Airflow Organization in a Transformable Shelter

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Abstract. The environmental control system of a shelter can provide comfortable temperature, air velocity and fresh air supply for members indoor, protecting them from the extreme weathers or oxygen-poor environment in the field. A shelter with transformable walls will have a large available space including the core module and extended modules for diverse demands such as dining or sleeping. The airflows in such a limited space can be inevitably influenced by walls and furniture. In the study, a transformable shelter with top supply and bottom return air organization mode was taken as the research object. The air supply duct on the ceiling of the shelter was designed to uniform the supplying air quantity through each outlet by adding baffles in the duct. Baffles can also make the export winds nearly perpendicular to the duct wall. The indoor airflow velocity and temperature fields in the condition of people gathering for dinner were obtained by simulation, so as that in the condition of people scattering for sleeping. In the dining condition, the barriers to the uniform airflow and temperature are the crowd occupying the core module. In the sleeping condition, the dominating barriers are the walls between different modules. The airflows were uniformed between different modules by opening apertures across the partitions. In view of human comfort, a comprehensive evaluation of the air flow organization was given, which presents an essential reference for system design and optimization.

Keywords: transformable shelter, airflow organization, dining and sleeping condition, human comfort

1. Introduction

The environmental control system of a shelter can provide comfortable temperature, air velocity and fresh air supply for members indoor, protecting them from the extreme weathers or oxygen-poor environment in the field. The dimension of a vehicle-mounted shelter is limited by the vehicle. The expandable shelters with a small original volume and a high volume expansion ratio [1] have come into being. Common expandable shelters include origami-inspired shelters [2, 3] and rigid wall shelters.

Airflow organization includes optimization of air temperature and velocity distribution as well as the thermal comfort for personnel inside. Airflow organizations in an enclosed or semi-enclosed space such as accommodation [4], automobile cabin [5, 6] and highway sleeper coach [7] have been studied through experiments [8] and simulations [9, 10] comprehensively.

A shelter with transformable walls can stay on the vehicle and enlarge the space by moving the walls. The transformable shelter can provide spaces for diverse demands of personnel at different times and the requirements are also different for diverse use conditions. In this work, to cater to the different requirements of diverse using conditions, the airflow distribution inside has been simulated. The main factors impacting the airflow have been explored and several attempts have been made to optimize the airflow in the shelter.

2. Models and methods

The shelter before expansion can be hosted by a vehicle and are in the size of 6961 mm (L) × 2478 mm (W) × 2546 mm (H). When the shelter is transformed for dinner or sleeping, its size increases to 8866
mm (L) × 6336 mm (W) × 2546 mm (H). The transformed shelter consists of core module, left and right wing modules and front and back cells, as shown in Figure 1(a). The thickness of the shelter walls is 50 mm. An upper-supply and bottom-return airflow mode is used in the shelter. The air supply duct is located on the ceiling of the core module and front cell. The air return ducts are located on the bottom edges of the three modules. The width and height of the cross section of the air supply duct are 900 mm and 150 mm respectively. The closed tail of the air duct is 500 mm from the back cell. 9 pairs of air intakes are arranged on the vertical sides of the air duct, as shown in Figure 1(b). The air intakes are in the same size of 303 mm × 100 mm, and the distance between the adjacent intakes is 696 mm. The thickness of air duct wall is 5 mm.

When dining, members are gathering and standing in both sides of the long table in the closed space of the core module, seen in Figure 1(c). The area of the table is 6,000 mm × 600 mm and 750 mm from the floor. There are 10 members on each side of the table, each with a height of 1750 mm and a cross section size of 400 mm × 300 mm. When sleeping, members are scattering and lying on the beds hung on the walls of the core and wing modules, seen in Figure 1(d). There are 30 beds in total with 6 beds in core module and 12 beds in each wing module. The size of the bed is 1900 mm (L) × 700 mm (W) × 80 mm (H), and that of person is 1750 mm (L) × 600 mm (W) × 200 mm (H). The materials of the shelter walls and the duct walls are hardboard and stainless steel respectively. The beds and table are made of hardwood. Physical properties of persons are assumed to be the same as that of liquid water.

