Development Closed-loop Oscillating Heat Pipe with Check Valves (CLOHP/CV) to Enhance Heat Removal from Automobile Air-conditioner

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***Abstract*— The paper presented the application of the Closed-loop oscillating heat pipe with check valves (CLOHP/CV) to enhance heat extraction from the condenser of the automobile air-conditioner (AAC). The CLOHP/CV used R-134a as working fluid, filling 50% by volume. There were 3 designs having 4, 6 and 8 loops, and tested by varying tilted angle; 0º, 30º, 45º and 60º. The surface temperature of evaporator and condenser sections increased with the tilted angle and number of CLOHP/CV loops. The 8 loops CLOHP/CV tilted by 60 degrees provided maximum heat transfer rate 3,789 W, convection heat transfer coefficient 4,028 W/m2·ºC, and minimum thermal resistance 0.63 ºC/kW. The CLOHP/CV was tested with a demonstration unit of automobile air-conditioner at TNI. The COP and EER of the AAC using CLOHP/CV for enhancing heat removal from the condensing coil were 6.50 and 22.16 Btu/h/W, respectively. The maximum effectiveness of CLOHP/CV was nearly 0.5 when implementing to enhance heat releasing at AAC. Therefore, the 8-loops tilted by 60-degree CLOPH/CV was effectively enhancing performance of the automobile air-conditioner.**

***Keywords*— Closed-loop oscillating heat pipe with check valves, CLOHP/CV, Heat transfer enhancement, Thermal resistance, automobile air-conditioner**

I. INTRODUCTION

Thailand has hot and humid climate condition; therefore, air-conditioning is very important, especially in residential and transportation sectors. An automobile air-conditioner (AAC) consisted of a compressor, a condenser, a receiver/dryer, an expansion valve and an evaporator [1]. The AAC efficiency might be improved to save fuel consumption, by various approaches such as; better choice of refrigerants, application of heat pipe for dehumidification of ambient air, temperature reduction by liquid intercooler [2], heat rejection enhancement and the condenser by heat pipe [3], etc.

Heat pipe was a type of heat exchanger performing rapidly heat transfer. The heat pipe has advantage over conventional heat exchanger due to no moving parts, no mechanical parts, and not required supplied electricity. It can transfer large amount of heat over a relatively long length with a comparatively small temperature difference, possibly reduce the operating and maintenance cost.

In 2004, Suwan Waowaew et al. [4] studied the application of closed-loop oscillating heat pipe to improve performance of the turbo charge diesel engine. The test results showed that the engine performance of CLOHP had higher torque per area and power per area of 9.2 and 9.2 times, respectively when compared with intercooler. In 2013, Burban et al. [5] experimented on a pulsating heat pipe for hybrid vehicle applications. The most obviously performance with regard to inclination -45ₒ, were very interesting for a terrestrial application.

The results from literatures reviewed that the Closed-loop oscillating heat pipe with check valves (CLOHP/CV) has potential to enhance performance of AAC leading to the objective of this research. The CLOHP/CV was introduced to the condensing coil of the AAC to reduce the ambient air temperature before reaching the condenser and enhancing heat extraction from the condensing coil as well. Three designs of CLOHP/CV were primarily tested for their performance. Then COP and EER of the AAC would be analyzed in comparison with the case without CLOHP/CV

II. CLOSED-LOOP OSCILLATING HEAT PIPE WITH CHECK VALVES (CLOHP/CV)

A closed-loop oscillating heat pipe with check valves (CLOHP/CV) in Fig 1 is made of a copper capillary tube closed at the ends; bent into several turns, and installed a check valve for controlling the flow direction of working fluid.

In general the CLOHP/CV has 3 sections; an evaporator section, an adiabatic section and a condenser section. When, hot air passed over the evaporator section, the vapor bubbles and liquid plugs moving in the axial direction inside the tube. Then, the vapor bubbles have grown to big size increasing driving force strongly and rapidly, and moved to the condenser section. The heat transfer performance depended on type and size of heat pipe, characteristics, working fluid, temperature of heat source at the evaporator and heat sink at the condenser sections.

