

Research of Control Countermeasures for 3D Uneven Solar Radiation with Automatic Air Conditioning Systems for Automobiles

Isao TSUNODA*

Hironori SHUTO*

Ikuo TAKAMATSU*

ABSTRACT

A new automobile air conditioning system was developed that is capable of maintaining passenger comfort under changing and uneven solar radiation conditions. This project differentiated the solar radiation energy that is absorbed by the human body affecting passengers directly, and energy that is absorbed by the car body and radiated to the passengers by means of the cabin air. Values for these two were then derived for every position of the sun. Based on the results, a map was created that enables the air conditioning system to change the coefficient adjusting for the influence of solar radiation. A control system has been developed that calculates the position of the sun relative to the automobile by means of a Global Positioning System, and provides only as much cooling as is needed to offset the amount of solar radiation energy absorbed by the passengers according to the position of the sun. An automobile with this air conditioning system installed was subjected to field study tests, which confirmed that passengers felt a constant level of comfort even when the direction of the sunlight changed with respect to the car body.

1. Introduction

An air conditioning system for an automobile is unlike that for a building in that a considerable part of the heat input from outside is composed of radiation energy from the sun. Consequently, automatic air conditioning systems are equipped with sunbeam sensors in order to control the outlet air temperature and airflow rate according to the intensity of the solar radiation. The conditions in an automobile are such that the solar radiation may hit the passengers directly. In such cases, the direct solar radiation energy that contacts the human body will vary according to such factors as the position of the sun and the location of the passenger. Therefore, it is not sufficient to simply control the cabin temperature in order to maintain uniform comfort.

The control of uneven solar radiation can be accomplished by such means as 2-dimensional sunbeam sensors⁽¹⁾⁽²⁾ and the use of two sunbeam sensors. However, it is not possible to compensate for the effects of uneven solar radiation throughout the cooling region, which changes according to the complex interaction of the sun, the automobile, and the human body. A method has already been developed for calculating the position of the sun from the location of the vehicle, and then using the relationship of this position with solar radiation intensity to control the autoair conditioning system with respect to uneven solar radiation.⁽³⁾ However, there has been no case as yet where the actual control amount was determined.

This paper describes our study of an auto air conditioning system that is capable of controlling the atmosphere

comfortably throughout the area of uneven solar radiation by analyzing the heat conveyed to the vehicle and passengers from solar radiation energy.

2. Analysis of comfort factors

2.1 Factors in comfort

One of the factors in automobile passenger comfort is the thermal environment of the cabin, which is determined by the three factors of heat transfer (convection, radiation, and conduction). These factors are different during the day and at night, during different seasons, and so on. At night, for example, the heat transfer caused by the temperature difference between the cabin and the outside environment, together with the movement of heat caused by ventilation, determine the thermal environment. During the day, the radiation energy from the sun becomes an additional factor that has a significant affect.

Apart from these factors of comfort that determine the thermal environment, there is also the factor of preference. According to standards such as ISO 7730, differences due to individual preferences are distributed over a range like that shown in Fig. 1.

Passenger comfort is ordinarily determined by the combination of these factors. However, the cabin of an automobile is a confined space, and the locations of the passengers are more or less fixed. The glass window area is large relative to the cabin volume, so direct sunlight on the passengers causes them to feel hot. This has a greater impact than the other factors.

* Tochigi R&D Center

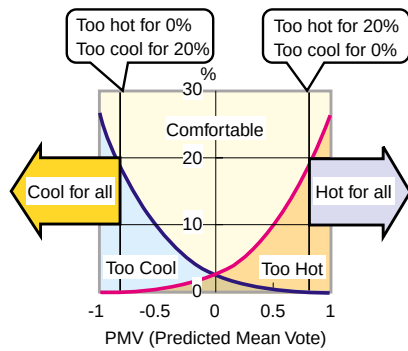


Fig. 1 Preference Distribution chart

2.2 Heat input to passengers

When there is little sunlight, the air temperature inside the car cabin is determined by the heat transmitted from outside, ventilation, air conditioning, and so on. When there is a lot of sunlight, the radiation energy from the sun becomes a larger factor, and, there is little movement of heat due to heat transfer, especially when the ambient temperature is close to the controlled cabin temperature. At such times, therefore, this radiant energy makes up the greater part of the heat input from outside the cabin.

