

The Analysis of the Power-Assisted Air-conditioning System in Vehicle

Yu-Tsen Shih* Jieng-Jang Liu[†] and Hsing-Feng Liu[‡]

* Automotive Research and Testing Center,

No. 6, Lugong S. 7th Rd., Lugang, Changhua County, Taiwan, R.O.C.

*Email: kimshih@artc.org.tw

^{†‡} Department of Mechanical Engineering, National Taiwan University, Taipei

[†]Email: jjliu@ntu.edu.tw, [‡]Email: r96522818@ntu.edu.tw

ABSTRACT

For traditional vehicle, the compressor in air-conditioning system (A/C system) is belt-driven by the engine power through the crankshaft. For the idling stop vehicle, the electric power-assisted A/C system is essential for replacing the belt-driven mechanism. In this paper, the saving on fuel economic and performance on energy usage are evaluated for the electric-powered A/C system and the design of auxiliary motor is elaborated for the idling-stop vehicle. The result shows that the fuel consumption increases in 14.2% during the idling condition when the compressor of A/C system is driven by engine. For the power-assisted A/C proposed in this paper, however, the fuel consumption would be decreased more than 30% for the vehicle in highway fuel economy cycle (HWFET cycle) developed by the US EPA. In such a condition, the energy saving is achievable and the heat exchange ability in idling stop period is capable for keeping the desired cabin temperature. Besides, by considering the limited space in engine compartment, a brushless DC motor is properly designed and fabricated for the application to the auxiliary power in the A/C system of an idling-stop vehicle.

Key word: Vehicle, air condition, idling stop

INTRODUCTION

For the traditional vehicle, the cabin temperature is maintained by the frequently switching of electromagnetic clutch, which connects the engine power to the compressor. The power that transferred to the A/C compressor depends on the power and speed that the engine supplies directly. The transferred power can't be in accordance with the demand for refrigerating, exerting a tremendous influence to fuel consumption of the engine. According to an investigation conducted by ITRI, fuel economy of vehicles will be deteriorated in average of 12~21% if air conditioning is engaged [1].

Recently, Denso Corporation in Japan showed that the electric A/C not only can be able to control the cabin temperature steadily but also reduce the power demand while providing the same thermal load as that in traditional belt-driven A/C [2]. Under the same thermal load, the electric powered compressor consumes less energy and increases the driving mileage more than 10%. Matsushita Japan also showed that the A/C compressor actuated by variable frequency technology can be able to maintain the cabin temperature more efficiently [3].

For hybrid vehicle, Denso Japan proposed a 2-Way driven compressor which is driven by engine and/or auxiliary motor when engine is running [4]. During engine stop, the compressor is actuated by assisted motor exclusively. It is shown that the fuel economic can be improved 8% comparing to the traditional belt-driven vehicle.

THE POWER-ASSISTED AIR-CONDITIONING

The power-assisted A/C during the idling stop period produces zero exhaust emission and needs no fossil fuel. It is known that the engine consumes more fuel while the A/C compressor is working, as compared with the case without the A/C operation. In this paper, we carried out experiments to investigate the effects of A/C operation on the fuel economy. For the belt-driven A/C system, the effects of A/C operation on the exhaust emissions are also examined. The A/C system considered in this paper consists of engine, generator, battery, compressor, and auxiliary motor. In order to evaluate the benefits gained from the auxiliary electric A/C system, two types of platform are examined to compare the outcomes for the system with and without the auxiliary air conditioning. In the first type of platform, the A/C compressor is driven by the engine through an electric clutch. For the second type of platform, the auxiliary motor propels the A/C

