Title:
Prototyping of an Olfactory Display supported by CFD Simulations

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Introduction:

The sense of smell has been mostly neglected in Western society for a long time. It has only been a few years since research has highlighted the importance of this sense for perceiving the environment around us, enriching the users' experiences, and making them more engaging. Researchers are increasingly committed to study methods and tools to exploit the use of the sense of smell in products and services to improve their User Experience. In recent years, studies on digital olfaction have advanced in many directions. Moreover, several prototypes of devices delivering smells, named Olfactory Displays, have been developed and tested. Olfactory Displays are devices controlled by computers that generate and deliver scented air, eventually smelled by the users [4]. The olfactory display generates scented air from odorous materials kept in a stocked form (liquid, soaked in porous materials, gelled, etc.) by using techniques like heating, airflow vaporization, atomization, and transmits it to the human olfactory organ through delivery systems, as pipes, directed airflow, and direct injection [4]. The development of an olfactory display is based on the characteristics of the olfactory process. Smell is a chemical media and still there is no consensus on the classification of "primary" scents. Therefore, olfactory displays and applications including smells use a limited number of smell components, according to the scenarios to develop. In the last decade, several methods for scent generation and delivery have been developed and used to implement a variety of applications (such as [3]). The authors have developed applications based on the use of odors to stimulate users' attention and make the reading experience more immersive [1], to improve the quality of the users' experience of artworks [2], and to improve the immersiveness of Extended Reality experiences. Olfactory displays are not technologically mature, since many technical issues remain unsolved, which are related to olfaction, such as adaptation, detection and recognition thresholds. Some companies have proposed commercial versions of the devices for personal use. Recent examples are the Vaqso device (https://vaqso.com/), the Olorama scents generator (https://www.olorama.com), and the Feelreal device (https://feelreal.com/).

All research prototypes and commercial devices have several limitations regarding the number of odors they can produce, their size and wearability, and more generally their performances. For these reasons, the commercial devices have not penetrated the market yet. Many studies in the literature report experimental activities based on a "trial-and-error" approach, which prevent a comparative analysis of designed solutions and of their technical performances, thus leading to prototypes with low potential to become future products.

The work presented in this paper aims at advancing the know-how for designing and implementing olfactory displays proposing an innovative framework. The paper illustrates the framework, provides a description of its main steps, and presents a case study to demonstrate its use in the design of a new wearable olfactory display. The paper describes in detail the Computational Fluid Dynamics simulation of the designed Olfactory Display, which is included in one of the steps of the framework, since it has proven to be particularly effective in the identification of optimal design solutions.

Main Idea and Case study

The framework aims at supporting researchers in the design of a new Olfactory Display, by suggesting the most appropriate methods and tools to use to obtain the optimal design solution. The framework is based on experimental activities, and integrates parametric modeling, Computational Fluid Dynamics (CFD) simulation, and rapid prototyping technologies to continuously evaluate possible alternative solutions and rapidly converge to a final one.

The framework consists of the following 6 steps:

1 Definition of Requirements (based on the specific application)
2 Selection of the components for the generation and delivery of smells from a library of technological solutions reported in the literature [4]
3 Design of the Olfactory Display layout and shape
4 Experimental activities, including parametric modeling, CFD simulation, and rapid prototyping
5 Comparative tests and evaluation of the data collected in the tests
6 Refinement of the Olfactory Display layout and shape

Steps from 3 to 6 should be repeated in a loop until the desired design solution is achieved.

As a first case study to evaluate the experimental framework it was decided to design and develop a wearable olfactory display to be used in open and closed environments, to relax in stressful moments, improve moods and evoke positive emotions.

For what concerns the Requirements definition (step 1) the Olfactory Displays must be portable (in a bag or a backpack) and wearable, must weigh a maximum of 400 gr. The device must deliver three smells, even simultaneously, which can be reloaded or replaced by the users according to their preferences.

In step 2 of the framework, the *piezoelectric mesh atomizer* technology has been selected, which allows producing and delivering a sparse scented mist (air with suspended droplets) starting from water in which one or more essences have been diluted. This technology has been selected as the most appropriate for wearable devices since it allows small size, lightweight, and high degree of safety.