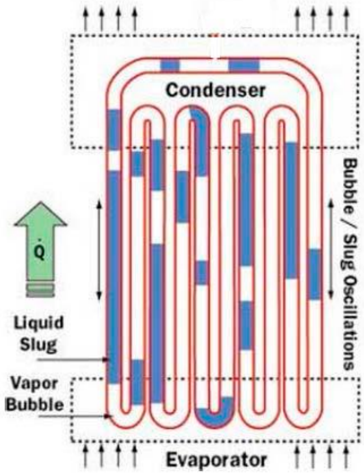

Fig. 1 The schematic of CLOHP/CV [6]

To evaluate performance of the CLOHP/CV, it is necessary to determine heat transfer rate, convection heat transfer coefficient, and thermal resistance. The effectiveness of heat pipe should be determined when integrated to the system. The heat transfer rate of CLOHP/CV is defined as in equation (1):

$$\dot{Q} = \dot{m}.C_p.(T_0 - T_i) \quad (1)$$

Where, is mass flow rate of air (kg/s), is specific heat of air (J/kg·°C), T_0 *and* T_i is the outlet and inlet air temperature (°C) respectively. The convection heat transfer coefficient of CLOHP/CV is defined as in equation (2):

$$h_c = \frac{\dot{Q}_c}{A\Delta T_{LM}} \quad (2)$$

Where, $\dot{Q}$ is heat transfer rate at condenser section of heat pipe (W), A is area of heat pipe (m^2) and ΔT_{LM} is the log mean temperature difference calculated from equation (3)

$$\Delta T_{LM} = \frac{(T_w - T_i) - (T_w - T_o)}{In\,(\frac{T_w - T_i}{T_w - T_0})} \quad (3)$$

Where, T_w is surface temperature of CLOHP/CV at condenser section, T_i *and* T_0 are the inlet and outlet air temperature at condenser section, respectively. The thermal resistance of CLOHP/CV is defined as in equation (4):

$$R_{th} = \frac{(T_{e,ave} - T_{c,ave})}{\dot{Q}_{out}} \quad (4)$$

Where $T_{e,ave}$, $T_{c,ave}$ are the average temperature of evaporator section and condenser section (°C), respectively and $\dot{Q}_{out}$ is heat transfer rate at condenser section. The performance of heat pipe; effectiveness of CLOHP/CV when integrated to the condensing coil of AAC is defined as in equation (5):

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}} \quad (5)$$

The CLOHP/CV is installed at AAC condenser to reduce cooling air temperature, considering ambient air for cooling the AAC condenser as cold fluid and refrigerant of AAC as hot fluid. To determine the maximum heat transfer rate, the heat capacity or multiplication product of mass and specific heat (M.Cp) of the hot and cold fluid must be compared. The minimum value $(M.Cp)_{min}$ will be used in calculating the maximum heat transfer rate, and the rest is for computing actual heat transfer rate.

III. THE VAPOR COMPRESSION REFRIGERATION CYCLE

The AAC is operated based on vapor compression refrigeration cycle comprising of compressor, evaporator, condenser and expansion valve. The Coefficient of performance (COP) of the refrigeration cycle can be calculated as the ratio of heat extraction at the evaporator and the input work to compressor in equation (6). The performance is possibly reported as the Energy Efficient Ratio (EER) as in equation (9).

$$COP = \frac{\dot{Q}_e}{\dot{W}_{comp}} \quad (6)$$

$$EER = COP \times 3412.3 \quad (7)$$

IV. EXPERIMENTAL

The experimental setup was divided to two main parts: (A) Performance test of CLOHP/CV having different designs (B) The performance test with the AAC demonstration unit.

