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Utilizing heat pipe heat exchanger to reduce the energy consumption of airborne infection isolation hospital room HVAC system

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**Keywords:** Heat-pipe heat exchanger, HVAC, Airborne infection isolation room, Recovery energy

**Abstract**

The COVID-19 pandemic in early 2020 became a global issue and received substantial attention worldwide. In a hospital, airborne infection isolation (AII) room is significant to prevent the spread of the virus to patients and medical personnel. This research aims to improve the design of the HVAC system of AII room used for removing contaminated air by making physical changes through the addition of heat pipe heat exchanger (HPHE). Experiments were conducted with varying fresh air inlet temperature between 30 and 45 °C and velocity between 1.5 and 2.5 m/s with three configurations of HPHE to investigate the performance of the HVAC system in the AII room. To ensure the HVAC system with HPHE meets the AII room requirements, this study carried out a smoke test as well as pressure and hourly air volume measurement tests between the exhaust and supply air sides. The results showed that the design of ventilation coupled with HPHE could meet the standards for the AII room. The HPHE succeeded in reducing energy consumption through pre-cooling of fresh air before entering the cooling coil device, with the highest temperature difference of 9.4 °C. The highest energy recovery was 767 W at 0.080 m³/s air volume, which can handle 46% of the total HVAC system load at operating conditions and enhance the combined efficiency of the HVAC system. Based on the results, it can be concluded that the HPHE can be coupled in the HVAC system of the hospital AII room that is safe from cross-contamination which significantly reduces the energy consumption.

**1. Introduction**

The worldwide outbreak of COVID-19 in early 2020 became a global issue and received significant attention. Controlling its spread has become a major challenge. The spread routes of COVID-19 are primarily through droplets of saliva or discharge from the nose (emitted from an infected person fall to the surrounding surfaces within about 1–2 m (insert citation). The coronavirus has a size of 80–160 nm (insert citation) and remains active for hours to several days in the surfaces depending on the composition [4]. This shows that keeping 1–2 m away from an infected person may not be enough, so increasing the ventilation is expected to be very useful as it actively removes harmful particles from the environment [2]. One strategy to control the spread of coronavirus is by isolating and caring for the infected person early [5]. The infected person must be isolated in a special room in the hospital, for example, the airborne infection isolation (AII) room. The main function of this room is to prevent the spread of the virus to patients and medical personnel. However, the comfort of patients and medical personnel also requires attention. Hence, an HVAC system is installed in the room.

In the AII room of the hospital, HVAC systems must be installed efficiently to ensure the demand for indoor environmental conditions for patients and medical personnel [6]. ANSI/ASHRAE/ASHE Standard 170–2017 dictates that an AII room in the hospital requires a supply of a minimum of 12 air changes per hour (ACH) with an indoor air temperature of 21–24 °C, and a maximum relative humidity (RH) of 60% [7]. The room should also remain under negative pressure with a minimum pressure difference of 2.5 Pa [7,8].

The HVAC systems have a critical role in providing indoor thermal comfort, so its demand in buildings will continue to increase in the future. In commercial buildings, the HVAC system consumes the highest
energy, which contributed to 40%-60% of total energy use in the building [9,10]. Therefore, the energy efficiency in buildings has prime attention worldwide amid concerns about supply difficulties of energy sources and environmental impacts of their utilization [9]. In the building sector, hospitals have the highest energy consumption per unit floor area compared to other buildings [6]. Improving the design of integrated electrical and mechanical components, implementing computerized control systems and optimal operation of plants are some of the steps that can be taken to improve energy-efficient HVAC systems in buildings [11]. However, this method requires regular maintenance, hence, more difficult to implement.

The HVAC systems also account for most of the energy losses in buildings. Therefore, to get a more efficient system as well as to reduce gas emissions simultaneously, waste heat recovery from the HVAC system can be implemented [12]. Energy recovery from the waste heat significantly reduces energy consumption in HVAC system [13–15]. Heat recovery works when two sources are at different temperatures which are usually known as an air-to-air energy recovery system [12]. Recently, there are many types of heat recovery systems used to recover energy loss in buildings such as fixed plate, rotary wheel, run-around system, and heat pipe etc. [16,17].

