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Performance evaluation and analysis of EV air-conditioning system

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Abstract

The electric air conditioning system is in relation to the comfort of the electric vehicle. In this paper, the influence of several parameters on the electric air conditioning system was studied. The model of the air conditioning system was developed based on the thermodynamic and the performance testing results of the components. The model was coded on the Matlab/Simulink platform and simulated. The simulation results show that the ventilation ratio and the indoor blower speed could be used to remove the heat entered the cabin in a short time. Therefore, these two parameters could be used as the major control parameters for the developing thermostat controller.

Keywords: electric vehicle, electric air-conditioning system, scroll compressor

1. Introduction

The electric vehicle (EV) is now a popular research topic for the vehicle manufacturer and the academic around the world. Most of the researches focus on the advanced energy storage device and the power-train technology to improve the performance of EV. Regardless of the mileage and driving performance improvement, several electrical accessory systems are implemented on the EV to provide functions which are related to safety and comfort. One of these accessory systems is the electric air-conditioning (A/C) system.

The development of the electrical AC system provides several advantages to the EV performance. The electric AC system is driven by an electric compressor which includes a compressor and an electric motor. The electric compressor had been developed and installed in the EV or the hybrid vehicle for the past decade [1], [2]. Because of the electric compressor, the electric AC system can operate at arbitrarily rotating speed according to the controller which can provide adequate and sufficient refrigeration performance. Therefore, the energy consumption of the A/C system can be controlled precisely which is helpful to improve the vehicle driving mileage.

In this paper, the model of the electric A/C system, which included a condenser, an evaporator, an electric compressor and an expansion valve, was built and simulated to study the influence of several parameters on the A/C system performance of the EV.

2. Air Conditioning System Modeling

The electric A/C system model includes the condenser, the evaporator and the expansion valve. The model of these components was developed based on the thermodynamics in the refrigeration cycle or the performance testing results.

2.1 Thermal Load of the Vehicle Cabin

In order to provide a sufficient cooling ability to the passengers, the specifications of the electric compressor should be chosen carefully. Therefore, the thermal load to the vehicle cabin was analyzed firstly. The thermal load comes from various sources which include (a) heat transferred from the vehicle environment, (b) heat generated by the human body, (c) the radiation heat comes from the sun and (d) the other accessory systems [3]. The model of these heat sources were modeled according to the heat transfer pattern and coded in the simulation program.

2.2 Scroll Compressor

Once the thermal load of the cabin was calculated, the specification of the compressor was chosen. In this study, a scroll compressor was chosen to drive the refrigerant. The scroll compressor is gradually being adopted in the modern vehicle because of the compact size and low malfunction rate. In the electric vehicle, the compressor is driven by an electric motor instead of the engine. Therefore, the speed of the compressor can be arbitrarily operated to provide adequate cooling performance according to the control strategy. This is quite different from the traditional vehicle which the compressor speed is in proportion to the engine speed. The performance of the compressor used in this study was built into a lookup table based on the testing data form the manufacturer as shown in Figure 1.

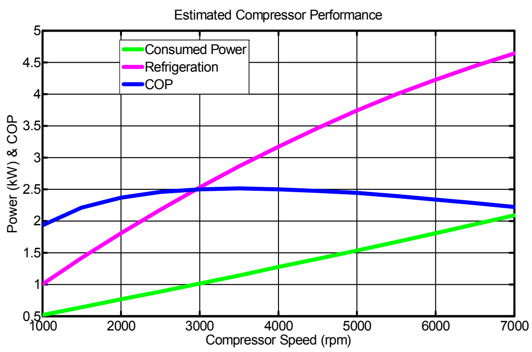

Figure 1: performance map of the scroll cmpressor

2.3 Electric Motor

A DC brushless motor was used to drive the compressor. Therefore, the motor specification could be decided based on the compressor performance. The motor specification is shown in Table 1. The operating voltage was chosen to be the same as the EV powertrain system. The output power and the operating speed were designed based on the performance map in Figure 1. The detail parameters of the motor which were designed to satisfy the demanded performance are also shown in Table 1. Figure 2 shows the simulated result of the Torque-Speed relationship of the DC motor.

