# EXPERIMENTAL STUDY OF MULTI-FIN HEAT PIPE HEAT EXCHANGER FOR ENERGY EFFICIENCY IN OPERATING ROOM AIR SYSTEMS

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# EXPERIMENTAL STUDY OF MULTI-FIN HEAT PIPE HEAT EXCHANGER FOR ENERGY EFFICIENCY IN OPERATING ROOM AIR SYSTEMS

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## ABSTRACT

This study was conduct to identify the effectiveness and heat recovery values of heat pipe heat exchangers (HPHEs) in heating ventilating air conditioning (HVAC) ducting systems. HPHEs are passive modules which provide the energy recovery function in HVAC systems. In this research the HPHE module consist of 42 heat pipe tubes equipped with 120 wavy fins on the evaporator and condenser sections. In this study the HPHE module was tested with a three-row configuration design, and at inlet airflow temperatures of 28, 30, 35, 40, and 45ºC. The velocity of inlet air also varied, at 1, 1.5, and 2 m/s. The results show that in the three-row configuration the inlet temperature decreased by a maximum of 10.3°C. This configuration also has an HPHE effectiveness value of between 47.9 and 54.4%. The highest effectiveness value (54.4%) was obtained at inlet air velocity and temperature of 1 m/s and 45ºC, respectively. The highest HPHE heat recovery value was 5,368 W at 2 m/s inlet air velocity, giving a 51.7% HPHE effectiveness rating. This HPHE system can be considered as saving energy for HVAC systems.

*Keywords:* Heat pipe heat exchanger; Heat recovery; HVAC; Multi-wavy fins; Operating room

## 1. INTRODUCTION

A hospital is a public health facility that contains a wide range of room types. Among these are rooms with administrative, emergency, pharmacy, laboratory, isolation, intensive-care unit, and operating room functions. Some of these environments have specific requirements for electrical, air circulation, medical gas, and air conditioning systems. In particular, operating rooms have strict specifications often referring to existing standards. An operating room also has to operate with non-stop air conditioning systems. According to the standards of the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), operating rooms are required to have a specific type of HVAC system in terms of a number of indicators, such as temperature, relative humidity, cleanliness, and air changes per hour (Standard, 1999; Balaras et al., 2007). These indicators are an absolute requirement for maintaining the indoor air quality and thermal comfort of the operating room. The operating room temperature range is 20−24°C and the relative humidity range is 30−60%. The number of indoor air changes required is at least 20 per hour. HVAC operating-room systems are usually designed with non-stop operations and to strict air conditioning quality. This ensures the minimum cleanliness of the air, which is important for the health of patients.

However, this type of arrangement consumes large amounts of energy and requires regular

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maintenance, thus increasing the production costs of the hospital. According to Vakiloroaya et al., 2014), HVAC systems are the highest consumers of energy in commercial buildings (Vakiloroaya et al., 2014). Coad et al. also state that annual energy consumption for health facilities is typically around 686 kWh/m$^2$ (Coad et al., 2005). Thus, it is necessary to put effort into optimizing the energy consumption of HVAC systems without decreasing their quality.

Conservation of energy, usually associated with security, reliability, and energy saving, has been investigated by many researchers globally. Some studies which relate closely to the scope of this present research have been carried out recently (Mahajan et al., 2015; Putra et al., 2016; Putra et al., 2017). Energy conservation is very important for improving the performance of energy systems, extending working hours, and optimizing energy use. Energy saving and indoor environmental quality are major points of concern for designers, owners, researchers, and governments (Rasouli et al., 2013). It is important for all parties to take part in finding solutions to these problems.