Since the coronavirus spreads via airborne transmission, the use of heat recovery devices is not recommended [2,7] due to the possibility of leakage in those devices that can carry the virus attached to particles from the exhaust air side to the fresh airside. For example, a rotary heat wheel exchanger may be sensitive to leakage that requires mixing return air and supply air [2]. However, the heat recovery devices in which the fresh air side and exhaust air side components are completely separated to prevent cross-contamination can be used as an exception [7]. Out of the four types mentioned before, heat pipes possess some advantages including not requiring any external electricity input, no moving parts, no cross-contamination, easy cleaning, compact, suitability with naturally ventilated building, fully reversible, and high reliability [16].

Heat pipe heat exchanger (HPHE) is a heat transfer device that consists of individual closed tubes containing a wick structure on the inner surface of the tube, and vapor space are filled with a proper working fluid under vacuum condition [15,18]. Heat pipes have very high thermal conductivity and using the latent heat of evaporation to transfer heat over long distances with small temperature differences [18, 19]. Axially, the heat pipe consists of three sections, namely the evaporator, adiabatic section, and condenser. Heat is absorbed in the evaporator section and causing the liquid to vaporize and move to the adiabatic section and then to the condenser section. In the condenser, heat is released, so the vapor will change to liquid again and return to the evaporator by capillary forces or gravity [15,19]. This cycle will continue as long as heat is received in the evaporator section. The use of a simple device with no moving parts and without using additional energy are advantages of the heat pipes in a heat recovery system [19, 20].

In order to have efficient energy use in hospitals, where the inlet and return air should not be mixed, HPHE is recommended for heat recovery equipment in the HVAC system [21]. The HPHE is installed in the ducting of the HVAC system, where the hot side of HPHE is placed in the fresh air duct, to reduce the fresh-air temperature before entering the cooling-coil device [10,13,21–23]. Many researchers have investigated the thermal performance and energy saving of utilization HPHE with different forms and designs [10,21,24–28].

Noie-Baghban and Majideian [20] investigated the utilization of HPHE to the HVAC system in a hospital operating room. Heat pipes were arranged in three rows and a total of eight heat pipes in a staggered configuration. The results showed that thermal effectiveness of that arrangement was 0.16. Ahmadzadehtalatapeh and Yau [29] also carried the investigation of using HPHE in the HVAC system. The HVAC system was tested under standard conditions by using HPHE in four, six, and eight rows in a staggered configuration with 11 pipes/row. The room air temperature was set at 24 °C. The highest effectiveness was 45% for configurations eight rows and the highest energy saving of 455 MW [29]. Muhammadiyah et al. [22] added 120 multi-wavy fins to the evaporator and the condenser side of HPHE of the HVAC system. The HPHE consisting of 42 pipes was arranged staggered in 3 rows. The maximum effectiveness and the highest heat recovery were 54.4% and 5.368 W, respectively. Nakkaew et al. [30] investigated the use of heat pipes to enhance the performance of the split-type air conditioner. The heat pipe was installed in the tube between the compressor and condenser part of the split air conditioner. The results show that the use of a heat pipe set can increase the split-type air conditioner’s performance. The air conditioners with heat pipe set increase energy efficiency ratio (EER) of air by about 3.11% compared to that of conventional air conditioner [30].

The literature review showed that the use of HPHE as energy recovery equipment could reduce energy consumption in the HVAC system and various configurations result in the thermal effectiveness of HPHE of about 45–55% [12,16,22,29]. With the prediction of the high demand of HVAC for buildings in the future and with current COVID-19 pandemic, the development of new HPHE configuration for energy recovery with higher thermal effectiveness and energy-saving requires further investigation.

This research aims to improve the design of the HVAC system of All room used for removing contaminated air by making physical changes through the addition of HPHE. The HPHE has added to obtain an energy-efficient ventilation system and to ensure there is no contamination of the mixing at the inlet and exhaust ducts. The testing was conducted to investigate the performance of HPHE and its effect as energy recovery equipment on in the hospital All room.