Fig. 2 shows the route of heat input from solar radiation. This can be separated into two factors. One is the solar radiation that enters through the window and raises the temperature of interior materials and so on, thus raising the temperature of the air inside the cabin to thereby reach the passengers. The other factor is the radiation that strikes the passengers directly through the window and raises the temperature of their clothing and skin. With the former, the position of the sun makes relatively little difference, and it is easy to create a constant environment by using sunbeam sensors and so on to correct the cabin temperature. This is equivalent to the situation during a summer day when the solar altitude is high and the passengers are contacted directly by almost no sunlight.

In the case of the latter factor, the radiation energy will differ according to the relative positions of the passengers and windows, and so it will be different for every seat. Since the passenger is subject to a great deal of heat, the range of the difference made by the position of the sun is also large. This is equivalent to all the times apart from the daytime during the summer when the solar altitude is low.

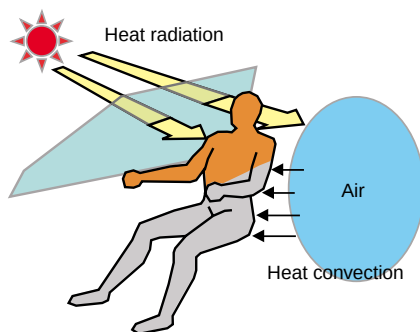


Fig. 2 The routes of solar radiation reaching passengers

3. Current status of and issues concerning solar radiation control

3.1 Current status of solar radiation control

Auto air conditioning systems ordinarily calculate the target air output temperature T_{ao} from the ambient temperature, cabin temperature, setting temperature, amount of sunlight, and so on using formula (1). The air output temperature is adjusted by using the heater unit to change the ratio of cool and hot air. This controls the thermal environment inside the cabin.

$$T_{ao} = F(T_{set}, T_{am}, T_r, T_{sun}) \quad (1)$$

T_{set} : Setting temperature

T_{am} : Temperature from ambient sensor

T_r : Temperature from cabin sensor

T_{sun} : Amount of sunlight

As to the radiation from the sun, the air output temperature is reduced in accordance with the amount of radiation energy detected by the sunbeam sensor so that the cabin area environment is maintained at a constant level.

The sunbeam sensor is installed in the cabin near the driver seat in a location that will tend to remain out of shadows. It is most commonly placed inside the front windshield above the instrument panel and toward the front. The sunbeam sensor gain is determined by the sensitivity of the sensor and the amount of attenuation from the front windshield that comes between the sensor and the sun. The amount of sunlight detected at this location represents the radiation energy from the sun.

3.2 Issues concerning solar radiation control

The amount of solar radiation that reaches the sunbeam sensor varies with the angle of incidence. The passengers, meanwhile, may be in a shadow or they may be bathed in sunlight depending on their positions relative to the windows. Therefore, depending upon the position of the sun, the amount of radiation detected by the sunbeam sensor may not necessarily coincide with the amount of radiation energy contacting the passengers. In order to confirm whether the actual output from the sunbeam sensor can represent the radiation energy for each position of the sun, we studied the relationship between the solar radiation striking the sunbeam sensor and the solar radiation striking the passengers in an ordinary sedan.

Fig. 3 shows the relationship between the solar radiation on the passengers and the vehicle with the sun at an altitude of 50° . The parts visible through the windows are the parts exposed to solar radiation. When the solar radiation strikes from the front, both the passengers and the sunbeam sensor are contacted by it. When the solar radiation is from the side, the sunbeam sensor and the passengers who are on the same side of the car as the sun are contacted by it, while the passengers on the opposite side are in a shadow. When the solar radiation is from the rear, the passengers in the front seat are in a shadow but the sunbeam sensor is contacted by it. This illustrates how the solar radiation contacting the passengers and the sunbeam sensor do not necessarily coincide. In the case of solar radiation from the side, there

