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Thermal comfort and energy saving in a vehicle compartment using a localized air-conditioning system

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HIGHLIGHTS

- Thermal comfort and energy saving of a localized air-conditioning system are investigated.
- Thermal comfort indices are numerically estimated by varying air distribution ratio.
- Performance is measured with the variations of air flow rate and air temperature.
- Energy saving is evaluated using the measured and the predicted data.

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ABSTRACT

A localized air-conditioning system is expected to decrease energy consumption by avoiding extra cooling on the vacant seats. However, the energy saving of the localized air-conditioning system with satisfactory thermal comfort has seldom been quantified. In this study, both thermal comfort in the vehicle compartment and energy saving of the localized air-conditioning system with the front and ceiling vents were investigated. Thermal comfort in the vehicle compartment with the front and ceiling vents was analyzed using computational fluid dynamics with empirical correlations for thermal indices. In addition, the performance of the air-conditioning unit was measured at various air flow rates and air temperatures. The energy consumption of the localized air-conditioning system with the optimized front and ceiling vents decreased by 20.8% and 30.2%, respectively, against the baseline, while satisfying the neutral thermal comfort at the vent air temperature of 9 °C.

1. Introduction

Most vehicles use an air-conditioning system to improve thermal comfort in the compartment. The air-conditioning system creates a thermally comfortable environment by controlling air temperature, humidity, and indoor air quality. However, the energy consumption in the air-conditioning unit tends to significantly affect fuel economy in vehicles. Therefore, the reduction in the energy consumption of the air-conditioning unit has become a major concern in the automotive industry. Many efforts have been made to cope with this issue in various ways [1–6]. Statistical data showing low occupancy rate in a vehicle [7] suggests that unnecessary cooling is often provided to the vacant seat areas in the conventional system. Therefore, a localized air-conditioning system, which is an intensive spot cooling system for the occupied area, is expected to decrease the energy consumption by avoiding extra cooling in the vacant seat areas.

Localized air-conditioning systems have been applied in heating, ventilation, and air-conditioning (HVAC) systems of office buildings. Personalized ventilation has been developed with supply air terminal devices around an occupant [8]. The air terminal devices spread the conditioned air to an occupant directly with the increased air speed. The increase in the air speed is very helpful for achieving thermal comfort, although the average air temperature increases. Accordingly, the personalized ventilation resulted in an energy saving without causing occupant dissatisfaction [9–11]. Localized air-conditioning has also been applied to vehicles. Ružić and Časnji [12] suggested personalized ventilation for a mobile machinery cabin. They predicted a decrease in the cooling load of the personalized ventilation using a simplified theoretical analysis. Huang et al. [13] developed a localized air-conditioning system by providing an air vent and outlet. The desired temperature was achieved in a specified area using the localized air-conditioning system, while a higher temperature was maintained in other areas. Kaushik et al. [14] showed that a localized (or spot) air-conditioning system was capable of delivering sufficient ther-

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Nomenclature

CFD	computational fluid dynamics
COP	coefficient of performance
DB	dry bulb temperature (°C or K)
E	energy transfer (J kg^{-1})
E_{st}	the rate of energy stored within the human body (W m^{-2})
f_{cl}	ratio of clothed surface area to nude surface area
h	enthalpy (J kg^{-1})
h_c	convective heat transfer coefficient (W m^{-2} K^{-1})
HVAC	heating, ventilation, and air-conditioning
I_{cl}	clothing insulation (clo = 0.155 m^2 K W^{-1})
J	diffusion flux of species (kg m^{-2} s^{-1})
k	effective conductivity (W m^{-1} K^{-1})
M	metabolic rate (W m^{-2})
M_w	external work per unit area (W m^{-2})
P	pressure (Pa)
P_a	vapor pressure in ambient air (Pa)
PMV	predicted mean vote
Q	capacity (kW)
R	air distribution ratio
SH	degree of superheat (°C or K)
T	temperature (°C or K)
T_a	air temperature (°C or K)
T_{cl}	mean temperature of the outer surface of the clothed body (°C)
T_r	mean radiant temperature (°C or K)
t	time (s)
v	velocity (m s^{-1})
$\dot{V}$	volumetric air flow rate (m^3 h^{-1})
WB	wet bulb temperature (°C or K)
W_{comp}	energy consumption (kW)

