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Research article

Energy conservation of HVAC systems in isolation rooms using heat pipe heat exchangers

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ABSTRACT

Isolation rooms are crucial in healthcare facilities to prevent the spread of infectious diseases. Infectious diseases can be transmitted to humans from humans or through animals known as zoonoses. With the increase in the number of COVID-19 cases, isolation rooms have become one of the most critical facilities in hospitals. Maintaining the correct temperature and humidity in these isolation rooms is a challenge, considering the heating, ventilation, and air conditioning (HVAC) systems that continuously consume large amounts of energy. With the application of energy conservation methods, the total energy consumption of HVAC systems can be reduced. Many studies have shown that the heat pipe heat exchanger (HPHE) technology can contribute significantly to energy savings using HVAC systems. In this study, the effectiveness of an HPHE on an HVAC system in an isolation room was examined, and the total energy reduction was quantified. The HPHE consisted of two rows with ten heat pipes in each row, arranged in a staggered configuration with fresh air temperature and mass flow variations. The inlet fresh air temperatures varied at 32, 35, 37, and 40 °C and fresh air velocities at 1.2, 1.6, 2.2, and 2.6 m/s. Using a chiller, the inlet fresh air was cooled to a comfortable temperature zone, approximately 24.4–25.2 °C, in the isolation room. Notably, higher velocities decreased the effectiveness of the HPHE. An increase in the flow rate enhanced the system, thereby improving the heat recovery value. The increase in the inlet fresh air temperature from 32 °C, that yielded an energy saving of 1.23 W, to 40 °C, resulted in a further energy saving of 1.85 W. The application of the HPHE in the HVAC system in isolation rooms represents a significant innovation that contributes to a reduction in total energy consumption.

1. Introduction

An isolation room is a facility that is a requirement of a public hospital. Isolation rooms are designed to prevent the spread of infectious diseases, including zoonoses [1,2]. The isolation room serves to isolate the existing air in the room such that the spread of the virus through the air can be minimized [3]. In 2021, statistical data from the World Health Organization (WHO) indicated that the zoonotic coronavirus (COVID-19) had spread to over 234 million cases [4]. The COVID-19 outbreak has prompted the world to

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reconsider health comprehensively. However, current sector-based and technology-driven solutions incur high costs, particularly in terms of energy consumption [5]. The system in a hospital accounts for the most considerable value of energy consumption that is 70% of the total energy consumption [6]. The air temperature must be maintained following the ASHRAE standard for isolation room temperature to maintain the air sterile, that is 20–24 °C, the air humidity range is 30%–60%, and the quantity of the indoor air change is at least 20 times per hour and that of the outside air change is at least 20–24 times per hour. The heating, ventilation, and air-conditioning (HVAC) system performs the air change process and continuously controls the air quality in the isolation room to achieve aseptic conditions [7].

According to Megashnee et al. the air change process requires a large amount of electrical energy [8]. Electric energy consumption of HVAC systems in large-scale hospitals is 36%. In an HVAC system, the incoming air is cooled by a *cooling coil* before entering the isolation room, increasing the relative humidity of the air; therefore, a dehumidification process must be conducted by increasing the heat. This results in a large amount of energy consumption by the HVAC system [9]. Therefore, system engineering must be applied to reduce the energy consumption. A heat pipe heat exchanger (HPHE) is one solution that can be applied. The amount of energy used by a cooling coil is reduced because the air is pre-cooled by the HPHE. Consequently, the efficiency of the HVAC system is increased compared with that of the HVAC systems without HPHE [10]. U-shaped heat pipes reduce the inlet temperature at the cooling coil by 1.73 °C with an effectiveness value of 7.64%. The highest heat recovery of 2190.43 kJ/h is obtained at an air velocity of 2.5 m/s, and the relative humidity is reduced by 12.2% [11].

