

A Calibrated Olfactory Display for High Fidelity Virtual Environments

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Abstract

Olfactory displays provide a means to reproduce olfactory stimuli for use in virtual environments. Many of the designs produced by researchers, strive to provide stimuli quickly to users and focus on improving usability and portability, yet concentrate less on providing high levels of accuracy to improve the fidelity of odour delivery. This paper provides the guidance to build a reproducible and low cost olfactory display which is able to provide odours to users in a virtual environment at accurate concentration levels that are typical in everyday interactions; this includes ranges of concentration below parts per million and into parts per billion. This paper investigates build concerns of the olfactometer and its proper calibration in order to ensure concentration accuracy of the device. An analysis is provided on the recovery rates of a specific compound after excitation. This analysis provides insight into how this result can be generalisable to the recovery rates of any volatile organic compound, given knowledge of the specific vapour pressure of the compound.

1. Introduction

Using odours in virtual environments (VEs) presents many challenges. Providing users with smells at an arbitrary concentration can lead to varying levels of immersion in the experience [HHMM15]. An odour applied too strongly risks reducing the immersion and delivering a concentration that is too low risks the user not noticing the stimulus at all. A correct balance has to be met such that the user is comfortable with the concentration delivered, but also the stimulus should match the concentration level they would be anticipating had it organically appeared in nature.

One of the other inherent difficulties when working with volatile organic compounds (VOCs), is that each odour has a unique chemical structure and physical properties. This makes it harder to generalise a presentation pipeline, from capture to delivery; as one approach that works for one compound may not be generalisable across all compounds. Researchers are thus presented with this multi-tiered problem which requires VOCs to be adequately characterised not only from a chemical property perspective but also considering specific parameters with regards to the environment and the display equipment used. Odour mixtures add to this complexity due to the presence of numerous chemical compounds. This also means that any smell used will have to be recalibrated and tested if any parameter is changed which in turn then makes reproducibility or any standardisation unattainable. Delivering VOCs at user specified concentrations is a challenging task. This requires

a smell display or 'olfactometer' which is able to produce odours at given concentration levels, for users in VEs. Additionally this would require some form of universal calibration which could take into account the varying chemical properties of different volatile odours requiring classification of compounds.

This paper addresses the above problems by creating a calibrated olfactometer which takes into account concentration and is able to display smells in an appropriate concentration range similar to real world conditions. This aims to standardise smell presentation by focussing on the properties of molecules and using that data to obtain repeatable metrics. The framework provided can then be used with any other VOCs via the use of readily available data tables. By providing odours at the correct concentrations found in real world environments, researchers can attempt to create environments with the knowledge that they are providing smell experiences which offer the highest fidelity by mimicking real world conditions and thus improve the fidelity of the VE.

The main contributions of this work are summarised in the following:

- A design of an olfactory display which and is capable of consistently delivering sub-ppm concentrations of volatile odours,
- As well as incorporating the inclusion of individual properties of VOCs to improve concentration accuracy,
- A generic and repeatable experimental process for the calibration procedure for the device,

- An analysis on the rate at which a volatile odour is replenished from its liquid form, in a volume of air, for a specific compound post-excitation and a methodology for generalising this result to other VOCs.

2. Background and Related Work

Many different smell displays or 'olfactometers' have been designed and built, by researchers, for applications of smell within VEs. The designs of these displays are varied and there is a diversity of methods employed. For the most part, researchers have focused on being able to deliver smells to the user as quickly as possible and thus as temporally accurate as possible. The goal of these devices has been to be able to reduce the onset time (time taken to reach the user from the display) and thus be able to present odours on cue and in tandem with other visual and/or sound stimuli. A secondary goal has also been to make systems more portable and practical; systems which are easy to use such that specialists in the field are not required for their use.

Yanagida et al. [YKN*04] built a vortex canon which would blast smells towards users via rings of air. This incorporated head tracking of a user to ensure the air mixture was delivered to the correct space. This would mean odours could be presented to users in a non-invasive fashion. The setup for this device is time-intensive since the chamber required liquid smell to be injected and allowed to vaporise, and needed cleaning between subsequent compound delivery.

Yamada et al. [YYT*06] used a portable air pump design fitted into a backpack to allow portability and movement. This design allows for different strengths of three odours which are controlled by the resistance level of a potentiometer limiting the voltage given to the air pump. Thus the main way of controlling concentration is by increasing airflow. This can mean that as the fans increase in speed, users are likely to notice perceptual variations from the different airflows and thus experience a lack of consistency between varying trials.