Subsequently, in step 3, the layout and shape of the Olfactory Display have been defined (Figure 1). Each piezoelectric mesh atomizer has been connected to a single cartridge containing scented water to avoid mixing smells. Besides, to allow cartridges refill and replace, two separate parts have been created, one containing the scented water, and the other the electronics. Experimental studies have shown that if the cartridge is placed under the piezoelectric mesh atomizer after a few cycles the mechanism stops working and requires the user’s intervention. Therefore, it was decided to place the piezoelectric mesh atomizers under the cartridge. Immediately after the atomizer, a U-shaped channel was inserted, which allows the scented mist to be conveyed upwards, i.e., towards the user's nose.

In step 4, the parametric model of the Olfactory Display has been developed, which has been used to manufacture the first physical prototype created using rapid prototyping techniques (Figure 1). CFD simulation of the digital prototype has been performed and is described in the detail below.

Comparative tests of the real prototype and the CFD simulation have been performed in step 5. About the real prototype, some operating problems occurred, related to the passage of the scented mist through the output channel and the speed of the same. Consequently, it was decided to simulate the integration of a fan to help the mist to escape the Olfactory Display, decreasing the probability for the mist to condensate on the channel walls and for the particles to coalesce. Specifically, a set of CFD simulations have been set up and performed. CFD simulations allowed us to simulate various design solutions (different shapes of the output channel, different positions of the piezoelectric mesh atomizers, the performances with/without the fan, etc.) and compare the simulation data with those obtained with the real prototype to verify the accuracy of the simulations and optimize the design.

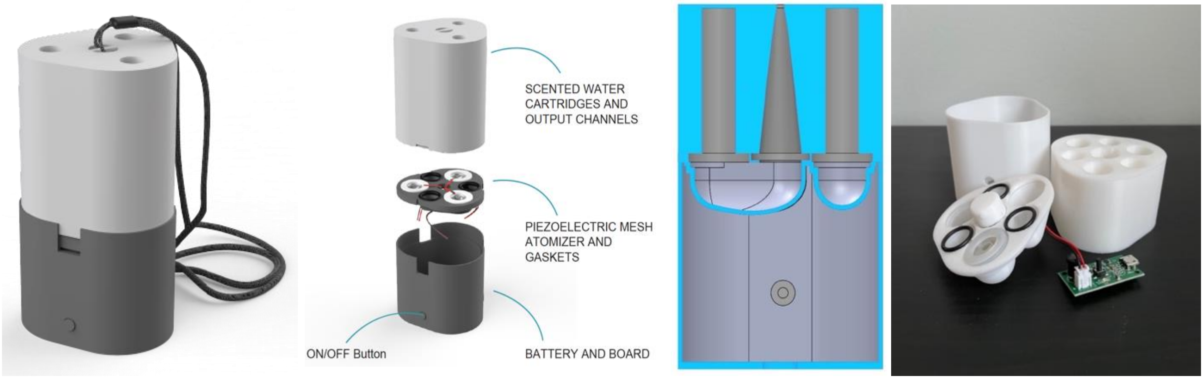

Fig. 1: Parametric 3D model of the designed Olfactory Display and real prototype.

A 2D multiphase transient simulation is used to simulate the behavior of the mist between the piezoceramic mesh atomizer and the atmosphere. As CFD simulations for multiphase flows are quite challenging, some hypotheses have been made. First, the fluid domain has been simplified to obtain its 2D projection on the midplane of the device. Despite reducing the domain of a 3D volume to a 2D planar surface may lead to inaccuracies in turbulence-related quantities, it makes the simulation convergence easier to reach, especially considering the kind of models employed to account for the particles' behavior (see below). On the other hand, a 2D domain still allows us to draw some considerations that can be beneficial for prototyping such a device.

