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An experimental Investigation of effectiveness of a closed-end flat heat pipe heat exchanger (CEFHPHE)

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Abstract

The effectiveness of a closed-end flat heat pipe heat exchanger (CEFHPHE) was investigated experimentally. The CEFHPHE consists of three parts, which include the evaporator, adiabatic and condenser sections that the lengths were 300, 100 and 300 mm respectively. The standard copper tube with inner diameter of 8.6 mm and 0.46 mm thick was pressed to reform its cross sectional area for a flat tube, and then bent to many U-shapes, which was closed at both ends. The water was used for working fluid with filling ratios of 45% of internal volume. In experiments, hot air was used for supplying the heat to the evaporator section with different temperatures (105-145°C), and different velocities (0.5-2.0 m/s). Fresh air was used for cooling condenser section with temperature approximately 30°C, and was kept constant velocity at 0.5 m/s. The experimental results indicated that the effectiveness of CEFHPHE increase with the inlet hot air temperature, and decrease with the increase of hot air velocity. In addition, the effectiveness of the CEFHPHE obtained from the experiments varied between 0.35 and 0.74.

Keywords : Heat exchanger, Heat recovery, Heat pipe, Flat tube.

1. Introduction

Conventional heat pipe heat exchanger (CHPHE) is a widely used application which consists of number of individual conventional heat pipe. The CHPHE comprises of three parts; evaporator, adiabatic and condenser sections. The evaporator section is the part that is always at the bottom due to the condensate returning to this section by gravity force. The simplicity construction, no wick structure, high effectiveness and high compactness are the advantages of this application. At high heat load, however, there are a

number of limitations, such as entrainment, boiling and vapor pressure limit etc., that dramatically affect to its thermal performance.

A flat heat pipe heat exchanger (FHPHE) is developed from the CHPHE for the compact heat exchanger. Srimuang et al. [1] reported the effects of flat thickness, evaporator length, and type and filling ratios of working fluid on performances of the FHPHE. Their results, these parameters have affected to thermal performances of FHPHE. Furthermore, their suggested as to reduce cross-section area of heat pipe significant

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affected to its temperature operation and heat transfer characteristics.

In similar study, Amatachaya and Srimuang [2] investigated experimentally the thermal performance of FHPHE, and compared with the CHPHE. Their result, the FHPHE is higher thermal performance than CHPHE. Recently, Rithidech and Srimuang [3] reported an equation for prediction the heat rate of vertical flat heat pipe (VFHP).

As review of previous works about applications of the heat pipe for heat recovery, numerous research works of experimental and theoretical studied on thermal performance of the heat pipe heat exchanger for heat recovery. Noie and Majidian [4] designed, constructed and tested HPHE for heat recovery from surgery room in hospitals. In their experiment, the atmospheric air heated by the electric heater of 1500 W, and velocity of hot air for across the evaporator section was 2.3 m/s. Their results the maximum effectiveness was 0.16. Yang et al. [5] investigated experimentally and theoretically the CHPHE for warm up air in a large bus by heating applying automotive exhaust gas. They tested with the temperature of exhaust gas across the evaporator section was varied range between 100 and 300°C. Their reported, the CHPHE was a maximum effectiveness of 28%. Lukitubudi et al. [6] designed, constructed and tested the CHPHE for medium temperature (below 300°C) heat recovery in bakeries. Their conditional testes, the air face velocities were varied from 1.5 to 5 m/s and the heat inputs the evaporator section were varied between 4 and 20 kW. And the exhaust gas temperature inlet into the evaporator section of 300°C. Their results shown the CHPHE's effectiveness were between 0.18 and 0.63. Habeebullah et al. [7] reported the heat recovery from the exhaust gas of industrial gas turbine engines by using heat pipe. The exhaust gas temperature was flow through the evaporator section of 300°C. Their

results shown the system is able to extract between 70 and 93% of the technically recoverable energy from exhaust gases. El-Baky and Mohamad [8] investigated experimentally HPHE for heat recovery in air conditioning. Their results shown that the temperature changes of the fresh and return air were increased with the increase of inlet temperature of the fresh air. The effectiveness for both evaporator and condenser sections were increased to about 0.48. Lin et al. [9] studied numerically the CHPHE for recovering waste heat in drying cycle. The simulation results shown that the computational fluid dynamics (CFD) modelling was able to optimise the design of the heat pipe fin stack. Riffat and Gan [10] reported the thermal performance of the three types of heat pipe heat recovery unit for naturally ventilated building. Their results shown the air velocity flow through the HPHE had significance influence on the effectiveness of heat recovery. The effectiveness decreased with increasing air velocity, and the effectiveness was also affected by the shape of fin and pipe arrangement. Noie [11] investigated the thermal performance of an air to air thermosyphon heat exchanger. His conditional experiments, the temperature inputs the evaporator were varied between 100 to 250°C while the heat input evaporator section were varied between 18 and 72 kW. The both of hot and cool air velocity across the HPHE were 0.5 to 5.5 m/s. His results shown that the HPHE's effectiveness were between 0.37 and 0.65.