Matsukura et al. [Mat10] used fans to present odours of different fruit teas. Open vessels containing hot tea were used and naturally emitted odours as the water evaporated. Airflows created by fans were then used to push odours to participants. They also later designed a smell display using directed airflows created by miniature fans with a computer monitor [MYI13]. Airflows from opposite sides of the screen were directed towards each other collapsing in the middle and forced outward toward participants looking at the visual display.

Lündstrom et al. [LGA*10] used both glass and polycarbonate plastic vessels containing liquid odours with an airflow produced by a centralised air compressor system in a lab. Airflow was used to push the vapourised headspace odours from the vessels through individual solenoid valves.

Nakamoto et al. [NHAA14] designed an olfactometer which used a pump to provide liquid odours to a specialised plate. This liquid would then be vaporised via high frequency sound waves applied to the plate. The high oscillation frequency excites the liquid molecules and transfers enough energy to allow them to over-

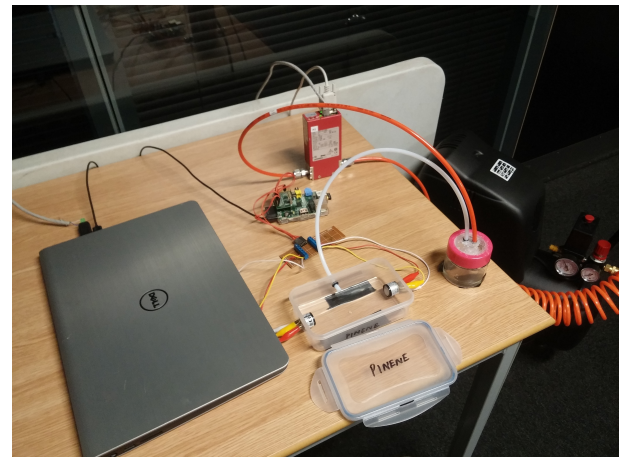
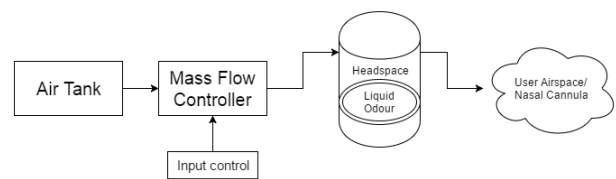


Figure 1: Diagram of olfactometer design

come their respective enthalpy of vaporisation. This design is limited however by the need for high voltages to power and control the device.

Ischer et al. [IBM*14], similarly to Lündstrom et al., used glass tubes with cotton swabs soaked with liquid odourants inside. Airflow was used to flush the vapourised headspace odours from the tubes via a series of solenoids. The headspace refers to the volume of air above a solid or liquid substance which becomes saturated with the gaseous form of the substance as it vaporises over time. Whilst the design is relatively robust accounting for avenues of contamination and consistencies of the flow, they do not go as far as to quantify in parts per million (ppm) the concentrations being used.

Abid et al. [ALLW15] used piezoelectric films to deliver liquid odours. Applying a voltage to the film causes the film to expand and lowering the voltage causes the film to contract back. They used this phenomena to oscillate droplets into the air, after placing the film over a small reservoir of liquid odour. This small size of the film allowed for a compact design. The main limitation of these types of devices is that the droplets produced are tiny balls of liquid and not vapour, making it difficult to measure the concentration.

The focus on making olfactory displays increasingly modular and mobile with faster odour onset times, there has been less focus on accuracy. Accuracy in this context is referring to how close the experience of the smell in the virtual environment is to a real smell experience. Odours are ultimately made up of varying concentrations of volatile molecules with small molecular masses and being able to mimic the relevant concentrations would allow researchers to provide a true high fidelity olfactory experience.

3. Olfactometer Build

This olfactometer was designed to allow for small concentration outputs which are more typical in nature and day to day interactions and as such would need to be able to present stimuli in the sub-ppm region. It was also important that this be a low cost solution so that similar solutions can be deployed in other research facilities with ease. As such, everything used in the set up is readily available through various online retailers. The most expensive parts in the proposed system are the digital mass flow controllers (DMFC) which retail between 300-500 GBP per unit with cheaper models from other manufacturers. The remaining parts can be purchased for less than 150 GBP, the bulk of which is down to the air compressor with tank bringing the total to 650 GBP using only 1 DMFC. In comparison, the price of commercially available, specialised olfactometers can reach into the tens of thousands of GBP [SCS, Olf, Sce].