The analysis has been set as transient and the effect of gravity has been enabled (it can have an impact on the trajectory of the particle). The realizable k-ε model has been chosen and a discrete approach has been selected to account for the presence of the water droplets. Multiphase flows can be simulated in a variety of ways, depending on the type of phenomena that are in the scope of the simulation. The mist generated by the piezoelectric mesh atomizers consists of fluid streams (air) with suspended droplets of liquid water. The Discrete Particle Method (DPM) has been considered in this study. It is a Euler-Lagrange approach where the fluid pressure and velocity fields are computed by solving the Navier-Stokes equations, while the tracking of discrete phase (the droplets in this case) is derived from the calculated flow field. The particles can act as passive stream (one-way coupling) or interact with the fluid flow (two-ways coupling): in our case, the interaction with the continuous phase has been enabled. The droplet collision and coalescence are tracked in the simulation using the O'Rourke algorithm [5].

The fluid domain has been discretized with quadrilateral-dominant quadratic elements of 0,1 mm length inside the fluid region. An inflation layer control has been added to all the walls to catch the rapid changes in the flow's variables close to the walls and to get the appropriate y+ value for the turbulence model selected (i.e., the k-ε requires y+ values between 100 and 300). Six layers are generated with a growing ratio of 1,2 and a first-layer thickness of 10 µm. On the edge where V_p is applied, 50 elements have been imposed because the number of particles injected in the volume is going to depend on the number of elements on the injection edge. The mesh parameters just described have been decided after a mesh independent study. The result is shown in Figure 2 (the mesh shown has been scaled up for the sake of its visibility).

Figure 2 shows a graphical representation of the boundary conditions. The pressure at the outlet of the domain (P_{out}) has been set at 0 Pa, as a 101325 Pa operating pressure has been set at 48 mm. V_p represents the velocity input for the particle stream, whose activation time has been set at 0.5 s. V_{fan} is the velocity inlet condition for the airflow coming from the fan.

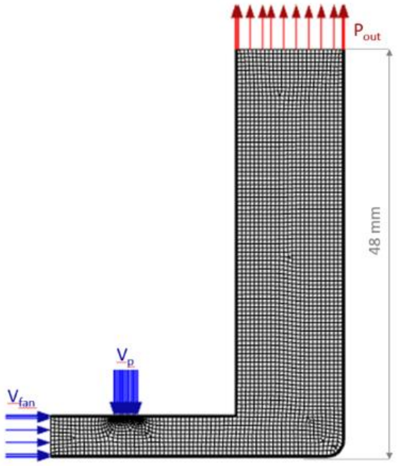

Fig. 2: Mesh and boundary conditions of the fluid domain.

Simulation #	*Vp [m/s]*	*Vfan [m/s]*	*Simulation #*	*Vp [m/s]*	*Vfan [m/s]*
S1	0,2	0	S7	0,4	0
S2		0,1	S8		0,1
S3		0,2	S9		0,2
S4		0,3	S10		0,3
S5		0,4	S11		0,4
S6		0,5	S12		0,5

Tab. 1: Velocity inlet magnitudes of the particle (V_p) and the fan (V_{fan}) for the 12 simulations.

A total of 12 different simulations have been run to understand the impact of having different inlet velocities and, the magnitude for the inlet boundary conditions changes according to the values reported in Table 1. The particles are injected from the same surface where V_p is applied with a constant velocity and an inert behavior. An inert particle is a discrete phase element that obeys the force balance and as prescribed by the DPM model, its velocity equates the one of surrounding flow. The injection lasts for 0.5 s (as V_p does) with a total mass flow rate of 1.4e-5 kg/s (as prescribed by the atomizer specifications) and a discrete random walk model is employed to predict the dispersion of particles due to turbulence in the fluid phase using a stochastic method. The rest of the boundaries are stationary walls. Regarding the boundary condition for the discrete phase, the inlets and the outlet allow the particle to escape the domain while the walls trap the particle (i.e., the trajectory tracking is terminated when the particle collides with the wall). The last boundary conditions allow the simulation to account (to a certain extent) for the condensation and coalescence phenomena of the particles on the wall that has been observed experimentally.

