outlet 2			–	

2. 4. Performance indicators

The WAHE device performance evaluation is measured by comparing the thermal conditions of the air at the inlet point, outlet point, and outside air temperature. For analysis, several indicators used are:

a. Decrease in temperature at the outlet (T_{Outlet}) compared to the inlet (T_{Inlet}) in the ventilation duct.

b. Heat transfer from air to water in a heat exchanger (Q_{HE}).

c. Energy saving (ES) obtained based on the building occupancy scenario.

The heat transfer that occurs from air to water (Q_{HE}, in Watt) and energy saving (E_S, kWh) is calculated based on the amount of air mass flow that flows in the air duct $\dot{m}$ (5.63 $kg \cdot min^{-1}$) using the (1), where the density of air at room temperature is 1.204 $kg \cdot m^{-3}$, air thermal capacity C_{Air} (1.005 $kJ \cdot kg^{-1} \cdot K^{-1}$), inlet temperature T_{Inlet} (K) and outlet temperature T_{Outlet} (K).

$$Q_{HE} = \dot{m} \times C_{Air} \times (T_{Outlet} - T_{Inlet}). \quad (1)$$

3. Results and discussion

3. 1. Presentation of outdoor conditions

Data on outdoor temperature, humidity, and daylighting level at the study site for August 21st 2022 from 05:00 a.m. to 05:00 p.m. are presented in (**Fig. 4**). The measurement data shows that the minimum, maximum and average values of the outside air temperature were recorded at 26.0 °C, 32.0 °C and 29.23 °C, consecutively. In the morning until 08:00 a.m., the outside air temperature is still within the limits of thermal comfort, between 26.0 °C and 27.75 °C. This temperature is within the tolerance limits of the thermal comfort set for the Indonesian territory, with a comfort temperature setup of 25 °C ± 1.5 °C [36, 37]. Along with the increase in the intensity of solar radiation, the ambient temperature rose gradually. It happened until it reached the highest temperature of 32.0 °C, which occurred at 02:29 p.m. Regarding the Indonesian thermal regulation SNI 03-6197 [36], from 09:00 a.m. to the afternoon, the outside air temperature during the day varies from 27.5 °C to 32.0 °C (**Fig. 4**). In addition, the location humidity at the measurement time was rather high with the average, minimum and maximum value of air humidity is 96.02 %, 87.82 %, and 99.9 %, consecutively. The high temperature and humidity of the air will cause thermal discomfort for residents. To improve thermal comfort, the air temperature must be lowered to the recommended comfort limit. On the contrary, the results of measuring the level of lighting at the location obtained data that the intensity of daylighting ranged between 0 lux (night) and

79.17 lux (day). In this study, the research location did not receive direct radiation from the sun. Natural lighting comes from diffuse sky radiation.

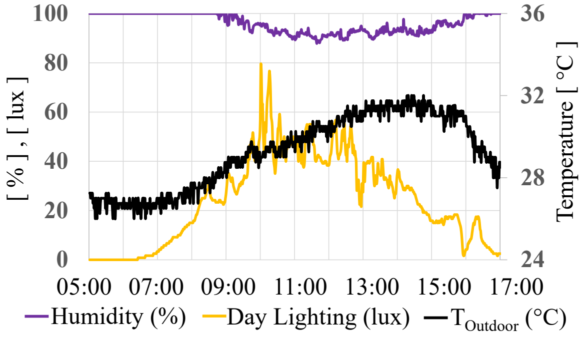


Fig. 4. In-situ outdoor local climate characteristics during the day on August 21st 2022, from 5 a.m. to 5 p.m.

3. 2. WAHE's temperature analysis

The results of outside air temperature measurements (T_{Outlet}), inlet air temperature (T_{Inlet}), outlet air temperature (T_{Outlet}) and water temperature (T_{Water}) during the experiment with a time step of 1 minute can be seen in **Fig. 5**. The outside air temperature (T_{Outlet}) changes quite significantly between day and night with an amplitude of 6.0 °C. Meanwhile, in water, the temperature fluctuation (T_{Water}) between day and night is lower, with a maximum amplitude of only 3.5 °C. The slight change in water temperature is caused by the thermal inertia effect. It happened due to the high thermal capacity of water compared to air. The response of temperature changes to changes in heat gain made by water is slower than the air. During the day, the heat gain absorbed by the air (solar radiation, other heat gains) will cause a significant increase in temperature. Meanwhile, water, with a large thermal inertia, will have a lower temperature during the day than the air temperature, with a maximum difference of 5.0 °C. This temperature difference is potentially be used as passive cooling for high-temperature air (**Fig. 5**).