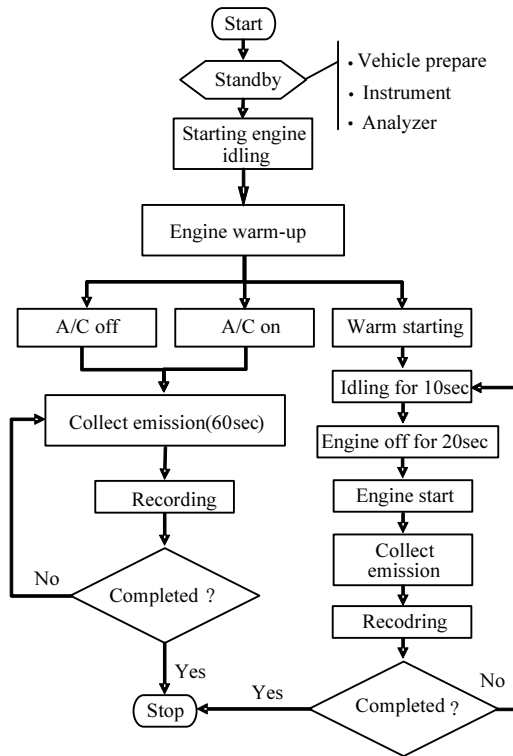


Figure 1 Emission testing procedure

Table 1
The instruments setup for emission test

Testing equipment	Specification
Vehicle	Mitsubishi Savrin 2.0 (2003)
Fuel rate meter	AVL 733S
Emission analyzer	HORIBA MEXT-554JA

compressor during the idling period to ensure the air condition system in operation.

Effect for A/C Operation in Idling

Figure 1 shows the testing procedure of the fuel consumption and exhaust emission for the cases with and without the A/C operation during the engine idling. The vehicle is warm up for sufficient period before testing and feed with the standard FTP No. 4 test gasoline. Fuel consumption and emissions testing were performed on a 2003 SAVRIN produced by MITSUBISHI MOTORS at Automotive Research and Testing Center (ARTC) in Taiwan. ARTC was established to improve the R&D of vehicle related technology, including the product quality, and the internationally recognized testing and certification services. The center is an ISO-9002 accredited testing facility and meets all EPA requirements for fuel economy and emissions testing. The temperature of testing room is maintained at 30°C and the target temperature of passenger cabin is designed to 23°C. The testing equipments are illustrated in Table 1.

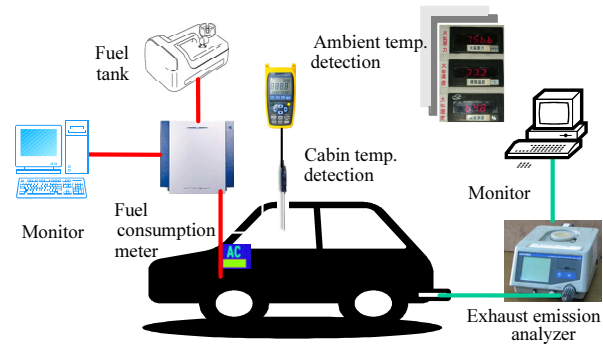


Figure 2 Emission testing construction

Table 2
The effect on fuel consumption and exhaust emission

	Without A/C	With A/C	Warm starting
Fuel consumption rate (g/sec)	0.246	0.281	0.066 ¹
CO (%)	0	0.01	1.18
HC (ppm)	3	3	677 ²
CO ₂ (%)	18.6	18.86	16.14
O ₂ (%)	1.09	1.04	2.59

1: The cranking for start has average in 2.1 sec

2: The maximum value of HC

The detailed testing facility including emission analyzer, temperature control system, cabin temperature sensor and fuel consumption meter is shown in Fig. 2. By taking average measurement data of 12 cycles, the experimental results in idling are shown in Table 2 where the comparison of fuel consumption and emission for the cases with and without A/C operation for 60 sec/cycle is analyzed. It is seen that the average fuel rate is 0.246 g/sec when the A/C is not in operation. Such fuel energy is needed for the engine in normal idling operation. As the A/C is in operation, the fuel rate of 0.281 g/sec is measured for idling condition, equivalent to an increasing of 14.2% fuel to propel the A/C system. In contrast to such a variation in fuel consumption, however, it is observed that the A/C operation has little effect on exhaust emission. The emission control system always keeps the exhaust gases in the desired level.

For an idling-stop vehicle, it is also important to know how much the effect on the fuel consumption and emission as the engine switches on and off frequently. When the engine starts after a short period of turning off, referred to as the warm-starting operation, the engine control system feeds more fuel than the normal idling to ensure a stable starting procedure. Significant emission is evident right after the engine taking a warm starting. For fewer second later, however, the emission will be stabilized to the condition for normal idling.

