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ABSTRACT

The climate control load is the most significant auxiliary loads present in vehicles today. The peak climate control load of an AC system in sedan can be as large as the engine input power. As the attention on vehicle energy economy is rising worldwide, the energy-saving of mobile air conditioning is becoming more and more important. Most mobile AC systems nowadays draw air from outside the vehicle and cool it to the desired comfort level inside the vehicle. Lots of energy is wasted during this process due to continuously cooling the hotter outside air instead of cooling the "cooler" inside air. Compared to that, defaulting to recirculated cabin air will certainly be energy-saving. Though some studies have revealed the energy saving effectiveness under bench test conditions, it is still unclear how much energy can be saved when mobile AC systems are operated in different climates and driving patterns.

The GREEN-MAC-LCCP tool is modelled to evaluate the life cycle climate performance of mobile AC system, and it is well-accepted. This tool is capable of analysing the full cycle of greenhouse gas emissions (GHG) of alternative refrigerant systems and different system structures. In this article, the energy-saving effect of defaulting to recirculated cabin air is evaluated using GREEN-MAC-LCCP. It is found that 7%-48% of energy saving can be achieved under the calculated climate conditions.

1. INTRODUCTION

The air conditioning has become a necessary part in modern vehicle. It is also contributes to a large portion of the total energy consumption. The climate control load due to passengers' thermal comfort needs can have a significant impact on total energy economy. In electric vehicle (EV), this load can result in great range reduction. An 18% (Slezak, 2012)-53.7% (Rask, Duoba, Lohse-Busch, & Walsh, 2011) UDDS range reduction may occur due to cooling requirements in summer. Due to the great impact on vehicle range, the reduction of climate control load is drawing more and more attention. Load reduction measures, such as localized cooling (Chen, et al., 2015) and solar reflective glazing film on windshield have already been studied. The results are quite positive.

Among all parts of steady state climate control load, the ventilation load accounts for the largest part. In warm climate, the ambient temperature is higher than the air inside the cabin. Most of the vehicle AC systems draw air from outside of the vehicle (which refers to the OSA mode of HVAC) and cool it down to the desired comfort level. Lots of energy is wasted among this process, as the AC systems continuously cool the hotter outside air instead of having the AC system draw its supply air from the cooler air inside the vehicle. It is quite obvious that if the AC system draws its supply air from inside of the vehicle (which refers to the REC mode of HVAC), it will be much more energy-saving (Assessment and Standards Division, Office of Transportation and Air Quality, EPA, 2010). Obvious as it seems, there is little work done to quantitatively analyse the effect.

Unlike the residential AC systems, the working conditions of mobile AC systems are much wider. Besides, the working time of mobile AC systems strongly depend on passengers' usage habits and driving cycles. All these parameters make it very difficult to evaluate the energy consumption of mobile AC system. There are mainly three ways to analyse the climate performance of a particular system: the GWP of refrigerant, the TEWI method and LCCP analysis. Compared to GWP and TEWI, LCCP is more comprehensive, thus provides a better understanding of the key parameters in system life cycle climate impact. The GREEN-MAC-LCCP model is a useful tool in evaluating the climate performance of mobile AC system in fuel vehicle. It is well accepted worldwide, and has been widely used to analyse the life cycle climate performance. However, this method is developed for the fuel vehicle (FV), so it is not able to evaluate the climate performance of EV.

This paper will first adopt the GREEN-MAC-LCCP method and make it suitable for EV, then the energy-saving effect of defaulting to recirculated cabin air is quantitatively analysed. The performance data collected from the performance tests is used to supply the LCCP calculation. Then the energy-saving effect of defaulting to recirculated cabin air is evaluated under different climates.