A. Performance Test of CLOHP/CV

Fig. 2 shows the schematic diagram of the experimental setup to test performance of three models of CLOHP/CV having 4, 6 and 8 loops. The experiment unit was consisted of a hot (section) box, an adiabatic section and a cold (section) box. The parameters and variable are listed in Table I. The evaporator (or hot) section was heated by 800-W electric heater, using fan to force heating air. The adiabatic section was insulated with an isolation tape to prevent heat loss to surroundings. The condenser (or cold) section was circulated by cold water from ice storage tank to reduce cooling air temperature and to enhance heat removal from the heat pipe condenser.

TABLE II Experimental Parameters

Parameters	Details
The controlled parameters: • Tube inner diameter • Number of check valve • Working fluids • Working fluids filling ratio	 2.03 mm. 1 R134a 50% by volume
The variable parameters: • Tilted angle • Number of CLOHP/CV loops • Heat transfer area	 0º, 30º, 45º and 60º 4, 6 and 8 loops 0.0385, 0.0595 and 0.0805 m2

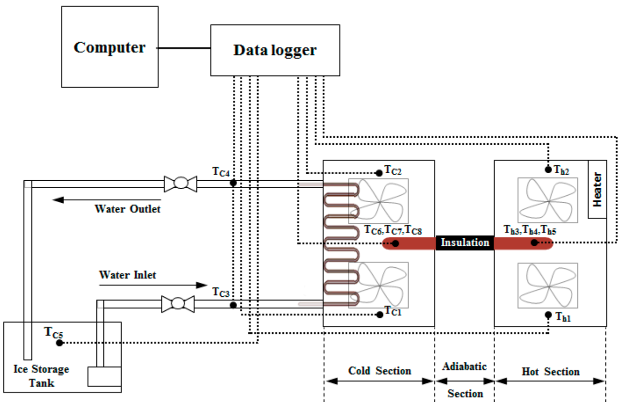

Fig. 2 The schematic diagram of the experimental setup

The CLOHP/CV was installed by the measuring instruments consisted of a Thermocouple type K, an Anemometer and a Data logger (YOKOKAWA MW100). The measurement points of temperature are depicted in Fig. 2. The temperature in each location was recorded every 5 seconds, and the air flow rate was measured by the Anemometer. Each experiment was adjusted by different loops; 4, 6, 8 loops of CLOHP/CV meaning different heat transfer area, and different tilted angle of 0, 30, 45, 60 degrees. The best design and tilted angle of CLOHP/CV was chosen for the experiment in part B.

B. The performance test with the AAC demonstration unit

The selected CLOHP/CV model was installed at the inlet side of the condensing coil of the AAC model. There were 4 cases; (1-2) CLOHP/CV installed in front of but separated from the condensing coil at the left and right sides, and (3-4) extending the condenser coil area by attaching the CLOHP/CV to the left and the right side of condensing coil. The demonstration unit of AAC was operated while recorded temperatures at different locations as shown in Fig. 3. The AAC performance in term of COP and EER were analyzed and compared between the case of with and without the CLOHP/CV.

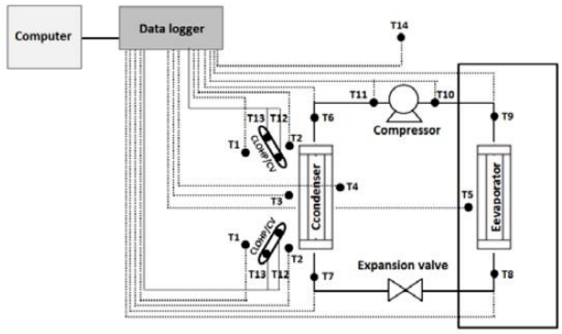

Fig. 3 The schematic diagram of experimental setup with the Car Air-Conditioner Model

V. Results and Discussion

The experimental results analysis were described in five sections; (A) Temperature distribution of CLOHP/CV with time, (B) Variation of heat transfer rate, (C) Variation of convection heat transfer coefficient, (D) Variation of thermal resistance and (D) Effect of CLOHP/CV on AAC performance.

