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Performance Enhancement of Electric Bus Air Conditioning System by Heat Pipe Equipment (Experimental Study)

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Abstract: Electric Vehicles (EVs) are considered a significant way to minimize dependence on fossil fuel. As one of the most energy-consuming auxiliary components in EVs, air conditioning should enhance its performance and minimize the power and energy consumption. In this experiment, a modular air conditioner prototype with additional heat pipe components for an electric bus air conditioner has been successfully constructed. In this study, a modular AC system testing was carried out before and after using heat pipes at various ambient temperature conditions. The results reveal that the heat pipes utilization in the modular AC system for electric buses increases the cooling capacity by about 15%, and reduces the power input level of the AC system by about 28%. This has contributed to raising of the system's Energy Efficiency Ratio (EER) of around 30%, and the heat pipe's average effectiveness of 7,5%.

Keywords: Electric bus, air conditioning system, performance, heat pipe.

1. Introduction

The use of electric transportation cars is considered a significant way to lessen dependence on fossil fuels, deliver more efficient operation, reduce global warming effects generated by carbon emissions[1], solve the challenges of carbon-neutrality[2], overcome the pollution[3] and emission from internal combustion engine[4]. As carbon emission had reached a serious level[5], electric vehicles potentially play an important role to solve the energy and environmental problems[6] caused by the current public transportation system.

The opportunities for electric vehicles (EV) have been opened by global warming problems and fossil fuel depletion. In addition, high energy-efficient vehicle development is accelerated by battery technology advances.

The field of transportation requires high energy consumption. As a result, electric Vehicles could be a good choice to minimize the global warming effect[7]. The ranges of EVs have become the main barriers to their application worldwide due to the limited battery capacity. On the energy side, electricity has the opportunity to replace fossil fuels with various sources of energy (energy source diversification). This will secure energy supplies and use of renewable energy sources widely.

One of the auxiliary devices in EVs is the modular air conditioning (AC) system. AC system provides interior comfort of thermal environment (involves temperature, relative humidity, and air velocity) in the vehicle and ensures the safety of driving visibility (by defogging and deicing)[8].

Air temperature and humidity are a couple of main comfort factors in the cabin sensed by passengers[9]. Comfort atmosphere in the cabin is also a safety factor in driving[10].

As the auxiliary device that consumes the most energy, the performance of the air conditioning (AC) system has a significant effect on the EVs' range. Since the AC system consumes electricity, the range of the vehicle mileage drops dramatically when the AC system operates. New and innovative approaches are needed to provide comfort desired by passengers, in an efficient way.

Iritani and Suzuki[11] designed an air conditioning system and heat pump with R-134a refrigerant for electric vehicles by using one 4-way valve, two expansion valves (EXV) and multiple control valves to ensure the direction flow of refrigerants when switching the operational mode (cooling and heating). The system performed cooling, heating, demisting, and dehumidifying. The experiments result in the COP of the system was 2.9 and 2.3 at ambient temperature conditions of 40 °C and -10 °C respectively.

Umezu and Noyama[12] released an electric vehicle air conditioning system named "i-MiEV" which includes a refrigerant cycle with a compressor that electrically supplied the power for refrigeration and heat pump cycles. The vehicle test results in the electric vehicle range decreases by about 15% when the AC system is operated.

A vapor compression air conditioning refrigeration system with an ejector on Prius electric vehicle was introduced by Brodie et al[13]. A two-phase ejector was used to raise up the system's efficiency, by its insertion into the evaporator to minimize device volume. As a result, the ejector system optimized cooling system performance, and reduced the consumption of the compressor's power by 11% until 24%.

Cichong Liu et al.[14] investigated the competitiveness of heat pump air conditioning system by using hydrocarbon refrigerants (propane-R290) in electric vehicles under various operating conditions, and compared them with CO_2 refrigerants. The variables include the effects of outdoor air temperature, the percentage of ambient air recirculation, the speed of the rotary compressor and the debit of the inside and outside air on the system performance. Results express that the R-290 refrigerant's heat pump system has higher competitiveness in the higher outdoor environment temperature (above -10 °C), while the system with CO_2 refrigerant has higher competitive at the lower outdoor environment temperature (around -20° C). The heat pump system with R290 refrigerant is a better solution for electric vehicles due to its COP, which exceeded the CO_2 system's one at high outdoor environment temperatures. Furthermore, its operating pressure is lower than CO_2 system.

Dandong Wang[15] evaluated the heating capacity of CO_2 refrigerant's heat pump system equipped with a Series Gas Cooler (SGC) in low temperature conditions. The experiment compared the effects of the charged CO_2 refrigerant amount, gas cooler configuration, and ratio of indoor recirculating air on the heat pump's performance characteristics. The use of SGC result in higher performance of the heat pump by up to 33% and 32% in term of capacity and COP respectively, than that using single One Gas Cooler (OGC) only. At very low ambient temperatures of -20° C, the system design of heat pump with CO_2 refrigerant had heating capacity of 5.6 kW and COP 1.8, which far exceeded the performance of the conventional PTC heater for an electric vehicle.