2. ADAPTION OF LCCP MODEL

According to Stella, the calculation result of GREEN-MAC-LCCP is in the form of equivalent CO_2 emission (Papasavva, Hill, & Andersen, 2010). Classified by the causes, the emissions can be divided into direct emission and indirect emission. As the aim of this paper is to evaluate the energy-saving effect of defaulting to recirculation cabin air, the comparison is made between the system energy consumption of defaulting to REC and defaulting to OSA. The direct emission part due to refrigerant leakage and the indirect emissions due to system manufactory, transportation and end-of-life are not included, as they remain all the same in the compared circumstances.

2.1. Main difference in LCCP Model between FV and EV

One of the major differences between FV and EV is that the main power source of fuel vehicle is the engine. During the operation of AC system, the power of the compressor is provided by the engine though a belt. As a result, the speed of compressor in fuel vehicle AC system is determined by the engine speed. Besides, the electricity needed to power the blower in HVAC and cooling fan is also provided by the engine. Unlike FV, the main power source of EV is the battery. The power of compressor, blower and cooling fan comes directly from it. This will result in two differences: first, the compressor speed of the electric compressor is no longer coupled with the motor speed. Second, there is no need to take the power conversion efficiency of internal combustion engine into consideration.

Another major difference between FV and EV is the surface temperature of engine/motor. During the idling of engine, the high temperature of engine surface as well as the low facing velocity of condenser result in a high intake air temperature of condenser. However, in EV, this phenomenon is not that obvious. So the LCCP model of EV should be adopted accordingly to these two difference.

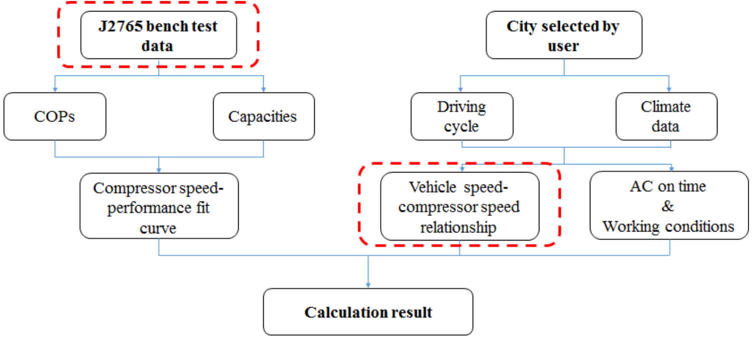

Figure 1 Flow chart of system energy consumption calculation

Figure 1 illustrates the LCCP calculation flow chart of system operation energy consumption. From the figure it is clear that the main differences lie in the bench test conditions and vehicle speed-compressor speed relationships, which have been introduced above. In order to adapt the calculation method, changes must be made in these two parts.

2.2. Basic Assumptions of EV LCCP Model

In order to found new relationships between vehicle speed and compressor speed, some basic assumptions are made here, list as follows:

- The control aim of the air conditioning system is to satisfy the comforting needs of passengers. In order to do that, the compressor speed is adjusted to provide enough cooling capacity to the cabin. In this case, the temperature of the evaporator exit air should meet the requirement of SAE standard J2765. To be specific, a 3℃ or 10℃ evaporator exit air temperature should be achieved according to the standard. Under the high ambient temperature conditions such as 35 ℃ and 45℃, the compressor should be operated in full speed if 3℃ or 10℃ evaporator exit air temperature cannot be achieved. Under the low ambient temperature condition when frost on evaporator will occur, the compressor speed should be high enough to prevent frosting.

- The intake air volume flow rate of the cabin under OSA mode is a function of vehicle speed. This relationship have been experimentally proved by lots of researches. The air flow rate of evaporator is same with the air intake flow rate of the cabin under OSA mode. The average air flow rate under OSA mode is taken as the evaporator air flow rate under REC mode.
- The condenser intake air temperature under vehicle idling conditions is the same with ambient temperature in EV, as the surface temperature of motor is relatively low compared to internal combustion engine.