As mentioned above, it can be concluded that the many parameters have affects to the effectiveness of the CHPHE: the geometric characteristics, the velocity and temperature of air flow across, the heat input into evaporator section.

Recently, a closed end oscillating heat pipe (CEOHP) was discovered by Rithidech et al. [12] which was higher thermal performance than the CHPHE. In generally, the CEOHP made from a capillary tube in a

serpentine manner and closed each end. There was noticed from the reported, the CEOHP was thermally more advantage due to the possibility of working fluid the circulation.

For improvement of the thermal performance of a HPHE, the cross-sectional area of CHPHE was reformed. A circular tube was bent to U-shape and pressed for a flat tube, and then closed each end. It was called a closed-end flat heat pipe heat exchanger (CEFHPHE), was shown in Figure 1.

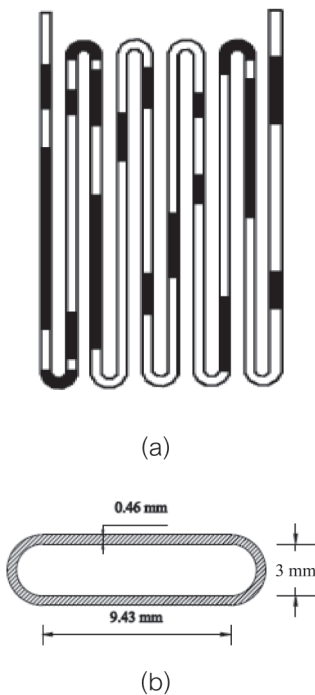


Figure 1 The CEFHPHE (a) five turns (b) cross section of flat tube.

Nowaday, there is no information about effectiveness of the CEFHPHE. The present research aimed to investigate the effects of hot air velocities and temperatures which across to evaporator section on the effectiveness of the CEFHPHE. The results may provide additional information for application the CEFHPHE to heat recovery.

2. A design of the CEFHPHE

The CEFHPHE was designed for an air to air heat exchanger. The hot air temperature flows across the evaporator section was varied in the range of 105-145°C. It was desired to have a CEFHPHE capable of increasing fresh air ambient temperature from about 30 to 140°C or more. The CEFHPHE made by a standard copper has inner diameter of 8.6 mm and wall thickness of 0.46 mm. The tube was bent for many U-shape and then pressed in a mold to reform its cross-section into a flattened tube of 3 mm, pressed thickness (y).

The maximum heat flux of CEFHPHE was calculated by Ku equation. The Ku indicates the ratio of heat flux through the CEFHPHE to the critical heat flux of the working fluid. The heat flux of CEFHPHE was presented by Rithidech and Srimuang [3] as following equation;

$$q = 0.0144 \left[Bo^4 \left(\frac{L_e}{4R_h} \right)^{0.9} Ja^{1.8} Pr^2 \left(\frac{\rho_v}{\rho_l} \right)^{1.8} \right]^{0.130} \times \rho_v h_{fg} \left[\sigma g \left(\frac{\rho_v - \rho_l}{\rho_v^2} \right) \right]^{\frac{1}{4}} \quad (1)$$

The air flow into the cross-sectional area of the evaporator or condenser section of the CEFHPHE was 300 x 300 mm. The lengths of both the evaporator and condenser sections of the CEFHPHE were 300 mm and its central adiabatic section had a length of 100 mm. Thermal performance of the CEFHPHE can be represented by the effectiveness. It was defined as the ratio of the actual heat transfer rate of the CEFHPHE to the maximum possible heat transfer rate between the air streams. In this study was assumed that the specific heat of the air through the CEFHPHE to be constant, and there was no heat loss from the CEFHPHE as it was completely insulated. The effectiveness can be

calculated as follows:

$$\text{If } \dot{m}_h C_{p,h} < \dot{m}_c C_{p,c}$$

$$\varepsilon = \frac{\dot{m}_h C_{p,h} (T_{h,in} - T_{h,out})}{(\dot{m}_c C_{p,c})_{\min} (T_{h,in} - T_{c,in})} \quad (2)$$

$$\text{If } \dot{m}_h C_{p,h} > \dot{m}_c C_{p,c}$$

$$\varepsilon = \frac{\dot{m}_c C_{p,c} (T_{c,out} - T_{c,in})}{(\dot{m}_h C_{p,h})_{\min} (T_{h,in} - T_{c,in})} \quad (3)$$