Noie-Baghban and Majideian (2000) were the first researchers which investigate the use of HPHEs in the air system of a hospital surgery room. The HPHE effectiveness of 0.16 was achieved for their experiment result. It was relatively poor due to the high pitch-to-diameter ratio of the heat pipe tube and the shortcomings of fins. El-Baky and Mohamed (2007) applied HPHE to an air system by flowing fresh water at the inlet ducting (the evaporator section) and flowing the air return/exhaust water at the outlet ducting or condenser section. HPHE effectiveness value increases when the temperature of inlet water (evaporator section) is increased. Danielewicz et al. (2014) set the variables to include overall heat transfer, effectiveness, pressure drop, and heat exchanger duty based on flow characteristics and thermosiphon configurations in heat exchangers. The effectiveness increases with increasing numbers of rows, but the effectiveness value will decrease as air mass flow value is increased. Increasing the mass flow value causes insufficient exposure to cold flow pipes. The results showed that there was not enough time for the thermal energy released by the pipe to be absorbed. Putra et al. (2017) performed an investigation by testing an HPHE module within the air duct system. The heat pipe tubes were arranged in a staggered manner in several configuration variations. Their results showed that HPHEs can apparently reduce energy consumption in air conditioning systems.

To continue the experimental work of Putra et al. (2017) this study uses an HPHE module which has been modified with multi-wavy fins. The heat pipes are also arranged in three rows and fitted into a galvanized iron frame. A total 120 multi-wavy fins were inserted in the evaporator and condenser sections. The main purpose of these fins is to maximize the heat recovery effect of HPHEs used in our previous work. The expected experimental results are improvements in both HPHE effectiveness and heat recovery values.

## 2. METHODOLOGY

### 2.1. Experimental Design

The heat pipe material was copper, at 720 mm in length and 10 mm in diameter. Sintered copper was used as the wick structure and water as the working fluid. The working fluid was injected at a 50% filling ratio. The length of the evaporator, condenser and adiabatic sections were 24.5, 25.5 and 22 cm, respectively. 42 heat pipes were used in a single HPHE module, arranged in three rows. Each row comprised 14 heat pipes in the staggered arrangements shown in Figure 1a. The wavy fin material was made from 0.105 mm thick aluminum. The fin dimensions were 345 mm in length and 76 mm in width. Each of the evaporator and condenser sections was installed with 120 wavy fins. The distance between the wavy fins (pitch) in the HPHE was 2 mm. Equations 1 to 4 were used to calculate the effectiveness value of the HPHE module.

$$Q_{act} = \dot{m}_h C_{ph} \left( T_{e,in} - T_{e,out} \right) \tag{1}$$

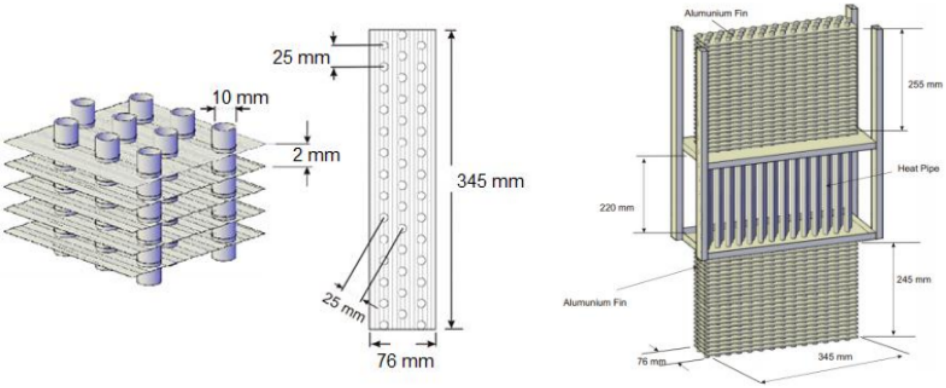
$$Q_{max} = \dot{m}_c C_{pc}\left(T_{e,in} - T_{c,in}\right) \tag{2}$$