The experimental results in Table 2 also show the outcome for the warm-starting operation, where the

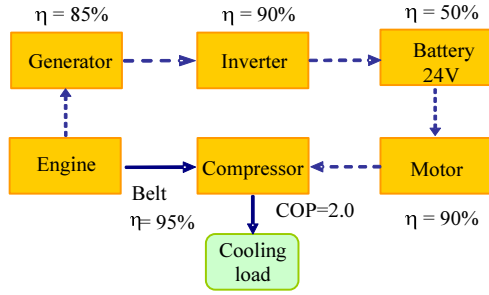


Figure 3 The energy cycle for power-assisted air-conditioning

engine is settled for 10 sec in idling and followed by 20 sec for turned off. Such arrangement is to simulate the vehicles stop for a comparatively short time, for example, while they stop and wait for signal change on the road for 30 sec. In average, the engine needs 2.1 sec for warm starting with fuel rate in 0.066 g/sec, 27% of more fuel is needed compared with normal idling operation. Furthermore, the warm-starting affects exhaust emission as well, as the significant discharge of HC is visible when the richest air-fuel ratio is poured into cylinder during the starting process. To make the comparison more clear, the HC value in Table 2 shows the contrasts between the maximum value of HC before the steady state and those at normal idling condition. It is evident that even the warm starting, the serious exhaust emission is inevitable, even the power-assisted A/C system is implemented.

Evaluation of Energy Saving Performance

For the power-assisted A/C vehicle, the electric energy for the auxiliary motor during idling stop comes from the battery, in which the energy was charged previously. In order to evaluate the performance gained by the auxiliary electric A/C system, the energy exchange cycle for the total system is examined, based on the energy efficiency for the individual component. The energy cycle for the A/C system, as demonstrated in Fig. 3, shows the analytical evaluation for the power-assisted A/C system, where the efficiency for each item is assigned with practical value. In this cycle, the generator transfers the engine power to electricity with efficiency of 85% and the regulator converts the A/C power to DC power with efficiency of 90%. For the lead-acid battery, it is estimated that the discharging efficiency is around of 50% in large discharge current of 2C [5]. Furthermore, the total efficiency of auxiliary motor is 90% while the coefficient of performance (COP) of the air conditioning system is 2. In consequence, the electric energy used to propel motor is transferred from the engine power in a series of transferring process, whereas each process dissipates some energy during transferring. With respect to the energy transfer efficiency, it is important to know how much the fuel energy is needed by the engine to generate the required electric power so that the equivalent amount

Table 3
The parameters for performance evaluation

Item	Parameter	Value	Note
1	Max. thermal exchange capacity	7.1 kW	ambient temp. 35°C, cabin temp. 23°C
2	Engine idling speed	750 rpm	
3	Thermal capacity during idling stop	3717.4 W	ambient temp. 30°C, cabin temp. 23°C
4	COP	2.0	
5	Power required by compressor	1858.7 W	ambient temp. 30°C, cabin temp. 23°C
6	Belt efficiency	95%	
7	Motor efficiency	90%	
8	Generator efficiency	85%	
9	Battery discharge rate	50%	
10	Converter efficiency	90%	
11	Battery Voltage	12 V × 2 series	
12	Battery capacity	40Ah	
13	Idling stop time	< 180 sec	

of heat transfer in A/C system could be maintained the same as the regular belt-driven powered A/C system.

Table 3 illustrates the detailed parameters regarding the evaluation of system performance, where the maximum thermal exchanging capacity required of 7.1 kW and the thermal load in idling period of 3717.4 W are the estimated results for vehicles with the ambient temperature in 30°C and the cabin temperature is designed for 23°C as shown in [6]. In this study, the US Federal Test Procedure (FTP-75) is used to simulate the driving conditions for the on-road vehicles. Instead of knowing the electric energy needed by motor, the equivalent fuel consumption rate $\dot{m}$ (g/sec) for specific driving pattern of FTP-75 can be formulated as following,

$$\dot{m} = \frac{d}{FC_{driving}} \times \frac{S_{driving}}{t_{driving}} \quad (1)$$