The other way to raise the performance of electric AC system is by reduce the heat load with minimum unless without any input added. Heat pipe heat exchanger is a passive device with high conductivity value [16] that is used for heat recovery and aimed for recovering sensible heat. The advantage of heat pipes utilization is enabling a high amount of heat transferred through a small area dimension without the need to add extra power into the system. Moreover, it also has simple design and easy manufacturing. The heat pipe has three zones, namely the evaporator, adiabatic, and condenser zone. Evaporator section can be found at one end, where heat is absorbed and causes the working fluid in the tube to evaporate. The fluid will then flow through the adiabatic zone to the condenser zone where the vapor is condensed and heat is released. The working fluid will then change phase to liquid again and will flow to the evaporator section. Heat pipes have a particular application in fresh air handling units especially in hot and humid climates[17] like Indonesia as tropical zone[18]. They optimize the efficiency of dehumidifier in humidity removal and minimize the energy consumed in the process.

Mostafa Abd El-Baky[19] investigated the heat transfer performance and effectiveness of the heat exchanger system by connecting the outdoor air flow from the environment and exhaust air flow (from indoor) with heat pipe heat exchanger. The research showed that the heat transfer effectivity of the heat pipe's evaporator and condenser parts raised up by 48%, when the incoming out air temperature rose to 40°C. The mass flow rate ratio of indoor and outdoor air's effect was positive at the evaporator side, while that effect was negative at the condenser side. The heat pipe system increased enthalpy ratio up to 85% compared to conventional air mixing system as the intake outdoor air temperature increased. The optimum effectivity occurred when the temperature of the fresh air inlet was near the operating temperature of the heat pipe fluid.

Hussam Jouhara[20] examined the energy and economic saving potentials of wraparound heat pipe to a standard dehumidification system. The aim of the new heat pipe technology usage was to provide comfortable ventilation air. The investigation included a quantitative analysis of the conventional system operating costs compared with use of heat pipe systems. The analysis also considered the initial capital costs in the return of investment analysis, where the initial cost used for heat pipe's production to replace standard air conditioning system was cheaper than the cost savings, due to the reduction in device material used. They also presented a thermal modeling analysis of both internal and external heat pipes for various applications[21]. CFD modeling for heat pipes implements a specific, user defined function (UDF) to simulate the system accurately. Furthermore, they used a water-filled gravitational thermosiphon type heat pipe[17] that was designed and fabricated as a loop heat pipe and attached around the chilled water cooling coil to increase the efficiency of reducing humidity and proved lower energy consumption.

Y.H. Yau and M. Ahmadzadehtalatapeh[22] reported that the wraparound heat pipe heat exchanger (HPHX) pre-cooled the incoming air and increased the cooling capacity by 21%, as well as increased condensate of cooling coil about 42%.

Nakkaew et al.[23] studied the application of heat pipes to improve AC performance. A set of heat pipes consisting of heat pipes with deionized water, mounts, and plate fins, was installed and settled at the AC compressor's discharge line and functions as de-super-heating. The experiment resulted in the increasing ratio of energy efficiency (EER) of AC with heat pipe set by 3.11%.

Eidan et al.[24] conducted an experiment to test the thermal performance of a window AC system equipped with heat pipe heat exchanger on the liquid refrigerant and compressor suction side. In the experiment, they used various working fluids in the heat pipe, that are distilled water, acetone, and R-134a. The experiment results in the reduction of the power consumption of compressor that uses heat pipe heat exchanger. So, the coefficient of performance (COP) of the AC system increased. The use of this type of heat pipe heat exchanger provides a power consumption savings of 2.195% compared to a standard system without heat pipe heat exchanger. Thermosyphon heat exchangers (THEs) were also used by Eidan et al.[25], who were investigating the possibilities for energy savings and humidity management in HVAC systems.

Ragil Sukarno et al. conducted laboratory-scale experiment to investigate the reduce of energy consumption by air-to-air heat pipe heat exchanger in the airborne infection isolation room[26] and by multi-stage heat-pipe heat exchanger in the operating room[27].

Alshukri et al. studied the functionality enhancement of heat pipe evacuated tube collector (HPETC) with the integration of enhanced paraffin wax[28] and implemented on the various tube collectors[29]. Additionally, they examined how the design of the structure, the techniques, the working fluids, and the use of storage systems affected the performance of the heat pipe solar collector[30].

In this research, a set of wraparound heat pipes was attached to an Electric bus air conditioning system, and proposed as an alternative for power saving in a 12-m electric bus, which is known to have high energy consumption due to its air conditioning operations. The heat pipe is used to enhance the performance of the electric bus modular air conditioning system in terms of its heat removal from the recirculating air. Experimental studies were performed for thermal performance investigation of the electric bus air conditioning system under different ambient temperatures. The efficiency of the AC system has been studied under various operating conditions to compare the system's performance; one that uses heat pipes and another one that does not use heat pipes.

The contribution of this research is power saving alternative method to reduce the power consumption of Electric bus air conditioning system by attaching the wrapped around heat pipe. By additional component of heat pipes, modular air conditioners have a higher overall performance by raising cooling capacity by precooling the entering air, and lowering the power consumption, due to the declining of evaporator cooling load.

2. Experimental setup and test

Experimental setup

The electric bus air conditioning piping system was designed and built as Fig. 1. The modular AC system is consisting of 2 unit of vapor refrigerant compression line systems, each line consists of semi-hermetic mobile rotary scroll compressors (1), air-cooled condenser (2), electric expansion device (9), and evaporator (11).