$$\varepsilon = \frac{Q_{act}}{Q_{max}} \tag{3}$$

$$\varepsilon = \frac{(T_{e,in} - T_{e,out})}{(T_{e,in} - T_{c,in})} \tag{4}$$

### 2.2. Experimental Set-up

Figure 2 shows the test rig for the air duct system including the air conditioning system and test chamber, air heating system with thermostat control, data acquisition system, air flow measurement, electricity system include panel box, and HPHE module. The HPHE module was set in a vertical configuration based on a ducting configuration system. It consisted of 42 heat pipes inserted with a total of 240 wavy fins. The position of the HPHE inside the air duct system is shown in Figure 2. The evaporator of the HPHE module is inside the lower ducting and absorbs heat from inlet fresh air. The condenser section of the module is inside the upper ducting and was cooled by an outlet axial fan. The purpose of HPHE placement was to precool the inlet fresh air before it entered the cooling coil in the air conditioning system of the test chamber. Figures 1a and 1b show the schematic dimensions of the HPHE module. Relative humidity sensors (Phidget ®) were installed before and after the HPHE module, to record the moisture data of airflow. The captured data sent to a desktop PC via USB cable and stored for next analysis. Measurements of the temperature of the HPHE module and the air flow inside the air duct system were performed by type K thermocouples and captured by NI-9213 and 9174 acquisition devices linked to a PC.



(a) (b)

Figure 1 (a) Heat pipe heat exchanger; (b) Heat pipe heat exchanger dimensions

The fresh air inlet to the air duct system was heated by an air heating system. The heat was generated by an air heater with a 6000 W maximum capacity. A thermo controller was used to control the specific time of heater operation so that the inlet temperature could be kept at between 28 and 45°C. The cooling coil was placed after the HPHE module with air flow reference having 9000 BTU cooling capacity (± 1 hp). The cooling coil was design to perform the cooling process inside the test chamber with a specific refrigeration load. The test chamber volume was approximately 310×150×150 $cm^3$. The air flow speed of the air duct system was set by adjusting the variable resistor of the fan-speed controller to specific velocities (1, 1.5, and 2 m/s). Air velocity was measured using a hotwire sensor (Lutron Instruments®). The configuration of the HPHE was also tested for one row, two rows, and three rows. Each configuration was tested in the air system, and air flow was provided at the evaporator inlet with variable temperatures of 28, 30, 35, 40, and 45°C.

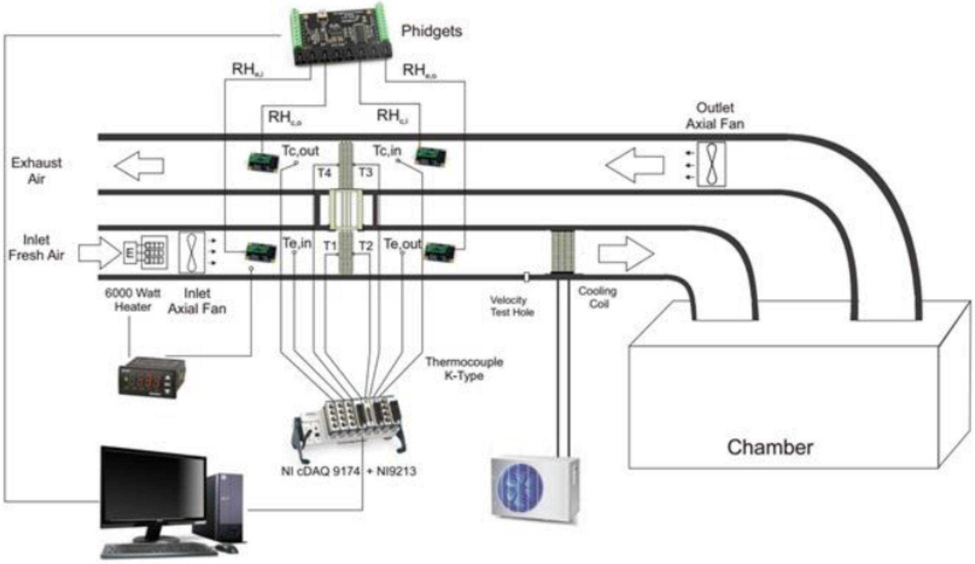


Figure 2 Experiment set-up and apparatus (test rig)

