Simulations of Airflow and Substance Concentration around a Human Body

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Abstract In order to predict airflow and suspended substance concentration around a human body, we developed a geometric model of the human form and generated grids around it for Computational Fluid Dynamics (CFD). According to a CFSV model proposed by us we made a domain that included a geometric human model and generated the grids within this domain. By using this model with the grids and the developed CFD program, it is possible to simulate the airflow and the transfer of a suspended substance around the body. The simulated airflow provided a different velocity profile for each region of the body due to the characteristics of the body shape. The simulated distribution of the suspended substance concentration demonstrates how usable the present model is for quantifying a substance in any exposed region of the body. J Physiol Anthropol 21 (5): 215–222, 2002 http://www.jstage.jst.go.jp/en/

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Introduction

The aim of this study is to analyze airflow around a human body using a numerical simulation. The airflow plays a very important role in transferring chemical materials, bacteria, viruses, radioactive aerosols, heat, and vapors that physiologically influence a living body (Botkin and Keller, 1995; Samet and Spengler, 1991). Therefore, in order to predict the concentrations of substances near the body, it is necessary to understand airflow patterns around the body.

It is known that airflow around a human body has characteristics that are specific to each part in the body (Clark and Cox, 1974a and b). As well, the behavior of substances in close proximity to the body seems to vary in each region. If a substance were to be ingested through inhalation, for example, predicting the concentration of that substance near the mouth would be especially important. On the other hand, if a substance were absorbed through dermal pathways, it would be equally important to understand their distributions and concentrations on the skin surface (Batterman et al., 1996).

In addition, airflow around the human body influences thermal physiological conditions within the body because the rate of convective heat transfer on the body surface depends on air velocity (Fanger, 1970; Galimidi et al., 1979). Furthermore, Clark (1981) indicates that posture influences the rate of heat transfer from the body because as posture changes, so does the airflow. In order to simulate thermal physiological conditions (Stilwijk and Hardy, 1966; Gordon et al., 1976; Werner and Buse, 1988; Yokoyama et al., 1997), it is necessary to estimate environmental factors such as air velocity and temperature with respect to regional characteristics of the body.

Although measurements using a Schlieren optical system (Clark and Cox, 1974a), smoke, or sensor devices such as hot wire anemometers or thermocouple probes have been made in the airflow around the human body, it has been impossible to obtain the necessary information due to the complex shape of the body.

With the recent steady improvements in computers, Computational Fluid Dynamics (CFD) has been frequently used as a powerful method for fluid analysis for various purposes before final, if any, experimental testing (Fletcher, 1991). However, it is difficult to conduct airflow experiments around the human body. Nevertheless, CFD
can provide circumstantial information. In order to use CFD for analysis of airflow around a human body, it is essential to use a numerical simulation with a geometric model of the human form. However, a parallelepiped, a cylinder, a combination of several of them, or a simple curved object (Murakami et al., 1996) have been used to serve as geometric models of human forms because such shapes lend themselves well to generating grids. On the other hand, three-dimensional geometric models that closely approximate an actual body form have been developed along with the recent progress in computer graphics technology and disclosures of databases for sizes of the human body (Banvard et al., 1998; Okabe et al., 1992; Imaoka, 1996). The model that we have developed and used for analysis is capable of assuming several postures (Kakuta et al., 2001).

CFD simulation requires that grids be generated around the body. We made a domain that included a geometric human model and generated the grids within this domain. We simulated the airflow by installing this domain into an actual calculation space for CFD. This paper demonstrates a method for a numerical analysis and results of the airflow around the body. Furthermore, the simulated results of a substance transfer around the body are indicated.

**Methods**

**A geometric human model**

To numerically simulate airflow around a human body, a geometric human model is needed to be installed into a calculation region. The geometric model closely resembles the actual shape of a body and mimics three positions (Fig. 1): standing, sitting, and lying on the back. The body size is that of an average Japanese male based on several anatomical databases (Sato, 1992; Peterson, 1980). The surface of this model is composed of 1,228 quadrilateral elements. In addition, the number of the divided elements can be changed arbitrarily.

**Grid generation around the geometric human model**

The grids are generated within a closed domain that is a 1200×1200×1600 mm rectangular parallelepiped containing a geometric human model in a seated position (Fig. 2). Domains of 1000×800×2000 mm and 1000×2000×600 mm are used for a standing position and a supine position, respectively. These domains surrounding the human model named *domain-unit* can be used as a part of an actual calculation space. That is, the domain-unit can connect another domain, contain the other smaller domain, or be contained in the larger domain.

The domain-unit is divided into several sub-domains since it is impossible to generate the entire grid at once because of its complicated form. The grids around the body are generated as follows: (1) Prepare coordinates on the body surface from an anatomical database, (2) Divide the domain-unit into several sub-domains including the typical body segments (head, upper arm, thigh, foot, etc.),

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**Fig. 1** Geometric human models.

