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Development of Automotive Air-Conditioning System Test Rig for Hybrid Electric Vehicles

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Abstract. Introducing nanoparticles in liquid-based mixtures began to gain attention in various industries. This is supported by previous studies to improve the performance and provide energy saving for the system. Among its uses is in the VCRS and automotive air conditioning (AAC) system. The lubricant used in this system has the potential to have a good effect on the performance. Before testing the nanolubricant enhancement performance, an automotive air conditioning (AAC) system test rig based on hybrid electric vehicles (HEV) AC system has to be developed; therefore, this paper presented the development process of AAC test rig specific for the HEV. In order to analyze the performance, 11 thermocouples, a digital pressure gauge with data logger, and AC/DC power clamp were assembled and used. After that, the experiment was conducted with five different initial refrigerant charges and three different compressor speeds. This method was applied to both pure POE lubricant and SiO_2/POE nanolubricant. Then, the heat absorbs, compressor work, and coefficient of performance (COP) were evaluated. The highest average COP for SiO_2/POE nanolubricant was achieved at a 40 % duty cycle (2520 RPM) speed with a value of 2.84. The highest enhancement of the COP is 25.1% at 60% duty cycle (3180 RPM) speed with 160 grams of initial refrigerant charged an average enhancement of the COP is 13.16%.

1. Introduction

Thermal comfort, especially in the vehicle cabin, is essential as it can enhance the driving experience. The vehicle cabin can be considered a closed environment, making temperature and humidity control more challenging than other conditions [1]. Particularly in countries close to the equator, heat conduction, convection, and radiation from the solar system affect passengers' thermal comfort inside the vehicle cabin. Hence, the automotive air conditioning system (AAC) is a vital part of controlling such an environment. In order to provide thermal comfort to vehicle passengers, the AAC system needs to work hard to cool off the environment inside the vehicle, as the outside temperature is high while having various humidity depending on the weather conditions of the environment.

The modern hybrid vehicle employed an electric compressor to decrease the parasitic load in the hybrid vehicle. If the conventional belt-driven vehicle is used, the engine must operate more often as the temperature difference increases between targeted and cabin temperature, affecting the driving range. Tae et al. [2] pointed out that the electric compressor's control system can be further improved by 2.65% just by controlling the compressor's speed more effectively thru simulator optimization. Furthermore, excellent thermodynamic systems provide many improvements to the AAC system's efficiency [3]. AAC's thermodynamics performance can be enhanced by reducing compressor load and increasing refrigeration effect, or both. Applying nanolubricant to the current hybrid vehicle air conditioning system can help the enhancement, as mentioned earlier. This contributes to an energy-efficient system and improves the whole system performance [4, 5].

In this study, the lubricant in the compressor becomes the main factor that plays a role in determining the performance of an AAC system. The role of the lubricant in the compressor is to protect and reduce the friction between two surfaces that slide together [6]. Nanolubricant technology has improved dramatically over the years. By implementing this technology to the vehicle air-conditioning system, it is expected that the system will have better efficiency rather than using the conventional lubricant. The nanoparticles inside the lubricant will improve their thermal transport properties, thus increasing the condenser and evaporator's efficiency. It is proved by Hamisa et al. [7] in terms of the performance between single and composite nanolubricant. However, the effects on the system's pressure are yet to be confirmed. Furthermore, the tribological properties enhancement, such as friction reduction and wear properties at high pressure, can reduce the compressor's load and increase its lifespan [8, 9].

David et al. [10] studied the effect of polyolester refrigeration oil in diamond nanoparticles form at various mass concentrations between 0.1% to 0.5%. The system performance has increased by 4% and 8% for 0.1% and 0.5% nanoparticles, respectively. The refrigeration cycle is also increased by 4.2% and 7% for 0.1% and 0.5% respectively. Redhwan et al. [11] investigated the Al_2O_3/PAG nanolubricant performance for a compact vehicle mobile air conditioning (MAC) system. They found the enhancement in the coefficient of performance (COP), reduction in compressor work, and enhancement in the cooling capacity up to 31%, 26%, and 32%, respectively, for 0.010% volume concentration. Sharif et al. [12] found that the maximum increase and the average COP enhancement for SiO_2/PAG nanolubricants are 24% and 10.5%, respectively, and concluded that the COP was the highest at 0.05% volume concentration for all compressor speeds. More studies can be found on a different approach to increasing the performance by utilizing nanolubricant [13-19].

