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IMPACT OF A THREE-DIMENSIONAL AIR-CONDITIONING SYSTEM ON THERMAL COMFORT: AN EXPERIMENTAL STUDY

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ABSTRACT−This paper investigates the impact of a three-dimensional (3D) air-conditioning (AC) system on cabin thermal comfort. Current AC systems are dependent on the cooling performance of Heating, Ventilation, and Air-Conditioning (HVAC) systems located inside the front instrument panel and supplying cold air from the front to the rear cabin. This results in a difference in perceived thermal comfort between the front and back seats due to a number of factors, including solar radiation through the windows, blower air path, and individual environmental differences. The 3D AC system was designed to improve the thermal comfort of passengers. In order to simulate the 3D AC system, an auxiliary blower was adapted for rear passengers. A cooling performance test and thermal comfort evaluation were conducted, with the blower at various positions in the cabin. According to the experiment results, four positions of the auxiliary blower showed cooling comfort ratings similar to those of the current HVAC system environment, and the thermal comfort ratings in the 3D AC experiment showed improvement. In other words, 3D AC system can reduce energy consumption, because it can reach the set temperature with less AC system operation.

KEY WORDS : HVAC(Heating, Ventilation and Air-Conditioning), 3D AC(Three-dimensional air-conditioning), Thermal comfort, Auto-temperature control, Fresh-recirculation control, PMV(Predicted Mean Vote), PPD(Predicted Percentage Dissatisfied), Auxiliary blower unit

1. INTRODUCTION

With the improvement of living standards, people are spending more time inside cars, and automobile development is becoming more human centered. As evaluation standards of the automobile market are transitioning toward safety, comfort, and convenience, the role of Heating, Ventilation and Air-Conditioning (HVAC) systems is expanding as well. HVAC systems control and distribute temperature and wind to provide an optimal and pleasant thermal environment inside the car regardless of the external environment. HVAC systems are core functional components that create a cabin environment that expands the role of the automobile beyond a transportation means to a provider of comfort. Such automotive HVAC systems come with very complicated flowage, as they supply wind to the cabin by forcing the circulation and mixture of the direction, intensity, and temperature of the wind in order to effectively achieve comfortable conditions within a small indoor space. Moreover, they deliver cool or warm wind from the front cabin to the rear cabin, which results in different thermal conditions depending on passengers' location. It is difficult to thermally satisfy all passengers with the current automotive HVAC systems.

Lee and Park (2007) studied the PMV according to cabin shape and passenger positions and numerically analyzed that heat loss different across conditions. They deducted the thermal comfort modification factor and quantified thermal satisfaction. The results showed that when the cooling air volume was discharged from the front to the back, front cabin passengers were thermally satisfied whereas rear cabin passengers did not feel cool enough due to the lack of air volume in the back seat. When the wind direction was changed from rear to front, front cabin passengers showed more dissatisfaction.

In order to analyze the cabin thermal environment, Nagano *et al*. (2012) created a reduced cabin model based on JASE standards, ran experiments in the heating and AC chambers, and compared results with numerical analysis. They found that, on the floor, the effect of radiation was predominant, and in the instrument panel, the effect of the convection was strongest in determining the cabin thermal environment.

Miyamoto *et al*. (2012) modeled the cabin and driver through numerical analysis to reduce the energy consumed when the HVAC operates in electric vehicles. Moreover, they reviewed the validity of the zone air-conditioning (AC) system by analytically the thermal environment in many different conditions.

Kohri (2009) compared and analyzed a densely modeled thermal mannequin and a simply modeled thermal

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mannequin in different air flow conditions with the ISO 14505 standard and compared the mannequin's strengths and weaknesses.

Kim *et al*. (2010) ran an analytic study on the thermal comfort of passengers during initial air-conditioned operating. Numerical analysis modeled the cabin and passenger like an actual automobile and analyzed the thermal difference between passengers' feet and chest and between the front and rear cabin. It was concluded that the thermal difference differed across different seats. Other studies have also predicted the thermal comfort of cabins or cooling performance using numerical analysis or optimized ventilation performance through flow field visualization using lasers (Lee, 2000; Kim *et al*., 2009).

This study introduces the concept of three-dimensional (3D) AC in order to provide identical thermal comfort to passengers in all seats. In addition to the HVAC installed in the front cabin, 3D AC provides additional wind through auxiliary blower units installed in the ceiling, shelf, or floor of the rear cabin.

This paper reviews the validity of 3D AC by testing and analyzing its effect on cabin cooling performance and passengers' thermal comfort.