Table 1 Physical properties of the related materials

| object       | material  | Roughness, | Density, kg/m³ | thermal conductivity, W/(m·K) | specific heat capacity, J/(kg·K) |
|--------------|-----------|------------|----------------|-------------------------------|---------------------------------|
| /            | air a     | /          | 1.207          | 0.026                         | 1007                            |
| module wall  | hardboard b | 0.5       | 640            | 0.094                         | 1170                            |
| duct wall    | stainless steel b | 0.15     | 7900           | 14.9                          | 477                            |
| bed, table   | hardwood b | 0.5       | 720            | 0.16                          | 1255                            |
| body (water) | (water) b | 2         | 1000           | 0.6                           | 4180                            |

a: built-in parameter of I-DEAS software.
b: appendix of Fundamentals of Heat and Mass Transfer, Sixth Edition.

I-DEAS software combines Computational Fluid Dynamics (CFD) and thermal solution technology with finite element method (FEM). It can be used to simulate the flow and temperature fields in the shelter. The calculation conditions of the models are given below. The air entrance of the air supply duct is a fan with a volumetric flow rate of 3500 m³/h, and the air temperature is 17 ℃. Each outlet of the...
return duct is a vent to the environment. The roughness of all the surfaces are listed in Table 1. The heat production power of each person is 900 W/m², and the surface temperature is assumed to be 33 °C. The shelter is located facing west at the Tuotuo River with an altitude of 4,500 m and an atmospheric pressure of 58,477 Pa. In the steady-state calculations, the ambient temperature is set as 40 °C.

To evaluate the performance of an airflow organization system, from the perspective of technicality, in addition to the averages of indoor temperature and velocity, the non-uniform coefficients of temperature ($K_T$) and velocity ($K_v$) are also needed. A non-uniform coefficient is the ratio of the root mean square (RMS) of a parameter to its average. Thus we have:

$$K_T = \frac{\sigma_T}{T_p}, \quad \sigma_T = \sqrt{\frac{\sum(T - T)^2}{n - 1}}, \quad T_p = \frac{\sum T}{n}$$

$$K_v = \frac{\sigma_v}{v_p}, \quad \sigma_v = \sqrt{\frac{\sum(v - v)^2}{n - 1}}, \quad v_p = \frac{\sum v}{n}$$

where $T$ and $v$ are the temperature and velocity, $\sigma_T$ and $\sigma_v$ are the RMS of temperature and velocity, $T_p$ and $v_p$ are the averages of the temperature and velocity, respectively, $n$ is the number of measuring points. The smaller the non-uniform coefficient, the better the uniformity of temperature and velocity fields.

From the perspective of comfort, human comfort can be used as an evaluation indicator. The effective temperature difference $\theta$, which can reflect the difference between perceived and actual temperatures, has an expression synthesizing the influences of temperature and airflow as

$$\theta = (T - T_a) - M(v - v_r)$$

where $T_a$ is the given room temperature, usually the indoor average temperature $T_p$, $v_r$ is the designing velocity of 0.15 m/s, $M$ is the temperature value equivalent to the unit velocity effect with a value of 7.66 °C/(m·s⁻¹). If $\theta$ varies in the range from -1.7 to 1.1 °C, the members inside feel comfortable. The proportion of measuring points in this range is the air diffusion performance index (ADPI). When the ADPI is larger than 80%, this airflow organization can be considered satisfying.

### 3. Results and discussion

The airflow in the shelter needs to be organized and optimized for the uniform and appropriate air temperature and velocity, guaranteeing the human comfort indoor. In view of the complexity of the optimization process, only some significant results are given below.

The uniformities of the air temperature and velocity in the shelter depend on the uniformity of supplied air quantity through each intakes of the shelter, namely the outlets of the duct. The air supply should be optimized before the indoor airflow organization.

After entering the duct from entrance, the air is gradually diverted into the shelter from the outlets along the initial flow direction. To uniform the supplied air quantity, baffles are added at the downstream side of each outlet to control the airflow velocity and direction. The shape, length and direction of the baffles can be adjusted. Straight-shaped baffles can make the mass flow rate from each outlet nearly equal. However, the air from the outlet rushes into the rear space of the core module along the fixed direction of baffles, causing air stagnation in the front space, which is detrimental to the uniformity of air velocity. The arc-shaped baffles are optimized from the straight-shaped ones, whose shape is a quarter of a cylinder wall. The radius of the baffle at each outlet gradually increases, as shown in Figure 2(a). After multiple optimization calculation, the radius data in Table 2 are obtained, which can make the mass flow rate of each outlet nearly equal.

