

## Application of Computational Fluid Dynamics Simulation to Olfactory Display

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### Abstract

*An olfactory display is a device that delivers various odors to the user's nose. It can be used to add special effects to movies and virtual reality systems by releasing odors relevant to the scenes shown on the screen. To provide high-presence olfactory stimuli to the user, the olfactory display must be able to generate realistic smells with appropriate intensities in a timely manner. Here we propose to use computational fluid dynamics (CFD) simulations in conjunction with the olfactory display. In the proposed system, a CFD solver is employed to calculate the turbulent airflow field in the given environment and the dispersal of odor molecules from their source. An odor blender is used to generate the odor with the concentration determined based on the calculated odor distribution. Experimental results on presenting odor stimuli synchronously with a movie clip and generating odor stimuli together with a changing airflow field show the effectiveness of the proposed system for the delivery of high-presence olfactory stimuli.*

### 1. Introduction

An olfactory display is a device that delivers smells to the user's nose (Fig. 1). Generally, it is assumed that smells are released in a synchronized way with visual images and sounds. It can be used to add "special effects" to a movie by releasing smells relevant to specific scenes shown on the screen. Adding smells to a movie is effective in making specific scenes extremely impressive [1]. The olfactory display can also be used in conjunction with a virtual reality system. Nakaizumi, et al. stated that an experience of a virtual world without smells would be like being in a spacesuit having no contact with the air in the virtual world [2]. The olfactory display is expected to bring a higher level of presence to the immersive virtual reality system.

In order to achieve successful presentation of smells, there are some technical issues that need to be solved. Most of the research work so far is addressed to generation and delivery of the smells [1-4]. Considering the diversity of olfactory receptor cells, it is unlikely that an arbitrary smell

can be generated from a small set of primary odors. Therefore, in a typical olfactory display, one mixture of chemicals in liquid or solid form is prepared for the generation of each specific smell. The vaporized smells are delivered to the user's nose through tubing [1, 3] or the smells are vaporized directly at the nostrils using inkjet devices [4]. A device that shoots vortex rings of air can also be used to deliver smells to the user's nose [2].

How to adjust the strength of a smell is also a problem. The appropriate release rate of an odorant for a faint scent drifting in the air and that for a malodor hitting the nose can be extremely different. Our current interest is to establish a method that enables automatic adjustment of the release rate of smells. Diffusion of odor molecules into air is an extremely slow process, and the diffusion length for one hour is only a few tens of centimeters [5]. In most indoor and outdoor environments, airflow velocity dominates the slow diffusion rate. Even in a closed room, there usually is airflow in the order of centimeters per second, which is created by small temperature variations in the room [6]. Since the dispersal of odorants is mainly determined by the airflow field, we propose to use computational fluid dynamics (CFD) to simulate the airflow field and the concentration distribution in the given environment. An

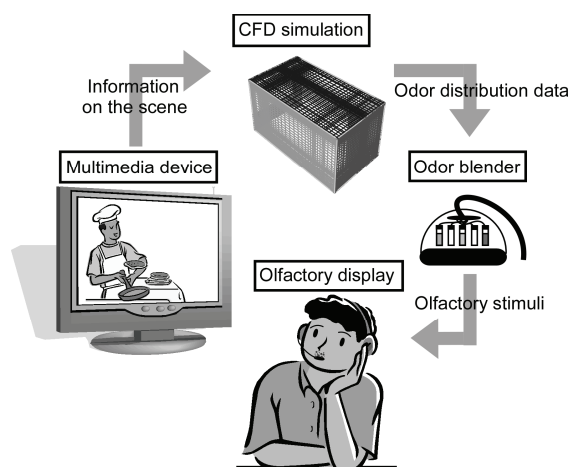


Figure 1: Schematic diagram of an olfactory display with CFD simulation software.