An HPHE can increase the HVAC efficiency and gain heat recovery, affecting energy savings, as Suleiman et al. [12] proved by adding an HPHE to an HVAC system with 40 heat pipes. The results indicated that increasing the heat flux and decreasing the air velocity increased the effectiveness of the HPHE performance. The highest effectiveness value was 0.646 at a heat flux of 1400 W/m^2 at an air velocity of 1 m/s, and the highest heat recovery value was 923.4 W at an air velocity of 2 m/s. Ibnu Hakim et al. [12] conducted a study by adding a two-row U-shaped HPHE at the inlet wrapped around a cooling coil, and the results showed energy savings of 288.1 and 340.2 W and a 21.6% reduction in the relative humidity. Abdelaziz et al. [13] conducted a study on adding a wickless HPHE to air conditioning equipment, and the results showed a 30% reduction in energy owing to the addition of a wickless HPHE with a diameter of 10.2 mm. Economic analysis showed a downward trend in electricity consumption costs, with a payback period of approximately three years and a service life of 20 years. Furthermore, Abdallah et al. [14] showed that the use of HPHE with the addition of nanofluid and temperature variations increased the effectiveness of the heat pipe by 0.59346–883.284 W at an inlet air temperature of 55 °C and air velocity of 1 m/s. This research shows that the objective of using an HPHE in HVAC systems has not been in-depth on the prototype of the room.

However, the use of an HPHE in HVAC systems within isolation rooms has not been extensively explored at the prototype level. Bhattacharyya et al. [15] investigated the effectiveness of conditioned fresh air released by HVAC systems in isolation rooms and analyzed airflow modelling with aerosol purifiers, indicating higher energy requirements. Similarly, Amahjour et al. [16] focused on the air circulation efficiency in AC ventilation and exhaust air conditions for hospital isolation rooms. Whereas they effectively evaluated the HVAC system efficiency, they did not investigate energy conservation in-depth. Noie Baghban and Majideian [17] explored the utilization of an HPHE in operating room HVAC systems and revealed the need for significant thermal effectiveness. Their findings offered an opportunity to conduct experiments on energy conservation using various HPHE configurations in isolation rooms, lacking extensive energy conservation research. Furthermore, whereas prior research has explored the use of an HPHE in commercial spaces and examined their heat recovery performance, the optimal heat recovery is achieved when the incoming fresh air temperature surpasses the temperature of the exhaust air leaving the room [18].

A literature review shows that adding an HPHE to an HVAC system can improve the performance and reduce the energy consumption. Some researchers have observed the effects of an HPHE on HVAC in commercial, operating, and hospital rooms for energy conservation. This study is the first to experimentally investigate the energy conservation potential of an HPHE in isolation rooms that have higher requirements for temperature, humidity, and air change than other hospital facilities. In this study, the effectiveness of an HPHE on an HVAC system in an isolation room was examined, and the total energy reduction was quantified.

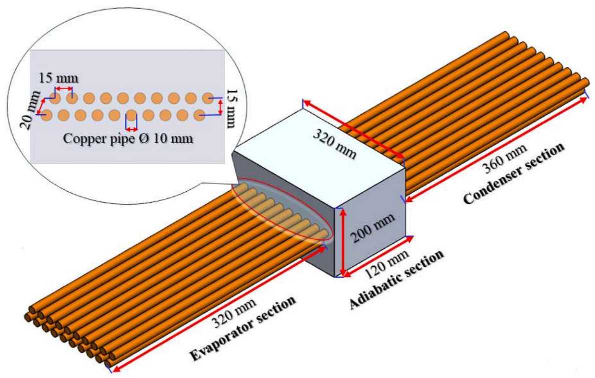

Fig. 1. Design and size of an HPHE.

2. Methodology

2.1. Test facility design

This study used an experimental test method consisting of an isolation simulation chamber with a mini-HVAC and complete duct systems. The simulation chamber acted as an isolation room with controllable temperature and pressure. The temperature was controlled using a cooling coil, and the pressure was maintained at 2.1 Pa. The room size was scaled to the actual size of a standard ASHRAE isolation room (1:10). The duct system consisted of one inlet and one outlet from the side of the simulator room. Polyurethane (PU) was used as the base insulation material in the duct section and isolation chamber. An HPHE consisted of two rows of heat pipes arranged in a configuration of 10 pipes per row, and the HPHE module did not use a fin on either side. The heat pipe tubes were made of copper, and the inner surface contained a sintered copper wick structure. The heat pipe used was a straight type, and the working fluid was in the form of water. The outer diameter of the heat pipe was 10 mm, evaporator length was 320 mm, adiabatic section length was 120 mm, condenser section length was 360 mm, and copper tube thickness was 2 mm, as illustrated in Fig. 1.

