Effect of Air Exchange due to Door Opening on the Transient Thermal Environment in a Vehicle

Hideaki NAGANO¹*, Taki SATO¹**, Itsuhei KOHRI¹*** and Yuzuru YOSHINAMI²

¹Tokyo City University, 1-28-1, Tamazutsumi, Setagaya-ku, Tokyo, Japan
Tel.: +81 3-5707-0104
Email: *hnagano@tcu.ac.jp, **g1481211@tcu.ac.jp, ***ikohri@tcu.ac.jp
²Nissan Motor Co., Ltd., 560-2, Okatsukoku, Atsugi-shi, Kanagawa, Japan
Tel.: +81 50-3789-5980
E-mail: yoshinami@mail.nissan.co.jp

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Abstract

During winter, much of the energy contained within the battery of an electric vehicle is consumed by the air heating system. This energy consumption reduces the cruising distance of an electric vehicle. Additionally, stop-and-go driving, i.e., having many stops while driving, and frequent door opening/closing are typical of the operation of lightweight trucks used by home delivery services in residential areas; these behaviors lead to air exchange between the outside environment and the vehicle interior. This air exchange puts additional burden on the heating system and influences the thermal comfort of the driver. The effect of door opening needs to be investigated to develop a more effective heating system for electric vehicles. In this study, numerical simulations of a right-hand drive vehicle were performed to evaluate the variation in the thermal environment of the vehicle cabin when the door is opened and closed in relatively severe winter temperatures. The result showed that the average vehicle interior air temperature decreased at a rate of 2 °C/s during door movement. The warm interior air rose as it moved outward because of buoyancy. Simultaneously, cold outdoor air flowed into the lower region of the cabin. The total heat loss was approximately 57 kJ when the door was left open for 3 s and 37 kJ when the door was left open for 1 s. The standard new effective temperature (SET*) of the driver decreased at almost the same rate as the air temperature. The equivalent temperature on the right side of the driver’s body decreased drastically and rapidly as a result of the door opening. In contrast, the equivalent temperature on the left side of the driver’s body decreased more gradually. The equivalent temperature of the driver’s head remained consistent throughout the opening and closing of the door. The equivalent temperature of the driver’s hand, which is a thermally sensitive part of the body, was affected by the air temperature change caused by the door opening. The door movement itself had less to do with these results than the temperature difference between the vehicle interior and the environment. Thus, this discussion is applicable to a wide range of winter situations. The temperature difference is the trigger for the air exchange. The results of this study suggest that heat radiators may be more effective than air heating in improving the thermal comfort experienced by the driver because they do not cause an air temperature difference, which would reduce the amount of air exchange.

Keywords: In-vehicle environment, unsteady simulation, CFD, door movement, thermal environment

INTRODUCTION

In recent years, the energy sources for vehicles have gradually changed. The combustion efficiency of gasoline engines has been improved, and their heat exhaust has decreased. In addition, electric batteries and fuel cells have been used as energy sources for vehicles. Heating, ventilation, and air conditioning (HVAC) systems provide cabin air heating in the winter. However, it is difficult to harness exhaust heat as a heat source for air heating systems. In electric vehicles and fuel cell vehicles, the air heating system draws energy from the battery, which decreases the cruising distance (Nakane et al., 2010). Kohri et al. (2014) estimated HVAC load and demonstrated its impact on cruising
distance. According to their calculations, the load consists mostly of the ventilation load for air heating during winter. Hirai et al. (2012) proposed a new HVAC system that reduces outdoor air intake and increases the recirculation ratio in order to decrease the ventilation load.

Transient thermal comfort is an important topic regarding vehicle interior design. There are several studies on the transient thermal sensation response during warm-up and cool-down conditions (Brown and Jones, 1997). Such previous studies have focused on normal passenger vehicles. However, few reports consider the environment inside truck cabins, especially for transient conditions. Some trucks have very high floor temperatures owing to engine components, and their influence on thermal comfort has been investigated (Siqueira et al., 2002). The air-cooling effect on the thermal comfort of the truck driver has been analyzed via numerical simulation (Zhang et al., 2015).

Some typical conditions of truck driving for home delivery services in residential areas are stop-and-go driving, i.e., having many stops while driving, and frequent door opening/closing. These conditions lead to air exchange between the external environment and vehicle interior. Only in the field of architectural environment has the transient air exchange of door movement ever been studied: analysis of indoor air contaminants or cross ventilation in a clean room or smoking room (Matsudaira et al., 2004; Lee et al., 2014). However, the thermal environment has never been considered, only indoor air quality. Since making this observation, the authors have investigated the effect of door movement on air exchange with numerical simulation, and the results proved that the temperature difference between the inside and outside was the most influential effect, resulting in a waste of energy (Sato et al., 2014).