2. Materials and method

2.1. All room design

Isolation rooms are intended to control the airflow in the room so that the number of infectious particles is reduced which reduces the

| Nomenclatures | Description |
|---------------|-------------|
| T [°C] | Temperature |
| m [kg/s] | Mass flow rate |
| c_p [kJ/kg-K] | Specific heat |
| q_cooling [W] | Cooling energy |
| Q_recovery [W] | Recovery energy |
| COP [–] | Coefficient of performance |
| RER [W/W] | Recovery energy ratio |
| CEF [–] | Combined efficiency |
| Y_r [–] | Ratio of net cooling capacity HPHE to net cooling capacity system (HVAC) |
| S | Associated error |
| V m/s | Velocity |

| Special characters | Description |
|-------------------|-------------|
| ε [–] | Effectiveness |

| Subscripts | Description |
|------------|-------------|
| e,in | Fresh air inlet (evaporator inlet section) |
| e,out | Fresh air outlet (evaporator outlet section) |
| c,in | Exhaust air inlet (condenser inlet section) |
| c,out | Exhaust air outlet (condenser outlet section) |
| SA | Supply air to the conditioned room |
| fan | Fan |
| comp | Compressor |
| EA | Exhaust air |

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chance of the occurrence of airborne infection transmission within a health facility. The important design aspects in the isolation room are to control the quantity and quality of the intake or exhaust air and maintain difference in pressures between the intake or exhaust airs of the room [31]. According to ASHRAE/ASHE Standard 170–2017 [7], a minimum negative pressure of 2.5 Pa is required to be maintained. To maintain negative pressure in the room, the exhaust air (EA) volume must be at least 10% higher than that of supply fresh air (SA) volume [8]. Isolation rooms usually consist of the patient room, bathroom and anteroom, as shown in Fig. 1 [8, 31]. In testing the ventilation system, the isolation room was only focused on the patient (AII) room, as shown in Fig. 2.

As mentioned previously, to reduce the concentration of pollutants, the AII room was designed to achieve a minimum of 12 ACH. The square diffuser was placed at the top of the room to SA, so that fresh air flows from healthcare workers towards the patients and should be removed from closer to the patients [7]. The two exhaust grills were located near the patients about 0.25 m above the floor. The room wall was isolated and assumed to be adiabatic. The total sensible load in the AII room due to patients, healthcare workers, lamps, and medical equipment were assumed and set to be 200 W. The volume of supply air was varied from 205 m$^3$/h to 342 m$^3$/h and the exhaust air varied from 342 m$^3$/h to 396 m$^3$/h to achieve 12 ACH. To ensure the HVAC system with HPHE meets the AII room requirements, this study carried out a smoke test as well as pressure and hourly air volume measurement tests between the exhaust and supply air sides.

### 2.2. Experimental apparatus

The experimental test model has been constructed and equipped with system control and measurement devices, as shown in Fig. 3. The HPHE was installed at two air ducts with $0.2 \times 0.16$ m$^2$ section areas of the air handling unit (AHU). The evaporator section was placed in the supply air duct and the condenser section in the exhaust air duct. Fresh air enters to the evaporator side of HPHE before passing through the cooling coil device and then enters to the conditioned room. The air from the conditioned room exits to the return air duct through the condenser side of the HPHE. To customize the fresh-air temperature in the evaporator section, a 6000-W heater equipped with a proportional-integral–temperature controller which was placed in the fresh air duct before the axial fan inlet.

The cooling coil device was supplied with chilled water by a direct water chilling system. A direct water chilling system consists of a compressor (R32), condenser, expansion device and an evaporator. It utilizes a refrigerated coil that was submerged directly into the tank of water that was used in this experiment. It was constructed to provide cold water and deliver it by a pump to the cooling coil device that was mounted in the supply duct section of the air-handling unit. The chilled water flow rate was measured by the rotameter. The heat dissipation from the air in the simulation room was 200 W.