2. EXPERIMENTAL EQUIPMENT AND METHOD

2.1. Automotive HVAC System

Unlike HVAC employed in buildings, offices, and households, automotive HVAC is enclosed with glass on all four sides apart from engine heating, and it is sensitive to thermal load due to poor insulation. To achieve thermal comfort using automotive HVAC, cool or warm air is supplied to the cabin, mixed together to control the temperature, and blown exclusively or combined towards the face, feet, or windshield on passenger demand, as shown in Figure 1.

A general observation of wind blowing in HVAC reveals that air is usually blown toward the face for cooling purposes, the feet for heating, and the windshield for defrosting the windshield. The air volume refers to the amount of wind that passes through the evaporator and heater core in the HVAC system, and the distribution of air volume is one index, along with temperature, that determines comfort. Left-right distribution is designed to discharge wind equally to the left and right as seen from the passengers' and driver's point of view, and up-down distribution refers to the amount of air that is discharged toward the passengers' feet and chests. In the past, optimal HVAC was determined by measuring the temperature and amount of wind with a thermocouple and air volume tester during the development process. Today, however, it is being developed to satisfy the thermal sensations of passengers. As the Korean automobile industry is elevating in status, cabin thermal comfort is also gaining increased importance as auto temperature control in HVAC is being disseminated to

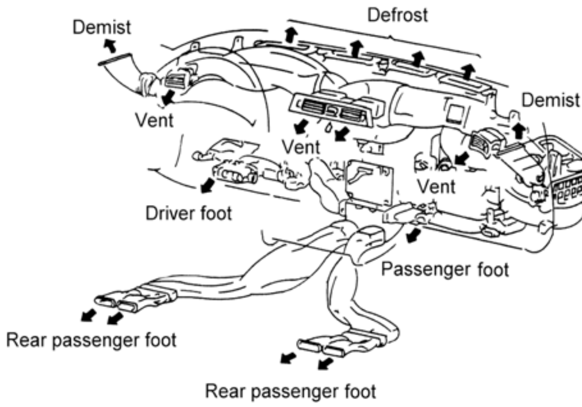

Figure 1. Schematic of air discharge directions in automotive HVAC system.

Chamber temp	-40–60°C
Wind speed	0–200km/h
Humidity	20–90%, RH
Dynamo absorption	210HP
Sun load	300–1400W/m^2

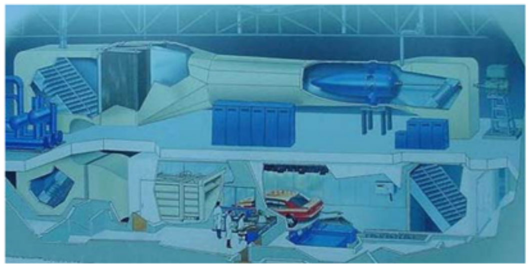

Figure 2. Specification and schematic of climate wind tunnel.

an even wider audience (Lee and Yoo, 2004).

2.2. Climate Wind Tunnel with Cool-down Performance Test

Figure 2 shows the schematic diagram and control range of Climate Wind Tunnel (CWT). The CWT is able to control temperature, humidity, sun radiation, and driving wind in a closed space and it is capable of various driving simulations at field state, including highway driving and hill driving. In order to examine the effect of 3D AC on air conditioner performance in the CWT, we installed auxiliary blower units to run a maximum AC experiment. Auxiliary blower units were installed in various locations in the rear component of the cabin, and effects on the maximum cooling performance were compared depending on each installation location.

Figure 3 shows test conditions and vehicle employed in the cool-down performance test in the CWT. The automobile was left in an outside temperature of 45°C and sun radiation of 1000 W/m^2 until the cabin temperature reached 60°C. In order to measure the average cabin temperature, eight T-

Ambient temperature	45.0±2°C
Sun load	1000W/m^2
HVAC control mode	Fresh–Max. Cool–Vent
Blowing voltage	Max. Hi
Driving conditions	50km/h, 100km/h, and Idle

Figure 3. Cool-down performance test conditions and test vehicle (YF Sonata).