Therefore, in this study, an automotive air-conditioning system test rig for hybrid electric vehicles has been developed to have a feasibility study of nanolubricant on the system. The outcome of this study is the test rig representing a hybrid vehicle air conditioning system, while the outcome result is compressor work and heat absorb at the different refrigerant charge and coefficient of performance of the system before and after using nanolubricant to the system. The system is developed according to SAE International standard, J2765 OCT 2008.

2. Methodology

2.1. Development of test rig

The developed test rig comprises an air-conditioning vehicle component and uses an electrical compressor used in a hybrid vehicle to imitate the actual hybrid vehicle condition. The components include an electrically driven compressor, PWM controller, piping system, and heater. Figure 1 shows the test rig, while Table 1 shows the detailed components used.

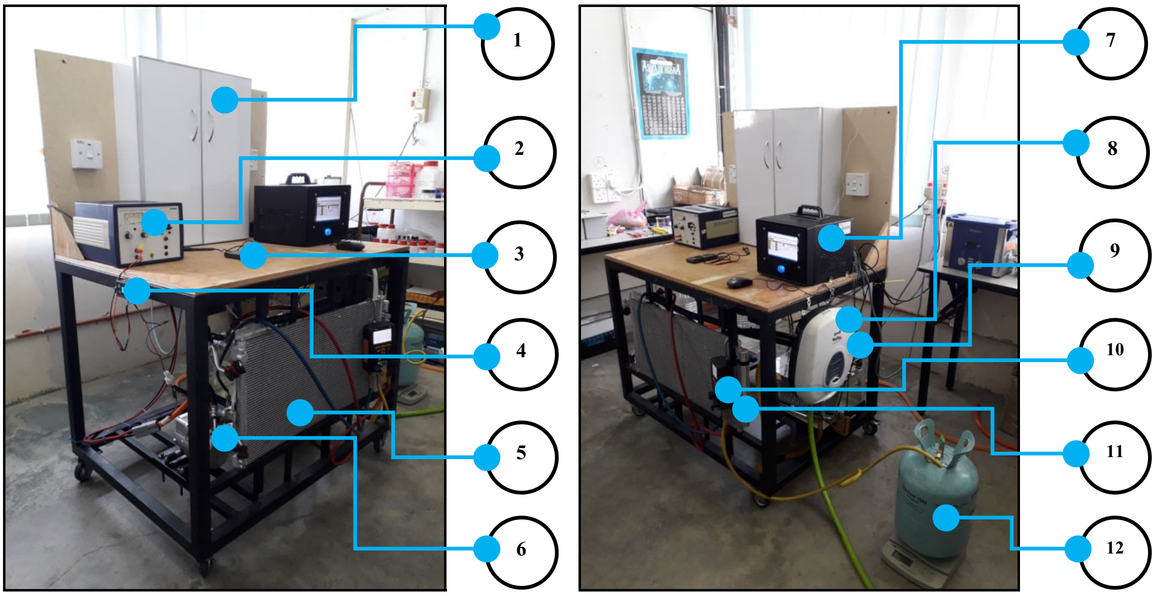

Figure 1. Hybrid AAC test rig

Table 1. List of Main Component for HEV AAC Test Rig

No.	Description	No.	Description
1	Distribution box	7	Data logger module
2	Power supply	8	Water heater
3	AC/DC power clamp	9	Evaporator inside the water bath
4	PWM Controller	10	Digital Pressure Gauge
5	Condenser	11	Receiver Dryer
6	Electrically driven compressor	12	R1234a refrigerant and weight scale

This test rig uses Honda City Hybrid air-conditioning system running HFC-R134a. The system is then retrofitted with a speed adjustable electric driven compressor using a PWM controller while maintaining other original air-conditioning parts such as the condenser, evaporator, and expansion valve. By adjusting the PWM input with varying the duty cycle, the compressor's speed can be adjusted and varies between 1200-3200rpm. The water bath system is one of the main components of this test rig. It is equipped with a fully thermal insulated tank, a flow meter with a 2-ways inlet, and 2-ways outlet pipes for achieving homogenous water temperature in the water bath. The water bath system is used to immerse the evaporator in water for ease and get consistent evaporator temperature measurement reading. This method is done according to ASHRAE 41.9-2000 for calculation of Coefficient of Performance (COP). The water heater acts to regulate the water inlet temperature and the flow rate.