The fresh air temperature was varied at 30–45 $^\circ$C with an increment of 5 $^\circ$C, and the fresh air velocity was changed between 1.5, 2.0 and 2.5 m/s. Type-K thermocouples connected to NI 9214 module were used to measure air temperatures. This module, with an accuracy of $\pm 0.01$ $^\circ$C, was connected to a data-acquisition device (NI cDAQ-9174). The fresh air and exhaust air inlet velocities were measured at the centre of the duct using hotwire anemometer Lutron AM-4204 sensors with an accuracy of $\pm 0.1$ m/s. Digital manometer HT-1890 and Dwyer static pressure tip were used for measuring differential pressure of exhaust and supply of AII room, and pressure drop in the HPHE. The experimental setup of this research is shown in Fig. 4. The air temperature in the inlet and outlet section of the evaporator and condenser were measured by four thermocouples at each point, as shown in Fig. 4. The section temperature was taken from the average temperature of the four measuring points in each section.

The HPHE consists of 4 tubes per row with outer diameters and a total length of 10 mm and 710 mm, respectively. The heat pipes were manufactured with the specified design specifications for this study. The heat-pipe was made of copper, in the inner surface contained a wick.
structure of sintered copper, and was filled with water as the working fluid at a filling ratio of 50%. The heat pipe consists of three sections, an evaporator section of 160 mm, an adiabatic section of 360 mm, and a condenser section of 190 mm. The HPHE was equipped with a continuous wavy fin to enhance the heat-transfer area. The fins were made of aluminium with a thickness of 0.105 mm and a fin spacing of 2 mm, as shown in Fig. 3. Tests were carried out on HVAC systems equipped with HPHE with 3, 6, and 9 rows of pipes arranged vertically in a staggered configuration. To prevent contamination particles from the return air, the return duct in this system was closed with a damper, so this system works with 100% recirculation to outdoor.

2.3. HPHE performance

Sensible effectiveness is a relevant parameter to describe the performance of HPHE. Effectiveness is described as the ratio of the actual heat transfer of an HPHE with respect to the maximum possible performance [21, 25, 27, 32–34], which is represented as equation (1).

\[
\varepsilon = \frac{T_{e, in} - T_{e, out}}{T_{c, in} - T_{e, in}} \tag{1}
\]

To determine sensible effectiveness, several conditions were assumed based on ASHRAE Standard 84–1991 recommendations [35] as follows:

- The airflow in the ducting was in a steady-state condition, and the air is perfectly mixed in each measurement condition so that all parameters measured represent each air state.
- HPHE operates in a steady-state for both fresh air supply and exhaust air during the experiment.
- HPHE is completely isolated so that no external energy is supplied into or lost from the HPHE between the inlet and outlet sides.

2.4. Energy saving

The HPHE was installed in the ducting of AHU of a hospital AII room. In HVAC systems without heat pipes, the cooling energy delivered to the conditioned room to meet the requirement of the room set-point \( Q_{\text{cooling}} \) can be estimated as:

\[
q_{\text{cooling}} = m \cdot c_p \cdot (T_{e, in} - T_{c, in}) \tag{2}
\]

The evaporator side of the HPHE was installed on the inlet side of the ducting as a pre-cooling device, while the condenser section was installed on the exhaust side of the air ducting system as shown in Figs. 1 and 2. The energy recovery obtained from HPHE is calculated by equation (3) [33, 36].

\[
q_{\text{recovery}} = m \cdot (c_p \cdot T_{c, in} - c_p \cdot T_{c, out}) \tag{3}
\]

2.5. HVAC performance

The recovery efficiency ratio (RER) was calculated to investigate the performance of HPHE as an energy recovery device. RER can be obtained by dividing the energy recovered by the power used to recover energy, as shown in equation (4) or 5. This term can be used for comparing HPHE performance to other energy recovery devices or conventional equipment [33, 37]. As a result, higher RER values produce higher energy savings of a system [17, 33, 37, 38].

\[
\text{RER}_{\text{sensible}} = \frac{\text{HPHE net sensible capacity}}{W_{\text{fan}} + W_{\text{comp}}} \tag{4}
\]

or

\[
\text{RER}_{\text{sensible}} = \frac{\varepsilon \cdot m \cdot c_p \cdot (T_{c, in} - T_{c, out})}{W_{\text{fan}} + W_{\text{comp}}} \tag{5}
\]

The performance of an HVAC system plant (HVAC equipped with HPHE) can be described by combining efficiency (CEF). An HVAC system plant with a higher CEF reflects a more efficient system. The Combined Efficiency of the cooling system (CEF\(_{\text{cooling}}\)) of an HVAC system plant with an HPHE, which is used as an energy recovery device can be defined as equation (6) or 7 [17, 33, 38].