2.3. Adoption of LCCP Model

2.3.1 Air intake rate of cabin under OSA mode

Knibbs have measured the ACH (Air Change per Hour) of 6 cars under different vehicle speed (Knibbs, Dear, & Atkinson, 2009), HVAC mode and blower level. SF_6 concentrate - decay method was used for the measurement, and the results showed good accuracy and repeatability. In this paper, the air intake volume flow rate of cabin - vehicle speed curve is acquired from an average of results under E3 test conditions. The fit curve is list as follows:

$$Q_v = 0.5629u + 265.34$$

Where Q_v is the air intake volume flow rate of cabin in m^3/h, u is the vehicle speed in $\mathrm{km/h}$.

2.3.2 Adaption of J2765 test matrix

With the work introduced above, the test matrix of J2765 can be adopted into Table 1.

Table 1 Adopted J2765 test matrix

Test No.	Amb. temp.	Condenser		Evaporator			HVAC mode	Eva. outlet temp.
		Inlet temp.	Facing velocity	Inlet temp.	RH	Air flow rate		
	℃	℃	$\mathrm{m/s}$	℃	%	m^3/h		℃
1	45	45	1.5	35	25	290	REC	3
2	45	45	2	35	25	290	REC	3
3	45	45	3	35	25	290	REC	3
4	45	45	4	35	25	290	REC	3
5/9	35	35	1.5	35/25	40/50	271.0/290	OSA/REC	3
6/10	35	35	2	35/25	40/50	279.4/290	OSA/REC	3
7/11	35	35	3	35/25	40/50	301.9/290	OSA/REC	3
8/12	35	35	4	35/25	40/50	310.4/290	OSA/REC	3
13/25	25	25	1.5	25	80	271.0	OSA	3/10
14/26	25	25	2	25	80	279.4	OSA	3/10
15/27	25	25	3	25	80	301.9	OSA	3/10
16/28	25	25	4	25	80	310.4	OSA	3/10
17/29	25	25	1.5	25	50	271.0	OSA	3/10
18/30	25	25	2	25	50	279.4	OSA	3/10
19/31	25	25	3	25	50	301.9	OSA	3/10
20/32	25	25	4	25	50	310.4	OSA	3/10
21/33	15	15	1.5	15	80	271.0	OSA	3/10
22/34	15	15	2	15	80	279.4	OSA	3/10
23/35	15	15	3	15	80	301.9	OSA	3/10
24/36	15	15	4	15	80	310.4	OSA	3/10

Some tips should be noted here:

- The compressor speed should be adjusted according to the evaporator outlet temperature, so it is not listed here.
- The ambient temperature set for defaulting to recirculated is 25°C. When the ambient temperature is above 25°C, the HVAC will automatically set to REC mode. For REC mode, the evaporator intake temperature is 25°C under 35°Cambient condition; for OSA mode, the evaporator intake temperature is the same as ambient temperature.
- The air inlet rate of REC mode is set to the average value of OSA mode, which is 290 m^3/h.

3. EXPERIMENTAL SETUP

3.1. Test Rig Introduction

The experiments were carried out on the automobile air conditioning test rig shown in Figure 2. The test rig consists of indoor and outdoor environmental chambers, compressor room and control unit.