3. Experimental apparatus and procedure for experiments

In order to study thermal performance of the CEFHPHE, a special test rig was constructed and setup. A schematic diagram of test rig was shown in Figure 2. The test rig consists of two centrifugal fans, a centrifugal fan used for hot air circulated flow through the evaporator section while another centrifugal fan used for cool air to flow through the condenser section. The electrical heaters (total capacity of 3 kW) used to supply heat into air for the evaporator section.

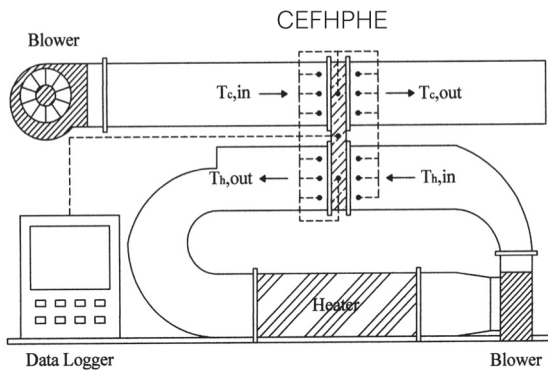


Figure 2 The experimental rig for tests the effectiveness of a CEFHPHE.

A data logger (YOKOGAWA MV 1000 with at $\pm 1^\circ\text{C}$ accuracy, 24 channels signal and -200 to 1100°C measurement temperature range) was used together with type K thermocouple (OMEGA with $\pm 1^\circ\text{C}$ accuracy) for recorded temperatures. There are two

rectangular zinc ducts; one for hot air, and the other for cool air. Both the air ducts were insulated with glass wool of 5 mm thickness. The air velocities meter (Pitot tube probes, brand of testo model 445, with $\pm 0.05\%$ accuracy) used for measured air velocities of both streams.

In order to investigate the effectiveness of the CEFHPHE, a series of tests was performed. Test began by charging the CEFHPHE with water which used the four directional joint. This joint consisted of 4 valves, which connected to a working fluid filling set, pressure gage, CEFHPHE and a vacuum device. The non-condensable gas (NCG) in the CEFHPHE was first eliminated via one of the four valves using a vacuum pump. The desired working fluid was then filled into the CEFHPHE via the filling set using the pipette tube, which was able to fill working fluid $1\text{--}10\text{ cm}^3$. In each test, the ambient air temperature flow into the condenser section of the CEFHPHE was approximately 30°C while the inlet hot air temperatures into the evaporator section were varied in range 105 to 145°C . And the hot air velocities were varied from 0.5 to 2.0 m/s .

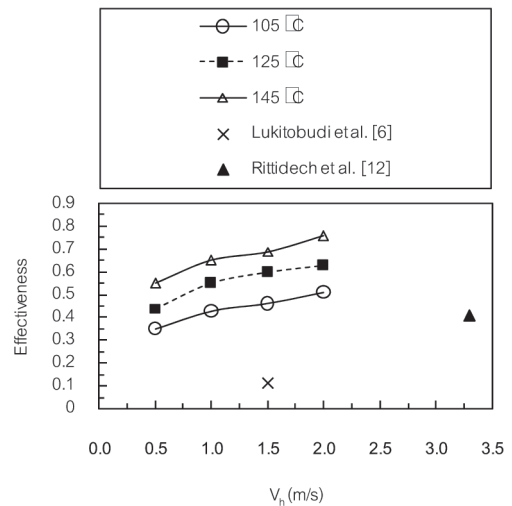


Figure 3 The effects of hot air velocities on the effectiveness for $V_c = 0.5\text{ m/s}$.

4. Results and discussion

4.1 The effects of hot air velocities on effectiveness

This experiments were performed at constant the cool air velocity that flow into condenser section, and different the inlet temperature and velocities flow into evaporator section. The hot air flow into evaporator section was varied from 0.5 to 2 m/s. Figure 3 shows the effects of hot air velocities on the effectiveness of the CEFHPHE with constant cool air velocity of 0.5 m/s.