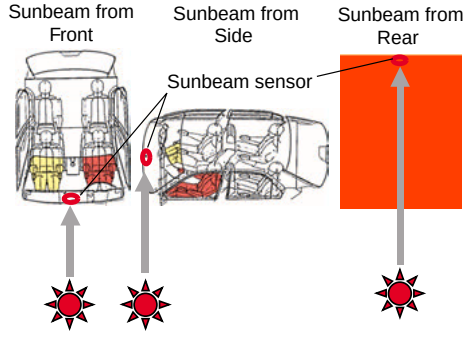


Fig. 3 Comparison of solar radiation on sunbeam sensor and on passengers

will also be a difference between passengers in the right and left seats. Therefore, simple air conditioning control based only on the sunbeam sensor cannot provide comfortable air conditioning to all passengers.

3.3 The effect of uneven solar radiation caused by the sun's position

As described above, the heat balance of the passengers is disrupted when the amount of heat received by their bodies and the amount of solar correction differ, so that passengers may feel hot or cold depending on the direction of the solar radiation. This type of problem must be resolved by making the amount of sunbeam sensor compensation for solar radiation and the amount of radiation energy contacting the passengers coincide.

Fig. 4 shows the position of the sun in relation to the vehicle, as it will be used below.

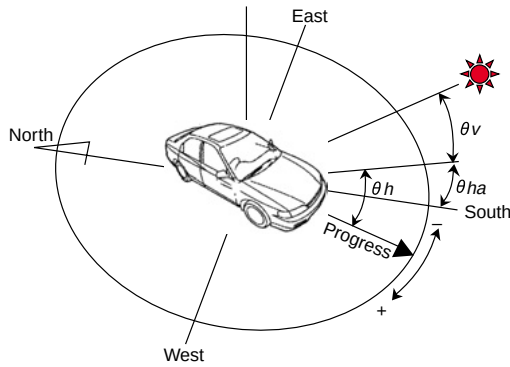


Fig. 4 Description of sun position

θ_h : Relative solar azimuth in relation to the progress of the car

θ_v : Solar altitude

θ_{ha} : Absolute solar azimuth in relation to the South

The actual location where the amount of solar radiation is detected and the locations and conditions of the passengers are different. We verified this quantitatively by comparing the relationships of the sunbeam sensor output and the amount of radiation energy contacting the passengers with respect to the position of the sun. In this way, we verified whether temperature corrections made due to the output of the sunbeam sensor were able to compensate for the amount of heat received by the passengers from solar radiation.

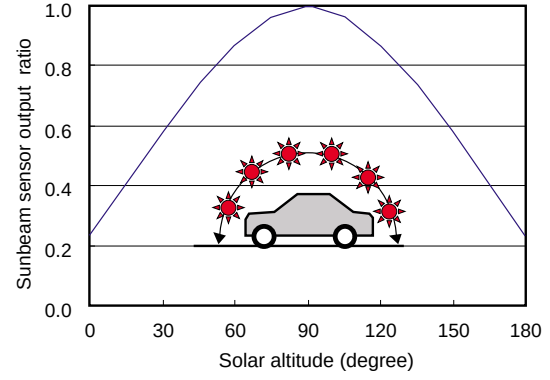


Fig. 5 Sunbeam sensor output ratio

The output of a sunbeam sensor unit varies with the solar altitude, depending upon the directivity of the sensor, as shown in Fig. 5.

The sunbeam sensor unit does not possess directivity with respect to direction, but since the sensor is installed inside the front windshield, the amount of sunlight reaching the sensor changes with the angle of incidence on the glass. The sunbeam sensor output changes that are actually used for control are shown in Fig. 6 with respect to solar altitude and azimuth.

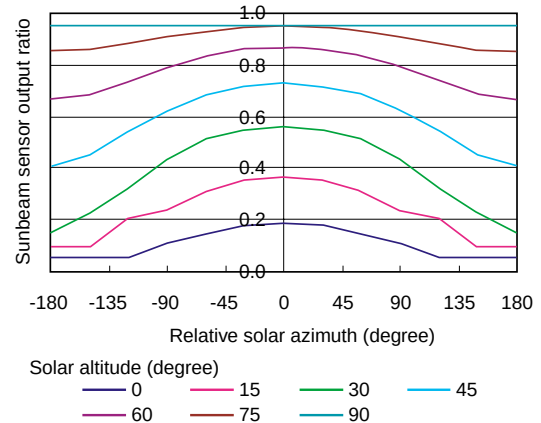


Fig. 6 Sunbeam sensor output ratio in car

The maximum output occurs when the sun is positioned at the front center of the car. The farther the sun's position is to the side of the car, the smaller the angle of incidence on the glass becomes. As a result, the output diminishes and the correction is reduced.