For circulation, the air in the pipe is blown by an inline duct fan (**Fig. 3, *a***). The mechanical movement of the blower fan causes a heating effect that can increase the air temperature on the ventilator inlet side close to the blower (T_{Inlet}). The air has a temperature increase of 2.0–4.35 °C due to heat absorption when it passes through a rotating blower. This significant temperature increase will affect the occupants' thermal comfort if the air is distributed directly to the room. To increase comfort, the rising air temperature on the inlet side can be lowered by using a passive cooling medium of water in the heat exchanger before being distributed into the room. In addition, the graph in **Fig. 5** shows that changes in air temperature at the inlet have the same tendency as changes in outside air.

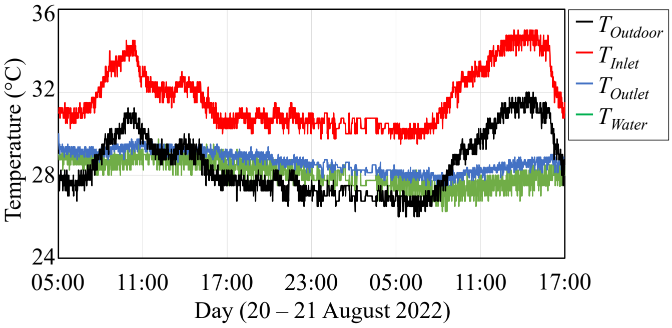


Fig. 5. Temperature changes in the heat exchanger system

3. 3. Heat transfer and cooling effectiveness

The value of heat transfer between water and air is analyzed from the decrease in air temperature after passing through the PVC hose heat exchanger. The heat in the air at the inlet is transferred to water, which has a lower temperature. The decrease in average air temperature after passing through the cooling medium ($\Delta T = T_{Inlet} - T_{Oulet}$) obtained was 3.05 °C, and a maximum decrease was 6.88 °C occurring during the day (red line versus blue line in **Fig. 5**). While at night, the temperature drops that at the outlet is lower, around 0.8–2.88 °C. The large heat transfer during the day is caused by the high-temperature difference between the inlet air and water. Because air has a low thermal capacity, it is easier for the air temperature to decrease when moving from air to water. Meanwhile, with a higher thermal capacity, the heat absorbed from the air does not significantly affect the temperature increase directly.

Fig. 6 displays the amount of heat released from the air to the water in the reservoir. Based on the graph, it is clear that the higher heat release occurred during the day between 10:00 a.m. to 02:00 p.m. During the experiment, the maximum heat transferable was 0.52 kW during the day between 01:00 p.m. to 02:00 p.m. During 36 hours of measurement, the hourly average power transfer was 0.23 kW (**Fig. 6**).

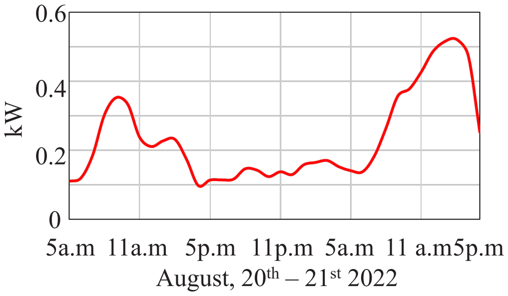


Fig. 6. Power transferred from air to water in a heat exchanger

3. 4. Passive cooling potential

The passive cooling potential of the WAHE device was analyzed by considering the occupancy pattern of the building. This experiment studies two types of buildings with different occupancy patterns; residential homes and offices (tertiary). In residential buildings, residents are present from 06 p.m. to 07 a.m. to relax and rest. Meanwhile, from 08:00 a.m. to 05:00 p.m., residents leave the house to carry out various activities in other places, such as at school, in the office, etc. On the other hand, different residential patterns are found in office buildings. The occupants are present at the office from 08 a.m. to 08 p.m. The mechanical ventilation system is usually activated to maintain thermal comfort in the building during occupancy. If the fan blower is always activated for 36 hours of measurement, then the total degree hour (*DH*) of decreasing air temperature obtained is 88.91 °C·h (accumulated for 36 hours). Degree hour decrease in air temperature represents the cooling energy gain obtained from water, which is equivalent to 8.38 kWh (**Table 2**). After calculating, the average cooling energy gain generated by the WAHE device is 0.232 kWh per hour.