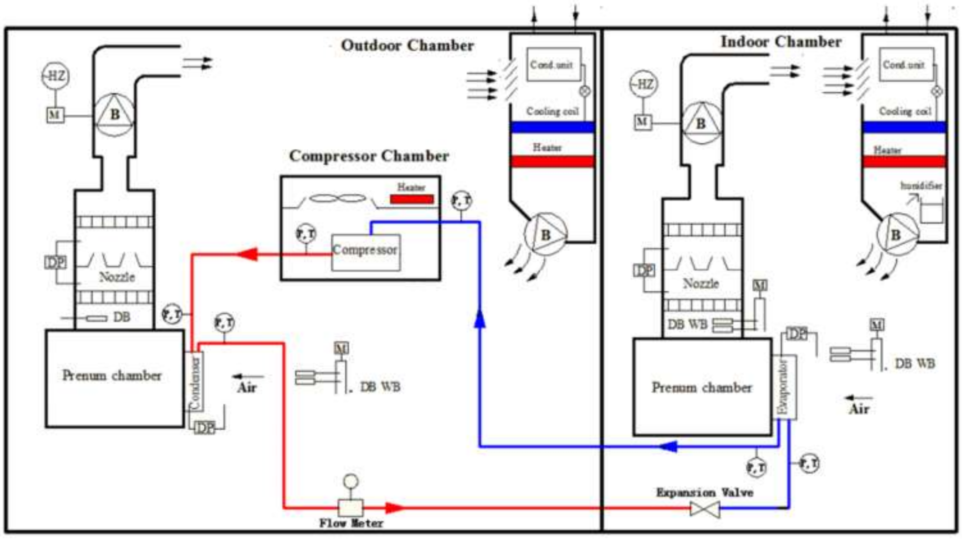

Figure 2. Automotive air-conditioning test bench

The main part of the test rig is the indoor and outdoor environmental chambers, both have individual environmental control units. Environmental parameters are controlled accurately by coolers, heaters and humidifier in the control units. Both chambers have standard wind tunnels to regulate the air volume passing though heat exchangers. Air volume of wind tunnels are calculated from the pressure drops of air passing though the nozzles, while the air flow rates are adjusted by variable speed blowers.

Dry bulb and wet bulb temperature of upstream and downstream of evaporator and condenser are measured by psychometric air sample units based on ASHRAE standards, which are used for calculating enthalpy change of air passing though the heat exchangers. Thus, air side cooling capacities and heat discharges of systems can be obtained by the products of air flow rates and enthalpy changes. Seven groups of pressure transducer and thermal couple are installed in different parts of refrigeration cycle to collect pressures and temperatures. Mass flow rates of refrigerants are measured by mass flow meter, so the enthalpy changes and heat exchanges can be calculated.

The control unit is placed outside of the environmental chamber and all the data and parameters can be collected or controlled by computer automatically.

The accuracy of transducers are list in Table 2.

Table 2. Measure parameters and accuracy.

Measure parameters	Accuracy	Range
Temperature	±0.5 °C	-40-200 °C
Ref. pressure	±10.0 kPa	0-3000 kPa
Air pressure	±2.0 Pa	0-500 Pa
Ref. mass flow rate	±1.5 kg/h	0-500 kg/h
Compressor speed	±10 RPM	0-6000 RPM
Compressor torque	±0.02 N·m	0-50 N·m

The uncertainty of measurements can be calculate according to Moffatt's method, listing in Table 3.

Table 3. Uncertainty of parameters measurement.

Parameters	Heat exchange	Compressor input power	COP	Air volume
Uncertainty	±3%	±2.4%	±3%	±1.9%

3.2. Experimental Setup

The tested system originates from an air conditioning system in an EV that is produced and sold in China. The parameters of main components are list in Table 4.

Table 4. Component details.

Component	Parameters
Compressor	Electric scroll compressor, 34cc
Evaporator	200mm*220mm*38mm micro channel parallel flow HX 2 slabs, 31 rows per slab
Condenser	620mm*364mm*16mm micro channel parallel flow HX,37 rows
Expansion device	TXV, 1.5TR

3.3. Test Conditions

Test conditions of the experiment are listed in Table 1. A charging test was carried out using the charging test condition list in J2765 with compressor speed of 3500 rpm. The optimized charging amount is 850g.

The refrigerant was recycled and the system was vacuumed after the charging test. Then the system was again, charged with 850g R134a and tested according to Table 1. All the data were collected when the system was in steady state.