Table 1 Demanded performance of the DC motor

Demanded motor performance	
Operating Voltage (V)	330
Output power (W)	< 2300
Operating speed (rpm)	< 7000
DC Motor specifications	
Stator length (mm)	45
Permanent magnet	Nd-Fe-B (N35H)
Silicon steel	35CS470
Output torque (N-m)	3.2
Back emf (V)	235
Efficiency	~ 90%
Volume (cm)	L 18.2 x W 14.5 x H 15.5

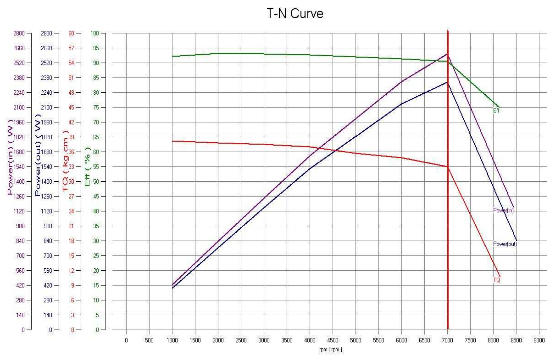

Figure 2: Torque-speed curve of the DC motor

2.4 Evaporator and Condenser

The evaporator and the condenser are simply heat exchangers that transfer heat from the cabin to the environment. Therefore, the thermal dynamics of the condenser and the evaporator can be expressed based on the heat exchange phenomena between the refrigerant and the air. The heat transferred from the refrigerant to the heat exchanger wall is

$$\dot{m}_r c \frac{dT_r}{dx} = h_w \pi d_c \left(T_w - T_r\right) \qquad (1)$$

where $\dot{m}_r$ is the mass flow rate of the refrigerant, c is the specific heat of the refrigerant, h_w is the heat transfer coefficient between the refrigerant and the wall, d_c is the inner diameter of the heat exchanger, T_w and T_r are the temperature of the heat exchanger wall and the refrigerant, x is the distance from the entry of the heat exchanger. The refrigerant temperature at specific distance from the entry can be derived from Eq. (1)

$$T_r = T_w + (T_i - T_w)e^{-(xh_w \pi d_c)/(\dot{m}c)} \quad (2)$$

where T_i is the inlet temperature of the refrigerant. Therefore, the heat exchanged from the refrigerant to the exchanger wall can be expressed as

$$q_c = n_c \dot{m} c (T_i - T_w)e^{-(Lh_w \pi d_c)/(\dot{m}c)} \quad (3)$$

where L is the length of the channels.

The heat exchanged between the heat exchanger and the air can be derived as

$$q_h = A_h h_h (T_w - T_a) \quad (4)$$

where A_h is the effective heat exchange area of the exchanger, h_h is the heat transfer coefficient between the wall and the air, T_a is the inlet air temperature. In the steady operating situation, the heat transferred in Eq. (3) will equal to Eq. (4), and the temperature of the heat exchanger wall can be derived as

$$T_w = \frac{A_h h_h T_a + \dot{m} c T_i \left(1 - e^{-(Lh_w \pi d_c)/(\dot{m}c)}\right)}{A_h h_h + \dot{m} c \left(1 - e^{-(Lh_w \pi d_c)/(\dot{m}c)}\right)} \quad (5)$$

The refrigerant temperature at the exit of the heat exchanger can be solved by Eq. (2) and (5).

2.5 Expansion Valve

The expansion valve is used to decrease the refrigerant temperature from the condenser by decreasing the pressure. The valve also acts as a limit to the refrigerant flow rate which can be used to control the A/C system efficiency. The mass flow rate passed the valve is derived as

$$\dot{m}_i = c_d \rho_r A_{ev} \sqrt{\frac{2(P_u - P_d)}{\rho_r}} \quad (6)$$

where c_d is the specific heat, ρ_r is the refrigerant density, A_{ev} is the flow area of the expansion valve, P_u and P_d are the upstream and the downstream pressure of the expansion valve.

3. Air Conditioning System Simulation

The A/C system was coded and simulated on the Matlab/Simulink platform to study the influence of various system parameters to the cooling performance. The specifications of the vehicle are listed in Table 2 which was used to calculate the thermal load of the cabin. The thermal load of the EV was used to decide the operating conditions for the scroll compressor and the driven motor.