Airflow is used as the main emission method and simplifies the whole design greatly. Notably, being able to control how odours reach the user and thus the concentration users will perceive. With the use of a closed system outlined below, with airflow, and used by both Lündstrom et al. and Ischer et al. [LGA*10, IBM*14], there are fewer things to account for. In this particular setup, the only thing that needs to be controlled is the airflow and this is done via either limiting it to a percentage of its full amount and/or limiting the time it is permitted to output for.

The olfactometer was built, and calibrated by using photo-ionisation sensors to map displacements of saturated headspace to specific concentrations at the user end. It was imperative that all readings remained consistent between separate uses such that anyone using such a system would always get repeatable results. Bearing this in mind, a secondary set of experiments were carried out to quantify the required time between calibration measurements.

3.1. Process

The olfactometer was based upon an air flow method as this allowed emission of precise amounts of odour via direct displacement of air. An air tank with a combined compressor unit was used for the airflow with a charcoal filter attachment to provide a clean and filtered air supply, delivered at 1.5 Bar. This was connected to a maximum 1L per second DMFC which in turn was connected to an inlet on a 100ml reservoir containing the selected odours. An outlet pipe of 50cm was connected to the reservoir. The DMFC (Horiba SEC-Z512MGX) was controlled using a RS485 serial interface to USB connection on a laptop running an application which controlled the solenoid. The DMFCs output was tested using an Ellutia 7000 flow-meter. Several different flow rates were tested and the flow-meter showed no more than 8% variance from the expected output at flow rates lower than 100ml/min and 1% variance for flow rates above 100ml/min. Additional flow controllers with reservoirs can be added easily with a splitter on the air supply. Polyfluoroethylene (PTFE) piping was used to connect all the components together due to the materials' properties specifically its high inertness rating. This is down to the structure of the polymer, in which the carbon backbone is surrounded in fluorine atoms which form an unreactive and inert shield due to their fully occupied outer s

and p orbitals. Other materials could potentially be used in order to adsorb VOCs over time.

The olfactometer works on the basis that, by having an entirely sealed system from the air tank to the final emission from the outlet and opening the solenoid valve in the DMFCs for precisely timed amounts, there is an exact displacement of air which pushes the same amount of saturated, vapourised odour out from the headspace of the reservoir and presents it to the user. Figure 1 shows a diagram of this setup.

4. Olfactometer Calibration

In order to accurately quantify the emission from the olfactometer's air flow output, it is mandatory to calibrate the emissive concentration of the displayed VOC for a range of flow rates. This section discusses this process and introduces a repeatable process to calibrate ppm level coherency between target and actual output concentrations.

4.1. Materials and Procedure

The single molecule odours citral, alpha-pinene and isoamyl acetate, which have smells of lemon, pine, and pear/banana respectively, were used in the olfactometer reservoirs. These substances were chosen as they each have distinctive smells and score low on their hazard profiles which make them useful for olfactory experiments. The odours are single molecule compounds and were purchased from pharmaceutical companies at relatively low cost (approximately 35 GBP for 1 litre at 99.5% purity). The compounds were delivered and stored in glass bottles and transferred to the olfactometer reservoirs on use.

Two photo-ionisation detector (PID) cells were mounted on opposite sides within a 500ml airtight box, facing each other. The outlet from the reservoir was mounted perpendicular and between the two sensors and protruded 2cm inside the box. Bearing this in mind a 500ml box was chosen, as the average tidal volume of a human breath is around 500ml [Hul09] and as such any measurements in ppm could be directly applied to experiments in which the smells are presented to users either through a nasal cannula or directly around nose. Specific displacements, in ml, of odour were emitted out of the outlet from the olfactometer and into the box by varying the time of the burst and by adjusting the percentage opening solenoid valve in the DMFC. This gave a reading of volume in millilitres since it is a function of the 1L per minute output. Multiples of 10 percent intervals up to 100 were used in tandem with one second increments, starting from one second, as this gave small systematic displacements of air.

The photo-ionisation procedure consisted of using an Alphasense Photo-ionisation pellistor cell, which had an isobutylene (the calibration gas for the sensor) detection range of 5ppb-50ppm. All other substances have a measurement relative to this initial calibration and are accounted for by multiplying by the relevant correction factor. The PID cell was wired to a Raspberry Pi Model B microcomputer with an 18-bit resolution analogue to digital converter (ADC) hat module, with the microcomputer being powered by a USB 10000 mAh battery. The sensor outputted as a voltage and these were recorded using the ADC and a Python application.