The experimental research method used a control system and measurement devices, as shown in Fig. 2. The inlet fresh air entering the duct was controlled using a 750 W inverter motor against the centrifugal blower, thus obtaining variable fluid flow velocities. The temperature of the fresh air entering the duct was controlled using a 2,000 W heater equipped with a temperature controller placed after the inlet of the centrifugal blower. The aim was to adjust the temperature of the fresh air entering the duct in the evaporator section. The mini-HVAC device consisted of a cooling coil that circulated cool air through the cooling coil installed in the HVAC duct to the isolation room measurement devices, as shown in Fig. 2. Fresh air entered the duct and was controlled using a 750 W inverter motor against a centrifugal blower such that variations in the fluid flow velocity could be set. The air mass flow in the test was controlled at 1.2, 1.6, 2.2, and 2.6 m/s. The incoming fresh air passed through the evaporator-HPHE coil chiller to the insulation room. The airflow caused changes in temperature and humidity. The temperature of the incoming fresh air significantly affected the changes in the HPHE module, where the temperature of the fresh air entering the duct was controlled using a 2,000 W heater equipped with circuit and temperature controls. The inlet fresh air temperature was controlled at 29, 32, 35, 37, and 40 °C, and the temperature did not exceed 40 °C owing to the possibility of ambient temperature in Indonesia. The temperature of the incoming fresh air was maintained at a set point to determine the energy efficiency and effectiveness of the HPHE module in the mini-HVAC system. The system circulated cool air through the cooling coil installed in the HVAC duct. The changes in the airflow velocity and temperature at the evaporator-condenser of the HPHE also affected the air humidity. The relative humidity of the air was measured at the fresh air inlet (RH_e) and air exhaust duct before the condenser module (RH_c). Conservation should be achieved during these measurements to monitor the enthalpy trends in the isolation room.

2.2. Effectiveness

Sensible incoming effectiveness was used to determine the thermal performance of the HPHE from the inlet air side of the duct. Effectiveness is the most relevant parameter to describe HPHE performance. The effectiveness in equation (1) is defined as the ratio of the actual heat transfer to the maximum heat transfer in the heat exchanger. In an HPHE system, the sensible and total effectiveness can be considered equal ($\varepsilon_{sen} = \varepsilon_{tot}$) [19].

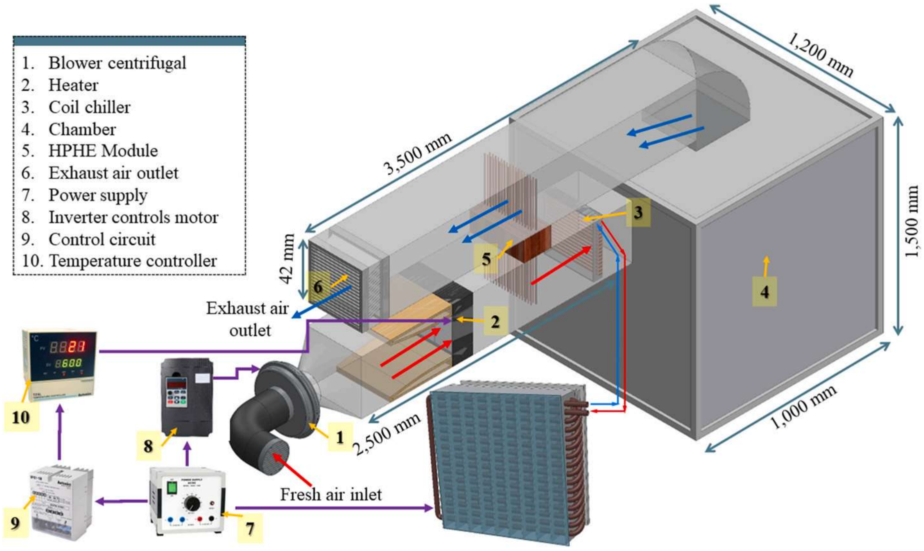

Fig. 2. Mini HVAC setup and size of the insulation room experimental model.

$$\varepsilon = \frac{Q_{act}}{Q_{max}} = \frac{T_{e,i} - T_{e,o}}{T_{e,i} - T_{c,i}}.100 \tag{1}$$

where ε represents the effectiveness of the HPHE (%), Q_{act} represents the actual heat transfer rate recovered (W), and Q_{max} represents the maximum possible heat transfer rate (W). The maximum heat transfer rate achievable by a heat exchanger depends on the inlet temperatures and minimum heat capacity rates of the fluids. Different temperatures $T_{e,i} – T_{e,o}$ in the evaporator section experimental setup ΔT_e (°C).