Table 2 Vehicle specifications

Vehicle specification	
Front windshield area(m2)	0.858
Rear windshield area (m2)	0.6832
Side glass area (m2)	1.0864
Inclination angle of Front windshield	52.33°
Inclination angle of Rear windshield	64.53°
Vehicle side area (m2)	3.9626
Tail area (m2)	1.5353
Rooftop area (m2)	3.348
Bottom area (m2)	6.552
Environment temperature (℃)	35
Cabin temperature (L)	23
Inclination angle of sun	30°

3.1 Simulation of the different indoor parameters

There are several parameters which are controlled or varied by the passengers to adjust the A/C system performance. These parameters were simulated to study the influence to the A/C system.

One of these parameters is the demanded temperature set by the passengers. Since the heat needed to be removed increases with the lower demanded temperature, the cooling air temperature, which is represented by the solid line in Figure 3, increases with the demanded temperature. It can be seen that the lower air temperature can remove higher amount of heat which is shown by the dot line in Figure 3.

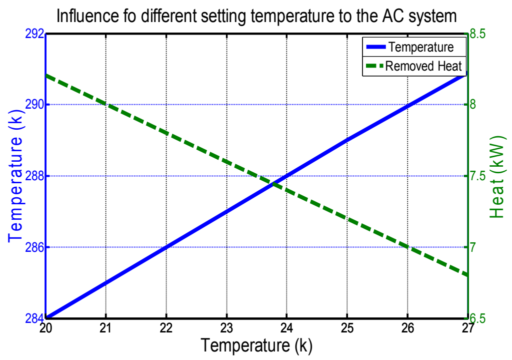

Figure 3: Influence of the demanded temperatures

The second parameter controlled by the passenger is the indoor blower speed. The change of the blower speed will vary the air flow rate passed the evaporator. The solid line in Figure 4 shows that the outlet air temperature increases with the air flow rate. It is due to the higher air flow rate shorten the time which the air passes the evaporator. Therefore, the heat absorbed by the refrigerant decreases and the outlet air temperature becomes higher. However, the heat removed by the A/C system still increases because the higher air flow rate as the dot line shown in Figure 4.

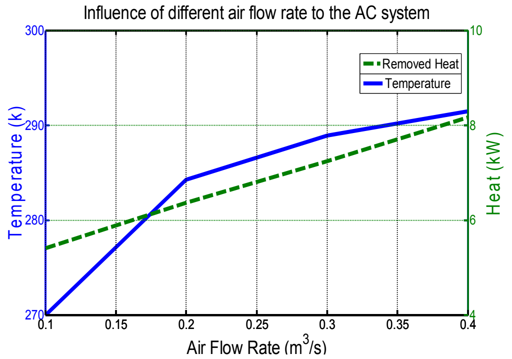

Figure 4: Influence of the different blower speed

The passenger number in the cabin is also an important factor for the A/C system to maintain constant temperature. The influence of the passenger number is shown in Figure 5. It can be seen that the outlet air temperature decreases in order to remove the additional heat which comes from the increased passenger.

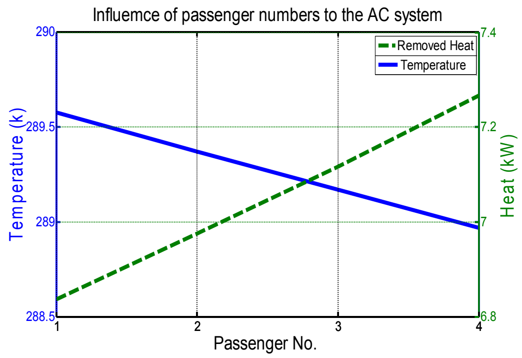

Figure 5: Influence of the different passenger number

The ventilation ratio is changed by the outdoor air valve damper. The higher the outdoor air flows into the cabin, the lower the cooling air in the cabin is recycled. Therefore, there is additional heat came into the cabin with the high temperature outdoor gas. Figure 6 shows the result of the outlet air temperature and the removed heat under different ventilation ratio. The outlet gas temperature decreases under low ventilation ratio to remove the additional heat came into the cabin as the dot line shown in Figure 6.

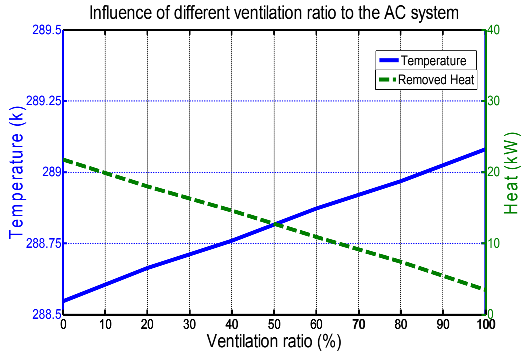

Figure 6: Influence of the different vantilation ratio

3.2 Simulation of the environment parameters

The change of the environment parameters simply change the amount of the heat entered the cabin. Three parameters, which are the environment temperature, the humidity and the solar load, are simulated to study the influence to the A/C system.