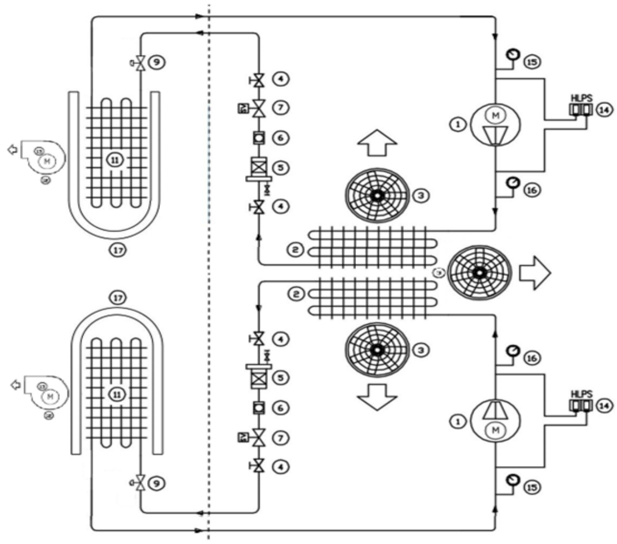


Fig. 1: Modular electric bus AC system with heat pipe

The electric compressors are two scroll type with 34cc displacement. The compressors used are semi-hermetic type; each works with 300-700 Volt direct current (DC) with the R407C refrigerant. These compressors also require polyol-ester lubricant (POE oil). The condenser and evaporator of AC system installed in this unit are finned tube coils. On the condenser side, an axial fan forces the heat by convective transfer, while on the evaporator side, it uses centrifugal blower. The pipe material for the heat exchanger is made of copper, while the fins are made of aluminum and the support frame material is 1,2 mm galvanized steel. The pipe configuration used is staggered with a horizontal distance of 21.65 mm and a vertical distance of 15 mm. The pipe diameter used is 3/8 inch for the condenser and 5/8 inch for the evaporator. In each heat exchanger, both in the condenser and evaporator, there are two cycles that are thermally coupled so that the design capacity for each unit is half the cooling capacity of the prototype AC unit. Therefore, the design capacity for one evaporator unit is 16 kW. The pipe is assembled by brazing.

The frame material used is galvanized with a thickness of 2 mm. The sizes of each indoor evaporator are 1500L * 200H * 120D (mm), while the condenser sizes are 1000L * 500W * 120D (mm) respectively. The electronic expansion valve is from Danfoss with type ETS 6-18. This expansion valve is for the refrigerant type R407C and is used in each refrigeration cycle line.

As the AC system work, the refrigerant fluid from the indoor evaporator coil is drawn and enters the compressor then sent to the outdoor condenser coil. The refrigerant passes through the indoor evaporator coils and absorbs heat from air flow driven by a blower, thereby the air flow provides a cooling process for the indoor air stream. After being compressed by the compressor, the high-pressure refrigerant enters the outdoor condenser coils and rejects heat into another cooling media, air stream driven by axial fans.

The electric bus modular AC design was equipped with set of heat pipes wrapped around the evaporator coil for return air pre-cooling and supply air recovery. The heat pipe is made of copper and contains working fluid saturated water with 50% filling. These heat pipes provide thermal coupling between warm air from the indoor cabin room with the cold leaving air on the AC's evaporator side, the working fluid in the heat pipe is completely isolated from the surrounding environment (hermetically sealed). The heat pipes used in the experiment are 80 wicked wraparound commercial copper heat pipes filled with 50% saturated water fluid. Every heat pipe is of 10 mm diameter, 180 mm leg of evaporator and condenser side respectively, also the 200 mm adiabatic zone (Fig. 2). The heat pipe arrangement is wrapped around the air conditioning evaporator, with the evaporator legs placed at the incoming air flow, while the condenser ones are placed at the outcoming air flow of the air conditioning evaporator. The adiabatic zones are insulated by Armaflex to avoid infiltration of ambient. The evaporator leg will precool the air flowing into the air conditioning evaporator, while the condenser leg will recover its high relative humidity to the comfort one.

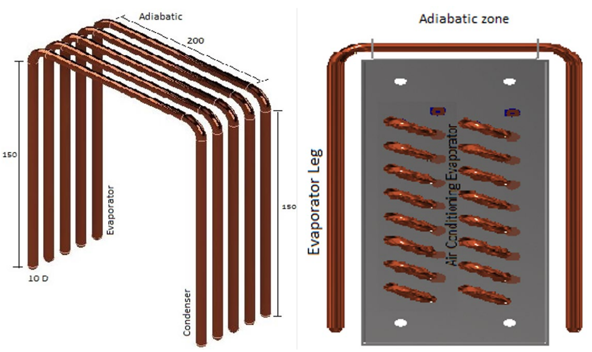


Fig. 2: Heat pipe and arrangement

Test methods

To investigate the air conditioner performance, measurement devices were used to measure the parameter at refrigerant side and air side. The measurement systems are shown in Fig. 3. The refrigerant side temperatures are measured at suction, discharge, and liquid line of the system, and sensed by K-type thermocouples, while the air ones are by J-type of dry and wet bulb thermocouples in the entering and leaving air of the indoor evaporator and outdoor condenser coils. The suction and discharge pressures of the compressors are measured by high- and low-pressure transducers. The evaporating and condensing pressures are represented by suction and discharge pressures, respectively. The volume flow rates of the air through the indoor evaporator coils are measured by measuring the pressure drop that represented velocity in the related duct with an orifice nozzle.