2.2 Calibration and installation of thermocouples

Table 2 shows the two sets of data with different conditions of water used during calibration. K-type thermocouples were K-type with 0.3 mm diameter and targeted for temperature span between -40°C to 375°C with tolerance ±1.5°C. The calibration of the thermocouple was done in contra with the Standard Platinum Thermometer (SPRT) as performed by [20] and [21].

Table 2. The location of thermocouple points and their calibration data [22].

Thermocouple Type/No.	**Temperature Measurements (°C)**		**Locations point / Remarks**
	Freezing	**Boiling**	
Platinum	0.0	100.0	Calibration set
1	0.1	100.1	Comp in
2	0.2	100.2	Comp out
3	0.0	100.1	Cond. in
4	0.0	100.0	Cond. out
5	-0.1	100.0	Exp. valve in
6	0.0	100.2	Exp. valve out
7	0.1	100.2	Evap. in
8	-0.1	100.0	Evap. out
9	-0.1	99.8	Water bath in
10	0.1	100.0	Water bath out1
11	0.1	100.1	Water bath out2

The accuracy of the measuring instrument is illustrated in Table 3. Uncertainty for each measuring device is summarized in the table. The temperature and pressure readings will be retrieved and stored in a PC using a data acquisition tool for analysis purposes [23].

Table 3. The summary for the uncertainties of the experimental parameters.

Parameters	**Full scale**	**Uncertainty**
K-type thermocouples, K	233.15 to 648.15	±1.5
Pressure gauge	0 - 200	±0.1
Weighing scale	0 - 25	±0.001
Water flow meter	0 - 100	±0.1

Figure 2 shows the points of thermocouples that have been installed. The system is installed with thermocouples at the various essential parts of the system to monitor and record the system's performance and finally to obtain the coefficient of performance value and refrigerant work. The temperature measurement was recorded and observed by a data logger. Pressure gauges monitor the pressure inside the refrigeration system. To measure the pressure, a digital pressure gauge with data logger ability was used. A flow meter is used to monitor the speed of the water bath from the heater to make sure it is constant. Fans are also installed to cool down the refrigerant inside the condenser. AC/DC Power clamp is used to monitor the power consumption used by the electrically driven compressor. The data is collected and logged before it can be analyzed. The result of the analyzed data can be found in section 3.