The results in Table 2 show that the maximum deviation of the mass flow rate of each pair of outlets is 13%. As can be seen from the air velocity field in Figure 2(b), the air velocity direction from each air outlet has been deflected with respect to the direction of air entering. The outflow directions of the outlets have been optimized with the export winds nearly perpendicular to the duct walls. Therefore, the air supply duct with arc-shaped baffles is applied to subsequent calculations.

| Table 2 The baffle radius and mass flux of each pair of outlets |
|---------------------|-----------------|-----------------|----------------|----------------|-----------------|----------------|-----------------|-----------------|-----------------|
| Baffle radius /mm    | #1  | #2  | #3  | #4  | #5  | #6  | #7  | #8  | #9  | average |
|----------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|---------|
|                      | 100 | 135 | 175 | 220 | 250 | 300 | 360 | 400 | /   | /       |

3
Figure 2 The schematic of air supply duct with arc-shaped baffles

The airflow velocity and temperature fields in the core module have been obtained by simulating the dining model in a steady-state condition. The distributions of air velocity in some typical cross sections are shown in Figure 3. As can be seen in top view (Figure 3(a)), there are regions with relative low velocity in the front and end parts in core module, so as in the top regions in lateral views (Figure 3(b)) and central regions in front views (Figure 3(c)). In most regions, the air velocity is lower than 0.63 m/s. Because the temperature of air is 17 ℃ and far lower than the ambient temperature of 40 ℃, the temperature in the regions with high air velocity is lower than that with low velocity.

Figure 3 Air velocity distributions in the cross sections of the core module
(a) top view, (b) lateral views, (c) front views.

Figure 4 Air temperature distributions in the cross sections of the core module
(a) top view, (b) lateral views, (c) front views.

As shown in Figure 4, the highest air temperature is below 21 ℃, which means that the refrigeration effect of the air supply of the environmental control system is powerful. The highest temperature occurs in the zones close to the feet of the persons standing in the front region of the module, and the air temperature shows a decreasing trend from the front to the back. Since the air enters the module backwards diagonally, there is more cold quantity obtained in back region than the front one in spite of

| mass flux /kg·(m²·s)⁻¹ | 1.27 | 1.25 | 1.20 | 1.16 | 1.10 | 1.20 | 1.28 | 1.28 | 1.40 | 1.24 |

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the equivalent air mass fluxes, resulting in the temperature difference between front and rear spaces.

Table 3 shows the statistical results of the air velocity and temperature in the horizontal section near the neck of the human bodies (Figure 3(a) and 5(a)). It can be seen that the ADPI in this section is not satisfying and far lower than the comfort index of 80%. In dining condition, the barriers to the uniform airflow and temperature are the persons.

Table 3 Statistical results of air velocity and temperature in a horizontal section

|       | average | RMS  | non-uniform coefficient | ADPI  |
|-------|---------|------|-------------------------|-------|
| velocity | 0.40 m/s | 0.21 m/s | 0.53                     | 37.9% |
| temperature | 18.7 °C | 0.7 °C | 0.04                     |       |

The airflow velocity field in shelter have been obtained by simulating the sleeping model in steady-state condition. The only passage from the core to the right wing module is the right door located on the wall of the front space, which is a dead zone for airflow and only a few fresh and cold air can be allocated in. The negative pressure occurred in the back of the right wing module leads to intrusion of the ambient air and affects the entire right wing module and front cell. Therefore, the situation of the air supply duct or the passages between the modules need to be optimized in order to obtain more uniform distribution of the air velocity and temperature.

The new air passages are carved on the walls of the core module. As shown in Figure 5(a), total four long narrow passages with a size of 200 mm × 5460 mm are carved 400 mm above bed rows. The airflow velocity fields of the improved sleeping model are shown in Figure 5(b). Compared with that of the original model, the airflow is fully developed and more uniform. The temperature fields shown in Figure 6 indicate that the temperature in each module is relative uniform and approximately 19 °C. The statistical results of the air velocity and temperature in the horizontal sections 100 mm above the top surfaces of human bodies (Figure 6) are listed in Table 4. The average velocities of two horizontal sections are 0.35 and 0.24 m/s, respectively. For upper section the ADPIs are lower than the comfort index of 80%, and for lower section, the ADPIs is higher than 80% except in left wing module.

Figure 5 Schematics of the improved sleeping model (a, green zones are air passages) and velocity fields in the expanded shelter (b) front view and (c) top view

Figure 6 Velocity fields in the expanded shelter
(a) isometric view, (b) top views, (c) lateral views and (d) front views
4. Conclusions
In this work, the temperature and velocity of the airflow in a transformable shelter are simulated in both steady and transient states. The air supply duct is optimized by adding arc-shaped baffles. In the dining model the dense crowd of the diners in the core module block the airflow, leading to a low human comfort, while in the sleeping model the dominating barriers are the walls between the modules.

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