The performance testing refers to the American Heating and Refrigeration Institute (AHRI) 340/360 testing standard, 2019. The temperature in the outdoor room is maintained at set condition during the test. Various temperatures of outdoor room are 29, 32, 35, 38 and 41 ^{o}C The data recorded on the calorimeter includes the wet bulb and dry bulb temperatures at the inlet and outlet indoor and outdoor unit, the pressure difference on the indoor supply unit, the input power supplied, and the test time. Interval of data taking is every 1 second.

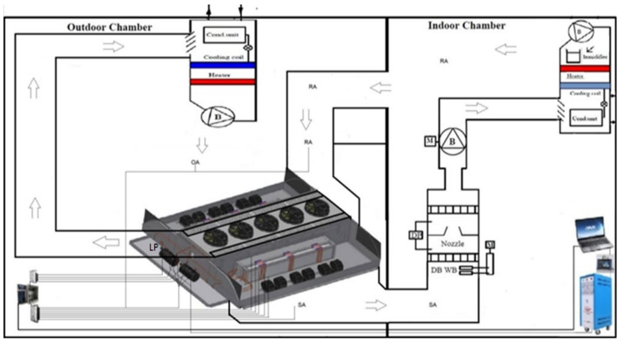


Fig. 3: Testing set-up

The recorded data on the Hioki PW3198 power quality analyzer (PQA) meter includes the power, voltage, and current input to the AC unit.

The test procedures are:

a. The outdoor room temperature is set at 29^{o}C.
b. After the Outdoor room temperature is steady, the AC system is turned on and the indoor is set at 26,7^{o}C and 50% relative humidity.
c. The fan and the indoor duct parts are turned on (heater and humidifier) to achieve the capacity load.
d. The AC system working pressures and temperatures, air db and wb temperatures, air pressure drop, electrical voltage and ampere are measured and recorded from initial until steady and maintained about 2 hours operation.
e. The test for heat pipe utilization is repeated by heat pipe installation at AC evaporator.
f. The Outdoor temperature setting is changed into 32, 35, 38 and 41 ^{o}C and steps b–e are repeated.

The measurement will result in the cooling capacity of the AC unit along with the air flow supply, the power consumption, energy efficiency ratio (EER) and heat pipe effectiveness.

The cooling capacity (Q_a) of the tested AC unit was determined by the heat transfer rate of the air, using Eq. (1), while the power consumption of the system was calculated with Eq. (2). The overall system Energy Efficiency Ratio (EER) was determined by Eq. (3), and the effectiveness of heat pipe was determined by Eq. (4).

$$Q_a = \dot{m}_a (h_{a,out} - h_{a,in}) = (h_{a,out} - h_{a,in}) \rho_a v_a A \quad (1)$$

$$W = U * I \quad (2)$$

$$EER = \frac{Q_a}{W} = \frac{Q_a}{U * I} \quad (3)$$

$$\varepsilon = \frac{T_{RA} - T_{in,ev}}{T_{RA} - T_{o,ev}} \quad (4)$$

v_a, which can be controlled in the wind tunnel, represents the flow velocity of the air in the–nozzle ducting, ρ_a represents density of the flowing air into the evaporator, while $h_{a,in}$ and $h_{a,out}$ represent enthalpy of the flowing air into and out of the evaporator respectively.

The experimental data and measured parameter of uncertainties are shown in table 1.

Table 1. Uncertainties of the experimental parameters and measured data.

Item	**Uncertainties**
Temperature sensors Thermocouple K Type, Pico TC-08	±0.1 °C
Digital power meter Hioki PQ3198	0.1% rdg
Pressure transducer	0.4 %
Air side pressure difference (Pa)	±0.2%

Uncertainty analysis was carried out using the equations described in (5-9) to confirm the calculated cooling capacity, effectiveness, and EER.

$$\frac{\delta h}{h} = \left(\left(\frac{\delta Td}{Td}\right)^2 + \left(\frac{\delta Tw}{Tw}\right)^2\right)^{\frac{1}{2}} \quad (5)$$

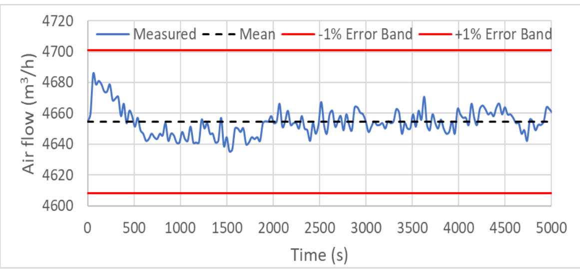
$$\frac{\delta Q}{Q} = \left[\left(\frac{\delta h}{h}\right)^2 + \left(\frac{\delta v}{v}\right)^2 + \left(\frac{\delta A}{A}\right)^2 + \left(\frac{\delta \rho}{\rho}\right)^2\right]^{\frac{1}{2}} \quad (6)$$

$$\frac{\delta W}{W} = \left(\left(\frac{\delta U}{U}\right)^2 + \left(\frac{\delta I}{I}\right)^2\right)^{\frac{1}{2}} \quad (7)$$