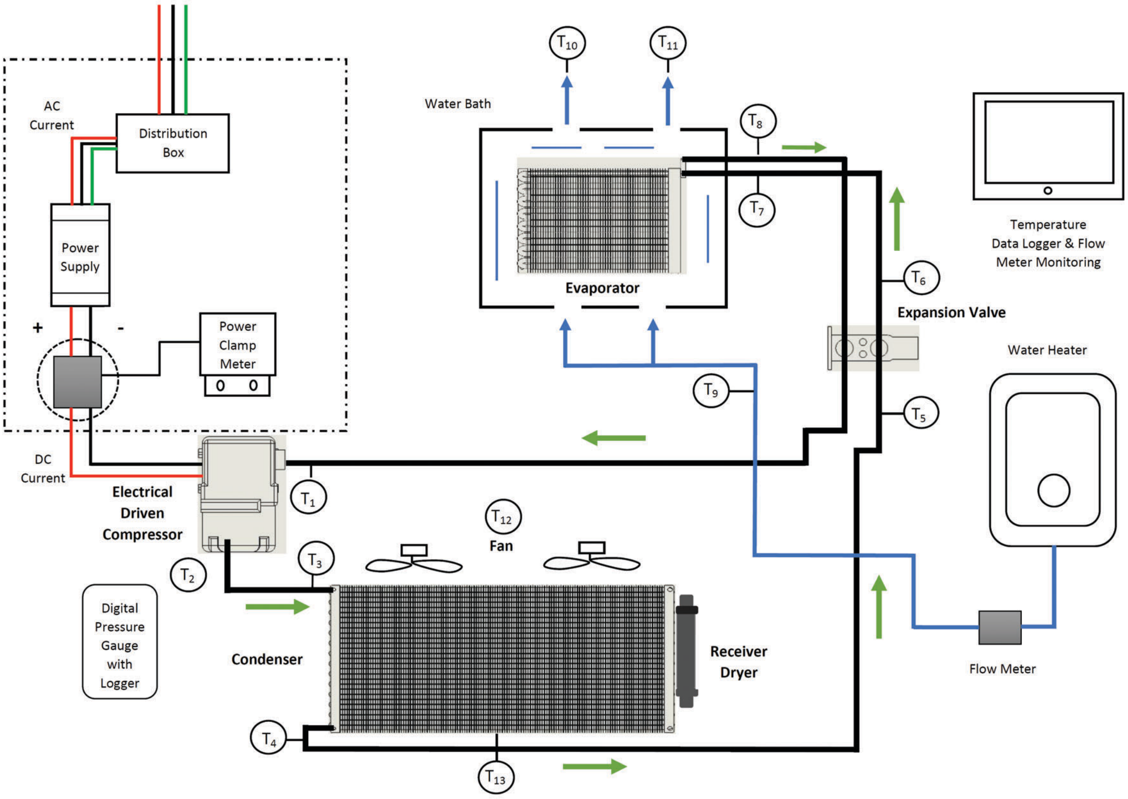

Figure 2. The schematic diagram of hybrid AAC system with thermocouple points

2.3. *Calculation Coefficient of Performance (COP) of the system*

For the experiment, this test rig has been located in a control room. The temperature and humidity of the room need to be monitored and controlled between 26.5 to 27.5°C and 45 to 65%, respectively. The hybrid AAC system will be charged with R134a refrigerant. The initial refrigerant charge is weighed in grams. The ranged of initial charged is between 120 to 160 grams. Firstly, the experiment ran with pure POE nanolubricant and continues with the SiO_2/POE nanolubricant. Before that, this nanolubricant has undergone a process of stability and properties experiments [24]. In this experiment, the temperatures and pressures data were collected for five different initial refrigerant charges with three different speeds for each refrigerant charge. Suggested by SAE International Standard, J2765 OCT 2008, the temperatures and pressures were assessed 15 minutes after the AAC system in a steady-state condition.

The measured data of temperatures and pressures gained from the specific point is critical. It is used to obtain the enthalpy value associated with heat absorption, compressor work, and the COP. The final average enthalpy value was obtained from the repeated data. From the enthalpy value, the heat absorb (Q_L), the compressor work (W_{in}), and coefficient of performance (COP) could be determined using equations (1), (2), and (3), respectively.

$$Q_L = h_1 - h_6 \tag{1}$$

Where $h_4 = h_6$ (Isentropic process)

$$W_{in} = h_2 - h_1 \tag{2}$$

$$COP = \frac{Q_L}{W_{in}} = \frac{h_1 - h_6}{h_2 - h_1} \tag{3}$$

3. Result and discussion

Figure 3 shows the compressor work per unit mass in the initial refrigerant charge function at three different compressor speeds. The compressor work increased as the compressor speed increased. The compressor work also increased by increasing the initial refrigerant charge. The result agreed with Atik et al. [25] and Hamisa et al. [7]. The observation has provided the same trend and pattern and concluded that the compressor work increased linearly with the amount of initial refrigerant charged.