2.3. Energy recovery

In HVAC systems, the evaporator side of the HPHE was installed on the inlet air duct side as a pre-cooling device, whereas the condenser side was installed on the exhaust air duct side. In HVAC systems without HPHE technology, the incoming fresh air at the ducts is typically overcooled from $T_{e,i}$ to $T_{e,o}$ until it reaches the dew point temperature and is then reheated for dehumidification. By adding the HPHE as a pre-cooling device, the cooling load of the mini-chiller cooling coil could be distributed, as shown in Equation (2) [20].

$$q_{lrecovery} = m \cdot c_p \left(T_{e,i} - T_{e,o}\right) \tag{2}$$

where $q_{hecovery}$ represents the energy recovery that can be achieved by applying the HPHE as a precooling device, m represents the mass flow rate (kg/s), and c_p represents the specific heat of the ambient air ($Jkg^{-1}K^{-1}$).

The experimental setup, site image, and thermocouple placement are shown in Fig. 3. The HPHE performance is affected by several parameters, including system operation and design parameters. Inlet (T_e) and outlet (T_c) air temperatures were measured with a K-type thermocouple connected to an Agilent 34970A acoustic data logger with an accuracy of ±0.02 °C. The inlet air temperature ($T_{\text{fresh air}}$) was varied using a controlled heater. The air passing through the heater flowed to the isolation room/chamber (T_r), and the incoming

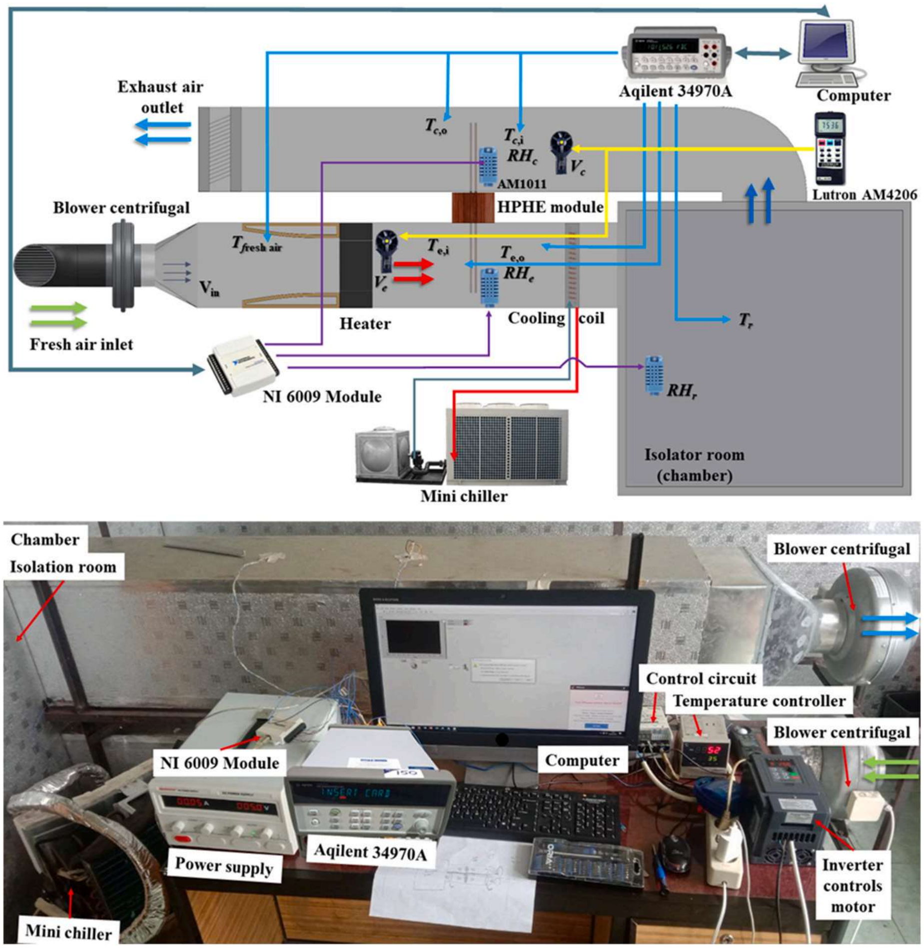

Fig. 3. Experimental setup and site image.

air was cooled using a cooling coil. The air velocities in the evaporator (V_e) and condenser sections (V_c) were measured using a Lutron AM-4204 anemometer sensor with an accuracy of ±0.1 m/s at the center of the duct.

3. Results and discussions

3.1. Performance of HPHE

This experiment assessed the performance of sequentially arranged HPHEs in two rows. Readings were recorded at 30-s intervals for each variation once steady-state conditions were achieved after the prototype operated for 360 s. Fig. 4 shows the air temperature profiles at the inlet and outlet of the evaporator and condenser sections, with an inlet air velocity of 1.2–2.6 m/s.