where d is the density of fuel (g/L), $FC_{driving}$ is the fuel consumption (km/L), $S_{driving}$ refers to the traveling distance (m), and $t_{driving}$ be the duration time (sec). In order to generate more electric power for motor operation during idling stop period, the additional fuel rate $\dot{M}_{motor}$ that the engine consumed can be deduced as

$$\dot{M}_{motor} = W_{motor} \times \frac{\dot{m}_{withA/C} - \dot{m}_{withoutA/C}}{W_{belt}} \quad (2)$$

where W_{motor} is the engine power needed to propel the motor, W_{belt} refers to the engine power to drive the A/C compressor, while the $\dot{m}_{withA/C}$ and $\dot{m}_{withoutA/C}$ are the fuel consumption rate with and without the A/C operation, respectively.

To compare the variations for different driving patterns, four particular driving conditions referring to as idling (stage 1), urban area speed (stage 2), free

Table 4

The emulation of energy saving for various driving pattern

	Stage 1	Stage 2	Stage 3	stage 4
Driving pattern	Idling	FTP-75 cycle	HWFET cycle	Weighted average
Thermal load (W)	3717.4 (ambient 30°C, cabin 23°C)			
COP	2.0			
Power needed by compressor (W)	1858.7			
Engine output power (W)	1956.5		5399.3	
$FC_{driving}$ with A/C off (km/L)	-	9.93	13.71	11.34
$FC_{driving}$ with A/C on (km/L)	-	7.90	12.10	9.36
Fuel rate with A/C off (g/sec)	0.246	0.704	0.510	0.617
Fuel rate with A/C on (g/sec)	0.281	0.885	0.578	0.747
Specific fuel rate for unit power from engine (g/sec)	-	0.093	0.035	0.067
Fuel rate consumed by motor (g/sec)	-	0.502	0.189	0.362
Energy saving in for unit power from engine (g/sec)	-	↑ 82.6%	↓ 32.7%	↑ 28.8%

way speed (stage 3) and average speed (stage 4) are examined. Table 4 shows the evaluation results for the corresponding driving patterns for each stage. During the idling period with A/C in operation, the fuel rate is 0.281 g/sec. If the idling stop is active, however, the fuel rate becomes 0.502 g/sec for the stage 2 driving condition. This implies that an additional 82.6% of fuel is required if the vehicle runs in urban speed and turns off the engine in idling period while the A/C is operated by the auxiliary motor using the electric energy stored in battery during the vehicle running in urban road. It is worth noting that, however, for the free way speed (stage 3) condition, the fuel rate decrease in 12% with A/C operation, comparing to the stage 1 operation. Specially, in case the electric energy, which is charged to battery during stage 3, is used to propel the auxiliary motor during idling stop period, and more than 30% of fuel decreasing is attainable. The high efficiency operation for the engine in free way speed makes the power-assisted A/C system more effective and potential. In view of the entire driving conditions, however, the fuel rate increases in 28.8% when the results of stages of 2 and 3 are averaged (stage 4).

THE AUXILIARY MOTOR DESIGN

For the application on the idling-stop vehicle, the compressor of A/C system is powered by the auxiliary motor during the engine stop period. The design

Table 5

Motor specifications and operation condition

	Item	Value
Motor	Rated Torque	13 Nm @ 1000 rpm
	Voltage	24 V
	Max. current (rms)	<100 A
	Stator diameter	<100 mm
	Winding	3 phase Y-connected
Operation	Working period	During idling stop
	Max. speed	1200 rpm
	Duration	<180 sec
Compressor	Type	Fixed displacement
	Displacement	140~180 cc/rev
	Thermal exchange capacity ¹	1~3 kW

1: For speed of 1000 rpm

procedure for the motor is introduced in this section, toward the objective of maximizing torque and minimizing torque ripple, subject to various constraints of geometry and material properties. First, sensitivity analysis is performed to examine the relationship between motor performance and design variables. By selecting a minimal number of design variables, the motor is designed in an optimal way by the multifunctional optimization system tool (MOST) [7]. A complete verification of design is then analyzed by the finite element method [8].

Specifications and Operating Condition

Table 5 shows the motor specifications in which the torque is 13 N·m at speed of 1000 rpm and the power source voltage in 24 V. The size of motor is limited by 100 mm in diameter and 50 mm in thickness. In order to interface between the engine structure, the motor is designed to link both the magnetic clutch and input shaft of compressor. By adding the motor in between, the compressor can be operated by either the belt-driven from engine or turning force from motor.