Ambient temperature	30°C
Weather	Sunny cloudy
Temperature setting	23°C→21°C→23°C→25°C→23°C
Intake air setting	Fresh→Recirculated→Fresh
Driving conditions	Highway, 80km/h

Figure 4. Thermal comfort test conditions and test vehicle (TG Grandeur).

type thermocouples were installed on the front and back seats (chest level). Thermocouples were also installed on each of the footrests, and two more were attached to the air discharge opening of the HVAC. To examine the effect of 3D AC, we installed eight thermocouples on the back seat and closely observed the temperature distribution according to the movement of cabin air flow. HVAC control was carried out according to set test standards, and driving conditions included city driving, highway driving, and parked conditions. The auxiliary blower unit positions are shown in Figure 3. Position 1 is baseline HVAC without an auxiliary blower unit in cabin, Position 2 is the ceiling of the back seat, Position 3 is the floor of the back seat, and Position 4 is rear shelf of the back seat.

2.3. Thermal Comfort of Fleet Test

Detailed experimental conditions of the thermal comfort test and locations of auxiliary blower units are shown in Figure 4. Based on the results from the tests on the CWT, experiments on thermal comfort evaluation were carried out with auxiliary blower units attached to the rear position of the back seat (designated as the optimal location). Thermocouples were identical to those used in the experiment on the CWT, and the CMP6 model from Kipp&Zonen was the pyrometer used to measure sun radiation. The sensitivity of the sun radiation sensor was 13.5 μW/m^2, the range of temperature used was –40–80ºC and it was able to measure sun radiation up to 4000 W/m^2. Data was obtained by connecting Agilent 34790 to a laptop computer, with data checked and saved in real time. The automobile drove down the West Coast Highway in Korea at a speed of 80 km/h while running tests on auto temperature setting control performance and fresh/recirculated air setting control performance, and four passengers sat in each seat to evaluate thermal comfort in real time.

Generally, thermal comfort is an index that shows one's satisfaction with the thermal environment in a given space, and it is commonly expressed through PMV (Predicted Mean Vote) and PPD (Predicted Percentage Dissatisfied). It quantifies the sensory state each individual feels within their body, which varies across temperature, air flow, and individual differences in quantity of activity, and amount of clothing (Lee *et al*., 2013).

This study included the effects of amount of clothing and metabolism, and in terms of environmental factors, it evaluated only one season, as it was not practical to run tests in different temperature conditions.

3. RESULTS AND DISCUSSION

3.1. Cool-down Performance Test

In environment control, auxiliary blower units were installed in different locations on the back seat. The effects on maximum cooling performance were tested, and the results are shown in Figure 5. First, the baseline automobile without auxiliary blower unit was tested for cooling performance under both 50 km/h and 100 km/h driving and idle conditions. Then, under identical test conditions, the location of the auxiliary blower unit was changed from Position 2, to Position 3, and to Position 4, mimicking 3D AC. The cold air temperature from HVAC from the baseline and different auxiliary blower unit positions were almost the same.

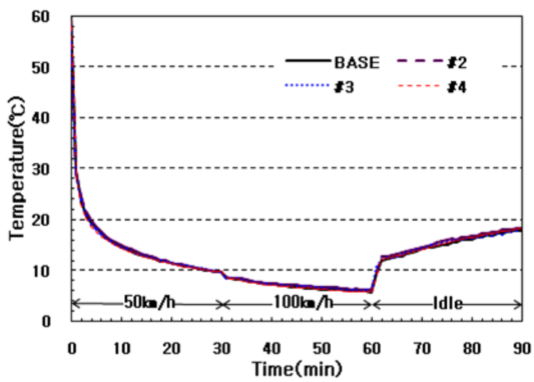

Figure 5. Experimental results of air discharge temperature at cool-down performance with various auxiliary blower positions.

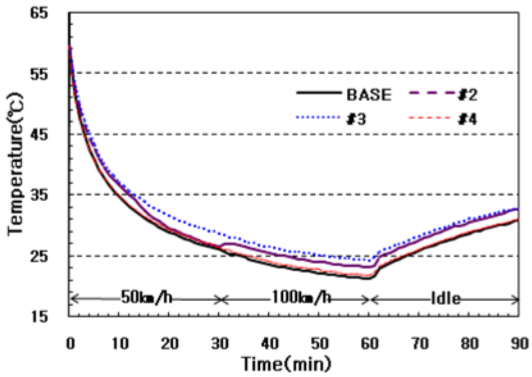

Figure 6. Experimental results of cabin temperature at cool-down performance with various auxiliary blower positions.