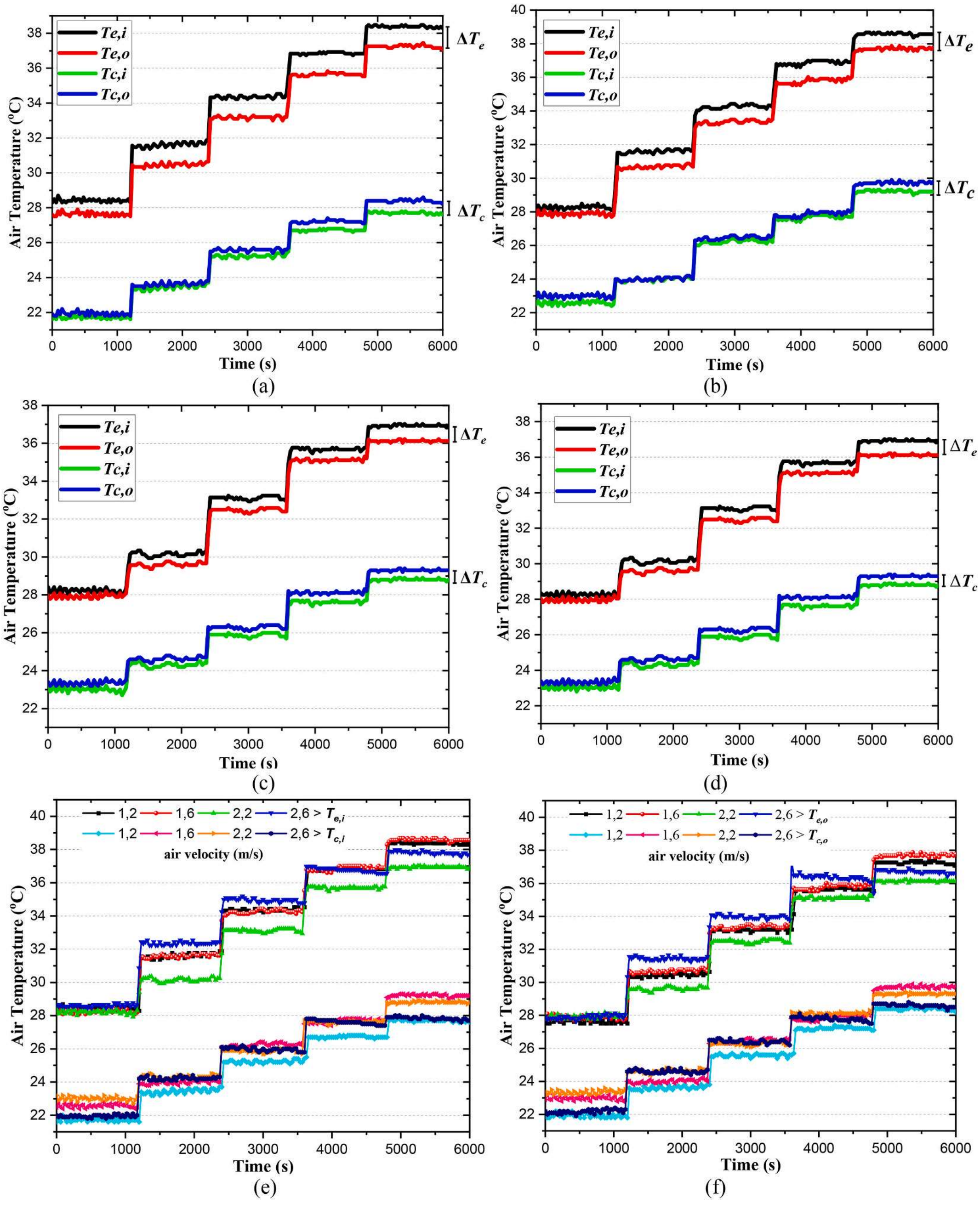

Fig. 4. Temperature profiles for an inlet air velocity of (a) 1.2 m/s, (b) 1.6 m/s, (c) 2.2 m/s, (d) 2.6 m/s, (e) input to air velocity, and (f) output to air velocity.