**Fig. 2** A domain-unit including a geometric human model.
respectively, (3) Divide a sub-domain between a fluid domain and a non-fluid domain that is, in this case, a part of the body segment, and (4) Generate the grids within each fluid domain and assign an identification number to each grid. These multi-sub-domains are shown as a two-dimensional schematic diagram in Fig. 3. In step (4), we used a transfinite interpolation (Thompson et al., 1985; Arcilla et al., 1991), an algebraic method for grid generation.

For grid generation and development of the CFD program, we have used a general system for 3D fluid analyses based on a CFSV model (Mizuta, 1995; 1997), which is an acronym for cells, faces, sides, and vertices. Refer to the CFSV model for the details of this model; however, the concept is based on the fact that each equation discretized for numerical analysis of three-dimensional continuous media is no other than the relationship among quantities on elements such as cells, faces, sides, and vertices (Mizuta et al., 2001). Due to this system, we have been able to generate the grids and develop the CFD programs with less load and time.

Among the grids around the body, Fig. 4 shows the grids within three different cross sections indicated in Fig. 2. The available memory size, the computer performance, and the purpose of CFD determine the total number of grids. Since the obtained geometric data can be translated into other data formats, the domain-unit can be incorporated into a region created by a CAD/CAE application.

**Calculation conditions for the airflow simulation**

An airflow simulation around a human body in a 1400×1400×2200 mm rectangular space, shown in Fig. 5, was carried out to demonstrate the applications of our model. A domain-unit of a body in a seated position was installed into this space.

Table 1 shows the calculation conditions used in CFD analysis based on the standard $k$–$\varepsilon$ model. For comparison, two boundary conditions of velocity were assumed as follows: Case 1) the air blows in from the floor with 0.5 m/s and exits from a 540×540 mm outlet in the ceiling, Case 2) the air blows in with 0.5 m/s from an area in the wall in front of the body model shown in Fig. 5 and exits from the ceiling outlet, and Case 3) conditions are the same as Case 2 except that the blow-in velocity is 0.25 m/s.

The gradient of the outlet velocity in a normal direction was set at zero. Accordingly, the outlet velocity was defined in volume balance with the inlet flow. The wall had a boundary condition of the generalized log law. The turbulent energy of the inlet was 3% of the kinetic energy of the inlet airflow. The dissipation rate of the floor was given by assigning 1% of a side length of a grid to the length scale of turbulence (Fletcher, 1991). The buoyancy caused by the temperature difference was assumed to be neglected.

**Calculation conditions for the substance transfer simulation**

When the distribution of airflow velocities is calculated, it is possible to predict the distribution of the concentration of a suspended substance, provided that the information about the properties and the source of the substance are known.

In this study, it is assumed that the source of a substance, whose generation rate is constant with time, 1.0 mg/s, is located at the bottom in front of the body as shown in Fig. 5. For the initial condition, the concentration within the whole space was set at zero. In
addition, the following assumptions were made: (1) the density of the substance is equal to that of air, and (2) the substance is not absorbed by the wall and the body surface.

Results

Airflow around the body

The velocity vectors of the airflow in typical horizontal and vertical cross sections are shown in Fig. 6 among the calculated results from Case 1. The configurations of these cross sections are shown in Fig. 5. The velocity profiles within cross sections A and B indicate that the main upflow from the floor to the outlet is occurring. Fig. 6 demonstrates well the main upflow as it is obstructed by the body. The exfoliations from and the re-attachments to this main flow occur in some regions near the body surface, which forms a complicated airflow with eddies in various scales. These results indicate the characteristics of the body shape. For example, the airflow generated by the collisions of the blowout flow with the hip, the thighs, the calves, and the feet is quite noticeable. The airflow in front of the abdomen and the chest and in the upper part of

both shoulders is relatively small in velocity.

The simulated results under another boundary condition, Case 2, shown in Fig. 7, demonstrate a horizontal airflow near the foot and an upflow along the back wall that can be attributed to the configuration between the body and the inlet. Since the inlet area in Case 2 is smaller than that in Case 1, some stagnant domains are apparently recognized in the top corners.

Distribution of the substance concentration around the body

Figure 8 (a) shows the distribution of a substance concentration in Case 1 at an elapsed time of 60 s. Since the substance transfer is governed more by convection than molecular diffusion, the diffusion depends on the airflow profile. Thus, along the airflow, the relatively high concentration domain moves upward from the source with time, while there is a low concentration domain in the stagnant domain. This upflow almost prevents the body from an exposure of the substance because the source of the substance flows up apart in front of the body and its velocity is relatively large. Figure 8 (b) shows the concentration profile in Case 2 at an elapsed time of 60 s. The highest concentration domain appears between a pair of feet and we can see the concentrations around the head and breasts where the velocities are smaller. Figure 8 (c) indicates that the pattern of a substance concentration in
Case 3 is similar to Case 2. However, as the ventilation rate in Case 3 is less than in Case 2, the concentration level around the body in Case 3 has a higher total.