In order to verify the solar correction that is actually required, we determined the relationship between the position of the sun and the radiation energy absorbed by the passengers in the automobile by the routes shown in Fig. 2, using an ordinary sedan as the model.

First, we determined the relationship between the solar altitude and the solar radiation energy absorbed by the cabin air from the sunlight entering through the window glass. This was used as a component that affects the cabin air temperature. The relationship, organized in terms of solar altitude, is shown in Fig. 7.

The radiation energy absorbed by the cabin air varies mainly with the solar altitude. It is clear that the amount of solar radiation energy absorbed increases as the altitude of the sun increases.

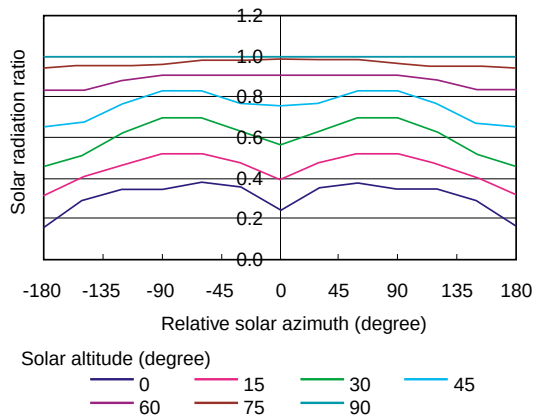


Fig. 7 Solar radiation affecting interior

Next, we determined how much of the radiation energy that passes through the windows and strikes the passengers contacts the passenger in the seat on the left side. The relationship with the position of the sun is as shown in Fig. 8. With high solar altitudes, the solar radiation received is strongest when the sun is on the passenger side. With low solar altitudes, however, the peak in solar radiation occurs instead when the sun is on the opposite side. The difference in radiation energy contact varies greatly particularly with the azimuth when the altitude is low.

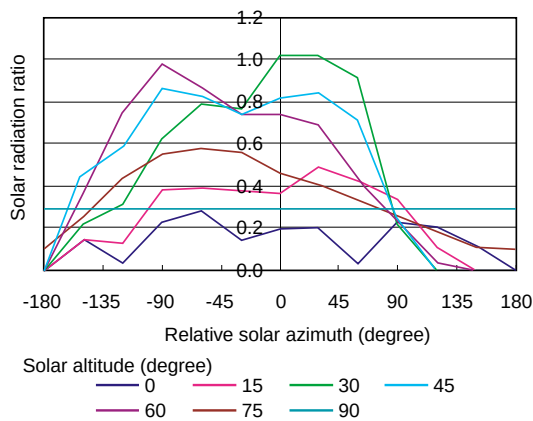


Fig. 8 Direct solar radiation reaching left passenger

The sum of these two amounts of heat is the radiation energy from the sun that contacts the passenger. This was arranged by the azimuth of the sun for the representative altitudes of 30° and 60° and compared with the sunbeam sensor output direction characteristics. It is apparent from the results shown in Fig. 9 and Fig. 10 that the amount of correction made by the sunbeam sensor is insufficient for the entire front area with respect to the actual radiation-energy received at a solar altitude of 30°. At a solar altitude of 60°, the correction is excessive in the rear and on the right, and insufficient on the left. Consequently, it was apparent that there are many areas where the solar correction does not work properly.