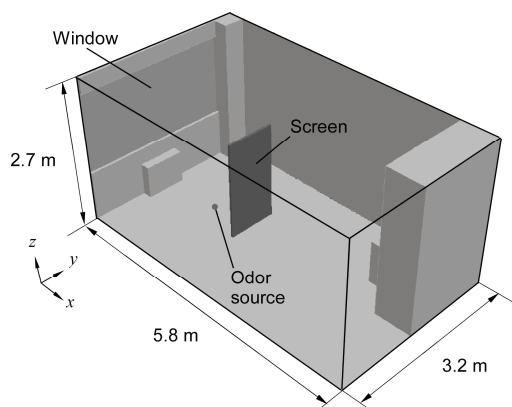


Figure 2: Room model with a screen and an odor source.

odor blender is used to generate the odor with the concentration determined based on the calculated odor distribution. Two sets of sensory tests are reported in this paper to show the effectiveness of the proposed system for the delivery of high-presence olfactory stimuli.

## 2. Method

The schematic diagram of the proposed system is shown in Fig. 1. The flat-panel TV is showing a movie in which a chef is cooking something using a frying pan. A CFD model is prepared to reproduce the scene in the simulation. After calculating the airflow field and the odor distribution, time-series data of the odor concentration corresponding to the location of the user's nose are extracted. Odor with the specified concentration is generated using an odor blender with a computer-controlled fluidic system [1]. The olfactory stimuli the user would experience in the real world are thus presented.

The airflow in the environment of a scale relevant to our daily lives is almost always turbulent, and therefore, computationally intensive calculation is required for the simulation. However, the highly accurate simulation of the chemical dispersal is not always required for the playback of odor stimuli since the users will not recognize small differences in the concentration. Moreover, a new odor is inhaled into the nostrils only once in several seconds under the normal breathing condition. Even when we intensively sniff, the time interval of the odor inhalation is around 0.5 s. Therefore, we sacrificed the accuracy for fast calculation as far as the qualitative behavior of the odor distribution is appropriately reproduced in the simulations.

In the experiments, the user (or the panel) of the olfactory display was assumed to be a small animal, e.g., a rabbit, released in a room where a teapot containing peach tea was placed. A room model shown in Fig. 2 was prepared for the CFD simulations. A screen was placed downwind from the source to disturb the odor distribution. The virtual room shown in Fig. 2 was modeled after a real

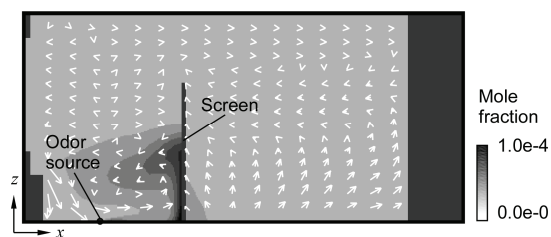


Figure 3: Airflow field (0–12 cm/s) and odor distribution on the vertical plane at mid-width of the room.

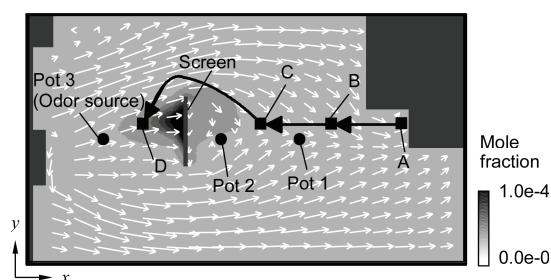


Figure 4: Airflow field (0–10 cm/s) and odor distribution on the horizontal plane at 20 cm from the floor.

room in our laboratory, and thus, comparison between the real and simulated data was enabled. The CFD calculation was done using a commercial software package (CFD2000, Adaptive Research).

In wintertime, air cooled down at the window goes down and spreads over the floor. The circulating convective airflow field is thus created. To simulate this situation, the temperature of the window was set to 283 K while the initial temperature of all walls and the air inside the room was set to 288 K. The odor source was assumed to be a 5 cm × 5 cm region releasing the odor vapor with the mole fraction of 0.05 at 500 ml/min. The molecular diffusion coefficient of the odorant into air was set to 0.1 cm<sup>2</sup>/s. Other properties of the released odor, e.g., the density and the specific heat, were assumed to be the same as air.