Greek symbols

ρ	density (kg m^{-3})
$\bar{\bar{\tau}}$	stress tensor (Pa)

Subscripts

a	air
c	cooling
ceiling	ceiling vents
eff	effective value
eq	equivalent
front	front vents
r	mean radiant
va	from vent

mal comfort at lower energy consumption. Ghosh et al. [15] reported that a localized air-conditioning system achieved less air flow by thirty to fifty percent of conventional HVACs under ideal conditions for nozzle location and air flow delivery.

The effect of the localized air-conditioning system on thermal comfort in a vehicle compartment has been investigated extensively. However, studies on the quantification of energy saving using localized air-conditioning in a vehicle are very limited. In this study, both thermal comfort and energy saving of a localized air-conditioning system with the front and ceiling vents were investigated in order to achieve effective occupancy cooling. Thermal comfort indices, such as predicted mean vote (PMV) [16] and equivalent temperature [17], were numerically estimated by varying the air distribution ratios in the front and the ceiling vents of the localized air-conditioning system. In addition, the performance of the air-conditioning unit was measured with the variations of the air flow rate and air temperature. Finally, the energy saving of the localized air-conditioning system was evaluated by combining the measured system performance with the predicted thermal comfort indices.

2. Numerical analysis and experiments

2.1. Numerical analysis on thermal comfort

The air is supplied to a vehicle compartment through vents. As described in Fig. 1, the air circulation inside the vehicle compartment was analyzed using FLUENT 14 [18]. The mass conservation, momentum equation, and energy equation were solved using the finite volume method.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v}\,\vec{v}) = -\nabla p + \nabla \cdot (\bar{\bar{\tau}}) + \rho \vec{g} + \vec{F} \tag{2}$$

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot \left(\vec{v}(\rho E + p)\right) = \nabla \cdot \left(k_{eff}\nabla T - \sum_j h_j \vec{J}_j + \left(\bar{\bar{\tau}}_{eff} \cdot \vec{v}\right)\right) \tag{3}$$

The fluid field was assumed as a turbulence flow, and the standard k–ε turbulent model was applied along with a scalable wall function. The density of air was estimated by applying an incompressible ideal gas law. The second-order implicit scheme was employed to solve the governing equations, and the SIMPLE algorithm [18] was employed for the coupling of pressure and velocity. In addition, the radiation heat transfer was considered using the

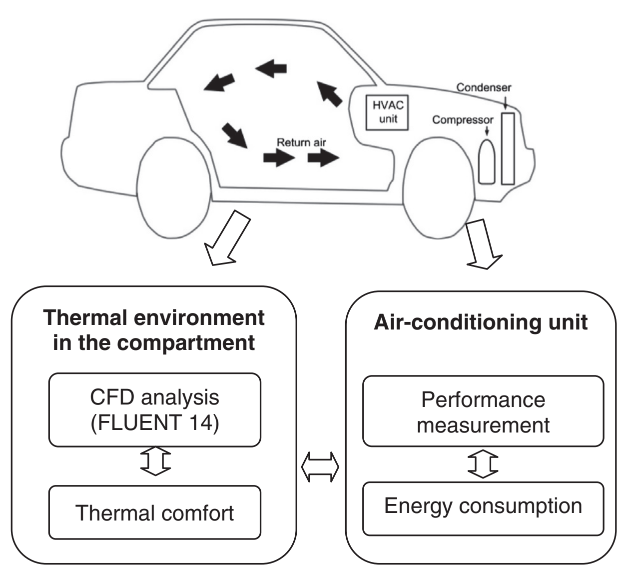

Fig. 1. Analysis method for thermal comfort and energy saving.