4. RESULT AND DISCUSSION

4.1. Data Collected from the Bench Tests

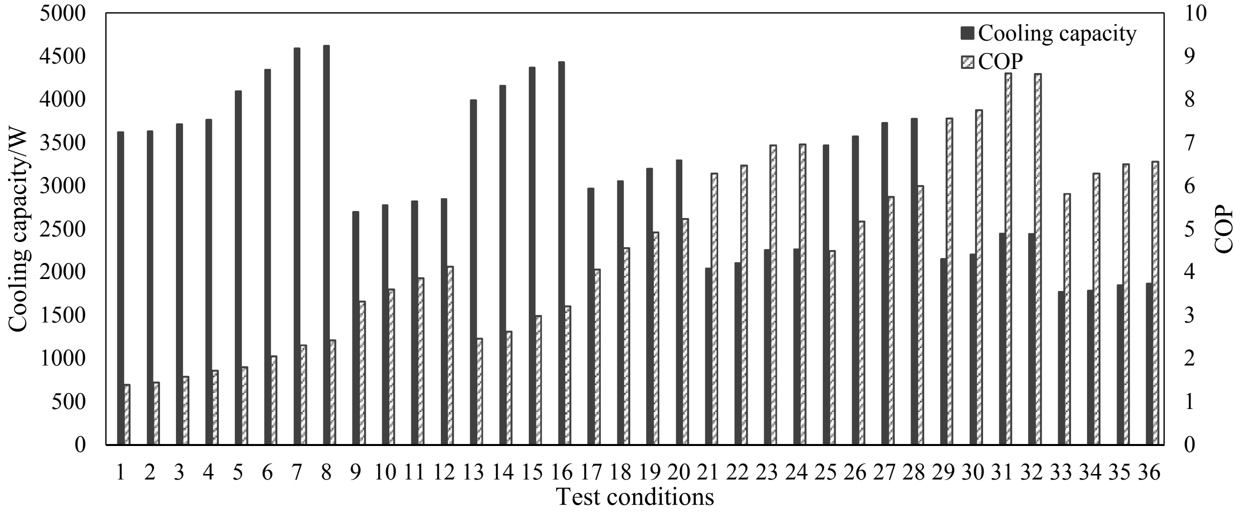

Figure 3 Overview of bench test data

Figure 3 gives an overview of the data collected from the bench tests. It clearly shows that the trends of system cooling capacities and COPs vary with the ambient. Basically, with a higher ambient temperature, the cooling capacity of the system becomes higher and COP becomes lower. Under high ambient temperature, more cooling capacity is needed to achieve a 3℃ evaporator outlet temperature, so the compressor speed becomes higher and cause a lower COP. Compared to test conditions No.5-8, the decrease in cooling capacities under test conditions No.9-12 reveals the energy-saving effect of defaulting to recirculation mode. Due to the high evaporator inlet temperature, the target 3 ℃ evaporator outlet temperature cannot be achieved, so the compressor works at full speed under test conditions No.5-8. However, under test conditions No.9-12, the compressor speed is reduced to 2700 rpm yet the evaporator and a lower evaporator outlet temperature is achieved.

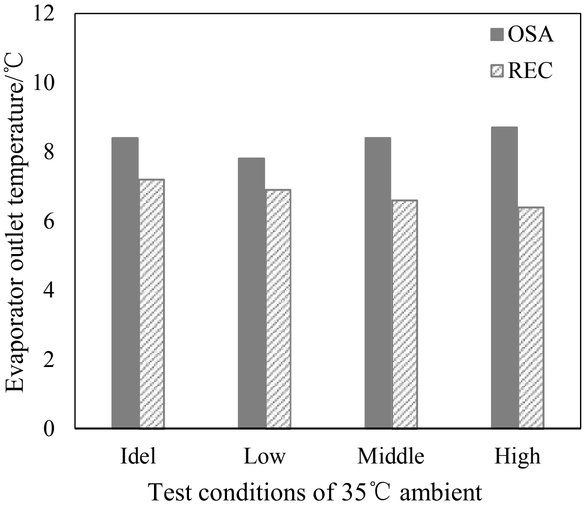

Figure 4 Comparison of evaporator outlet temperatures of OSA and REC mode under 35℃ ambient

The evaporator outlet temperatures of test conditions No.5-8 and 9-12 are shown in Figure 4. It can be seen that under all compared conditions the evaporator outlet temperatures of REC mode are lower than those of OSA mode, which indicates enough cooling capacity is provided under REC mode. The reduced compressor speed leads to a lower compressor input power and higher system COP, so less energy is required. The average capacity of test conditions No.9-12 is 36.9% lower than that of test conditions No.5-8, while the COP is 73.4% higher.