The temperature profile of the two-line HPHE at a fresh air velocity of 2.2 m/s indicated that the HPHE could reduce the temperature of the fresh air ($T_{e,i}$ to $T_{e,o}$) before passing through the cooling coil and simultaneously increase the temperature of the overcooled air in the condenser section ($T_{c,i}$ to $T_{c,o}$). The highest temperature difference in the initial evaporator section was 0.4 °C and that in the condenser section was 1.4 °C. However, when the heat pipe was supplied an increase in inlet air temperature, a decrease in the temperature difference on the evaporator side (ΔT_e) and an increase in the temperature difference on the condenser side (ΔT_c) were observed [21]. The results indicated that the heat absorbed by the heat pipe increased with the increase in the inlet air temperature on the evaporator side. The thermal resistance of the heat pipe and heat transfer could vary with changes in the temperature difference. These changes could affect the overall thermal resistance and decrease the thermal resistance of the HPHE as the evaporator temperature increases. Therefore, when operating a system with an HPHE, the effect of the increasing inlet air temperature on the evaporator must be considered [22].

This study demonstrated the regulation of air humidity in an HPHE system. In this experiment, the relative humidity of the air exiting ($RH_{e,o}$) the HPHE system was approximately 49%, whereas the incoming air had a relative humidity ($RH_{e,i}$) of approximately 50%. In addition to temperature reduction, the HPHE also decreased relative humidity by approximately 1%. A more detailed illustration is presented in Fig. 5.

Fig. 5 shows the enthalpy change from the inlet evaporator ($T_{e,i}$) to the outlet condenser ($T_{c,o}$). The fresh air temperature (inlet temperature) was 37.5 °C, with a relative humidity of 48.2%. After passing the HPHE evaporator, the temperature decreased to 36.3 °C

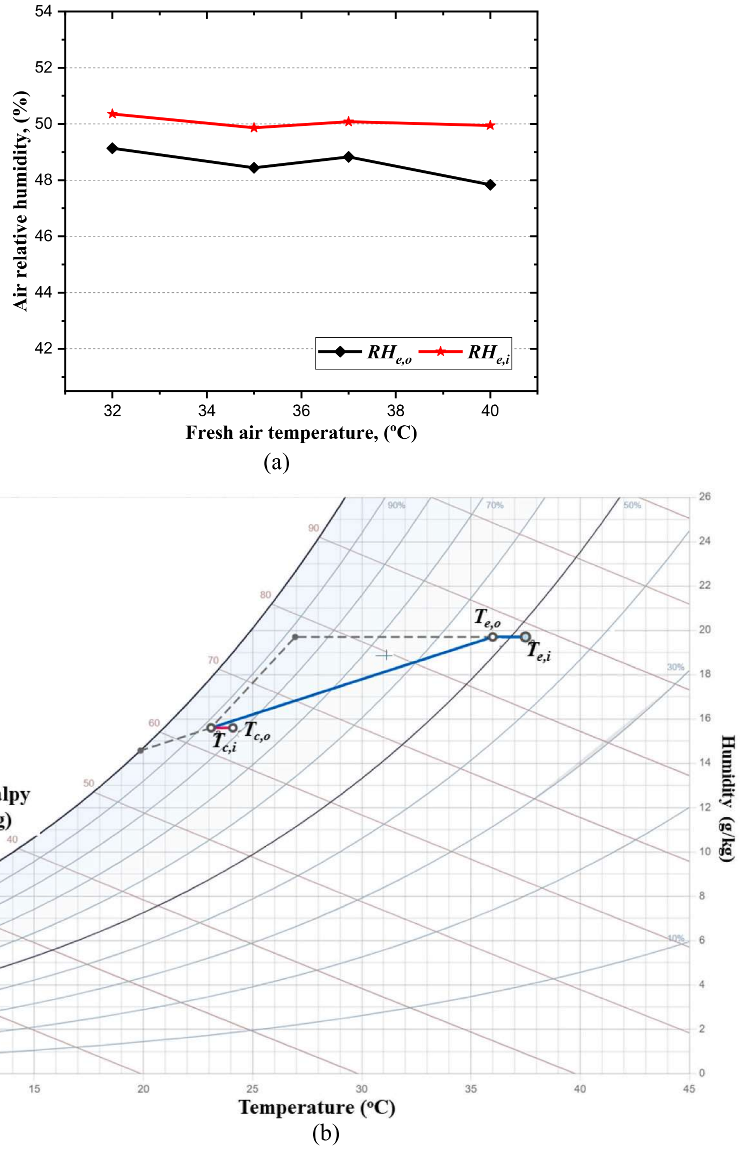

Fig. 5. (a) Relative humidity of air versus inlet fresh air temperature at an air velocity of 2.2 m/s and (b) representation of the processes on the Psychrometric chart.