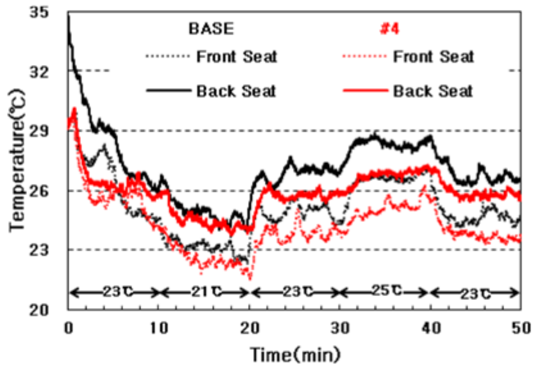

Figure 7. Chest positions temperature in thermal comfort test for auto temperature control performance.

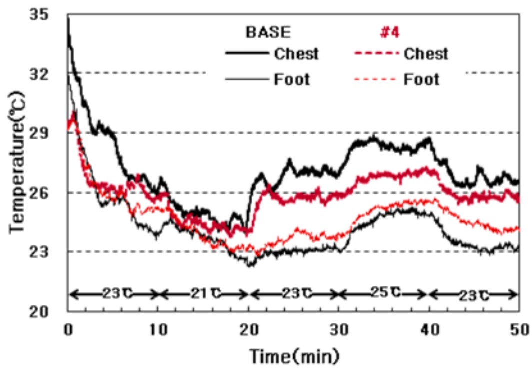

Figure 8. Back seat temperature in thermal comfort test for auto temperature control performance.

Figure 6 shows the average temperature in the cabin. The effects on maximum cooling performance were measured and analyzed. In the baseline automobile experiment, the cold air discharge direction stayed consistent as the wind blew towards the front and back seats (chest level). On the other hand, installing auxiliary blower units negatively affected maximum cooling performance, as the thermal load agitated front and back and up and down due to the confusion of the back seat air flow.

Putting the auxiliary blower units in Position 3, on the floor, caused the cold air to blow upward, resulting in a higher average cabin temperature at all times. In other words, this study found that auxiliary blower unit locations affected cabin air flow and thus cabin temperature. However, when auxiliary blower units were located in Position 4, the wind blew from the back of the back seat to the front seat.

Auxiliary blower units in this position had no effect on maximum cooling performance. Therefore, we selected Position 4, where it had the least effect on maximum cooling performance, as the optimal place for an auxiliary blower unit.

3.2. Thermal Comfort Test

The thermal comfort test was administered based on the results of the cool-down performance experiments described above in the CWT. Auto temperature setting control and fresh/recirculated air setting control performance tests were carried out with the auxiliary blower unit installed in Position 4 and the vehicle driving on the highway at a speed of 80 km/h.

The temperature was changed every ten minutes, as shown in Figure 7 and 8, and the thermal change was observed. In terms of setting fresh/recirculated air, we evaluated the temperature control performance determined according to the change in fresh air and recirculated air mode in Figure 9 and 10. In addition, we evaluated the thermal sensation each individual felt in the feet and chest area in order to evaluate passenger thermal comfort.

Figure 7 and 8 show the results of the temperature setting control performance test. The cabin temperature starts at approximately 30°C and gradually moves towards the set temperature. The cabin temperature in the base vehicle generally tends to follow the set temperature, but thermal differences are observed in the front and back seats, and in the chest and feet areas. On the other hand, test results in the 3D AC condition show that the thermal differences in the front and back seats and in chest and feet areas are less significant than in the base results.

Figure 9 and 10 show the results of the fresh/recirculated control performance test. Similar to findings in Figure 7 and 8, thermal differences in the front and back seats and in the chest and feet area are big compared to the set temperature. However, in the 3D AC simulation experiment, thermal differences between the front and back seats following set temperature are decreasing significantly. In particular, the chest area temperature in both the front and back seats has improved by approximately 2°C compared to baseline. Based on the results, we can infer that passengers in both the front and back seats will feel a similar degree of thermal comfort in 3D AC conditions.

Figure 11 is an evaluation of the thermal comfort of

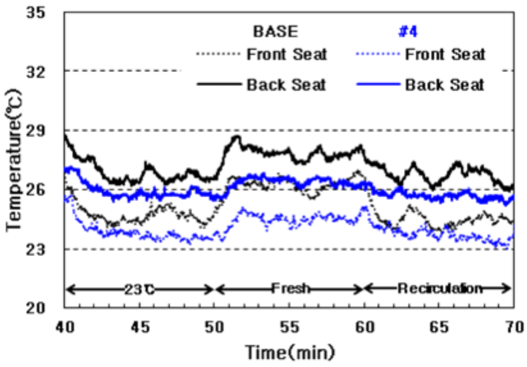

Figure 9. Chest positions temperature in thermal comfort for fresh/recirculated air control performance.