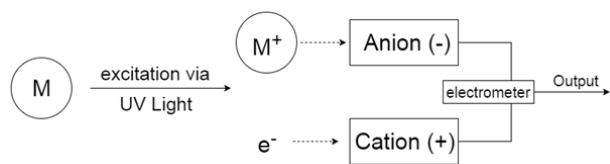


Figure 2: Diagram of photoionisation detector setup

The PID cell works by producing UV spectrum wavelength light within the space of the cell via a lamp rated at 10.6 eV which is a standard rating used in PIDs. This was chosen over higher rated lamps at 11.7eV, however these result in more compounds being ionised giving overall lower detectable results along with an increase in noise. The UV light then ionises (removes an electron from the molecule via excitation by absorbing the light) any airborne molecules which require 10.6 eV or less to ionise. The remaining charged particles then make contact with charged plates (anion/cation) and produce a charge which is proportional to the concentration of molecules present, as illustrated in Figure 2.

After a burst of odour was outputted to the box, time was allowed to let the two cells reach the same value (in volts later converted to ppm) to show that the smell had diffused equally in the box and that the final reading was used as the measurement for that given displacement in ml. These final readings were then replicated five times, averaged and plotted against their respective ml displacements.

4.2. Results

Figure 3 shows the graphs for each of the three substances when specific airflows in ml were displaced along with their respective measurements concentration as outputted by the PIDs. For the alpha-pinene only a few points could be plotted due to the high sensitivity the PID had to the substance. This effectively meant that all values were inflated which resulted in the upper limit of the sensor being reached far quicker than in comparison to the other substances. It can thus be seen that after correction for this sensitivity, the max readable concentration is around 15 ppm. The opposite happens with the isoamyl acetate with deflated values being corrected to higher concentrations.

4.3. Discussion

These experiments were conducted based on a series of assumptions regarding our odorous compounds and the environment they would be used in. The smells would be used at around standard conditions 293K and 100kPa. This was justified since most experiments tend to be done at around room temperature and standard atmospheric pressure and any variations within a few degrees would most likely be negligible except for very volatile compounds.

In Figure 3, plotting the collected data of ppm concentration against the volume displaced shows a linear relationship, as was expected, in all three cases. Each of the graphs can be used to estimate the displacement needed for a given concentration in that range. The PID detection range went from 5ppb to 50ppm however it is possible to get PIDs with broader ranges but at the cost of

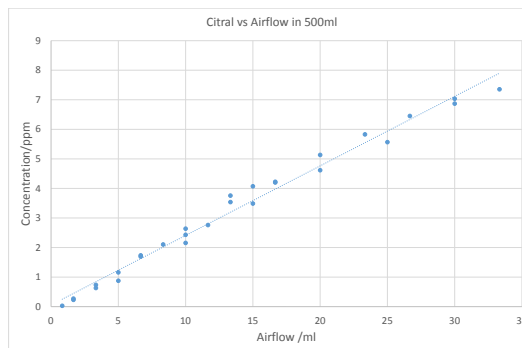
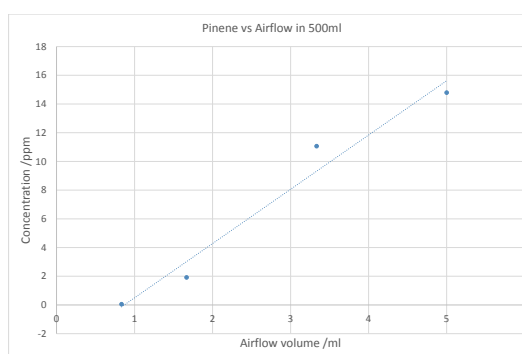
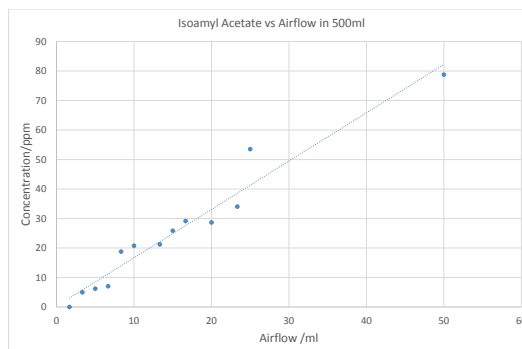


Figure 3: Graph of measured ppm concentrations of isoamyl acetate, alpha-pinene and citral against headspace volume displacements

less resolution. Some of the graphs show less than the 5ppb-50ppm range due to their relative sensitivity to the sensor. As a result readings have to be scaled with instrument sensitivity values provided by the manufacturer, increasing or decreasing the overall detection range further.