A. Temperature distribution of CLOHP/CV with time

The CLOHP/CV's surface temperature was measured at 3 points in each section; the evaporator section (Th3, Th4, Th5) and the condenser section (Tc6, Tc7, Tc8) in Fig. 3. The surface temperature of the evaporator was higher than that of the condenser sections, and increased with number of loops and tilted angle (Fig. 4-5). The CLOHP/CV with 8 loops tilting at 60º had the maximum surface temperature 52.9 ºC-54.9 ºC at the evaporator section and 51.8 ºC-52.2 ºC at the condenser section. The surface temperature of CLOHP/CV increased with number of loops because of increasing heat absorption area. The continuous heat input at the evaporator resulted in larger boiling of the working fluid inside the tube, leading to more frequency of heat transporting to the condenser. Therefore the higher heat convection rate to the condenser section was possible.

The temperature difference (ΔT) between evaporator and condenser section was shown in Fig. 6, the CLOHP/CV 8 loops at 60º tilted angle had low thermal resistance due to low ΔT but high heat transfer rate.

The variation of surface temperature with time of 8 loops CLOHP/CV at 60º before and after startup heat input to the evaporator section is shown in Fig.7. The temperature difference was changed rapidly after the 1800 seconds and then the gap was nearly constant at 4500 seconds.

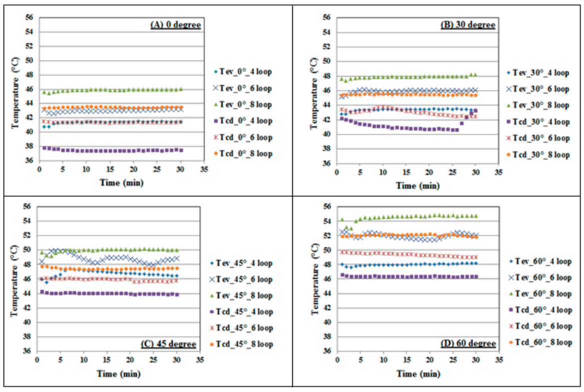

Fig. 4 Surface temperature of CLOHP/CV at evaporator and condenser section with time

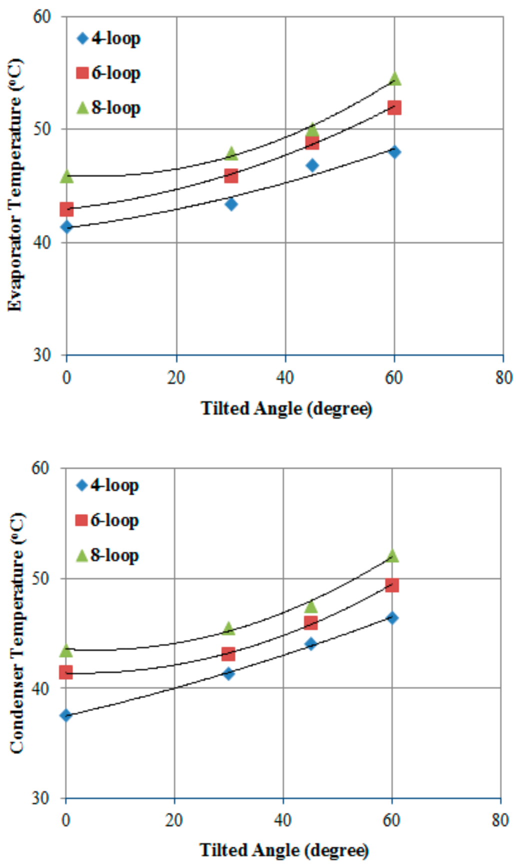

Fig. 5 Surface temperature of CLOHP/CV with tilted angle at evaporator and condenser section