Table 2

Cooling energy gain obtained by air from heat exchanger

Day	Time period	Full-active ventilation	Residential (dwelling)			Tertiary (office)		
		Energy	Occ	$\Delta T{\cdot}h$	Energy	Occ	$\Delta T{\cdot}h$	Energy
1	5 a.m.–7 a.m.	0.41	Yes	4.40	0.41	Non	4.40	Vent-off
	8 a.m.–5 p.m.	2.16	Non	24.15	Vent-off	Yes	28.13	2.65
	6 p.m.–8 p.m.	0.34	Yes	21.29	2.01			
	8 p.m.–12 a.m.	0.55				Non	17.30	Vent-off
2	12 a.m.–7 a.m.	1.05						
	8 a.m.–5 p.m.	3.86	Non	39.08	Vent-off	Yes	39.08	3.69
	–	8.38	Total		2.42	Total		6.34

Note: Occ is occupation period, $\Delta T{\cdot}h$ (°C) is average temperature difference in ($T_{Outlet} - T_{Intlet}$) within the experiment time, Energy is cooling energy gain in heat exchanger (kWh), Vent-off is fan blower time-off

To save energy, ventilation blower fans should be activated only during the occupancy period for each type of building. **Table 2** shows the potential for cooling energy gain based on the fan blower activation scenario according to the building occupancy pattern. The data shows that the total cooling energy gain obtained during the period of occupancy in residential buildings and tertiary buildings is 2.42 kWh and 6.34 kWh, consecutively. Because it is inhabited during the day when the outside air temperature is much hotter, the potential cooling energy gain in tertiary buildings is higher than in residential buildings. From the data in **Table 2**, for 24 hours (from August 20th, 06:00 p.m. to August 21st, 05:00 p.m.), the most significant potential passive cooling effect was obtained during the day, between 08:00 a.m. to 05:00 p.m., for 66.5 % of the total cooling gain. Therefore, this designed WAHE device is better operated during the day to maximize the passive cooling effect in the ventilation system of the building.

3. 5. Limitation and research development direction

This paper presents the interest in passive cooling technique in building ventilation systems by using the effect of the thermal inertia of water to decrease the air temperature before being distributed into the building. However, it should be noted that the passive cooling process is ineffective at night because the air temperature is relatively lower than the water temperature, which may cause an increase in room temperature. For further development in application of this technique, several conditions must be considered such as; the need for space for water container location; periodic water changes to avoid over saturation of heat absorption by water, water sanitation control to avoid mosquito colonies, etc. Indeed, this passive strategy is more suiTable to be applied in regions with abundant water resources (water ponds, rivers, rainwater, etc.). Another aspect that must be considered in this technique is the control of air humidity in ventilation system to ensure the occupants' thermal comfort. The outlook of this research is an analysis of the effectiveness of a passive cooling strategy using the thermal inertia effect of ground-water on ground-water-to-heat exchanger (*GwAHE*) device.

4. Conclusions

Experimental studies on the thermal performance of a Water to Air Heat Exchanger (WAHE) device have shown interest in integrating passive cooling strategies into building ventilation systems in tropical climates. The experimental results show that before being distributed into the room, the outside air temperature can be decreased significantly through a heat exchanger that uses water as a cooling medium. The maximum decrease in air temperature for 6.88 °C at the ventilator outlet occurs during the day when the difference between the temperature of the ventilator inlet and the water temperature reaches 8.0 °C. While at night, although not too significant, the low water temperature still has the potential to be used as a passive cooling medium for the air. The cooling energy gained by the air during the experiment was 8.3 kWh. To increase the effectiveness and energy efficiency, it is necessary to carefully consider the activation time of the fan blower ventilator by taking into account the building occupancy period and the potential cooling effect obtained.

Conflict of interest

The authors declare that there is no conflict of interest in relation to this paper, as well as the published research results, including the financial aspects of conducting the research, obtaining and using its results, as well as any non-financial personal relationships.

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Data availability

Data will be made available on reasonable request.

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