Research on vehicle cabin temperature and thermal comfort optimal control based on fuzzy PID

Changhao Piao*, Weiwei Wang, Ziyang Liu, Cunxue Wu, and Rongdi Yuan

1School of Automation, Chongqing University of Posts and Telecommunications, Chongqing 400065, China
2Chongqing Changan New Energy Science and Technology Co., Ltd., Chongqing, China

*Corresponding author: s180301040@stu.cqupt.edu.cn

Abstract. The heat load of the car compartment is complex and difficult to express with mathematical models. Therefore, this paper establishes a compartment physical model of an electric car through Amesim and simulates the heating process of the heat pump air conditioning system. Because the load of the passenger compartment of the car is complex and changeable, and the heat pump air-conditioning is a large inertia, hysteretic system. This study designs fuzzy rules and uses fuzzy PID to control the temperature of the passenger compartment. Fuzzy PID control has 1.6% less overshoot than PID control and 39 seconds less setting time. At the same time, this paper establishes a thermal comfort model of cabin temperature and humidity. It uses PMV (predicted average vote) and PDD (dissatisfied percentage) thermal comfort index to evaluate the passenger cabin’s thermal comfort. The PMV index controlled by fuzzy PID is more stable than the PMV controlled by PID.

1. Introduction

The air-conditioning system is an essential thermal management system for new energy vehicles. While providing heat, it consumes a large amount of electricity, which reduces the vehicle's cruising range by 15% [1-2]. In extreme conditions, vehicles' mileage using the air conditioning system has been reduced by 30-40% [3]. Therefore, the thermal comfort and energy consumption control of new energy vehicle air conditioners are crucial.

Automobile air-conditioning control methods are also constantly changing. On-off control is a widely used control algorithm [4]; PID feedback control is a commonly used control method in air-conditioning systems, with simple structure and high efficiency [5]. Because the air conditioning system is nonlinear, the external vehicle speed, solar radiation. Drastically change, the PID control effect is not ideal. Farzaneh et al. used a fuzzy control strategy to control the temperature of the passenger compartment, and established two independent modes of air conditioning system, one for the occupants. The cabin temperature is controlled, and thermal comfort is controlled [6]. NG et al. proposed an adaptive predictive controller for air conditioning chest pain based on an online training neural network, which can accurately predict the air conditioning system's dynamic characteristics and achieve precise control of the air conditioning system [7].
Fanger et al. proposed thermal comfort indicators PMV and PDD and set PMV=0 as thermal comfort conditions [8]. Paul Danca summarized the popular methods of evaluating thermal comfort in recent years and the crucial factors affecting thermal comfort [9].

2. cabin model establishment and thermal comfort index selection
In this article, the model of the cabin is established utilizing physical modeling. It analyzes the heat exchange between the engine room and the outside world, builds it through the AMESIM model, and simulates the heat pump air conditioning system. The working condition is that the heat pump system heats the cabin at a low temperature of -15°C. There are several standard thermal comfort models.

The thermal comfort model is selected PMV and PDD indicators to control and analyze the cabin temperature. Among them, the main factors affecting the PMV index are the temperature, humidity, and average radiance of the cabin.

2.1. Establishment of the physical model of the cabin
In the heat exchange model of the passenger compartment of a car, the primary heat exchange includes the front windshield, the rear windshield, the side window glass, the side body, the roof, and the environment for heat exchange. After the solar radiation passes through the glass, part of the heat will be refracted into the passenger compartment. Part of the heat will enter the passenger compartment through the glass to exchange heat with the car's environment. The dashboard will partially absorb the heat radiation transmitted through the front windshield. When solar radiation is relatively large, it will significantly impact the car's heat exchange. After the heat passes through the glass windows and the body, it exchanges heat with the air in the passenger compartment, affecting the passenger compartment's temperature and humidity.

Through the cabin model, combined heat pump air conditioning system, the air conditioning system's air outlet temperature is connected to the cabin. The initial temperature and ambient temperature of the passenger compartment are set to -15°C. To better verify the performance of the air conditioning system, the initial temperature of the body material is set to -15°C (simulating the car body soaking in an environment of -15°C for 8 hours), and the temperature of the passenger compartment is controlled by controlling the heat pump speed.