\[
CEF = \frac{\text{net cooling capacity HPHE} + \text{net cooling capacity by cooling coil}}{\text{electric power consumption HPHE} + \text{electric power consumption by cooling coil}} \tag{6}
\]
or

\[ CEF_{\text{cooling}} = \frac{1}{\frac{T_{e,\text{out}}}{T_{e,\text{in}}}} \]  

(7)

where:

\[ Y_C = \frac{\text{net cooling capacity HPHE}}{\text{net cooling capacity system (HVAC)}} \]  

(8)

3. Results and discussion

3.1. Performance of AII room

The AII room performance was evaluated with two methods, a smoke test and a measurement of pressures between the exhaust air and the supply air of AII \([8,39]\). The airflow direction in the AII room was checked with smoke testing, as shown in Fig. 5. Smoke testing also helps to evaluate how potential infectious pathogens were removed from the AII room \([8]\). The results showed the airflow did not spread indoors and was discharged through two EA were located under the patient.

In order to achieve an efficient HVAC system, the HPHE was added with variations of three rows, six rows, and nine rows. The inlet air velocity was varied between 1.5 m/s and 2.5 m/s with a step of 0.5 m/s, while exhaust air velocity was kept constant at 2.5 m/s considering the minimum requirements of 12 ACH. This test was carried out to find out which velocity gave the highest effectiveness of HPHE as well as the highest energy saving.

Fig. 6 shows the different pressure of the AII room over different airflow velocity ranges and three variations of HPHE. In HPHE, with nine rows and inlet air velocity of 2.0 m/s and 2.5 m/s, the differential pressure in the AII room is 0 Pa, so these conditions do not meet the requirements for the AII room since an AII room should remain under negative pressure with a minimum pressure difference of 2.5 Pa \([7,8]\). While with three and six rows, HPHE at all velocities met the minimum pressure requirements, with nine rows, only 1.5 m/s met the minimum pressure requirements for the AII room.

3.2. Performance of heat pipe heat exchanger

Several tests were conducted on the HPHE with 3, 6, and 9 rows in a staggered configuration to investigate the performance of the HPHE for energy recovery. The fresh-air inlet temperature and velocity were varied in some conditions. The reading was taken after steady-state conditions with intervals of 30 min for each variation. Fig. 7 shows the temperature profile for 6 rows HPHE and an inlet air velocity of 1.5 m/s. The figure depicts that the HPHE can reduce fresh air temperature (from \(T_{e,\text{in}}\) to \(T_{e,\text{out}}\)) before passing through to the cooling coil device. In the conventional HVAC system, fresh air must be overcooled from \((T_{e,\text{in}} \text{ to } T_{SA})\) before entering the conditioned room. It shows that HPHE was successful as a pre-cooling device and took away almost half of the cooling load of the system.

Fig. 7 shows the effect of the number of rows, fresh-air inlet temperature, and air velocity on the decreasing temperature in the evaporator section. The results indicate that increasing the fresh-air inlet temperature and several rows at the same velocity, raised the
temperature difference. From the evaluation of the pressure difference between the exhaust side and the supply air side of the AII room, the differential pressure with nine rows and inlet air velocity of 2.0 m/s and 2.5 m/s did not meet the requirements for AII room. Thus, these variations were not included in the analysis of HPHE performance.

In the HVAC system without HPHE, the fresh air temperature ($T_{e\text{-in}}$) must be overcooled to the supply temperature ($T_{SA}$). It means that the cooling load of the HVAC system was 100%. By applying HPHE as an energy recovery device, the cooling load of the HVAC system can be reduced. The highest temperature difference of $9.4^\circ C$ was obtained with nine rows of the HPHE, a fresh air inlet temperature of $45^\circ C$, and an air velocity of 1.5 m/s. In this condition, energy recovery obtained was 534 W of air volume 0.048 m$^3$/s and the total cooling energy of the HVAC system without HPHE was 934 W. It means that the HPHE handled almost 57% of the total cooling load of the system. The highest energy recovery of 767 W was obtained with six rows of the HPHE, a fresh air inlet temperature of $45^\circ C$, and an air velocity of 2.5 m/s or a flow of 0.080 m$^3$/s. In this condition, HPHE can handle almost 46% of 1681 W the total cooling load of the HVAC system. From the tests, the amount of energy recovery by using HPHE was obtained between 82 and 767 W from the entire cooling energy by HVAC of 581–1681 W. It shows that HPHE can handle from 10% to 57% of the total HVAC system load at operating conditions ($Y_c$), as shown in Fig. 8.