3.4 Methods for eliminating the effects of uneven solar radiation

Temperature and airflow rates were sought experimentally to determine how much the outlet air

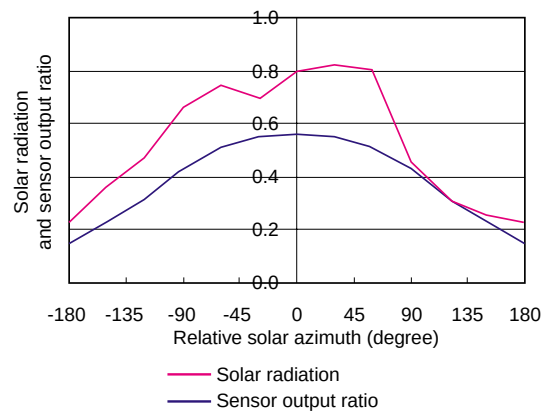


Fig. 9 Output ratio of the solar sensor and the heat ratio of the left passenger (Solar altitude 30°)

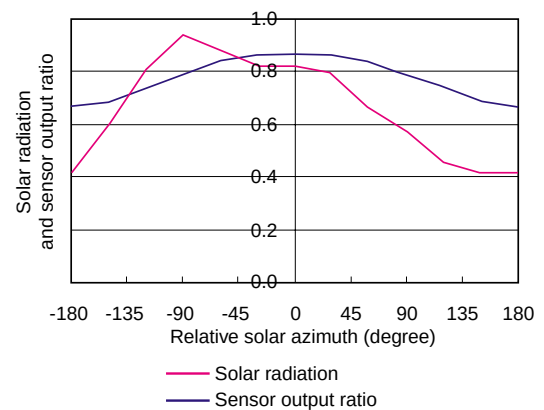


Fig. 10 Output ratio of the solar sensor and the heat ratio of the left passenger (Solar altitude 60°)

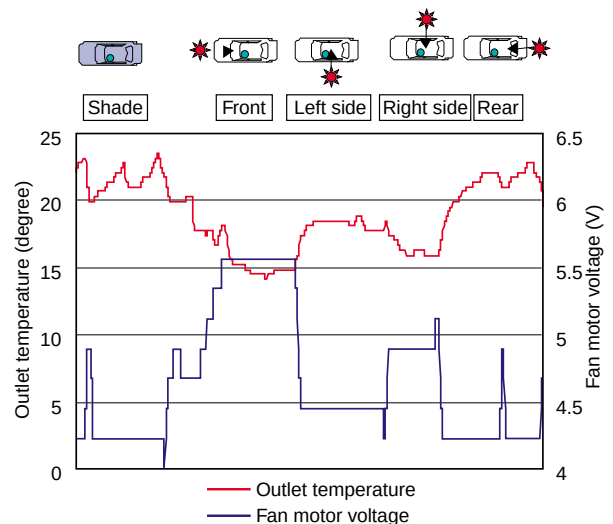


Fig. 11 Outlet temperature producing the same feeling

temperature should be lowered in order that passengers contacted by solar radiation will be at the same cooling level as those who are not.

The outlet air temperature was adjusted in a static vehicle to provide the same comfort to passengers in an actual car under different conditions as shown in Fig. 3. A comparison was made of the adjustments with sunlight from the front (maximum solar radiation condition), from the rear (when

the car body is contacted by solar radiation but the passengers are not), with sunlight from the left and right sides (when there is a difference between the left and the right), and with the car in a shadow (no solar radiation).

As shown in Fig. 11, there are conditions under which adjustment of the airflow rate and outlet air temperature can provide the same passenger comfort when the car is exposed to solar radiation and when it is not.

4. Control with respect to uneven solar radiation

4.1 Basic concept

The amount of radiation energy contacting a passenger changes in a complex manner with the solar altitude and azimuth of the sun. When the amount of correction for solar radiation that is detected by the sunbeam sensor changes with the position of the sun so that it coincides with the amount of radiation energy contacting the passenger, then it is possible to achieve a constant feeling of comfort regardless of the position of the sun.

This requires detection of the sun's position and a map that correlates the sunbeam sensor output with the radiation energy contacting the human body.