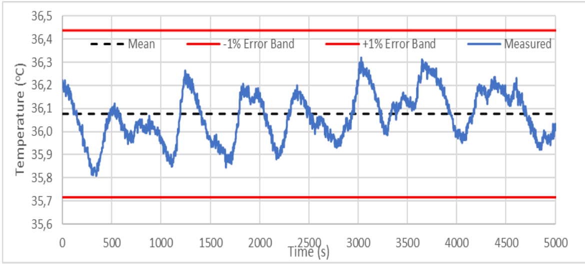
$$\frac{\delta EER}{EER} = \left(\left(\frac{\delta Q}{Q}\right)^2 + \left(\frac{\delta U}{U}\right)^2 + \left(\frac{\delta I}{I}\right)^2\right)^{\frac{1}{2}} \quad (8)$$

$$\frac{\delta \varepsilon}{\varepsilon} = \left(\left(\frac{\delta T_{RA}}{T_{RA}}\right)^2 + \left(\frac{\delta T_{in,ev}}{T_{in,ev}}\right)^2 + \left(\frac{\delta T_{o,ev}}{T_{o,ev}}\right)^2\right)^{\frac{1}{2}} \quad (9)$$

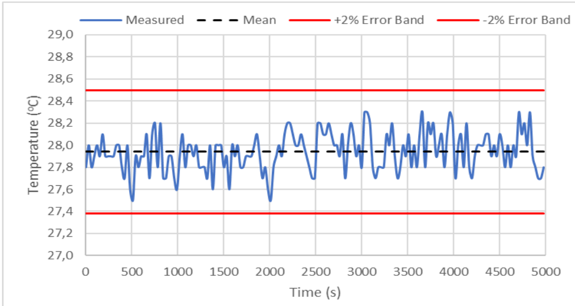
The controlled test parameters were outdoor and indoor test room temperatures that were set to remain stable in the range of tolerances, which were then applied to the system with and without wraparound heat pipes. The time-dependent change of the test parameters during the tests[31] are shown in Fig. 4.



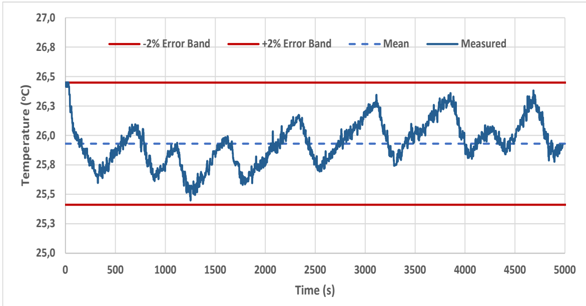
(a) Air flow



(b) Out air dry bulb temperature



(c.) Out air wet bulb temperature



(d) Indoor temperature

Fig. 4: Time-dependent change of (a) air flow, (b) dry bulb and (c) wet bulb of outdoor temperature, (d) indoor temperature.

The impact of heat pipe utilization on electric bus air conditioning system was examined in experimental system at varied outdoor (condenser air inlet) temperatures to determine its effect on the cooling performance. The ambient outdoor temperatures were set on 29°C, 32°C, 35°C, 38°C and 41°C to simulate the effects of the real ambient conditions.

In these works, the temperature's measurement uncertainties are ±1.5 %, which contains of ±0.02 °C measurements error by thermocouple. The air velocity measurements uncertainty is 0.2%. The error of the pressure measurements is 4%. The effectiveness uncertainty, which was calculated by immediately measuring values of temperature, is 1.7%.

3. Results and discussion

Tests were carried out at various outdoor chamber temperature (condenser air inlet) conditions that represent real ambient temperature condition. Heat pipes were attached at the evaporator.

Temperature profiles of the electric bus AC refrigeration system are shown in Fig. 5. The curve shows the temperature profiles in systems 1 and 2. These temperatures are that of the refrigerant entering the compressor (suction, T_s), leaving the compressor (discharge, T_d), refrigerant leaving the condenser (liquid line, T_{oc}), and also out door air temperature (T_{oA}) respectively. It shows that both systems 1 and 2 operate continuously to maintain the temperature conditions in the cabin.

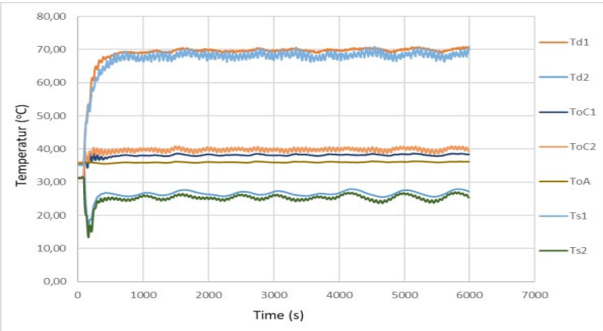


Fig. 5: Temperature profiles of testing

The cooling capacity for each testing is shown in Fig.6. The average cooling capacity of the system at 29°C, 32°C, 35°C, 38°C and 41°C without heat pipes testing is 19450 W, 18635, 23482 W, 22887 W, and 27495 W respectively, while that of the system using heat pipe at the same temperature is 21718 W, 20751 W, 26149 W, 25630 W, and 33127 W, respectively. The used cooling capacity depicts the heat load that rises by raising the outdoor temperature. The increase of the cooling capacity was obtained by precooling mechanism during the entering air flow through evaporator leg of heat pipe before entering AC's evaporator. The precooling mechanism was occurred with sensible cooling. Furthermore, the increase of cooling capacity at higher ambient (outdoor) temperature slightly higher than that at lower temperature. This is affected by effectiveness of heat pipe. The AC system equipped with heat pipes has a larger cooling capacity of about 15%, that is quite comparable as the Yau's result[22].