The experimental results indicated that the effectiveness had significant influence on the hot air flow into the evaporator section. The effectiveness increased with hot air velocity. It was observed that the minimum effectiveness occurred at $V_{h,i} = 0.5$ m/s which its minimum effectiveness for $T_{h,i}$ of 105, 125 and 145 °C were 0.35, 0.49 and 0.55, respectively. The maximum effectiveness occurred at $V_{h,i} = 2.0$ m/s for $T_{h,i}$ of 105, 125 and 145 °C were 0.51, 0.63 and 0.74, respectively. A comparison between the present study and the results of Lukitobudi et al. [6] and Rittidech et al. [12] was found that the effectiveness of CEFHPHE is higher than CHPHE and CEOHP. This is possibly because the boiling phenomena and the two-phase liquid moved from the evaporator to the condenser section better than in the CHPHE and CEOHP. This may be caused by the reduction of the cross sectional area of the CHPHE or CEOHP, which led to a decrease in internal volume. As a result, at the same filling ratio of working fluid, CHPHE or CEOHP required less working fluid and transferred heat faster. The results of present study can be confirmed that the cross sectional area had a relative size to let the bubble vapor move from the evaporator section to the condenser section. The movement of bubble vapor depends on its density and thickness of the liquid film that occurred from condensing of the bubble vapor in the condenser section.

4.2 The effects of hot air temperatures on effectiveness

The effect of the hot air temperatures that flow into the evaporator section on the effectiveness of the CEFHPHE is shown in Figure 4. We observed that the effectiveness increases with the inlet temperature. However, as the $T_{h,i}$ more 125 °C, the effectiveness increased slightly. The results from the present study agree with Noie [6], which reported that the effectiveness increases with the temperature and air velocity across the CEFHPHE.

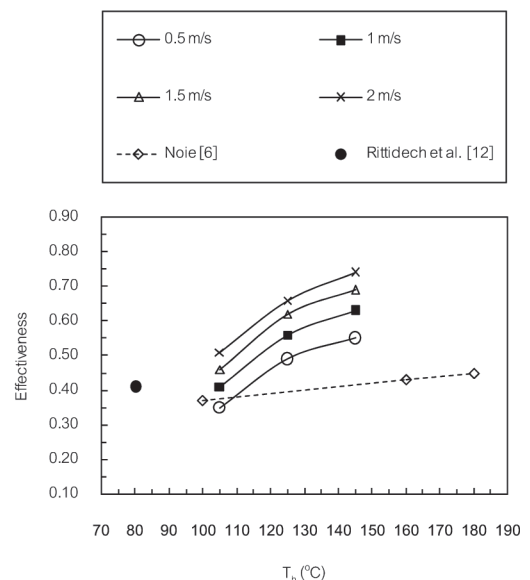


Figure 4 Relationship between hot air temperature and effectiveness.

It can be concluded that the effectiveness is a function of the temperature and the air face velocities flow across the CEFHPHE. Moreover, this study compared with Rittidech et al. [12]. It can be confirmed that the effectiveness of heat pipe can be improved by modification of the cross sectional area of the tube.

5. Conclusions

The effectiveness of CEFHPHE has been investigated experimentally by using water as working fluid and using air flowing through of both evaporator and condenser sections for exchange the heat.

The results demonstrated that the effectiveness was significantly affected by the hot air velocity and temperature flowing through the evaporator section. Obviously, the effectiveness increases with increasing the velocity and temperature of hot air. In this experiment, the obtained effectiveness of the CEFHPHE was 0.35 to 0.74.

6. Nomenclature

ID	inner diameter, mm
C_p	constant pressure specific heat, kJ/kg °C
L	length, m
\dot{m}	mass flow rate, kg/s
q	heat flux, kW/m ²
T	temperature, °C
R_h	hydraulics radius, m
h_{fg}	latent heat of vaporization, kJ/kg
Bo	Bond number $(4R_h \left[g \left(\frac{\rho_l - \rho_v}{\sigma} \right) \right]^{\frac{1}{2}})$
Ja	Jacob number $(\frac{h_{fg}}{C_{pl} T_v})$
Pr	Prandtl number $(\frac{\mu_l C_{pl}}{k_l})$
Ku	Kutateladza number $(q / \rho_v h_{fg} \left[\sigma g \left(\frac{\rho_v - \rho_l}{\rho_v^2} \right) \right]^{\frac{1}{4}})$

Greek symbols

ρ	density, kg/m ³
μ	viscosity, Pa s
σ	surface tension, N/m

Subscripts

c	condenser
e	evaporator
a	adiabatic
l	liquid
v	vapor

7. Acknowledgment

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8. References

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