Effectiveness is affected by the number of rows, fresh air inlet temperature and velocity. The investigation showed that the effectiveness of the HPHE increased with the increase of the number of rows and fresh-

Fig. 6. The pressure difference in the AII room with a variation in the number of row HPHE and inlet air velocity.

Fig. 7. Temperature profile for six rows HPHE.
7

air inlet temperature, as shown in Fig. 9. The highest effectiveness of the HPHE that meets the AII standard was 60% obtained in nine rows of HPHE, fresh air temperature of 45°C, and air inlet velocity effectiveness increases by increasing the number of HPHE rows of 1.5 m/s. The effectiveness shows an increase compared to previous studies ranging from 45 to 55% [12,16,22].

3.3. The effect of HPHE on cooling system efficiency

To compare HPHE performance to conventional equipment and other energy recovery equipment RER values can be used. These values have units of W/W [17]. The power required for HPHE operation is fan power ($W_{fan}$) due to pressure drop. Meanwhile, the compressor was not used in the operating of HPHE, so the compressor power ($W_{comp}$) was neglected in RER calculation. The additional fan power needed for operating HPHE was 4–27 W depending on the number of rows HPHE and fresh air velocity. The lowest additional fan power was 4 W in the condition of 3 rows HPHE and a fresh air velocity of 1.5 m/s. The highest fan power was 27 W occurred in the condition of 9 rows HPHE and fresh air velocity of 2.5 m/s.

Fig. 8. Ratio cooling capacity with respect to fresh air inlet temperature, air velocity, and the number of HPHE.

Fig. 9. Effectiveness of 9 rows HPHE with respect to $T_{e,in}$ and $V_{e,in}$.

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Fig. 10 (a) shows the RER of HPHE in 3 rows and RER in the same velocity 1.5 m/s with a variation of fresh air temperature. The highest RER obtained was 95.9 W/W when using three rows of HPHE at a fresh air inlet temperature of 45°C and an air velocity of 1.5 m/s. Whereas, the smallest RER obtained was 7.8 W/W when using nine rows of HPHE at a fresh air inlet temperature of 30°C and an air velocity of 2.5 m/s.

Fig. 10(b) illustrates that the higher RER values produce higher energy savings, which can be achieved with an increased fresh air temperature, and fewer number of rows. The fewer number of HPHE rows requires lower additional fan power, and compared to the energy recovery obtained, increase in fan power is negligible.

Fig. 10(b) showed the CEF of the HVAC system equipped with HPHE. The coefficient of performance (COP) of the system was taken as 3.0 during this investigation. The results showed that the smallest CEF obtained was 3.4 when using three rows of HPHE at a fresh air inlet temperature of 30°C and an air velocity of 1.5 m/s. In this condition, HPHE handled 14% of the total HVAC system load and RER was 21.2. The highest CEF obtained was 6.6 when using nine rows of HPHE at a fresh air inlet temperature of 45°C and an air velocity of 1.5 m/s. In this condition, HPHE can handle almost 57% of the total HVAC system load at operating conditions with RER of 79.4. These results indicate that the HPHE can enhance the performance of the HVAC system from COP of
3.0 to become in the range of 3.4–6.6 by using three, six, or nine rows of HPHE. Fig. 10 (b) indicated that the increase in the number of rows and fresh air inlet temperature would enhance HVAC performance indicated by the increasing value CEF. High energy recovery, low additional fan power, and high ratio net cooling capacity of HPHE (\( Y_c \)) will increase HVAC systems’ performance or CEF.

3.4. Uncertainty analysis

The K-type thermocouple which is connected to the NI-9214 module and data-acquisition device (NI cDAQ-9174) was employed to measure the temperature of \( T_{e,in}, T_{e,out}, T_{c,in}, T_{c,out} \). After calibration, the error associated with \((T_{c,in}, T_{c,out})\) was ±0.1 °C and The error associated with \((T_{e,in}, T_{e,out})\) was ±0.3 °C.