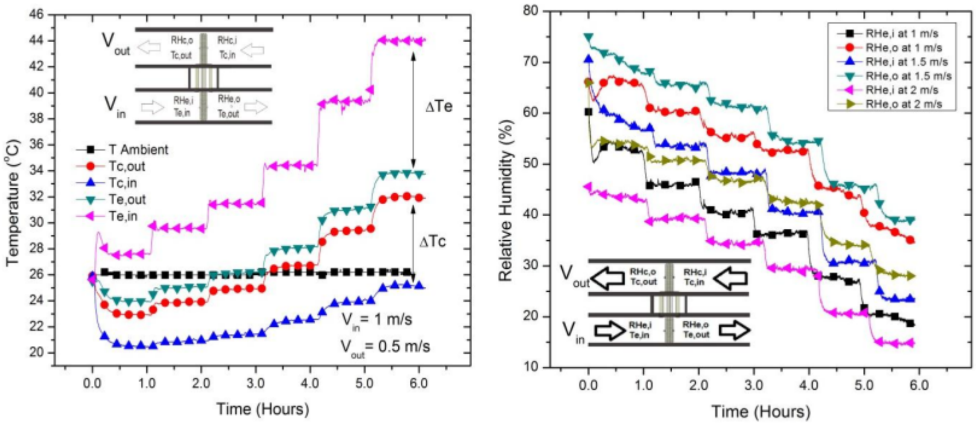
## 3. RESULTS AND DISCUSSION

The HPHE module was tested by varying the air temperature and inlet velocity of fresh air. The output of this test was the temperature drop profile in the evaporator area (ΔTe) and the temperature rise profile in the condenser area (ΔTc). ΔTe is the result of the precooling process in the HPHE evaporator section. The HPHE evaporator absorbs the heat from the airflow entering this section.

### 3.1. Effect of Inlet Air Temperature

As seen in Figure 3a, the air temperature in the evaporator inlet (Te,in) was reduced due to heat absorption by the evaporator section of the HPHE module. Increase in air temperature at the evaporator inlet (from 28°C up to 45°C) resulted in higher temperature differences between the air temperature inlet and the HPHE outlet (ΔTe = 6.68 K at inlet 45°C). The evaporator section took the heat of air flow and release it to the condenser section. The higher temperature inlet (Te,in) resulted in higher temperature differences (ΔTe). Increasing the inlet air temperature (Te,in) may have resulted in larger amounts of heat being absorbed by the HPHE evaporator. This would result in greater significance of the precooling process for the entering of supply airflow. The higher heat would be transferred from the evaporator section to the condenser section. This heat must be rejected from the condenser section to the ambient air with the aid of cold air flow from the test chamber. Figure 3a also shows the increases of temperature from the condenser (Tc,out) due to the heat release process at the condenser section of the HPHE module. The higher temperature condenser inlet (Tc,in) also resulted in higher temperature condenser outlet (Tc,out). The air temperature at the condenser outlet (Tc,out) increased from 2.28°C to 6.77°C as a result of more heat being released at the condenser section. Because the heat pipe is a passive device the heat exchanger process worked efficiently. In summary we can conclude that HPHE with multifins worked more efficiently with higher temperature of airflow in (supply air).

Figure 3b shows relative humidity data for the inlet and outlet evaporator sections. The relative humidity (RHe,in) of inlet fresh air is strongly affected by the temperature variation and is described very clearly by the psychrometric chart. The relative humidity of air entering the evaporator inlet (RHe,in) will increase after leaving the evaporator outlet (RHe,out). The decreasing of airflow temperature at the evaporator related with cooling and humidifiying process at psychrometric chart. The decreasing temperature of evaporator outlet reduces the saturation pressure of water vapor (Pws) of the evaporator out. It will increase the value of the ratio between the partial pressure of water vapor (Pw or partial pressure of water vapor) and Pws. The relative humidity of the evaporator inlet air (RHe,i) reached its highest value at $V_{in}$ = 1.5 m/s. This occurred because of the relative humidity of ambient air reaching the highest value during $V_{in}$ = 1.5 m/s (airflow velocity). Figure 3b shows that the relative humidity of evaporator outlet at Vin = 1.5 m/s has the highest value compared with Vin = 1 m/s and Vin = 2 m/s. The increase in relative humidity at the evaporator outlet (RHe,o) is caused by the process of decreasing air temperature in the evaporator area where the low temperature airflow from the test chamber cools the condenser sections. This process cools the condenser sections and the heat is released to the ambient environment. In contrast, the temperature (Tc,in) was increased due to the heat released from the condenser. This process leads to a decrease in the relative humidity of air in the HPHE condenser outlet (Wu et al., 1997).