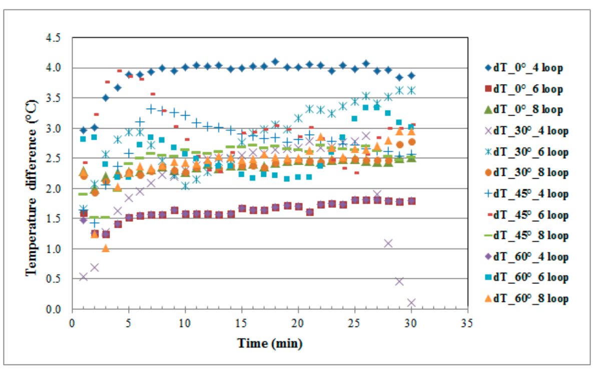

Fig. 6 Temperature difference of evaporator and condenser section with time

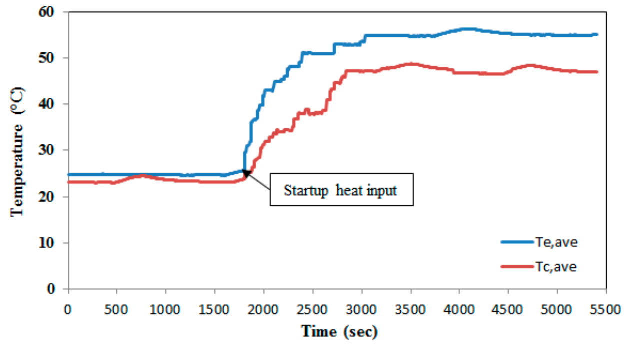

Fig. 7 Variation of surface temperature with time of 8 loops CLOHP/CV at 60°

B. Variation of heat transfer rate

The heat transfer rate of CLOHP/CV depends on operating temperature, heat pipe diameter, working fluids filling ratio, number of valve, number of loops, and tilted angle etc. In this research the effect of loop numbers and tilted angle is considered.

Fig. 8 shows the effect of the tilted angle on the heat transfer rate at the condenser section, adjusting tilted angle from the horizontal plane by 0°, 30°, 45° and 60°. When increased the tilted angle from 0° - 60°, the heat transfer rate also increased. Increasing number of loops means enlarging surface area that the heat transfer rate also increased.

The 60° tilted angle provided maximum heat transfer rate for 4, 6 and 8 loops as 1216 W, 2519 W, and 3789 W, respectively. This implied that the CLOHP/CV has higher performance at greater vertical operation mode. The heat transfer rate increased with the tilted angle since the working fluid in the tube can be rapidly raised to the condenser with buoyancy force, while the condensate easily returned to evaporator section augmenting by gravitational force, regarding key finding from Charoenswan et al. [8] that suggested the range of inclination angles between $0° \leq \emptyset \leq 90°$.

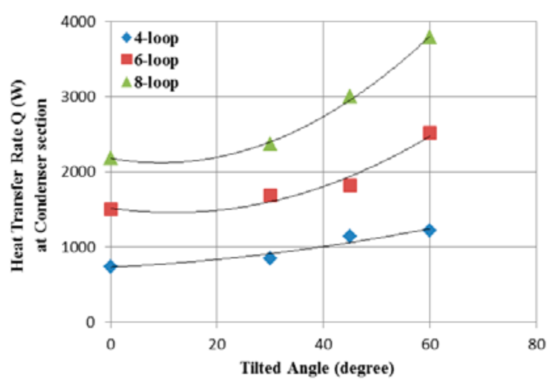

Fig. 8 Variation of heat transfer rate with tilted angle

C. Variation of convection heat transfer coefficient

Fig. 9 shows the effect of the tilted angle on the convection heat transfer coefficient at the condenser section calculated by equation (2). The convection heat transfer coefficient increased with number of loops and tilted angle. The 8 loops CLOHP/CV at 60° had the maximum convection heat transfer coefficient as 2149

W/m2·°C, indicating efficient heat removal by cooling air from the condenser section of the CLOHP/CV.