The effect of door opening on the thermal comfort of the driver should be considered. In situations that involve frequent exchanges of air, air heating is not efficient at maintaining the air temperature inside a vehicle at a certain level. The objective should not to maintain the air temperature, but rather to maintain the thermal comfort level of the driver. In this study, numerical simulation with computational fluid dynamics (CFD) was performed to analyze the air exchange during vehicle door movement and evaluate the change of the thermal environment of the driver in order to clarify the thermal influence of the air exchange in winter, which has large temperature differences between the indoor and the outdoor environments.

**METHOD**

**Modeling Approach**

In the present study, numerical simulation was used to analyze the effect of the movement of the truck door. Fig. 1 shows the truck cabin model used in this study. The model has three seats and an instrumental panel with a simplified shape. The trajectory of opening to closing the door on the right-hand side of a right-hand drive vehicle was modeled to simulate stop-and-go driving. A structured grid was constructed for analysis of transient moving transformation meshes (see Fig. 2). Other regions were resolved with an unstructured grid. Thus, the boundary between the door-moving region and the surrounding static region was a non-contiguous mesh that was divided into the lowest common part of the sides of both meshes for the calculation. In the door-moving region, the conservation of fluid mass matched the other regions because there was neither inflow nor outflow on the boundary of the door surface (ANSYS, 2013). The volume mesh was updated at each time step based on the new positions of the boundary. The moving velocity vector of the predefined door movement was taken into account in the conservation of fluid momentum via the first volume mesh on both sides of the moving door. Thus, the vector composition of the flow velocity with the mesh-moving velocity was calculated for the region adjacent to the moving boundary. The positive and negative pressures on the moving boundary were derived from such calculations of the velocity vector. The time step for the transient calculation of fluid dynamics and door movement was 0.01 s. Approximately 1.3 million mesh elements were used. Transient compressible flow was simulated to evaluate the effect of door opening and closing. The numerical simulation employed in this study involved coupled convection and radiation, and the parameters are shown in detail in Table 1. The renormalization group (RNG) $k$-$e$ model was employed as the turbulence model, and a second-order upwind scheme was selected as the differential scheme. The buoyancy force was taken into account using the variation of state for an ideal gas.

The analysis conducted in this study focused on the air exchange resulting from door movement. Thus, the HVAC system was assumed inactive, and no air was supplied to the cabin via the system. The initial indoor temperature was 25 °C, which was assumed as a comfortable temperature after establishing steady state through the HVAC system. The outdoor temperature was assumed to be -5 °C and the absolute humidity ratio of the air was assumed to be 0.00315 kg/kg (DA), which is equivalent to 95% relative humidity. These conditions correspond to a relatively severe winter night in Japan. The thermal boundary conditions of the
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Governing equation
- Compressible RANS equation
- Continuity equation
- Heat transfer equation

Solution algorithm
- SIMPLE

Differential scheme
- 2nd order upwind differential scheme

Turbulence model
- RNG $k$-$\varepsilon$ model

Time treatment
- Transient ($\Delta t = 0.01$ s)

Heat radiation model
- Discrete ordinates model

Table 1. Calculation conditions

| Parameter                        | Description                                      |
|----------------------------------|--------------------------------------------------|
| Governing equation              | Compressible RANS equation                       |
|                                  | Continuity equation                              |
|                                  | Heat transfer equation                           |
| Solution algorithm               | SIMPLE                                           |
| Differential scheme              | 2nd order upwind differential scheme             |
| Turbulence model                 | RNG $k$-$\varepsilon$ model                      |
| Time treatment                   | Transient ($\Delta t = 0.01$ s)                  |
| Heat radiation model             | Discrete ordinates model                        |

Fig 1. Cabin model and human model

Fig 2. Top view of mesh division of calculation region and trajectory of door opening
interior wall are given in Table 2. The window surfaces were treated as having a fixed temperature of 0 °C, and the wall temperature was assumed to be 15 °C. These values were determined by rough estimation of heat transfer based on the thermal conductance of the vehicle body and the temperature difference between the inside and the outside. The entire side door of the vehicle was modeled as a single wall, but the window of the door was not modeled separately. The amount of the heat loss through air exchange caused by the door movement was determined from the air mass inside the cabin, the constant pressure specific heat of air, and the temperature change.