The human nose is capable of smelling from the ppb (parts per billion) level upwards [LKB69], however, it is to be noted this is

the limit of detection i.e. the absolute minimum amount needed to notice there is an odour present. In typical day to day interactions and VEs, concentrations in the ppm range would typically be seen and thus this calculated range is far more practical.

The onset time for the smell to reach the sensor was relatively fast taking just over a second for the smallest airflows (>1ml) and reducing as the volume increased. This was seen by the amount of time it took for the PIDs to have a sudden noticeable change in readings.

There are some small limitations which occur due to the limits of the instrumentation. The PID can detect down to the parts per billion level however much like our nose, that is simply the lower limit of detection. When it comes to getting usable data, the readings fluctuate too much at low concentrations to get a discernible fixed reading. This can be down to the turbulent nature of gases and background noise in general. There are typically only a small handful of devices which can do portable gas sensing, namely: PIDs, Metal oxide sensors and some more complex devices like ion mobility spectrometers. The latter two, however, suffer greatly from humidity drift which is a big problem in any environment since humidity is very variable and is difficult to account for. PIDs do not suffer from this drawback at lower humidities synonymous with general room conditions (typically around 50%). The isobutylene calibration for the PID was also taken in the same environment prior to the readings to ensure consistency with regard to background readings.

The other limitations are with DMFC valves. Whilst the output of the air is consistently at the right level, to get smaller more accurate displacement of headspace for finer concentration control, higher quality solenoids with less delay are needed which would result in increasingly costlier setups. Nakamoto et al. [NKMY09] demonstrates this with their airflow olfactometer with rapidly switching solenoids and is able to switch as quick as 2ms. This also explains the difficulties to concentrations under 1ppm.

5. Recovery Time Measurement

In order to maintain consistent delivery of odours, the headspace of volatile odour has to stay constant at the same concentration, since every displacement of air that is delivered to the user will be a small proportion of this concentration, which will then, in turn, temporarily lower the concentration of the headspace. Subsequent deliveries will drop in accuracy due to this dilution, if the headspace is not allowed to re-equilibrate. To make sure that the saturation point had been reached for measurements for the calibration, the recovery times were measured to indicate how long must be waited before each measurement.

When a liquid is left in a closed system, an equilibrium is formed between its liquid or solid phase and its gas phase. The rate of vaporisation (from solid/liquid to gas) reaches the rate of condensation (from gas to solid/liquid) so there is no net transfer of substance between phases. In the case of the olfactometer reservoir, it is assumed this equilibrium has been reached before each emission. When this equilibrium is reached there is a saturation of the headspace with volatile odour. To test for this, the procedure outlined below was followed. Vapour pressures describes the pressure of the gaseous constituent of the compound in this thermodynamic

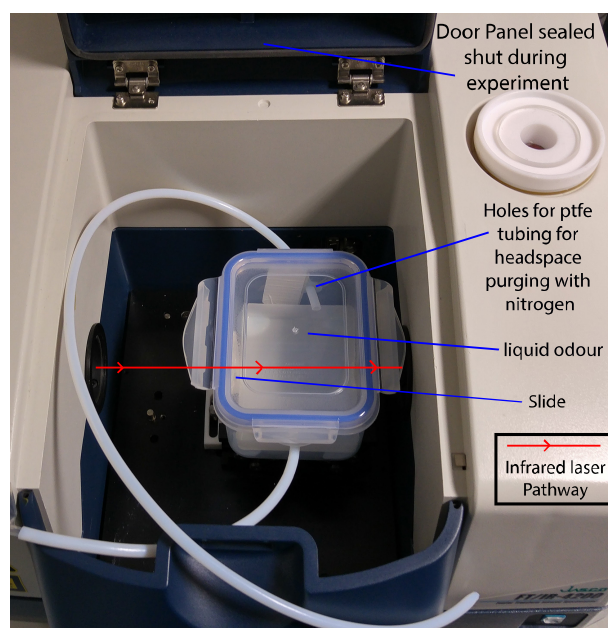


Figure 4: Diagram of vessel for measurement of headspace saturation mounted in the infra-red spectrometer. The infra-red light is released from an emitter on the left, travels through two slides on the box sides and reaches the detector on the right as indicated by the laser pathway.

equilibrium with its condensed phase, either liquid or solid, within this closed system. It varies with temperature. The vapour pressure also remains independent of the amount of liquid/solid substance present. Knowing this, the rate of headspace saturation for our box can be measured and thus a general rate of saturation in a time per volume per surface area ($\text{ml.cm}^{-2}.\text{s}^{-1}$) can be determined. This is applicable only for substances at a given vapour pressure and at a given temperature.