D. Variation of thermal resistance

The thermal resistance was defined as the ratio of averaged temperature difference between evaporator and condenser sections ($T_{e,ave} - T_{c,ave}$) and the heat transfer rate (Q) of condenser section as in equation (4). Fig. 10 shows the effect of tilted angle on the thermal resistance of CLOHP/CV at condenser section. The thermal resistance decreased with increasing tilted angle from 0° to 60° and increasing numbers of loops. The 8 loops CLOHP/CV had minimum thermal resistance value at 0°, 30°, 45° and 60° tilted angle as 1.10 °C/kW, 1.01 °C/kW, 0.83 °C/kW and 0.63°C/kW, respectively. The best one was 8 loops CLOHP/CV with 60° tilted angle with minimum R_{th} stating best effectiveness of heat pipe [9]. If the thermal resistance value is high, the heat transfer performance in tube is low. In contrary, low R_{th} means better heat transfer rate from the evaporator section to the condenser section.

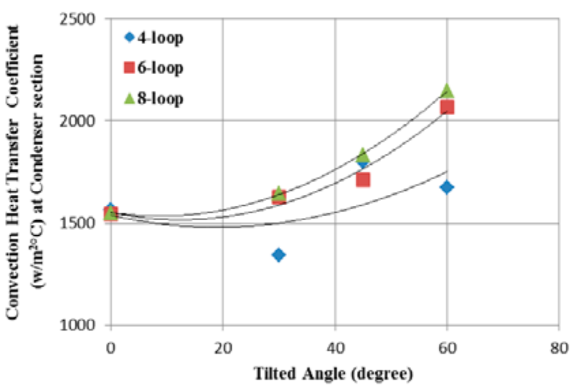

Fig. 9 Variation of convection heat transfer coefficient with tilted angle

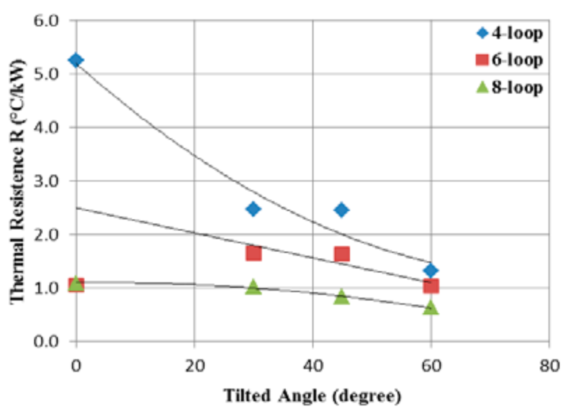

Fig. 10 Variation of thermal resistance with tilted angle

E. Effect of CLOHP/CV on automobile air-conditioner (AAC) performance

Fig. 11 and 12 show the COP and EER of AAC in case of without and with CLOHP/CV into 4 cases; case 1 and 2 means installing CLOHP/CV in front of but separated from the condenser at the left and right hand, while case 3 and 4 means directly attached to the condenser at the left and right hand sides. The AAC with CLOHP/CV had significantly higher COP and EER than existing system without CLOHP/CV, having COP and EER as 4.59 and 15.56.

The COP and EER in case of directly attaching CLOPH/CV to the condensing coil was considerably higher, because not only heat transfer enhancement by ambient air temperature reduction before reaching the condensing coil, but also extending heat transfer area of the condensing coil itself. The maximum COP and EER from the left side attachment that better air flowing through the experimental unit, was 6.50 and 22.16 Btu/h/W, respectively. The maximum effectiveness of CLOHP/CV when implementing to enhance heat removal of the AAC condensing coil was nearly 0.5 as illustrated in Fig. 13.