Motor Design

The motor design procedure follows the flowchart in Fig. 4. Following the specification as shown in Table 6, motor configuration is determined by comparing the ratio between the number of poles and slots and investigating possible winding methods. Second, under the same constraints of size, voltage and current, the maximum torque production and torque ripples are examined, and the concentrated winding is found better than the distributed winding due to the restriction of space. Finally, the electromagnetic analysis in a 3-D finite element model verifies the optimal design result from magnetic circuit model in a 2-D approximation. The electromagnetic analysis software, ANSOFT, provides both stationary and transient simulations of motor

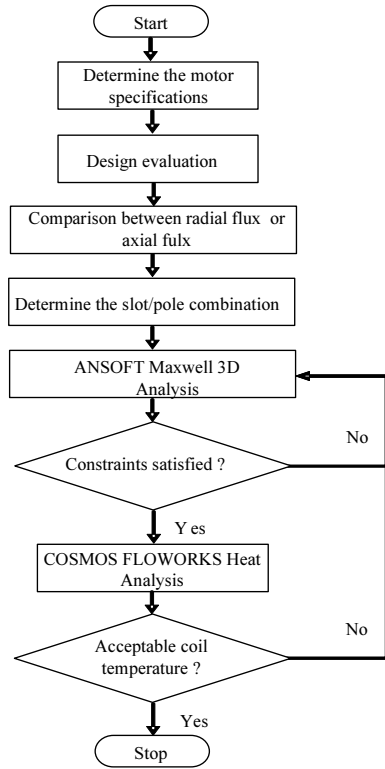


Figure 4 The auxiliary motor design procedure

Table 6
Specification of motor design

Item	Parameter	Item	Parameter
Magnetic	NdFe35	Air gap	0.4 mm
Stator	Steel 1008	No. of turns	24 turns
Rotor	Iron	Dia. of winding	1.628 mm
Winding	AWG-#14	Tooth length	10 mm
No. of Teeth	9	Tooth width	12 mm
No. of Poles	8	Width of magnetic	4 mm
Outside dia. of stator	50 mm	Back iron width of stator	5.5 mm
Inside dia. of rotor	24 mm	Back iron width of rotor	6 mm
Width of stator	50 mm	Slot packing factor	67.1%

performances in light of magnetic flux density distribution, torque distribution, torque ripples and back electromagnetism force (back emf). Heat and structure analysis on the thermal and structure vibration properties are also investigated. Finally, the 3-D construction and the fabricated prototype of the proposed motor are shown in Fig. 5.

The simulated torque and ripple for the well-designed motor are 15.5 N·m and 6.9%, respectively. In experimental result, the maximum torque approaches 13.11 N·m with the current in 62 A. As a result, the fabricated auxiliary motor is capable of driving the

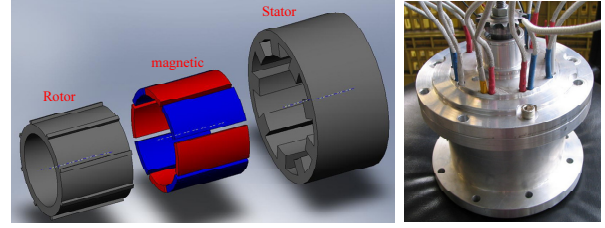


Figure 5 The 3-D construction and fabricated prototype

compressor in the target experiment vehicle.

CONCLUSION

The saving on fuel economic and performance on energy usage are evaluated for the electric-powered A/C system and the design of auxiliary motor is elaborated for the idling-stop vehicle. The result shows that the fuel consumption increases in 14.2% during the idling condition when the compressor of A/C system is driven by engine. However, the fuel consumption would be decreased more than 30% for the vehicle in free way speed driving pattern in power-assisted A/C system on an idling-stop vehicle. Besides, by considering the limited space in engine compartment, a brushless DC motor is properly designed and fabricated. The future work will focus on the experiment testing for the prototype A/C system, where compressor, magnetic clutch and auxiliary motor are assembled to complete the entire A/C system.

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