with an RH of 51.5%. Then, the air was cooled in the cooling coil, and the temperature reduced to 23.1 °C with an RH of 87.4%. In the isolation room (Chamber), the air flowed to the outlet through the HPHE condenser. In the condenser, the air absorbed the heat from the evaporator and increased the air temperature at the outlet to 24 °C; the RH changed to 82.8%. In this case, as shown in Fig. 5, at the HPHE, whether at the evaporator and condenser, there is no enthalpy change, only a temperature change. Relative humidity and temperature determine the comfort zone. A relative humidity ratio of 48.2–87.4% indicates the ability of air to hold water vapor [23,24]. The amount of water vapor present in the air per unit of dry air was analyzed by reviewing the water vapor content during cooling or heating the air [25,26]. The energy requirement for heating or cooling air was determined by the total energy present per unit mass of dry air [27].

Fig. 6 shows the temperature difference (ΔT_e) through the HPHE module, that is, inlet fresh air temperatures ($T_{e,i}$) with varying air mass flow rates (V). Notably, ΔT_e increased with an increase in $T_{e,i}$, the velocity rate of the inlet airflow. This was because, for a constant cold air temperature, the temperature difference between the incoming fresh air and the cold air increased as the fresh air temperature increased. Therefore, more heat was transferred from the incoming fresh air that increased the temperature difference; however, as the air velocity increased, the temperature difference in the evaporator decreased. Because of the increased mass flow rate, fresh air could pass through the HPHE faster, transferring heat more efficiently and in a shorter time [28,29].

3.2. HPHE effectiveness

The effectiveness of the HPHE must be reviewed because it directly impacts the overall performance and efficiency of the HVAC system. The effectiveness of the HPHE module was in the form of two rows and was reviewed based on the temperature of the incoming fresh air at each airflow mass rate speed.

As shown in Fig. 7, the heat pipe effectiveness at a condenser air velocity of 1.2 m/s was higher when the air velocity in the evaporator was lower. At evaporator air velocities of 1.6, 2.2, and 2.6 m/s, the heat pipe effectiveness was lower when the air velocity in the condenser was higher. The lowest effectiveness of 6.5% was observed at an air velocity of 2.6 m/s, whereas the highest effectiveness of 18% was achieved at an air velocity of 1.2 m/s. This result indicated that the air velocity increased in the evaporator owing to the heat transfer convection coefficient. The increased heat transfer capability of the system resulted in higher turbulence owing to the higher flow velocities. No contact occurred between the air exchanging heat in the HPHE [30]. This decreased the heat transfer ability between the air and the surface of the pipe. The increase in the flow velocity affected the magnitude of the convection coefficient and heat transfer capability. Therefore, the flow velocity had to be adjusted to achieve better effectiveness [31–34].

3.3. Energy recovery

In a conventional HVAC system, the cooling coil cools the incoming fresh inlet air ($T_{e,i}$) to the air temperature of the chamber ($T_{c,i}$). This application lowers the temperature of the incoming fresh air before the cooling coil device cools it, thereby decreasing the cooling energy of the chiller. With the application of the HPHE in the mini-HVAC system, and under the condition that the inlet air temperature is 40 °C with an air mass flow rate of 2.2 m/s, the temperature difference obtained was 4.0 °C, and the energy recovery obtained per second was 1.47 W. Energy recovery indicated that the HPHE absorbed heat before being cooled by the cooling coil. The effects of the inlet air temperature and air velocity on the energy recovery are shown in Fig. 8.

As shown in Fig. 8, at an air mass flow velocity of 2.6 m/s, an increase in energy recovery was observed. Meanwhile, at an inlet fresh air temperature of 32 °C, an energy recovery value of 1.23 W was obtained. In comparison, at 40 °C, the value increased to 1.85 W. This indicated the apparent correlation between higher airflow velocity and higher temperature difference [35–37]. An increase in airflow