The volume of the room was divided into 63 × 43 × 46 cells. The cells near the floor and around the screen were made small since those are the places where the turbulence is developed. All calculation was done using the standard *k-ε* model with a time step of 0.05 s. In this model, the calculation is simplified by obtaining only the time average of the airflow velocity and the odorant concentration. Although the high frequency fluctuations are not reproduced in the simulation, the model provides reasonable results even with a relatively coarse grid and a large time step. It was assumed that there was initially no movement in air. The development of the convective airflow field for 720 s was first calculated. The release of the odorant was then initiated, and the development of the odor distribution for 360 s was calculated. The airflow

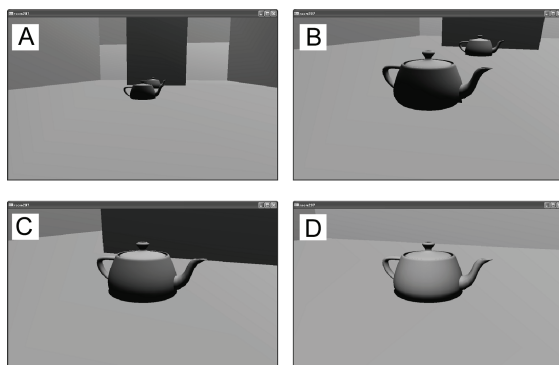


Figure 5: Snapshots captured from the movie clip. A–D correspond to points A–D in Fig. 4, respectively.

velocity and the odor concentration were recorded in the hard drive at 1 s interval. The total time required for the calculation of the 1080 s time period was approximately 42 hours.

Figure 3 shows the calculated airflow field and the distribution of the odor concentration at the mid-width of the room. The airflow near the left wall was pointing down because of the cold window. The airflow near the floor was pointing to the right, but was deflected upward by the screen. The odor distribution corresponds well to the airflow field. The released odor was first carried to the right, and then, raised by the screen. Figure 4 shows the airflow field and the odor distribution on a horizontal plane at 20 cm from the floor. The maximum of the odor concentration appeared not at the source location but at the upwind side of the screen since the source was placed directly on the floor, not at the height shown in Fig. 4. It can be seen that most part of the odor flux was deflected upward at the screen, but some part was flowing to the downwind side of the screen. The validity of the CFD simulation was confirmed by the odor distribution measurement in the real room using gas sensors.

### 3. Experiments

#### 3.1. Generating odor with a movie clip

Sensory tests were conducted with five undergraduate students as panelists. In the first set of tests, each panel was asked to experience the odor stimuli presented synchronously with a movie clip (Fig. 5). A small animal slowly moving along the path shown in Fig. 4 was assumed. Each panel saw three teapots along the path, and was asked which teapot was containing peach tea. The data obtained in the CFD simulation was used to control the odor blender. Teapot 3 was placed at the location of the odor source.

While moving along the path at 10 cm/s, the nose of the virtual animal was assumed to move on the horizontal plane at 20 cm from the floor. Figure 6 was obtained by

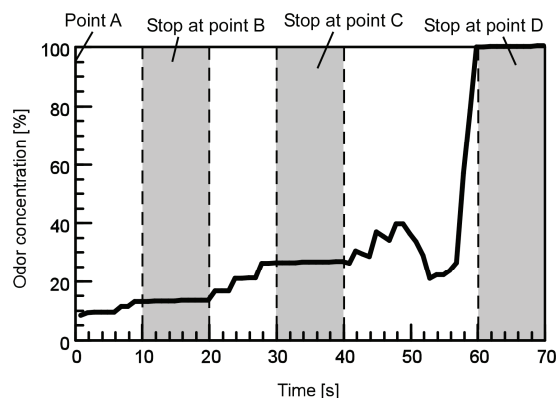


Figure 6: Variation in the odor concentration observed on the path shown in Fig. 4. A–D correspond to points A–D in Fig. 4, respectively. The shaded areas represent the time periods in which the virtual animal was stopping.

extracting the concentration values at appropriate coordinates and time instances from the CFD data. The obtained concentration was normalized by setting the maximum concentration on the path to 100%. Odor with the concentration specified in Fig. 6 was delivered to the panel's nose through a tube. The breathing cycle under a normal condition is about a few seconds. Therefore, the path was designed so that the virtual animal made a stop for ten seconds in front of each teapot.