The pressure-velocity scheme has been set as coupled, the spatial discretization for the momentum, the turbulence energy, and the dissipation rate as second-order upwind and transient formulation as second-order implicit. The time step for the simulation is 5 ms and 200 steps have been computed for a total simulation time of 1 s. The setup described above has been kept unchanged for all the 12 simulations performed.

Results and Discussion

To summarize the results of the simulations, the time for the first particle to escape the fluid domain and the percentage of escaped particles have been tracked. For the simulations S1 and S7, where the fan is deactivated, the particles struggle to reach the outlet in the time prescribed by the simulation (1 s): none of the particles escapes in S1, while only the 20% of them leave the domain in S7. When the piezo is deactivated after 0.5 s, the fluid flow does not have enough inertia to push the particle out of the channel. This situation is, in fact, what can be experienced by testing the device experimentally: all the droplets coalesce, and a puddle of liquid can be found on the bottom. As soon as the fan gets activated, the "efficiency" of the device improves. Figure 3 shows the particle residence time for S1 and S4 at the end of the simulation while Figure 4 summarizes the results for all the other simulations.

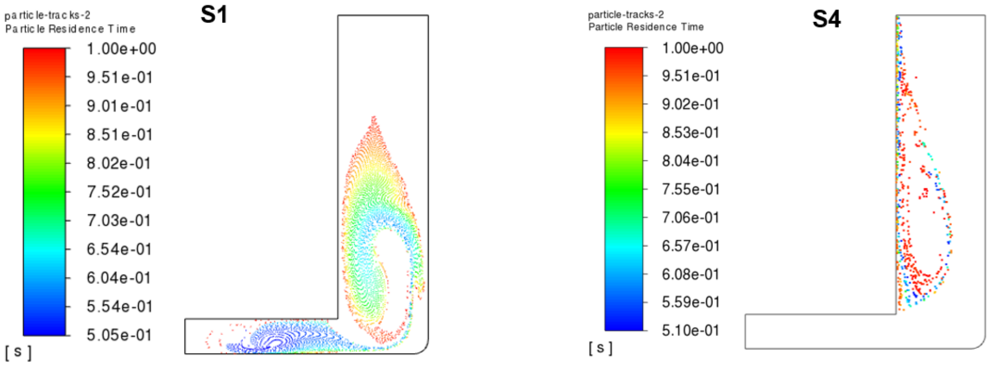

Fig. 3: Particle residence time for the simulation S1 (n the left) and S4 (on the right).

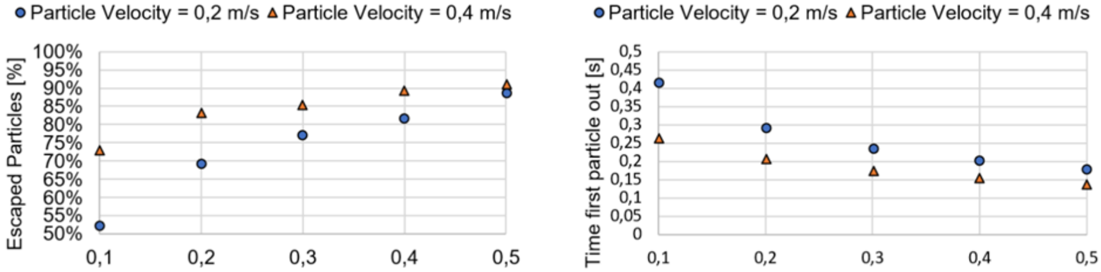

Fig. 4: Escaped particle percentage and time for the first particle to escape the volume.

The two main conclusions from the data presented here are: (i) the fan is an essential component for the prototype as it improves the percentage of particles that can escape the volume in 1 s, and (ii) there is no need to push the fan at the maximum speed since the marginal gain becomes low at the expenses of increasing the power consumption of the Olfactory Display.

Further investigation will be done in step 6 of the framework, by repeating the same study by changing the geometry of the device, looking for an optimal shape that maximizes the efficiency of the same. Furthermore, by calibrating the analysis properly, they can help design the experience by tuning the activation-deactivation time of the piezoelectric atomizer and the fan.

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