Table 2 shows the concentrations in each Case at several points near the body surfaces at 60 s. In Case 1, the concentrations in most regions are zero and the concentrations at the head and the foot are less than 0.01 ppb. On the other hand, the results in Case 2 and Case 3 have noticeable values. In Case 2, the value at the forearm is the largest and the values at the face and breasts are larger than in other regions. The comparison of the results in Case 1 and in Case 2 demonstrates that the different configurations of an air inlet and outlet yield the difference of the quantities of a substance in each region of the body. The variation of a boundary condition of velocity varies the velocity profile in the whole domain. Therefore, each concentration in Case 3 is not equal to half of that in Case 2, although the ventilation rate in Case 3 is equal to half of that in Case 2.

**Discussion**

It is significant to generate grids around the geometric human model that resembles an actual human body and simulate the airflow for estimating a human environment. In regard to human shapes, simple shapes such as a parallelepiped, a cylinder, or a combination of several of them have been used because such shapes lend...
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Fig. 8 Distribution of a simulated concentration of a substance (ppb) within Cross Section A (left) and Cross Section B (right) at an elapsed time of 60 s.

themselves well to generating grids. Increasing the numbers of the surface elements of our model and the grids in the space, the form more closely resembles an actual body, and the resolution of the computed distribution increases. However, an approximation limit of our model should be considered; e.g., fingers are indistinct and the model represents a naked body. For future study, the model should be modified or superseded by another model created by using computer graphics technology. If the bodies with various sizes and clothes are geometrically modeled, the same process as we used in this study can also generate grids and simulate the airflow.

Although, in CFD analysis, we adopted the methods that had provided many reliable results in the past, it is interesting to use another method and to compare results. In regard to a turbulence model, for example, it would be worthwhile to use Large Eddy Simulation (Fletcher, 1991). Another area deserving further exploration is the analysis of fluid behavior in a thin boundary layer near the skin.

In addition to the boundary condition, various factors influence the exposure level in each region, such as generation rate of a substance, substance property, and posture. Simulation using our model can quantify each factor's contribution to the exposure level. Considering inhaled substances, the concentration near the mouth seems to be useful, although an analysis of the airflow by respiration would be necessary in order to precisely quantify ingestion. In view of ingestion, a model and an analysis intended for a microscale mass transfer should be applied near the skin as well as near the mouth and nose. By using a reliable model for this purpose in combination with our model, it should be possible to precisely predict any substance.

It is expected that use of computer-aided systems for the design and simulation of human environments will increase. For occupational environments, some simulators that can estimate workload at each part of a body have been developed (e.g., Badler et al., 1993). In order to estimate the total condition of the body, a simulator that can predict environmental factors must also be needed. We believe that our system that simulates the airflow, one of the most important environmental factors, will be useful toward achieving this aim. Another factor we must consider is radiation (Kakuta et al., 2001) that includes insolation, X-ray, and thermal radiation because, considering the methods of transfer to the body, environmental factors might generally be categorized into two groups: airborne and radiation. We would like to integrate the above simulators and apply these simulators to an actual working environment.

Conclusions

In order to predict airflow around a human body, we developed a geometric human model capable of assuming
several postures. The model closely resembles an actual human body. Grids were generated around the geometric model. The installation of a domain unit that consists of this geometric model and the generated grids into an arbitrary domain allowed us to simulate the distributions of airflow velocity and concentration of a suspended substance.

The simulated airflow around the body showed a different velocity profile for each region of the body due to the characteristics of the body shape. The simulated distribution of the substance concentration demonstrated the practical application of the model for quantifying a substance in a specific region of the body. With an expectation of increased use of computer-aided systems for the design and simulation of human environments, we believe that the geometric model with the grids and the calculation method in this study have many possibilities for practical application.

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References
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Table 2 Substance concentrations near the surface in each region

<table>
<thead>
<tr>
<th>Region</th>
<th>Concentration [ppb]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Case 1</td>
</tr>
<tr>
<td>1 Face</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>2 Breast</td>
<td>0.0</td>
</tr>
<tr>
<td>3 Abdomen</td>
<td>0.0</td>
</tr>
<tr>
<td>4 Back</td>
<td>0.0</td>
</tr>
<tr>
<td>5 Forearm (right)</td>
<td>0.0</td>
</tr>
<tr>
<td>6 Thigh (right)</td>
<td>0.0</td>
</tr>
<tr>
<td>7 Calf (right)</td>
<td>0.0</td>
</tr>
<tr>
<td>8 Foot (right)</td>
<td>&lt;0.01</td>
</tr>
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