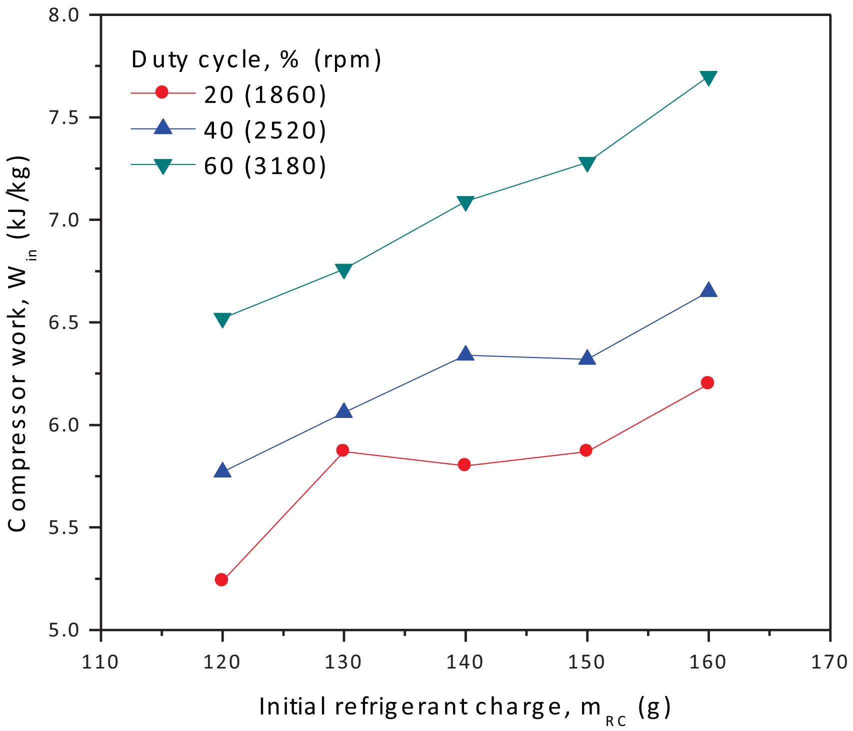

Figure 3. The graph of compressor work against the initial refrigerant charge

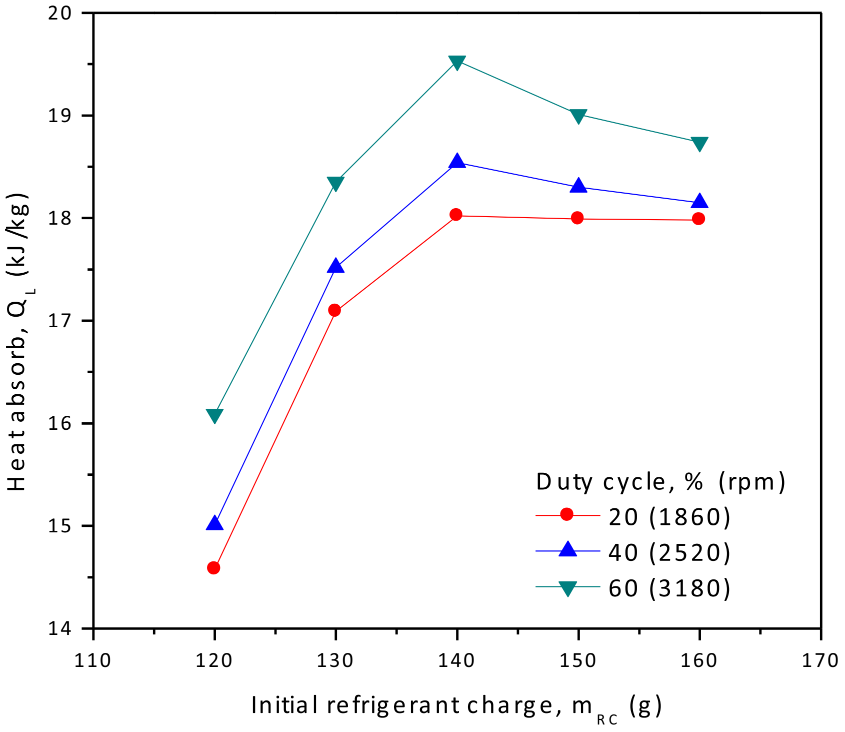

Figure 4. The graph of heat absorb against the initial refrigerant charge

Figure 4 shows the heat absorb against the initial refrigerant charge at different compressor speeds. The result of the trend is almost similar with compressor work at the various speeds which when the compressor speed increased, the heat absorb also increased. The heat absorbs also increased linearly by the increasing of the initial refrigerant charge. However, the maximum heat absorbs for three different compressor speeds were observed at 140 grams and decreased at 150 grams and 160 grams. It shows that the optimum heat absorption is at 140 grams. This trend agreed with Redhwan et al.[11] and Sharif et al. [12] observation.