4.2 Design of the control algorithm

The formula for calculating the target outlet air temperature T_{ao} utilizes formula (1), with the factor T_{sun} defined as a function of the solar altitude and relative solar azimuth (θ_v and θ_h). The sunbeam sensor directivity is standardized to a solar intensity at a normal surface. This is multiplied by the change in radiation energy contacting the passenger so that the amount of correction equals the change in solar radiation energy contacting the passenger. The correction coefficient for solar radiation, K_{sun} , is derived from formula (2).

$$K_{sun3D} = \frac{F \{F_h(\theta_v, \theta_h), F_r(\theta_v, \theta_h)\}}{F_s(\theta_v, \theta_h)} \quad (2)$$

$F_h(\theta_v, \theta_h)$: Coefficient of radiation energy directly contacting passenger

$F_r(\theta_v, \theta_h)$: Coefficient of radiation energy absorbed by cabin air

$F_s(\theta_v, \theta_h)$: Coefficient of sunbeam sensor directivity

4.3 Detection of solar position

There are various methods for detecting the position of the sun, such as the use of a 3D sunbeam sensor, calculating the position from a GPS signal, and so on. The system used to confirm operation while cruising derived the solar position from GPS signals, which can be obtained relatively simply and with high accuracy.

The latitude and longitude of the current position and the present time were obtained from the GPS signal. The altitude of the sun θ_v and the solar azimuth θ_{ha} in relation to the meridian were then calculated from the geometric relationship of the positions of the earth and the sun.

The GPS signal is further used to derive the direction of vehicle travel. This direction is then used with the absolute solar azimuth θ_{ha} to calculate the azimuth θ_h relative to the direction the vehicle is headed.

5. Results of verification on an actual vehicle

5.1 Configuration of test vehicle

A test vehicle was prepared to verify whether results from control of uneven solar radiation could be obtained using the 3D method on an actual vehicle.

An ordinary sedan was used as the base for the test vehicle. The sunbeam sensor was simply installed horizontally on the roof so that it would not be affected by the front windshield.

The solar altitude and azimuth were calculated using the signal from a GPS antenna input into a computer. The signal was sent to the auto air conditioning system ECU. The heater unit used to adjust the outlet air temperature was modified so that the left and right temperatures could be controlled separately. Outlet air temperature sensors were installed and their outputs were returned as feedback so that outlet temperature control would be accurate. The system was made capable of monitoring the outlet air temperature. The auto air conditioning system target air output temperature T_{ao} from formula (1) was set up separately for the left and right seats. Mapping was established so that the coefficient of correction for solar radiation could be used to control the gain of the sunbeam sensor according to the solar altitude and azimuth. The auto air conditioning system ECU was linked to a personal computer to allow monitoring of all sensor values as well as the solar altitude and azimuth.

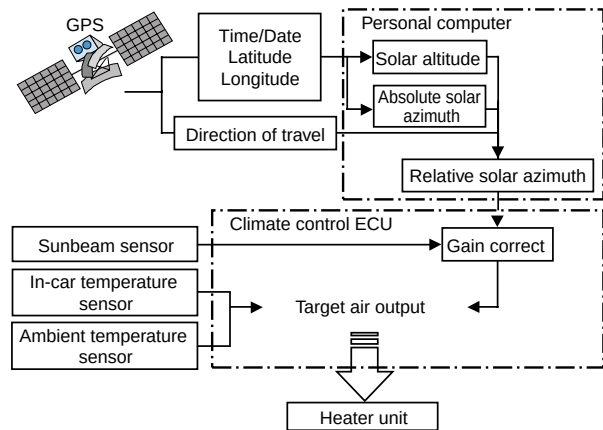


Fig. 12 Control flow chart

5.2 Test method

The test was conducted by a field study. Calculations were performed in advance using the date and time, latitude, and longitude to determine the angle at which solar radiation could be expected to strike at a particular time.

Examples of the relationship between solar altitude, azimuth, and time are shown in Table 1.

Using these data, the vehicle body was oriented to the direction for which verification was desired, the vehicle cruised in that direction, and passenger comfort was verified.

The results were evaluated for each seat according to the ratings given for passenger comfort on the scale shown in Table 2.