(a) (b)

Figure 3 (a) Temperature profile for $V_{in}$ = 1 m/s; (b) Relative humidity profile of HPHE module

Figure 4 shows the temperature drop (ΔTe) in the evaporator outlet being affected by the increase of the air temperature and velocity in the evaporator inlet. The temperature drop at 1.5 m/s was the lowest of the various velocities, but this lowest value should have occurred at 2 m/s of airflow velocity. If analyzed in consideration of the heat transfer process, the inlet air velocity affects the decrease in duration of heat transfer processes (Putra et al., 2017). Thus at evaporator inlet air velocity of 2 m/s a smaller ΔTe value should be obtained. The inlet evaporator velocity (Rhe,i) at 1.5 m/s has the highest relative humidity (Figure 3b). This may have related to the temperature drop at 1.5 m/s, as shown in the curve in Figure **4.** This should be investigated in more detail in a future study. The increasing of relative humidity will result in higher Nusselt numbers (Zhang et al., 2007).

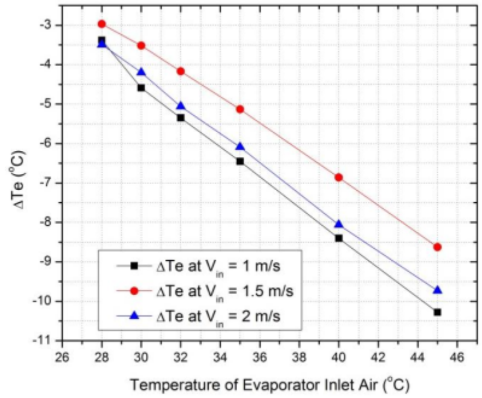
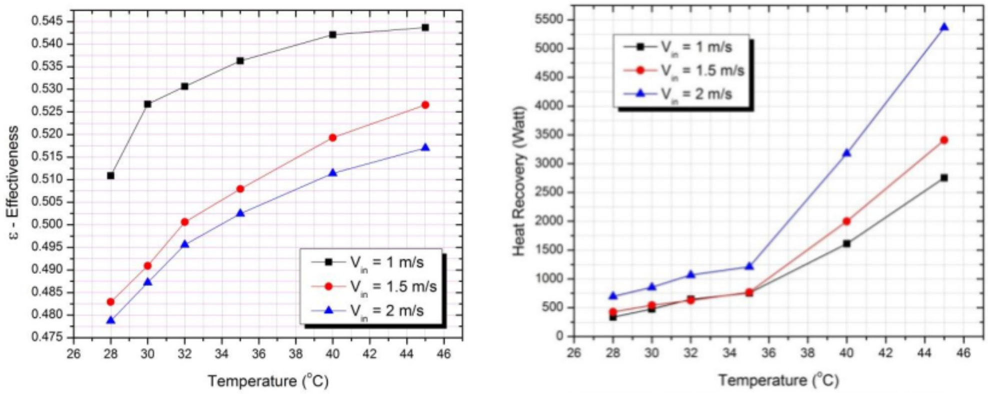


Figure 4 Value ΔTe based on $V_{in}$

The relative humidity of inlet fresh air of the HVAC system depends on the relative humidity of ambient air around the test rig. Airflow with high relative humidity when it enters the HPHE evaporator will result in a smaller drop in temperature. The heat absorption (sensible) resulted in temperature drop at the evaporator outlet air flow. The higher temperature drop is influenced by the increases in evaporator inlet temperature and by lower velocity of inlet air. Higher air velocity at the inlet will reduce the duration of heat transfer and as a result the amount of heat absorbed will decrease (Hassan, 2012; Danielewicz et al., 2014).



(a) (b)

Figure 5 (a) Effectiveness of HPHE; (b) Heat recovery of HPHE

### 3.2. HPHE Performance

Figure 5a shows that the effectiveness of HPHE increases with higher evaporator inlet air temperature. The increase of air flow temperature causes the amount of heat absorbed by the fins and heat pipe to rise and this heat will be absorbed and transferred to the condenser section. Figure 5a also shows that the lowest effectiveness value was recorded for the evaporator inlet with air velocity at 2 m/s and evaporator inlet air temperature of 28°C. The highest value of HPHE effectiveness was reached at 45°C with evaporator inlet air velocity of 1 m/s. The value of HPHE effectiveness will increase as the temperature of the evaporator inlet air increases (Firouzfar et al., 2012; Hassan, 2012).