4.2. Evaluation of Energy-saving Effect of Defaulting to Recirculation Air

Four cities across China with different climate conditions are chosen to study the overall energy-saving effect of defaulting to recirculation air. The chosen cities and their location and AC on time in four temperature bin are listed as Table 5:

Table 5 Location and climate condition of the evaluated cities

City	**Location**	**AC on time in each temperature bin / h**				
		0~10℃	**11~20℃**	**21~30℃**	**31~40℃**	**>40℃**
Harbin	126.6°E, 45.8°N	23.44	13.70	135.05	14.64	0
Beijing	116.4°E,39.9°N	15.48	9.81	148.11	77.37	0
Shanghai	121.4°E,34.5°N	97.13	6.76	162.64	92.01	0
Hong Kong	114.1°E,22.2°N	0	0.46	233.58	213.29	0

These four cities lie along the eastern coast of China. The total AC on time becomes longer and average humidity becomes higher in southern cities, and the time in high temperature bins becomes longer. The bench tests data are fed into the adopted LCCP model to evaluate the energy-saving effect. Other inputs, such as the power consumption of HVAC blower and cooling fan are set as the default input of GREEN-MAC-LCCP model.

Figure 5 illustrates the energy-saving effect of defaulting to REC in MAC system. From Harbin to Hong Kong, the energy-saving effect of defaulting to REC becomes larger. In different cities, the defaulting to REC when the ambient is above 25℃ can have an energy-saving effect of 7~48%. This is because the AC on time above 25℃ becomes longer in southern cities, so the defaulting to REC saves more energy. It is obvious that the defaulting to REC method will save lots of energy.

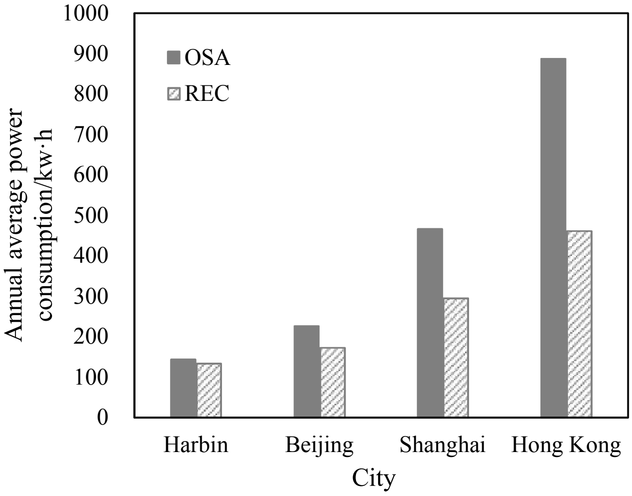

Figure 5 Energy-saving effect of defaulting to REC in evaluated cities

5. CONCLUSION

The energy-saving effect of defaulting to recirculation cabin air is quantitatively analysed in this paper. In order to do that, the GREEN-MAC-LCCP model of fuel vehicle is first adopted to electric vehicle, then the bench test based on the new model is performed to collect data. After that, four cities in China with different climate are chosen to evaluate the energy-saving effect.

The evaluation result show that the energy-saving effect of defaulting to REC is resulted from reduced cooling capacity need of vehicle. Less compression power is needed when the vehicle cooling needs decrease due to a lower evaporator inlet air temperature compared to OSA mode. In different cities, defaulting to REC can save 7~48% AC energy consumption compared to the OSA mode.

NOMENCLATURE

AC	air conditioning
Amb.	ambient
COP	coefficient of performance
EV	electric vehicle
Eva.	evaporator
FV	fuel vehicle
GHG	greenhouse gas emissions
LCCP	life cycle climate performance
REC	recirculation air
Temp.	temperature
OSA	outside air

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