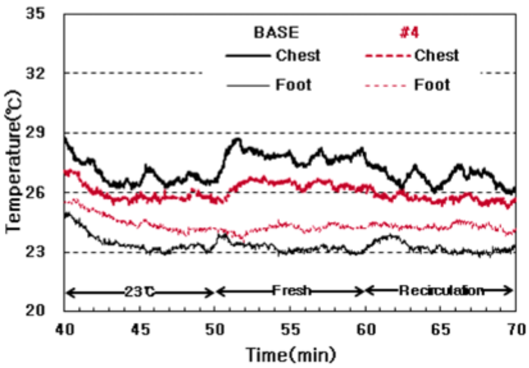

Figure 10. Back seat temperature in thermal comfort for fresh/recirculated air control performance.

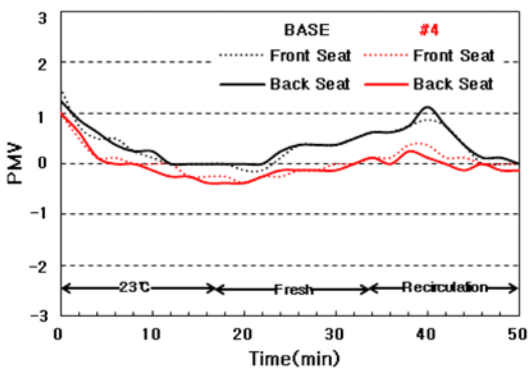

Figure 11. Comparison of thermal comfort evaluation for auto temperature control performance.

passengers from all seats during the testing of the temperature control performance of HVAC. The PMV differed slightly across passengers, but the average PMV in the 3D AC simulation experiment ranged from –0.3 to 0.2, which satisfies the optimal thermal sensation range of –0.5 to 0.5. However, the PMV in the base vehicle ranged from

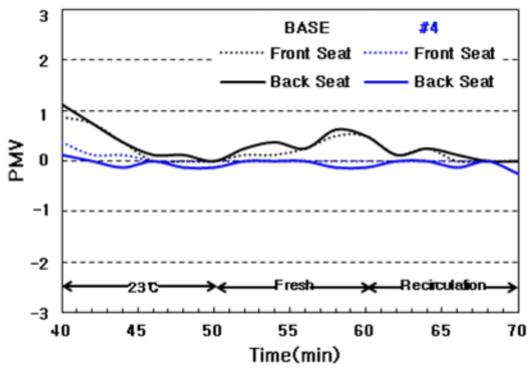

Figure 12. Comparison of thermal comfort evaluation for fresh/recirculated air control performance.

–0.1 to 1.0, which indicates that all passengers were feeling a bit hot in the cabin. According to thermal comfort test results, therefore, 3D AC diminishes the thermal difference between the front and back seats and between chest and feet areas and improves thermal sensation, ensuring sufficient validity.

Figure 12 is an evaluation of the thermal comfort of each seat during the testing of the fresh/recirculated control performance. PMV for the base vehicle exceeded 1 per section, and the average ranged from 0 to 0.8. In the 3D AC condition, however, the thermal sensation was close to zero with no particular section getting worse, showing that it remained very stable.

4. CONCLUSION

This study introduced the concept of an auxiliary blower unit in order to explore the effect of a 3D AC system on cabin thermal comfort and reviewed its validity. In the cool-down performance experiment, we ran a test on maximum cooling performance across different auxiliary blower locations and proposed the optimal location to install auxiliary blower unit. Through the thermal comfort experiment, we tested the auto set temperature control performance and fresh/recirculated control performance to compare front and back seat passengers' thermal sensations and obtained the following results.

Auxiliary blower units that simulate a 3D AC system affect maximum cooling performance depending on their locations, and we proposed the optimal position through cool-down performance tests.

The 3D AC system showed generally even thermal distribution in auto set temperature and fresh/recirculated control performance tests, and the chest area thermal difference between the front and back seats was improved by approximately 2ºC.

Results of the thermal comfort test showed that the PMV of passengers ranged from –0.3 to 0.2, which satisfied the PMV goal range of –0.5 to 0.5.

Based on results that showed that 3D AC systems are worth being applied to automotive HVAC, as they improve thermal comfort, this study proposes a new method of installing auxiliary blower units through 3D AC technology. Additionally required studies include research on 3D AC regarding thermal comfort across different environmental conditions, gender, and individual differences.

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