Figure 5b indicates that the increase of airflow velocity at the HPHE evaporator inlet also causes the amount of air mass entering the evaporator area to increase; thus, the amount of heat absorbed by the evaporator is larger. The increase in heat absorbed by the evaporator will decrease the airflow temperature of the HPHE evaporator sections. Heat recovery value is strongly influenced by the temperature and inlet air mass flow entering the evaporator area. The highest heat recovery value is obtained both at maximum evaporator inlet air velocity and the highest evaporator inlet air temperature. The lowest effectiveness is obtained at the lowest evaporator inlet air temperature. However, the effectiveness reaches the highest value at lowest evaporator inlet air velocity. Table 1 shows the heat recovery value from each velocity inlet ($V_{in}$) and temperature evaporator inlet (Te,in). The table also provides data from previous research (Putra et al., 2017). As seen in Table 1, the highest heat recovery value is 5,368 W, obtained by providing maximum evaporator inlet air velocity (2 m/s) and maximum inlet temperature (45°C). The lowest heat recovery (336.91 W) is obtained at evaporator inlet air velocity at 1 m/s and air temperature evaporator inlet at 28°C. Compared with our previous work, there are significant increases in HPHE with wavy fins in all inlet velocities and temperatures. At the lowest inlet velocity (1.0 m/s) and temperature inlet of 35°C, the heat recovery increases from 207.12 W in the previous research to 754.11 W (211.8%). At higher inlet velocity (2 m/s) and temperature of 35°C, the heat recovery increases from 267.67 W to 1207.82 W (451%). It can therefore be seen that there is significant effect from the utilization of multi-wavy-fin HPHE modules in hospital operating rooms.

Table 1 Heat recovery of HPHE

| Temperature (°C) | Heat recovery (W) | | | | | |
|---|---|---|---|---|---|---|
| | Velocity of inlet air to evaporator section | | | | | |
| | 1.0 (m/s) | 1.0 (m/s)* | 1.5 (m/s) | 1.5 (m/s)* | 2 (m/s) | 2 (m/s)* |
| 28 | 336.91 | n/a | 426.12 | n/a | 694.05 | n/a |
| 30 | 477.77 | 154.10 | 544.05 | 181.92 | 852.00 | 205.48 |
| 32 | 645.99 | n/a | 623.39 | n/a | 1066.75 | n/a |
| 35 | 754.11 | 207.12 | 767.44 | 226.90 | 1207.82 | 267.67 |
| 40 | 1610.25 | 255.60 | 1996.69 | 277.19 | 3176.98 | 327.54 |
| 45 | 2753.50 | 298.95 | 3409.21 | 330.05 | 5368.23 | 390.08 |

*(Putra et al., 2017)

## 4. CONCLUSION

In this study, HPHE was characterized by varying evaporator inlet air temperature and evaporator inlet air velocity. From the HPHE testing results it is concluded that the HPHE module was able to demonstrate its function as a heat recovery device. This can be seen in the precooling process of evaporator inlet air flow. HPHE shows significantly reduced energy use in HVAC systems and can be applied to such systems, especially in operating rooms. Changes in the effectiveness value of the HPHE module are seen by increasing the temperature and velocity of the HPHE evaporator inlet air. A slight decrease in the sensible effectiveness of the HPHE module occurs due to the increase of evaporator inlet air velocity. The highest heat recovery value is reached by providing maximum air mass flow rate and higher inlet air temperature. From the results, it can be stated that significant heat recovery effect was achieved from the HPHE module with wavy fins. At the lowest velocity inlet (1 m/s) and 35°C the multi-wavy fins increased the heat recovery by 211.8%, and an increase of 451% was achieved at the highest velocity input (2 m/s) and inlet temperature of 35°C.

## 5. ACKNOWLEDGEMENT

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