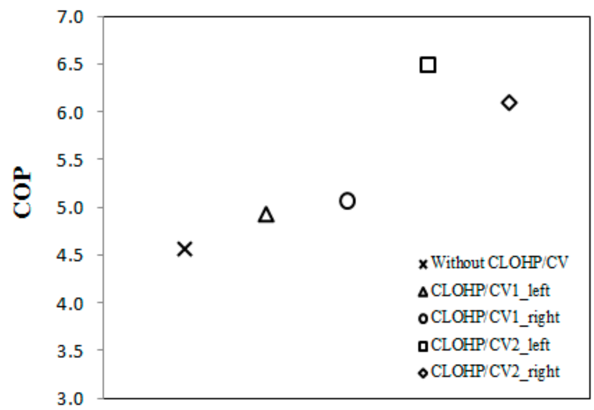

Fig. 11 Comparison of COP of car air-condition system

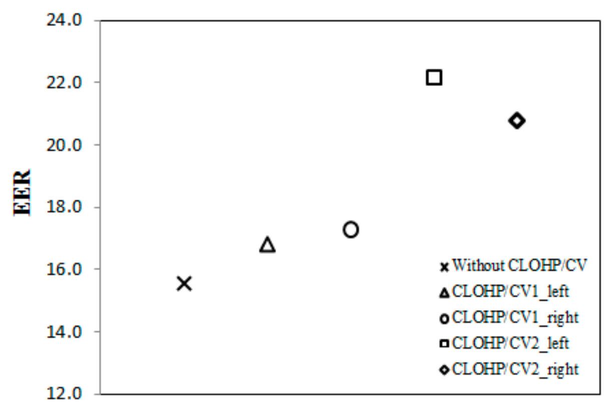

Fig. 12 Comparison of EER of car air-condition system

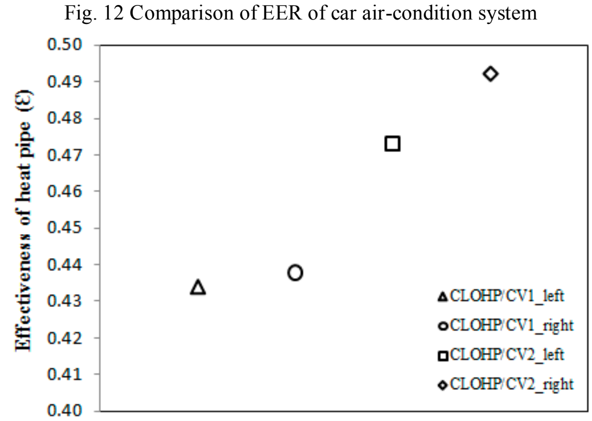

Fig. 13 Effectiveness of CLOHP/CV each position

VI.RESULTS AND DISCUSSION

The CLOHP/CV was developed for application to the automobile air-conditioner (AAC) and tested in the laboratory, then the selected CLOHP/CV design and tilted angle was installed to the demonstration unit of AAC leading to the following key findings:

1) The temperature difference between evaporator section and condenser section of the CLOHP/CV increased with number of loops and the tilted angle.

2) The heat transfer rate from the condenser section of CLOHP/CV increased with number of loops and the tilted angle from horizontal plane.

3) The convection heat transfer coefficient for air cooling at the condenser section of CLOHP/CV increased with number of loops and the tilted angle.

4) The thermal resistance of CLOHP/CV decreased with increased number of loops and the tilted angle, that low R_{th} means better heat transfer from the evaporator section to the condenser section.

5) The coefficient of performance (COP) and the energy efficient ratio (EER) of AAC integrated with CLOHP/CV was significantly improved. The maximum heat removal enhancement from the AAC condensing coil was achieved by using the 8 loops CLOHP/CV with 60o tilted angle, directly attached to the condensing coil surface.

VII. CONCLUSION

An automobile air-conditioner (AAC) is a crucial component in a car, while the efficient heat removal from the condensing coil of the refrigeration cycle is a must. The Closed-loop oscillating heat pipe with check valves (CLOHP/CV) was proposed to enhance heat transfer from the AAC condensing coil by either reducing the inlet ambient air or increasing heat extraction rate from the coil by extending heat exchange area. The research resulted showed that the CLOHP/CV having 8-loops with 60-degree tilted angle integrated to AAC by directly attached to the condensing coil, could significantly improve COP and EER of the AAC. Therefore, it has potential to apply the CLOHP/CV to enhance heat removal from the AAC.

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