**Conditions of Door Movement**

The transient angular velocity of the door is shown in Fig. 3. The maximum door opening angle was 57°, which is equivalent to 1 rad. The maximum angular velocity of the door opening and closing was 1 rad/s. Two cases were examined based on the duration of the door being open: 3 s for Case A and 1 s for Case B. The door moves for 1.5 s for each opening and closing action. The transient calculation ended 1 s after the door was closed. Thus, the total calculation times were 7 s and 5 s for Cases A and B, respectively.

**Evaluation of Thermal Environment Index**

The body of a human driver was modeled in the vehicle cabin as a simplified shape consisting of 16 body parts (Nagano et al., 2013). The driver was assumed to maintain a consistent driving posture throughout the analysis. Thus, the driver exiting or entering the cabin was not simulated. Oi et al. (2011) showed that heat conduction through the seat strongly affects the drivers’ thermal comfort. In this study, however, heat conduction through the seat was not taken into account. The purpose of this study was not to evaluate thermal comfort itself but rather the thermal environment and its fluctuations that are incurred by door movement. The standard new effective temperature (SET*) for the whole body was evaluated using the two-node human physiological model (Gagge et al., 1971). In addition, to evaluate the non-uniform thermal environment, the equivalent temperature for each body part was examined (ISO, 2007). A metabolic rate of 96 W/m\(^2\) was assumed as a normal human heat source, and a clothing insulation level of 1.09 clo (0.169 K·m\(^2\)/W) was assumed as the typical condition for winter in the calculations (SHASE, 2006). The average air temperature in the vicinity of the whole body was applied to calculate the SET*. In general, both SET* and the equivalent temperature evaluate the thermal environment based on the relationship between the heat loss of the body and the thermal sensation. Strictly speaking, such a relationship cannot be verified on the basis of transient conditions such as those affected by a vehicle door opening. However, the door opening influences the thermal environment variation, causing variation in human heat loss. This can reflect the variation in the thermal environment due to heat convection, radiation, and evaporative heat transfer. The effects of door movement were therefore verified in the present study using these indices.

**RESULTS AND DISCUSSION**

**Air Temperature and Airflow Variation**

Figs. 4 (a) and (b) show the variation in the average indoor temperature and the temperatures in the vicinity of the head and the foot for Cases A and B, respectively. The average temperature decreased almost linearly, at an average rate of 2 °C/s. The rate of temperature decrease was fairly consistent while the door opened and while it remained open. This means that air exchanged at the same rate when the door was initially opened and when the door was wide open. The

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Table 2. Thermal boundary conditions

| Wall segment                  | Thermal condition |
|------------------------------|-------------------|
| Front wind shield (glass)    | Fixed temperature |
| Rear window (glass)          | 0 °C              |
| Ceiling                      | Fixed temperature |
| Rear wall                    | 15 °C             |
| Side door                    | Adiabatic         |
| Floor                        |                   |
| Seats, instrumental panel    |                   |
| and other surfaces           |                   |

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Fig. 3. Angular velocity change of door opening and closing
temperature near the feet dropped to 0°C after 3 s had elapsed. In contrast, the temperature near the head changed very little. Therefore, temperature difference between the head and feet reached 25°C. After the door was closed, the average temperature was nearly unchanged but the temperatures at the head and feet increased. This occurred because the low temperature air was prevented from entering the cabin and the relatively high temperature air from the passenger side of the cabin mixed with the driver-side air.

In order to investigate this tendency, the variation of the air temperature distribution is shown in Fig. 5. After 2 s had elapsed, the cold air covered the thigh and the pelvis of the human body; after 3 s had elapsed, the pure outdoor air completely covered the lower body. The variation of the airflow is shown in Fig. 6. At the

Fig 4(a). Case A: air temperature variation
Fig 4(b). Case B: air temperature variation

Fig 5. Case B: variation of air temperature distribution

Fig 6. Case B: variation of airflow velocity distribution
beginning of the door movement, the airflow velocity inside the cabin was low. From 2 s to 3 s into the simulation, the airflow velocities at the lower and upper areas of the cabin were 0.6 m/s and 1.0 m/s velocity, respectively. Fig. 7 illustrates the airflow using temperature maps at 2.5 s for Case A. The warm indoor air rose as it moved outward because of buoyancy. Simultaneously, cold outdoor air flowed into the lower region of the cabin. The heat loss was calculated using the air temperature decrease. The total heat loss was approximately 57 kJ for Case A and 37 kJ for Case B. The 2 s of the door being open resulted in 20 kJ of additional energy loss. This means that there was 10 kW of heat loss during the extra time that the door was open.