Figure 1. Cabin temperature corresponding to different compressors
2.2. Thermal comfort evaluation index

The ASHRAE Standard 55 and the International Organization for Standardization Standard 7730 specify the temperature range most people feel satisfied with. These standards are mainly based on the PMV human thermal comfort model of Professor P. O. Fanger of the Danish University of Technology. Generally, the passenger compartment's thermal comfort mainly includes the following variables: temperature, relative humidity, and mean radiant temperature [10].

\[
PMV = [0.028+0.303\exp(-0.036M)]\cdot[M-W-E_c-E_{res}-C_{res}-H]
\]

\[
PDD = 100-95\cdot\exp(-0.03353\cdot PMV^4-0.2179\cdot PMV^2)
\]

In formula (1), \(M\) represents the human energy metabolism rate, \(W\) is the mechanical work done by the human body, \(E_c\) is the heat dissipation of human skin and sweat, \(E_{res}\) is the latent heat loss of human breathing, and \(C_{res}\) is the sensible heat loss of human breathing the quantity, \(H\) is the body surface and radiation loss.

| INDEX | -3      | -2      | -1      | 0   | 1   | 2   | 3   |
|-------|---------|---------|---------|-----|-----|-----|-----|
| PMV   | cold    | colder  | cooler  | comfort | Warmer | Warm | hot |

According to the thermal comfort index, when it is \(0.5<PMV<0.5\), \(PDD<10\%\), the passenger compartment is in a thermal comfort state. According to this index value, the passenger compartment's control algorithm is adjusted to control the passenger compartment's thermal comfort through the control strategy.

A thermal comfort model was established in AMESIM. Figures 4 and 5 show the thermal comfort index PMV and PDD values for PID control of the passenger compartment temperature from -15°C to 25°C.
3. Controller design
Due to the large inertia, hysteretic system of the heat pump air-conditioning system, when PID controls the temperature of the passenger compartment model, the temperature fluctuation will be relatively large. Due to the influence of other external environments, the control effect produced under different working conditions will be different. In this case, the fuzzy PID control algorithm is used to adjust the heat pump's speed. The passenger compartment's heat exchange is adjusted by adjusting the speed of the heat pump, thereby controlling the passenger's temperature compartment. For fuzzy PID control, customizing
different control rules will produce different control effects to control the passenger compartment's thermal comfort. The fuzzy PID control method is used in this study. In fuzzy PID control, the difference $E$ between the control set temperature and the model simulation temperature in the passenger compartment and the derivative of the difference $EC$ are used as the fuzzy PID input, and the KP, KI, and KD of the PID controller are output. Through the design of fuzzy rules, the control performance of the controller is better.

3.1. Selection of membership function
There are many kinds of membership functions, which have a particular influence on on-air control. In fuzzy control, the choice of membership function will directly affect the control effect. Common styles of membership are s-type, Gaussian, z-type, triangle, etc. This time the fuzzy control uses the middle triangle, with z-shaped membership functions on both sides. The range of $E$ is -50 to 50, and the range of $ec$ is -5 to 5. There are 7 fuzzy subsets. KP, KI, and KD also have 7 fuzzy subsets: NB, NM, NS, Z, PS, PM, PB.

3.2. Fuzzy rules.
This model mainly verifies the heat pump's heating performance in a low-temperature environment. The fuzzy rules are only the fuzzy rule set from low-temperature heating to average temperature. The first letter in brackets represents the fuzzy subset of KP, the second letter represents the fuzzy subset of KI, and the third letter represents the fuzzy subset of KD. The first row in the table represents the fuzzy subset of EC. The first column represents the fuzzy subset of E. The first letter in the parentheses of the table content represents the fuzzy subset of KP, and the second letter represents the fuzzy subset of KI. Three fuzzy subsets are representing KD. That constitutes the entire fuzzy rule set.