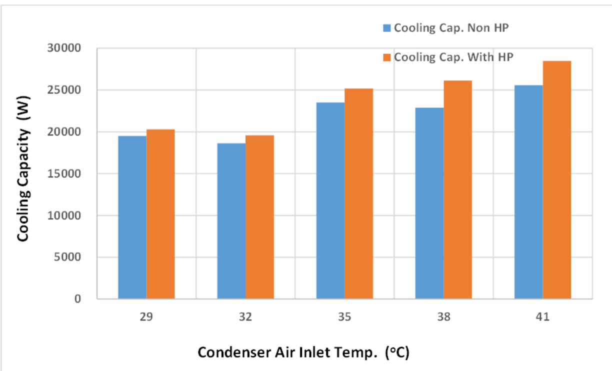
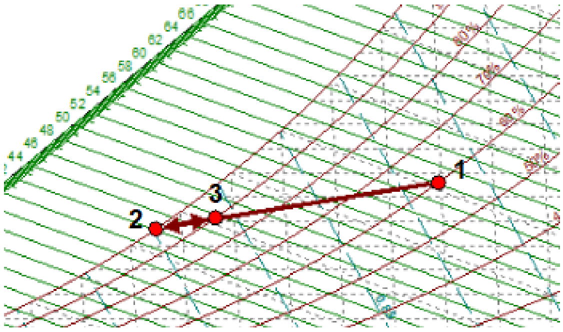
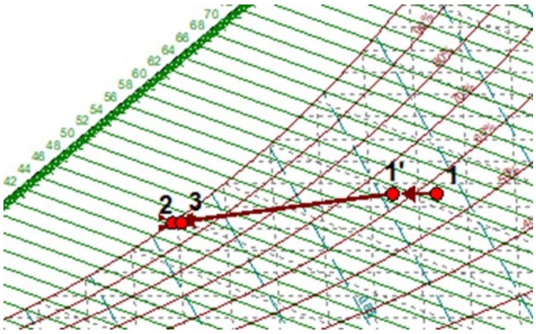


Fig. 6: Cooling capacity of each test

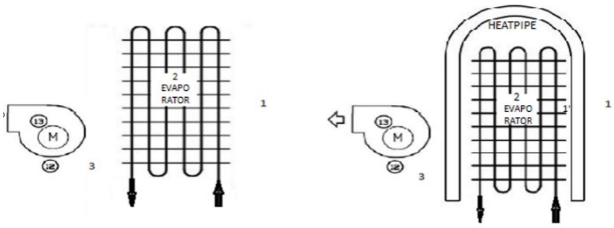
The cooling capacity's rise is obtained by lowering the temperature as precooling of entering air to AC evaporator by heat pipe, so it decreases the sensible load of the recirculated air as shown in Fig. 7.



(a) Air properties at test without heat pipe



(b) Air properties at test with heat pipe



(c) Arrangement without heat pipe, and (d) with heat pipe

Fig. 7: Plot of air properties at psychrometric diagram

The power consumption of the system in each test is shown in Fig. 8. At the beginning test of low outdoor temperatures (29°C and 32°C) both in tests with and without heat pipe, the power consumption was measured relatively high, but after a while it decreased by turning off one axial fan of the condensers (Fig. 8a and 8b). After that it was stable continuously. These indicated that the load of AC system was relatively small at low temperatures tests, while the power consumption of higher outdoor temperatures was stable in high power.

The average power consumptions of the test at 29°C, 32°C, 35°C, 38°C and 41°C without heat pipes are 6760 W, 7002 W, 7621 W, 7908 W and 8262 W respectively, while the power consumptions of the system using a heat pipe at the same temperature are 5160 W, 5365 W, 5938 W, 6261 W and 6573W respectively.