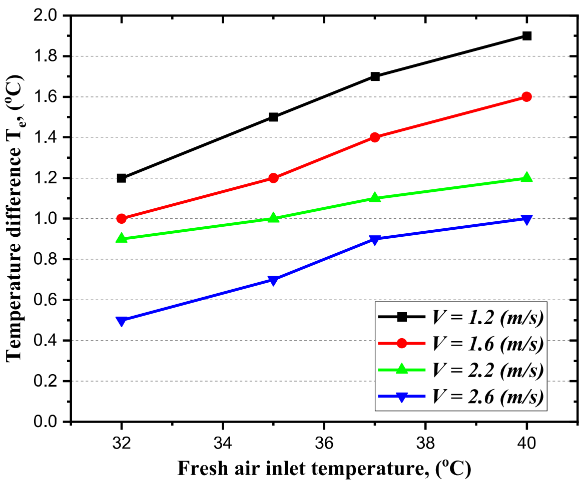

Fig. 6. Variations in the temperature difference (ΔT_e) with the inlet fresh air temperatures ($T_{e,i}$) at varying air mass flow rates (V).

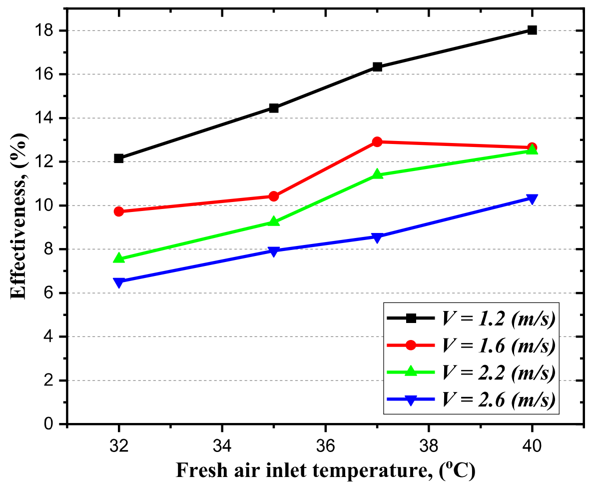

Fig. 7. Effectiveness of the two-row heat pipe module.

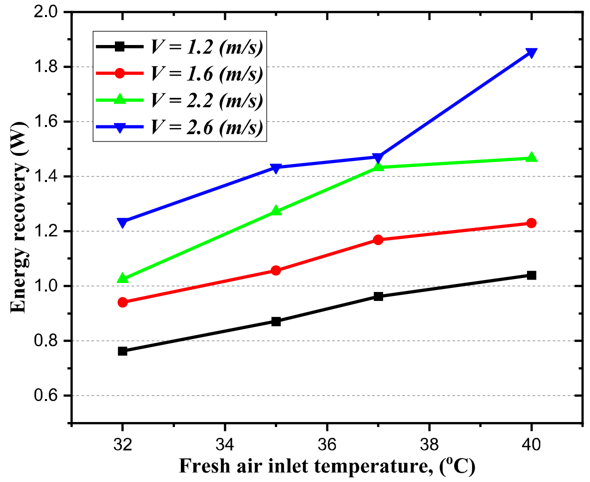

Fig. 8. Energy recovery profile regarding the mass of airflow rate velocity and fresh air inlet velocity.

velocity increased the air mass flow rate. In this context, an increase in the air mass flow rate contributes to an increase in the heat absorption of fresh air, that is performed by the HPHE, and increases the energy recovery of the system.

4. Conclusions

This study experimented with a control system, highlighting the importance of energy conservation in healthcare facilities, particularly in isolation rooms. This emphasizes the potential of the HPHE technology in improving the energy efficiency of HVAC systems. The HPHE can conserve energy in an HVAC system, particularly in isolation rooms. The increase in the inlet temperature increased the total energy recovery. A higher mass flow rate increased the total energy recovery, and a lower fresh air velocity increased the effectiveness of the HPHE. The maximum energy recovery of 1.85 W could be achieved at an inlet temperature of 40 °C and fresh air inlet velocity of 2.6 m/s, and the highest effectiveness was obtained at an inlet temperature of 40 °C and air velocity of 1.2 m/s. The relative humidity changed owing to the decrease in the inlet temperature through the evaporator. The application of an HPHE to an HVAC system in an isolation room provides a practical solution for improving the energy efficiency of isolation rooms.

CRediT authorship contribution statement

Fazri Amir: Data curation, Formal analysis, Investigation, Writing – original draft. **Samsul Rizal:** Conceptualization, Funding acquisition, Writing – review & editing. **Razali Thaib:** Data curation, Methodology. **Hamdani Umar:** Conceptualization, Data curation, Validation. **Ikramullah Ikramullah:** Software, Visualization, Writing – review & editing. **Nasruddin A. Abdullah:** Formal analysis, Methodology, Resources. **Teuku Azuar Rizal:** Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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