|       | PB    | PM     | PS     | Z      | NS     | NM     | NB     |
|-------|-------|--------|--------|--------|--------|--------|--------|
| PB    | (NB,NB,PM) | (PM,PS,PS) | (PS,PS,PS) | (PS,Z,Z) | (PS,NS,PS) | (Z,NS,NS) | (Z,NS,NS) |
| PM    | (PB,PS,Z) | (Z,NS,NS) | (NS,PS,NS) | (Z,NS,NM) | (Z,NS,NM) | (Z,Z,NS) | (Z,Z,NS) |
| PS    | (PS,NB,Z) | (Z,NB,NS) | (Z,NB,NM) | (Z,NB,NB) | (Z,NB,NM) | (Z,NB,NS) | (Z,NB,NM) |
| Z     | (PS,NB,NM) | (PS,NB,NM) | (NM,NB,NB) | (NM,NB,NM) | (NM,NB,NM) | (NM,NB,NM) | (NM,NB,NM) |

The establishment of fuzzy PID control rules in Matlab, the surface rules are shown in Figure 5, Figure 6, Figure 7.

![Figure 5](image_url)
Establish a fuzzy PID control strategy in Matlab, build the model with Amesim, and conduct a simulation test.

Through the joint simulation of Matlab and Amesim, the fuzzy control rules are written into the fis file of Matlab. Since fuzzy PID control's input and output are real physical values, it is necessary to limit the input and output of fuzzy PID control to prevent the output value from crossing the boundary affects the control effect.
4. System simulation and analysis
In the simulation, the member cabin’s initial temperature is set to -15°C, and the relative humidity is set to 50%. Due to the heating performance under the simulated low-temperature illusion, solar radiation is set to 50W. The simulation time is set to 600 seconds. The fuzzy PID control effect is compared with the PID control effect. The thermal comfort index under the two control modes is compared, and the control effect is analyzed.
Figure 10. Comparison of PMV

Figure 11. Comparison of PDD
The red curve represents the fuzzy PID control parameters in the above picture, and the dark blue represents the parameters under the PID control effect. In PID control, the value of KP is 110, the value of KI is 10, and the value of KD is 3.

In Figure 9, the overshoot of fuzzy PID control is 1.6%, the overshoot of PID control is 5.08%; the setting time of fuzzy PID is 173 seconds, the setting time of PID is 212 seconds; the rise time of fuzzy PID control is 202 seconds, the rise time of PID is 163 seconds. It can be seen from the data that the fuzzy PID control effect is better than the PID control effect except for the rise time, and it makes the temperature of the passenger compartment more gentle.

Table 2. Comparison of fuzzy PID and PID control effect

| INDEX      | Rising time | Overshoot | setting time | Steady-state error |
|------------|-------------|-----------|--------------|--------------------|
| fuzzy PID  | 202s        | 1.6%      | 173s         | 0.05°C             |
| PID        | 163s        | 5.08%     | 212s         | 0.09°C             |

Figure 10 shows that the thermal comfort performance of the PMV index using the fuzzy PID control effect is stable, and the thermal comfort under the PID control will oscillate to a certain extent.

In Figure 11, the PDD index is the same under the two control effects, and both are within the control range of the thermal comfort index, and PDD<10%.

In general, the control effect of using fuzzy PID is slightly better than that of PID control regardless of temperature control or thermal comfort control. In the low-temperature environment heat pump air conditioning system, fuzzy PID control can add advantages.

5. Conclusions
As the passenger compartment model's thermal load is difficult to establish using mathematical modeling, the study uses AMESIM simulation software to analyze the thermal load of the passenger compartment to realize physical modeling so that the heat exchange of the passenger compartment is more accurate and can be very good. It simulates the temperature and humidity information in the passenger compartment and establishes thermal comfort indicators PMV and PDD.

The heat pump air conditioning system is a nonlinear linear control system, and PID control is challenging to adapt to the complex working environment during the control process. By designing
fuzzy PID control rules, the overshoot of fuzzy PID control is 0.87°C less than PID control, and the stabilization time is less than 90 seconds. Simultaneously, by comparing the thermal comfort of the passenger compartment under fuzzy PID and PID control, the thermal comfort PMV index under fuzzy PID control is more stable.

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