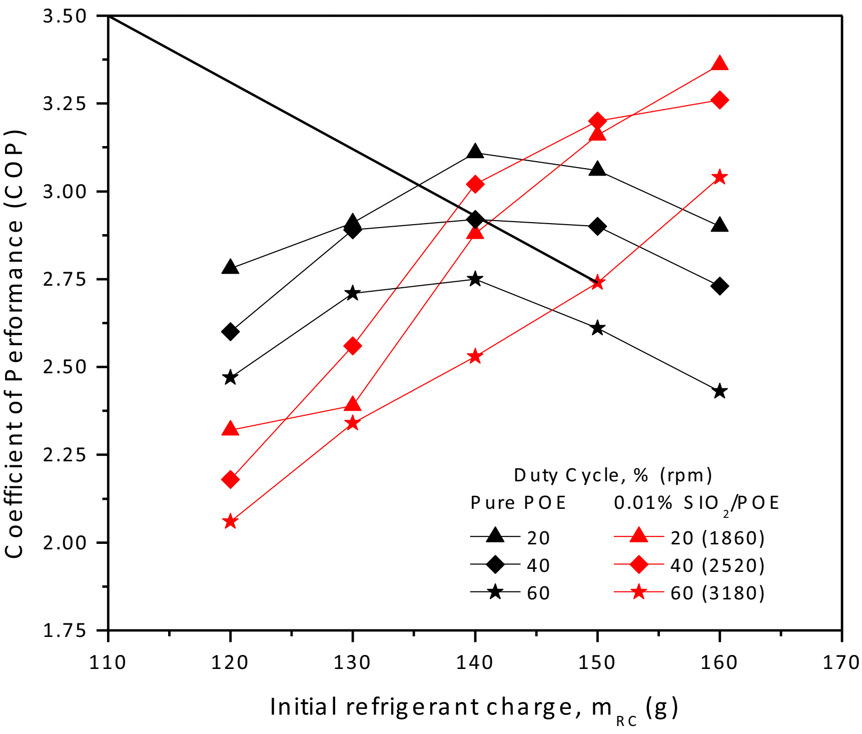

Figure 5. The graph of coefficient of performance against the initial refrigerant charge

Figure 5 shows the COP against initial refrigerant recharge at different compressor speeds. This is a preliminary experiment to test the effect of nanolubricant on the HEV AAC system compared with pure POE lubricant. The COP for POE keeps increasing with the initial refrigerant charge range between 120 to 140 grams. However, it decreases from the range of 140 to 160 grams. The same phenomenon appears at all compressor speeds applied. This is mainly because the oversupply of refrigerant has been a burden to the compressor to operate. Thus increasing drag and decreasing efficiency will result from the lower COP value. The COP results obtained reflect the heat absorb, which has been determined at plotted in Figure 4.

Otherwise, the COP for SiO_2/POE nanolubricant keeps increasing even at 150 gram and 160-gram initial refrigerant charge. This is a positive result because less compressor work leads to a higher COP. This is why we applied nanolubricant in the system, which is to get better lubricant properties for the compressor so that it has better efficiency, thus higher COP value [4, 12]. The highest average COP for SiO_2/POE nanolubricant has been determined at a 40 % duty cycle (2520 RPM) speed with a value of 2.84. The highest enhancement of the COP is 25.1% at 60% duty cycle (3180 RPM) speed with 160 grams of initial refrigerant charged an average enhancement of the COP is 13.16%.

4. Conclusion

The development of a test rig for a hybrid electric vehicle (HEV) air conditioning system has been carried out and explained clearly. The calibration and the location of the thermocouples are well-explained with the schematic diagram. The uncertainties of the experimental parameters also have been explained thoroughly. The compressor work, heat absorption, and COP have been carried out and plotted accordingly. Finally, the findings give the highest average COP for SiO_2/POE nanolubricant is 2.84 at 40 % duty cycle (2520 RPM) speed. The highest enhancement of the COP recorded is 25.1% at 60% duty cycle (3180 RPM) speed with 160 grams of initial refrigerant charged an average enhancement of the COP is 13.16%.

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