All five panels answered similarly to our questionnaire. All panels succeeded in locating the true odor source from the three pots. Although the odor was emanating from teapot 3, the smell of peach tea was also slightly perceived at point C when looking at teapot 2. The difference in the odor intensity led them to answer that the odor was coming from teapot 3.

#### 3.2. Generating odor with airflow

The scenario assumed in the second set of the sensory tests is shown in Fig. 7. An electric stand fan is set behind a teacup filled with peach tea. When the fan is turned on, it starts to oscillate by  $\pm 35^\circ$  with a period of 14 s. The airflow generated by the fan brings the odor molecules from the teacup to the panel's nose, and therefore, the panel perceives the smell periodically. The results of the CFD simulation are shown in Fig. 8. The fan was placed 1.1 m to the side from the odor source (i.e., the teacup). The panel was assumed to be at the point 10 cm from the teacup and looking toward the fan. The number of cells for the CFD calculation was  $43 \times 47 \times 32$ . The development of the airflow field for 900 s was first calculated. The release of the odorant was then initiated, and the development of the odor distribution for 360 s was calculated. The airflow velocity and the odor concentration were recorded in the hard drive at 1 s interval. The total time required for the calculation of the 1260 s time period was approximately 8



Figure 7: Electric fan and teacup.

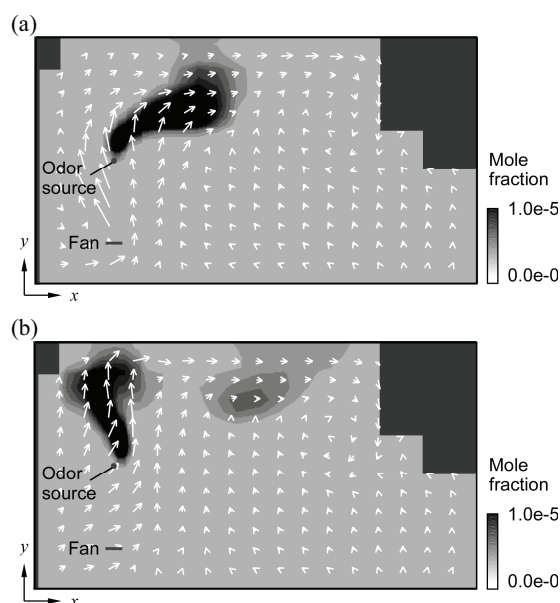


Figure 8: Airflow field (0–189 cm/s) and distribution of odor concentration after the introduction of the oscillating electric fan. (a) and (b) are the airflow and concentration fields 11 s and 18 s after starting to release the odorant.

hours.

In the sensory tests, each panel was asked to sit in front of a real electric fan at the specified distance. An empty teacup was placed in front of the panel to reproduce the assumed scenario. The odor was delivered to the panel using the odor blender while the fan provided the panel with the real oscillating airflow. All five panels answered to the questionnaire that they felt the change in the odor intensity as if there was peach tea in the cup. They also told us that the change in the odor intensity was synchronized with the oscillation of the airflow. The panels periodically felt the airflow at their faces. However, due to the distance

between the fan and the panel, there was a delay of a few seconds between the time when the fan came to face the panel and the time when the panel felt the strongest airflow. This delay was successfully reproduced in the CFD simulation. The odor with high concentration was delivered at the timing when the panel felt the puffs of airflow from the fan.

#### 4. Conclusions

We propose to use CFD simulations in conjunction with an olfactory display. By calculating the airflow field and the dispersal of an odorant in a virtual environment, the odor concentration at an arbitrary location can be obtained. The olfactory display can thus provide the user with olfactory stimuli with appropriate concentrations at proper timings. Encouraging results were obtained from the sensory tests. Future work will be addressed to accomplish simulations of more complicated scenarios. The computer model of the room used in the CFD simulations reported here was prepared manually based on the empirical knowledge on turbulent flow. Automatic generation of the room model and automatic grid generation for CFD simulations from the image shown on the screen are also interesting subjects for future work.

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