**SET* Variation**

The variation in the SET* of the driver’s whole body is shown in Fig. 8. For the initial conditions, the SET* was almost 25 °C when the air temperature was a uniform 25 °C. This value hardly reflects the impact of heat radiation, which was not remarkable because the SET* was calculated as a function of the relative humidity (95%) as well. After the initiation of door movement, the SET* began to decrease at a rate of approximately 1.5 °C/s. The heat capacity of the human body is taken into account in the two node model, which is why the SET* changes neither drastically nor rapidly in contrast to the equivalent temperature. The SET* ultimately reached approximately 16 °C for Case A and 18 °C for Case B. The 2-°C difference in the SET* is attributable to the additional 2-s duration during which the vehicle door was open. Even after the door was closed, the SET* increased at a rate of 0.3 °C/s. This was due to the air temperature increase during the final period of door closure, as mentioned above.

**Equivalent Temperature Variation**

The variations in the equivalent temperatures of various major parts of the driver’s body are shown in Figs. 9 (a) and (b). The equivalent temperature at the beginning was approximately 20 °C, so there was a 5 °C difference compared to the SET*. Both the SET* and equivalent temperature indicate the operative
temperature in the virtual uniform environment, which cause equivalent heat loss from the human body to the actual environment. The essential difference is the influence of the humidity. The value of 20 °C is likely the average of the air temperature and the radiative temperature. The wall and window temperatures were fixed at 15 °C and 0 °C, respectively. The other surfaces, like the seat and instrumental panel, which were in the vicinity of the human, were treated as being adiabatic. Therefore, the surface temperature could have been higher than the wall and the window because there was heat radiation from the human body (heat conduction was not simulated). The equivalent temperature changed more drastically and more rapidly than the SET* of the whole body. In particular, those of the hand and forearm of the right side of the driver decreased to levels similar to the outdoor temperature (-5 °C) within 1 s. Rapid temperature decreases were also observed for the upper arm and the thigh on the right side of the driver’s body. In contrast, the temperatures of various parts of the left side of the driver’s body declined gradually. The upper left arm maintained a high equivalent temperature of 20 °C to 16 °C. The equivalent temperature of the head remained almost constant at approximately 18 °C. The changes observed in the air temperature distribution suggest that the warm indoor air rose because of buoyancy. This is likely the reason for why the air temperature and the equivalent temperature around the head at a high level in the cabin did not decrease. The door started to close after 4.5 s, and the equivalent temperatures of some parts of the body exhibited reversals in their downward trends after 6 s. These results suggest that the influence of heat radiation from the side door surface (at a temperature of 15 °C) increased as a result of the door closing.

For Case B, for which the open duration was shorter, some of the driver’s body parts, such as the left hand and the lower left leg, did not reach temperatures as low as those observed for Case A. The differences were not negligible, which suggests that the driver could feel the differences in the thermal environment because the thermal sensitivity of the hand in particular is high compared to the other parts. These results suggest that radiant heating may be more effective than air heating in quickly improving the thermal sensations experienced by drivers in response to vehicle doors opening and closing. In addition, heat radiators hardly cause temperature differences between the vehicle interior and the environment. Therefore the air exchange due to door movement could be decreased.

CONCLUSIONS
Numerical simulation of the cabin environment of a truck with door movement was performed, and the results were analyzed to assess the energy loss due to air exchange and its impact on the thermal environment. The results indicate that the outflowing warm air rises when the door is opened and that cold air from outside the vehicle flows into the lower region of the cabin. The influence of buoyancy was found to be remarkable: the temperature difference between the indoor and outdoor environments was quite large. The SET* of the driver declined gradually, at a rate of 1.5 °C/s. The equivalent temperature changed more drastically and more rapidly than the SET*. The right side of the driver’s body was exposed to the outdoor air, and the driver’s equivalent temperature decreased rapidly when the door was opened. In contrast, the driver’s equivalent temperature increased when the door was closed. These results indicate that radiant heat transfer is more important than convective heat transfer for the transient heat loss of the driver. The air exchange between the vehicle interior and the environment was increased by the temperature difference, which caused such unsteadiness in the thermal environment within the vehicle. Obviously, if the temperature difference became smaller, the fluctuation range would become smaller, and the magnitude of heat loss from the cabin air would also become smaller. However, the variations of the temperature and the heat loss of the human body showed similar tendencies because the critical element of these phenomena is the temperature difference between the vehicle interior and the environment.

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