5.1. Materials and Procedure

Infra-red light spectrometry is an ideal analytical method for classifying compounds because all bonds between organic (carbon containing) molecules vibrate when excited and each bond has a characteristic vibration i.e. is excited at a particular wavelength. This makes it very useful for working out what compounds are present but it can also be used to detect changes between two states since if a molecule is present, that vibrates at a particular wavelength. This technique was thus employed to measure recovery times for the volatile odours. By using an infra-red instrument, the light can be used as a tool to measure the saturation of the headspace over time.

A vessel was built to measure the time to reach saturation within a fixed volume (see Figure 4). The vessel consisted of an airtight resealable polyethylene box, dimensions: 5cm x 9cm x 12cm, with 2cm x 4cm window holes cut out of parallel sides and covered with salt slides. The box was placed inside a JASCO 4200 FT-IR infra-red spectrometer such that the box slides aligned with

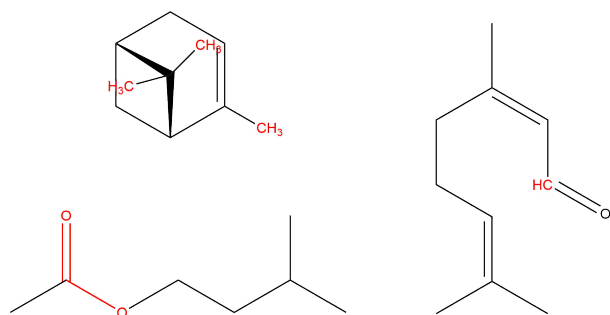


Figure 5: Chemical structures of the compounds used. On the top is alpha-pinene with the -CH₃ bond highlighted, on the bottom is isoamyl acetate with its ester bonds highlighted, and on the right is citral with the -C-H in the aldehyde bond highlighted.

the instrument laser 1.5cm from the base of the box. The slides created a pathway and allowed the infra-red laser to penetrate the headspace of the box and reach the instrument detector. Inlet and outlet holes were drilled in perpendicular sides to the slide sides. The holes then had PTFE tubing threaded 1cm into them. The box is illustrated in Figure 4. The same three substances were used for this procedure: citral, alpha-pinene and isoamyl acetate. 4cm³ of the smell was auto-pipetted into a small tray which fit the base surface area exactly such that the base was completely covered. The box was sealed and left to allow the odour to vapourise and reach equilibrium for 24 hours. The FT-IR instrument was set to scan the headspace of the box at wavelengths between 650cm⁻¹ to 4000cm⁻¹ at every 1cm⁻¹ per time period. The time period varied per substance: 15 seconds was used for isoamyl acetate and alpha-pinene and 60 seconds was used for citral since it had a much smaller vapour pressure and so it was expected to take much longer. The conditions used for the experiments was at 293K and 101kPa. After an initial baseline was recorded, the box was purged with nitrogen gas to clear the headspace for five minutes, then allowed to re-saturate.

5.2. Results

Figure 6 show the results of three different substances that were measured over time using the IR spectrometer. For each molecule, a characteristic bond vibration, specific to the molecule, was monitored over time to see the change in transmittance (%T) of light allowed through (see 4). The broad troughs or peaks refer to the time where the box was saturated with volatile compound to unsaturated (purged with pure nitrogen gas) back to saturated. Figure 5 shows the characteristic bond on the respective chemical structures of the compound used for the plots.

The relationship we draw between the recorded recovery time against the specific vapour pressure for the given substance is illustrated in Figure 7.

5.3. Discussion

Figure 6 shows the recovery time graphs and states the characteristic bond vibration used to characterise the compound. Each