Figure 7 shows the outlet air temperature and the heat removed by the A/C system under different environment temperatures. The outlet air temperature, which is represent by the solid line in Figure 7, slightly decreases as the environment temperature increases from 293 k to 313 k. It is due to the heat entered the cabin increases with the environment. Therefore, the cooling air temperature drops to remove the additional heat which is represented by the dot line shown in Figure 7.

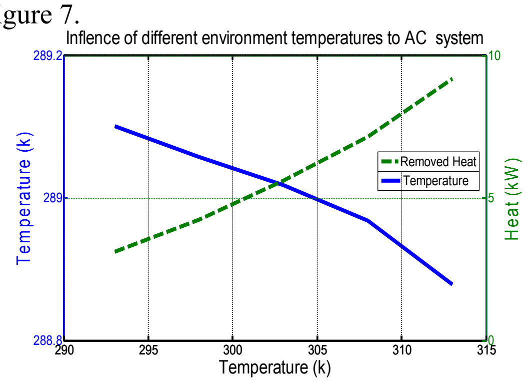

Figure 7: Influence of the environment tempratures

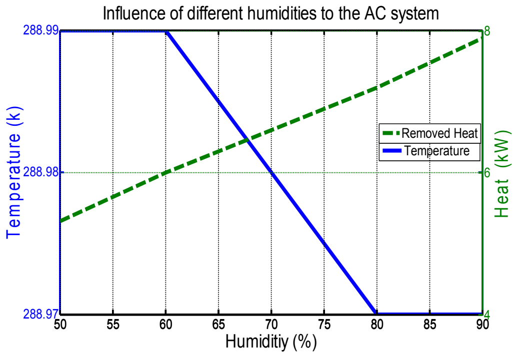

Figure 8: Influence of the different humidity

The influence of the humidity on the outlet air temperature is shown by the solid line in Figure 8. Since the outlet air temperature slightly decreases with the increased humidity, the humidity is only a minor parameter to the change of the outlet gas temperature. However, the A/C system needs to remove the condensation heat of the vapor because of the higher humidity. The increase the removed heat is represented by the dot line in Figure 8.

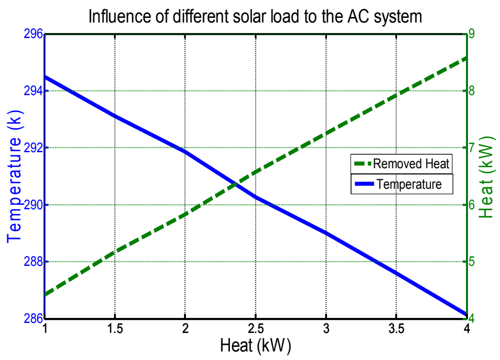

Figure 9: Influence of the different solar load

Figure 9 shows the behavior of the outlet air temperature and the heat removed by the A/C system under different solar load. If the solar load increases, the radiation heat which enters the cabin through the glass and the sheet metal will increases. Therefore, the outlet gas temperature has to decrease to remove the additional heat as shown with the solid line in Figure 9. The heat removed by the A/C system shows a linear relationship with the solar load as represent by the dot line in Figure 9.

4. Conclusion

In this paper, a semi-empirical model for the electric vehicle A/C system was built and simulated on the Matlab/Simulink platform. The influences of several parameters on the A/C system performance were studied. The simulation results show that the solar load and the environment temperature have greater impact on the A/C system. The simulation shows that lower ventilation ratio and higher blower speed can rapidly removed the additional heat which entered the cabin.

The simulation results could tell us whether parameters could be used in the thermostat controller development for the electric vehicle. The model can also be used to check if the chosen A/C system components specification could provide sufficient refrigeration capability to the electric vehicle or not.

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Po-Hsu Lin recevied his B.S., MSc and Ph.D degrees from the National Tsing Hua University, Taiwan, in 2000, 2002 and 2008 respectively. He is now an associate engineer in the R&D division of ARTC. The research topic is focused on the thermostat and energy-saving control strategy of the electric automotive air-conditioning system.