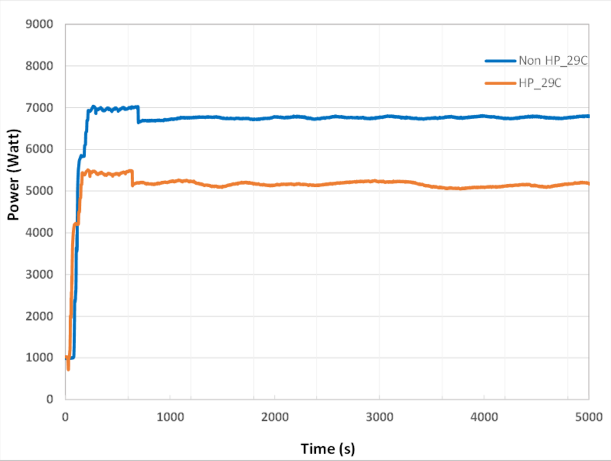


Fig.8a. Condenser air inlet temperature 29°C

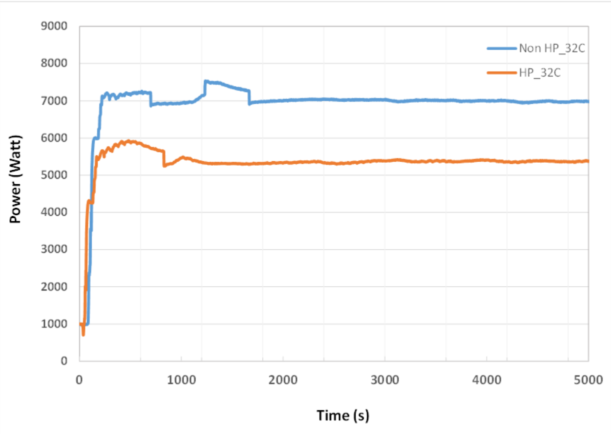


Fig.8b. Condenser air inlet Temperature 32°C

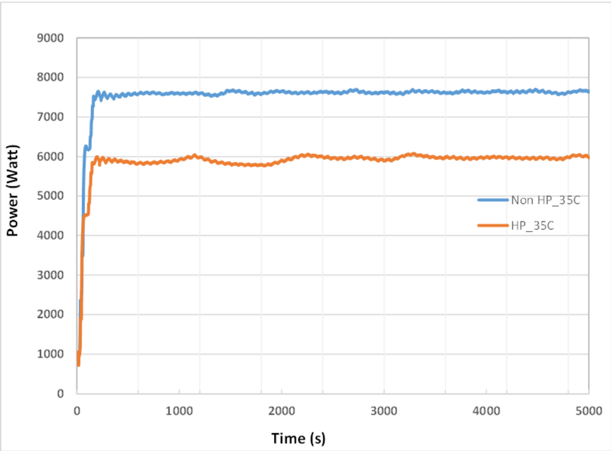


Fig.8c. Condenser air inlet Temperature 35°C

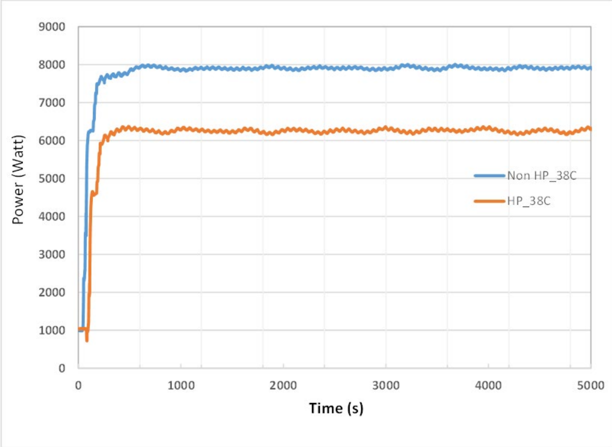
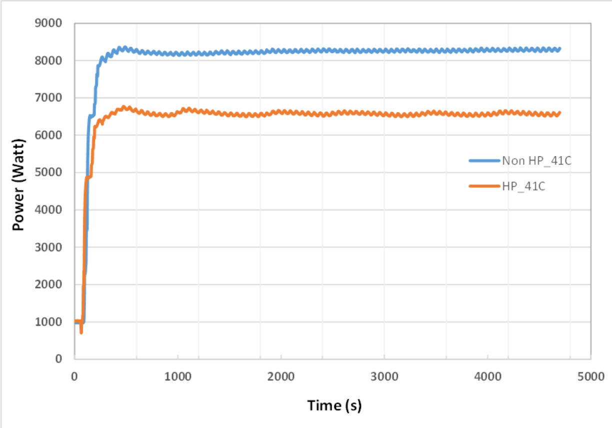


Fig.8d. Condenser air inlet Temperature 38°C



(e) Condenser air inlet Temperature 41°C

Fig. 8. Power consumption during each test.

The comparison of power consumption is shown in Fig. 9. It is shown that the AC system equipped with heat pipes has lower power consumption of about 28% in average close to that at ejector use in Brodie's work[13]. The decrease in the power consumption is slightly decline by raising the outdoor temperature. The decrease is as result of the thermal load decrease in the evaporator, which is caused by the evaporator's precooled intake air (sensible cooling). Consequently, the refrigerant flow in the evaporator, which is compressed by the compressor, also decreases.

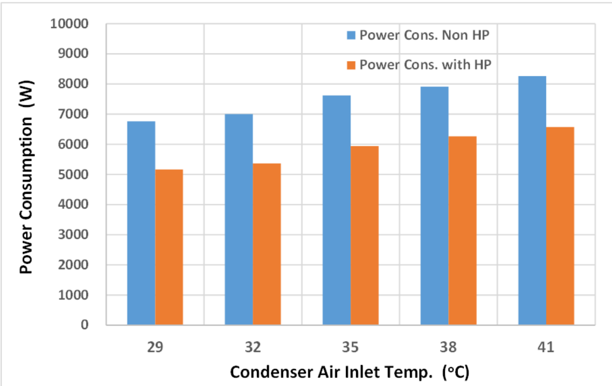
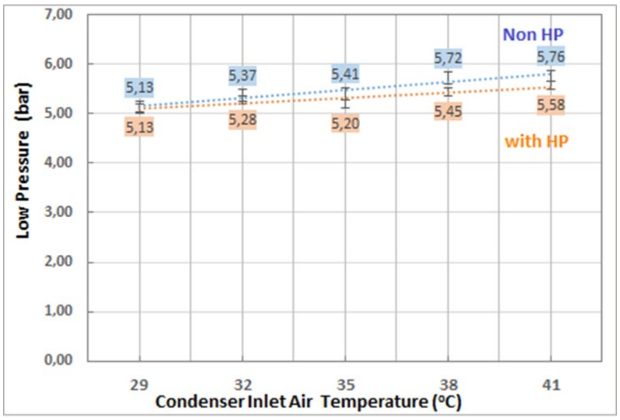
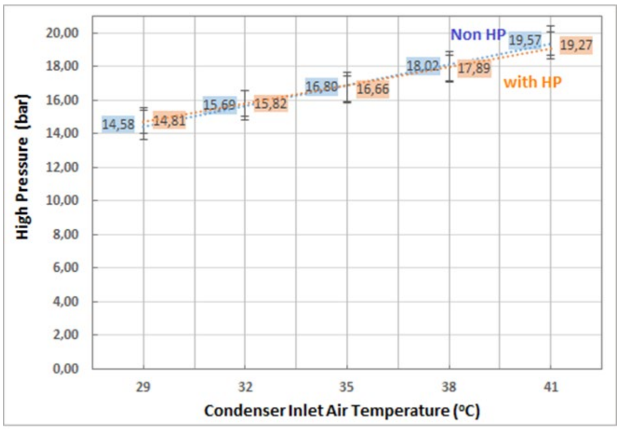