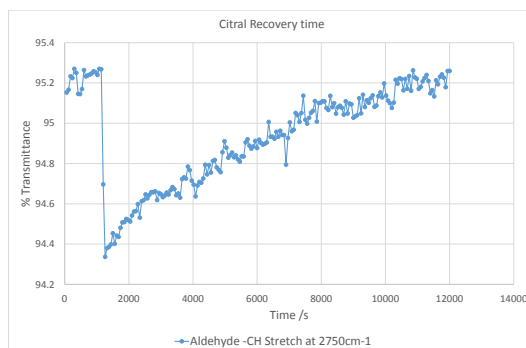
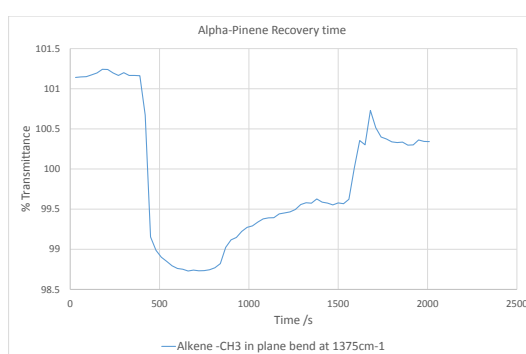
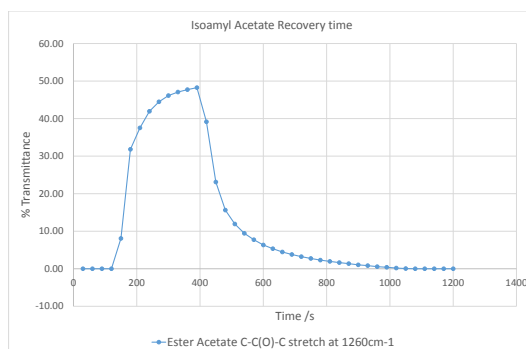


Figure 6: Graphs of isoamyl acetate, alpha-pinene and citral, over time, starting at saturation, being purged and allowed to re-saturate over time. Each of the three graphs show the measurement data obtained from the IR spectrometer instrument. In each case, an initial equilibrium transmittance level (unique to each compound) is shown followed by an increase for Isoamyl acetate and a decrease for Alpha pinene and citral as the headspace is purged using nitrogen gas. This is followed by the refilling of the headspace of the box with vaporous odour as the liquid odour naturally vaporises, eventually reaching the initial saturation level.

point is one scan of every 1cm^{-1} wavelength between 650cm^{-1} to 4000cm^{-1} . In each case we notice two distinct levels of transmittance. This illustrates the difference between the headspace in the two states - in the initial and final positions shows when it is saturated with volatile odours and the sudden peak or trough shows the purge with air. In each case the purging nitrogen was left on for approximately five minutes and then turned off. We count the recovery time from the last point/scan before the subsequent drop or rise indicating the headspace refilling with volatile odour.

Comparing the recovery times, i.e. time taken to saturate the 500ml headspace of the box to equilibrium, to the respective vapour pressures of the chemical compounds, it is clear that there is an obvious relationship. The higher the vapour pressure, the quicker it takes to saturate the headspace. This is to be expected since a higher vapour pressure means a volatile species vapourises more readily at a given temperature, however, by recording the recovery times the time taken for this happen can be quantified. This in turn correlates with vapour pressures in general at this temperature and from which again a linear relationship can be seen.

From the graphs it can be deduced it takes isoamyl acetate around 630 seconds, alpha-pinene around 870 seconds and citral around 9060 seconds to recover 500ml of headspace. By dividing this down to find a rate and plotting against their vapour pressures (4, 3, and 0.22 mmHg respectively), a positive correlation can be seen. However, whilst these three substances are shown to fit a trend, more substances are required for measurement with varying vapour pressures to confirm the linear fit.

Again this trend makes sense since quicker saturation rates for compounds with higher vapour pressures are expected, but allows us to somewhat quantify the process. This is important as it confirms the amount of time needed for recovery after a displacement of given ml using the presented olfactometer setup. This will also remain true for other compounds with different vapour pressures.

6. Conclusions

This work provides the tools to allow others to build and use an olfactometer which takes into account the concentration levels of odours which are typically present in day to day interactions.

An olfactometer design was proposed which could allow for this, by using the measurement of air displacements through the headspaces of liquid-vapour equilibriums of several volatile odours, and quantifying the concentration of odour removed, providing low-ppm and above levels.

Recovery times of these volatile odours were also measured in a given volume and used to approximate average recovery time rates dependent on surface area. It was also shown that these recovery rates should be applicable to any volatile compound providing the vapour pressure of the chosen compounds are known at 293K (20°C), as shown by the strong linear correlation between the vapour pressure of a substance and the rate at which it reaches saturation.

7. Future Work

Continuing on from the findings of this work, we will test the saturation rates for more substances, with a wide variance of vapour pressures to verify the trend that begins to show in this paper. One thing to note, is that because the saturation measurements rely solely on the vapour pressures of substances and the infra-red spectrometer, they do not necessarily have to have an odour since the relationship does not depend on this. This immediately grants more freedom in the substances that can be tested, so one can simply look up specific vapour pressures and find suitable compounds which match it.