The effectiveness of the HPHE can be estimated in equation (1). The uncertainties the effectiveness (\( S/e \)) can be determined as in equation (9)

\[
S = \sqrt{\left( \frac{S(T_{e,in} - T_{e,out})}{(T_{e,in} - T_{e,out})} \right)^2 + \left( \frac{S(T_{c,in} - T_{c,out})}{(T_{c,in} - T_{c,out})} \right)^2}
\]

where.

\[
S(T_{e,in} - T_{e,out}) = \text{the error associated with } (T_{e,in}, T_{e,out})
\]
\[
S(T_{c,in} - T_{c,out}) = \text{the error associated with } (T_{c,in}, T_{c,out})
\]

The energy recovery obtained from the HPHE can be estimated in equation (3). With the assumption that air density (\( \rho \)) and specific heat (\( C_p \)) are constant and there is no change in the ducting area (A), the uncertainties of the energy recovery (\( S/e_{recovery} \)) can be estimated as equation (10)

\[
S \sqrt{\frac{S}{V}} + S \sqrt{\frac{S}{T}}
\]

The fresh air inlet velocities were measured using hotwire anemometer Lutron AM-4204 sensor with an accuracy of ±0.1 m/s and the error associated with \((T_{e,in}, T_{e,out})\) was ±0.1 °C.

Based on equations (9) and (10), the maximum uncertainty of effectiveness (\( S/e \)) and energy recovery (\( S/e_{recovery} \)) were found ±10.6% and ±9.7% respectively.

4. Conclusions

The COVID-19 pandemic in early 2020 became a global issue and received substantial attention worldwide. In a hospital, airborne infection isolation (AII) room is significant to prevent the spread of the virus to patients and medical personnel. This research aims to improve the design of the HVAC system of the AII room used for removing contaminated air by making physical changes through the addition of HPHE. The result shows that the design of ventilation coupled with HPHE can meet the standard of an AII room. The smoke test results showed the airflow did not spread indoors but was discharged through two EA were located under the patient ensuring fresh air flow from healthcare workers towards the patients. The number of rows HPHE and inlet air velocity gives an effect on the differential pressure in the AII room. While with three and six rows, HPHE at all velocities met the minimum pressure requirements, with nine rows, only 1.5 m/s met the minimum pressure requirements for the AII room. The HPHE had successfully reduced the energy consumption of the HVAC system through pre-cooling of fresh air before entering the cooling coil device. In the condition where the number of rows HPHE and air velocity meet the AII room standards, the highest temperature difference of 9.4 °C and the highest effectiveness of 60% was obtained with nine rows of the HPHE, a fresh air inlet temperature of 45 °C, and an air velocity of 1.5 m/s. The highest energy recovery was 767 W in 0.080 m²/s air volume was obtained with six rows of the HPHE, a fresh air inlet temperature of 45 °C, and an air velocity of 2.5 m/s.

The amount of energy recovery by using HPHE was obtained between 82 and 767 W, and HPHE can handle from 10% to 57% of the total HVAC system load at operating conditions. The highest CEF obtained was 6.6 when using 9 rows of HPHE, a fresh air inlet temperature of 45 °C, and an air velocity of 1.5 m/s. These results have shown that the HVAC system in the AII room coupled with HPHE devices, can enhance CEF or performance of the HVAC system, reflecting in the increased energy efficiency of the HVAC system. High energy recovery, low additional fan power, and the high ratio of the net cooling capacity of HPHE will increase HVAC systems’ performance or CEF. Based on the results, it can be concluded that the HPHE can be coupled in the HVAC system of the hospital AII room that is safe from cross-contamination which significantly reduces the energy consumption.

CRediT authorship contribution statement

Ragil Sukarno: Investigation, Writing - original draft. Nandy Putra: Conceptualization, Methodology, Supervision, Writing - review & editing. Imansyah Ibu Hakim: Data curation, Validation. Fadhill Fuad Rachman: Investigation, Visualization. Teuku Meurah Indra Mahlia: Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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