5.3 Test results

Fig. 13 shows the results from verification of outlet air temperature control and passenger comfort performed in

Table 1 Test location and solar angle

Time	Solar altitude (°)	Absolute solar azimuth (°)
6:00	4.1	87.1
7:00	15.9	77.7
8:00	27.3	67.2
9:00	37.8	54.4
10:00	46.5	37.8
11:00	52.0	16.4
12:00	52.8	-8.3
13:00	48.7	-31.2
14:00	40.9	-49.4
15:00	31.0	-63.3
16:00	19.8	-74.4
17:00	8.0	-84.0

Longitude	140°E
Latitude	37°N
Date	09/19/00

Table 2 PWM scale

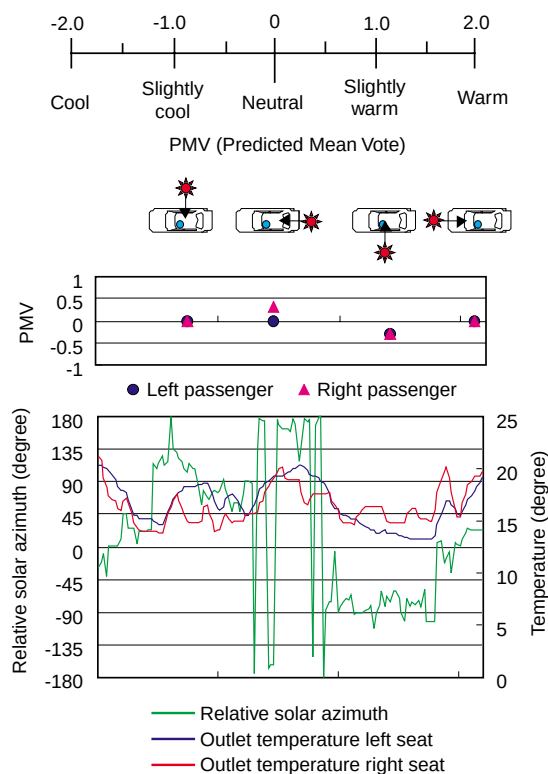


Fig. 13 Outlet temperature and feeling of passengers

each seat of a vehicle for each direction.

In the case of solar radiation entering from the right side, there is solar radiation directly contacting the passenger in the right seat. The outlet air temperature is therefore lowered on the right side, maintaining passenger comfort on both the left and right. Next, in the case of solar radiation from the rear, no solar radiation contacts either of the seats. The outlet air temperature is therefore raised. When the solar radiation comes from the left side, the outlet air temperature at the left seat is lowered to cancel out the heat from the uneven solar radiation on the left side. With solar radiation coming from the front, the passengers receive the most solar radiation. The outlet air temperature is therefore lowered and it is set to the same level on both the left and right.

These results show that matching the amount of radiation

energy with the amount of correction for solar radiation makes it possible to lower the outlet air temperature appropriately even when solar radiation contacts the passenger's body directly. We confirmed, therefore, that it is possible to maintain passenger comfort even when the position of the sun changes and there are changes in the unevenness of solar radiation.

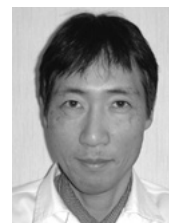
6. Conclusion

- (1) We focused our attention on the heat energy that results from solar radiation contacting passengers in an automobile. We divided this into the solar radiation that reaches the passenger directly through the windows, and that which is absorbed by the car body and reaches the passenger through the air that lies between. We determined both of these for each position of the sun.
- (2) The correction for solar radiation contacting the sunbeam sensor, which depends on sunbeam sensor directivity and the angle of incidence on the glass, was compared with the amount of solar radiation contacting the passengers with the sun at different positions. This demonstrated that the auto air conditioning system does not correct for solar radiation appropriately based on the position of the sun.
- (3) The results from analysis of the solar radiation energy contacting passengers were used to create a map that allows appropriate correction for solar radiation by the auto air conditioning system so as to lower the outlet air temperature according to the heat contacting the passenger.
- (4) A test vehicle was prepared with the capability for changing the outlet air temperature and airflow rate at each seat by means of a map. The results from verification during field tests confirmed that this method could achieve air conditioning control that would be comfortable day and night regardless of the position of the sun with respect to the vehicle.

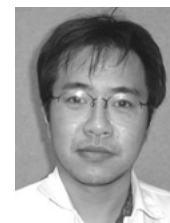
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authors



Isao TSUNODA



Hironori SHUTO



Ikuo TAKAMATSU