Whilst small variations in temperature are likely to not have a large affect on both calibration and saturation measurements, it would still be interesting to explore the extent of the temperature dependence as within a broader range, to examine and classify any relationships. This would also test the versatility for this method with regard to temperature dependence.

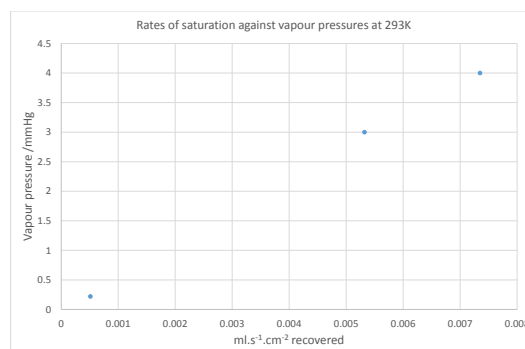


Figure 7: Graph showing the positive relationship between the vapour pressure of a substance against its measured saturation recovery time

References

- [ALLW15] ABID S. H., LI Z., LI R., WALEED J.: Anaglyph video smell presentation using micro-porous piezoelectric film olfactory display. *Displays* 39 (2015), 55–67. 2
- [HHMM15] HOWELL M. J., HERRERA N. S., MOORE A. G., McMAHAN R. P.: A reproducible olfactory display for exploring olfaction in immersive media experiences. *Multimedia Tools and Applications* (2015), 1–20. 1
- [Hul09] HULBERT D.: *Get Through MCEM Part A: MCQs*. CRC Press, 2009. 3
- [IBM*14] ISCHER M., BARON N., MERMOUD C., CAYEUX I., PORCHEROT C., SANDER D., DELPLANQUE S.: How incorporation of scents could enhance immersive virtual experiences. *Applied Olfactory Cognition* (2014), 119. 2, 3
- [LGA*10] LUNDSTRÖM J. N., GORDON A. R., ALDEN E. C., BOESVELDT S., ALBRECHT J.: Methods for building an inexpensive computer-controlled olfactometer for temporally-precise experiments. *International Journal of Psychophysiology* 78, 2 (2010), 179–189. 2, 3

- [LKB69] LEONARDOS G., KENDALL D., BARNARD N.: Odor threshold determinations of 53 odorant chemicals. *Journal of the Air Pollution Control Association* 19, 2 (1969), 91–95. 4
- [Mat10] MATSUKURA H.: Fluid dynamic considerations for realistic odor presentation using olfactory display. *Presence* 19, 6 (2010), 513–526. 2
- [MYI13] MATSUKURA H., YONEDA T., ISHIDA H.: Smelling screen: development and evaluation of an olfactory display system for presenting a virtual odor source. *IEEE transactions on visualization and computer graphics* 19, 4 (2013), 606–615. 2
- [NHAA14] NAKAMOTO T., HASHIMOTO K., AIZAWA T., ARIYAKUL Y.: Multi-component olfactory display with a saw atomizer and micropumps controlled by a tablet pc. In *2014 IEEE International Frequency Control Symposium (FCS)* (2014), IEEE, pp. 1–4. 2
- [NKMY09] NAKAMOTO T., KINOSHITA M., MURAKAMI K., YOSIRI A.: Demonstration of improved olfactory display using rapidly-switching solenoid valves. In *2009 IEEE Virtual Reality Conference* (2009), IEEE, pp. 301–302. 5
- [Olf] OLFASENSE: Olfasense to8 olfactometer. <https://www.olfasense.com/en/odour-measurement-equipment/T08-olfactometer>. Quoted price received in personal communication, date of quote: 2014-02-14. 3
- [Sce] SCENTROID: Sc300 portable olfactometer. <http://scentroid.com/sc302-olfactometer/>. Quoted price received in personal communication, date of quote: 2014-03-21. 3
- [SCS] ST. CROIX SENSORYS I.: The ac'scent international olfactometer. <http://www.fivesenses.com/acscnt-olfactometer.html>. Quoted price received in personal communication, date of quote: 2014-03-20. 3
- [YKN*04] YANAGIDA Y., KAWATO S., NOMA H., TOMONO A., TESUTANI N.: Projection based olfactory display with nose tracking. In *Virtual Reality, 2004. Proceedings. IEEE* (2004), IEEE, pp. 43–50. 2
- [YYT*06] YAMADA T., YOKOYAMA S., TANIKAWA T., HIROTA K., HIROSE M.: Wearable olfactory display: Using odor in outdoor environment. In *IEEE Virtual Reality Conference (VR 2006)* (2006), IEEE, pp. 199–206. 2