Fig. 9: Power consumption of AC system

The decrease in the refrigerant flow is indicated by the low-pressure side (Fig. 10-a), showing the pressure of the refrigerant that goes out of the evaporator and enters the compressor. The higher pressure, indicates more gas (refrigerant). Meanwhile, the high-pressure (Fig. 10-b) side is only affected by the outdoor air temperatures, instead of the heat pipe utilization. The position of the low-pressure sensor is located at the inlet compressor, while the high-pressure sensor is at the compressor outlet (Fig. 11).



(a) Low pressure



(b) High pressure

Fig. 10: Low (a) and high (b) pressure side

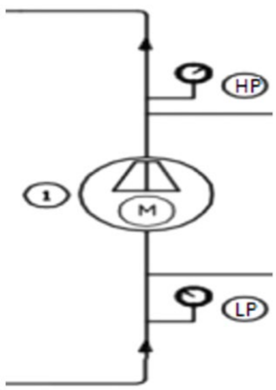


Fig. 11: Low (inlet) & High Pressure (outlet) at compressor

The Energy Efficiency Ratio's (EER's) comparison of the system for each test is shown in Fig. 12. It is shown that the AC system equipped with heat pipes performs a higher EER of about 30% in average as a result of increasing capacity and decreasing power consumption. The EER of the system at 29°C, 32°C, 35°C, 38°C and 41°C without heat pipes testing is 2.73, 2.52, 2.92, 2.69, and 3.33 respectively, while the EER of the system using heat pipe at same temperature is 3.93, 3.65, 4.24, 4.17, and 4.33; respectively.

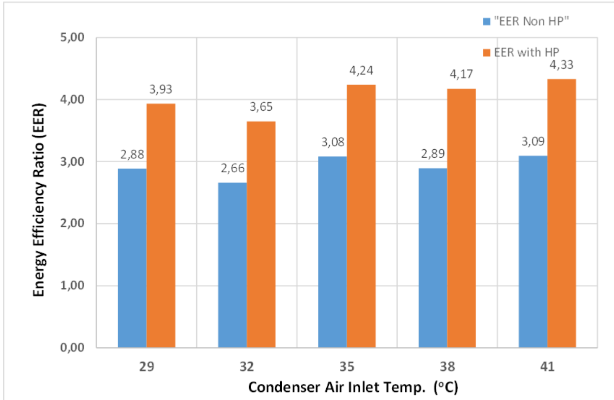


Fig. 12: Energy Efficiency Ratio (EER) of each testing

The heat pipe's effectiveness used in the experiment at each test is shown in Fig. 13. The effectiveness of the heat pipe indicates how effective the heat pipe absorbs and releases the heat of the flowing air. It was determined by comparing the drop in air temperature at the evaporator legs to the maximum temperature differences. The average effectiveness of the heat pipe is 7.5%.

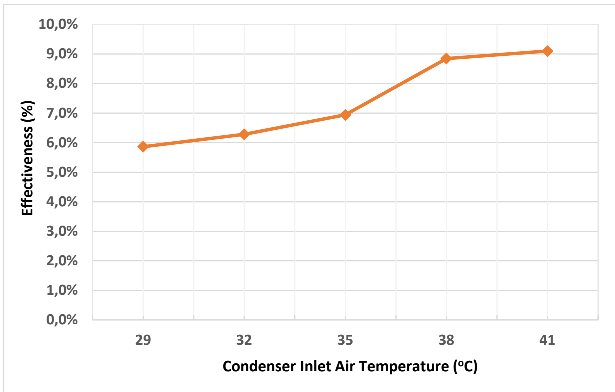


Fig. 13: Heat pipe effectiveness

4. Conclusion

The testing of the modular AC system was carried out by using and without using a heat pipe installation at various ambient (condenser inlet air) temperature conditions. By using a wraparound heat pipe arrangement with 7.5% effectiveness, the performance of the electric bus air conditioning system rises significantly. The tests results reveal that the use of heat pipes in the modular AC system for the electric bus raises the cooling capacity by about 15% (with the precooling mechanism of heat pipe), as well as reduces the consumed power of the AC system about 28% in average (by lowering the entering air thermal load). This resulted in an increase in the Energy Efficiency Ratio (EER) of the AC system of around 30%.

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Nomenclature

A	Cross sectional area (m^2)
EER	Energy Efficiency Ratio (-)
$h_{a,in}$	Air enthalpy entering the evaporator (kJ/kg)
$h_{a,out}$	Air enthalpy leaving the evaporator (kJ/kg)
I	Electric current (Ampere)
P	Pressure (Pa)
q	Air flow debit (m^3/h)
Q_a	Cooling capacity (Watt)
T	Temperature (ºC)
U	Voltage (volt)
W	power consumption (Watt)
ε	Effectiveness (%)
ρ_a	Air density (kg/m3)
v_a	Air velocity (m/s)

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