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ODORS IN INDOOR NON-INDUSTRIAL ENVIRONMENTS

BY

Demetrios J. Moschandreas, Ph.D.
Professor
Illinois Institute of Technology
Chicago, IL. 60616-3793

ABSTRACT

Perception of odoriferous air in indoor non-industrial environments has been understood as an index of less than acceptable indoor air. Many have claimed to measure indoor odors, a few have done it properly, and even fewer have used the generated data to reach well documented conclusions. This paper articulates engineering principles of odor measurement, highlights the findings of several milestone studies of indoor odors, discusses the sick building syndrome and a few innovative concepts of utilizing sensory measures to understand and control SBS, and reflects on the lack of deterministic models of indoor odor source-effect associations. It is concluded that the engineer assesses indoor odor sources and control strategies, integral elements of this paper, by measuring odor intensity and using building occupants as the sensory evaluators.

INTRODUCTION

The science of smelling is an interdisciplinary science that encompasses biology, physiology, chemistry, statistics, information theory, and environmental sciences. Like all other sciences, olfactory sciences have a basic research component and an engineering application component. The basic research component of odor sciences is probing into the possibility of integrating modern biophysical and molecular advances to study chemosensory processes. Issues addressed by sensory sciences include: the location of molecular events of chemosensory transduction, the process of peripheral inputs in the central system, the difference, if any, between responses to mixtures of chemical stimuli and responses to pure stimuli (Roper and Atema, 1987). Progress in the investigations of basic olfactory sciences research clearly affects application of odor sciences; environmental engineers, however, continue to apply principles of olfactory sciences to resolve current pollution questions. Indoor air sciences employ olfactory sciences as a sleuthing tool to investigate sources of indoor air pollution, to estimate the magnitude of the effect that an irritant may cause, and to gauge the effectiveness of mitigation strategies to reduce the impact of a pollution source.

Some indoor air investigators consider perception of odors in an indoor environment a symptom similar to a headache, or elevated temperature. Independently of whether odor perception is a symptom of an unnamed health effect in indoor non-occupational environments, it is a warning for the presence of low levels of contaminant. The nose is a sensitive instrument, it perceives the presence of pure chemicals and chemical mixtures at levels much lower than the detection limit of most conventional analytical instruments. The human nose samples continuously, there is a large number of human sensors, noses, in the indoor environment, most occupants are able to smell, and the cost of such odor monitoring is minimal. The task for the indoor air scientist is to harness this potential, and to avoid false positives as well as false negatives.

This paper gives a summary of odor sciences from the engineer's point of view, it assesses the tools of olfactory sciences used by indoor air investigators, presents some critical results found in the literature, discuses briefly an odor index being developed to relate frequency of SBS complaints with odor perception, and addresses indoor odor models or, more precisely, the lack of odor models for indoor environments. Odor sources and odor control strategies are addressed throughout the paper.

PRINCIPLES OF ODOR MEASUREMENT

Odor perception in an indoor environment is stimulated by exposure to low levels of an odorant or, usually in non-industrial environments, to a mixture of odorants. Measurements of odors are either analytical, i.e. measurement of odorant concentration, or sensory, i.e. measurement of odor attributes. When used to measure odors, analytical measurements of concentrations of target compounds usually are not fruitful for three reasons: (1) analytical methods are employed to save funds and consequently such efforts do not use the most advanced analytical methods; (2) target compounds are selected because they are known to be odorous, yet the presence of a small quantity of a minor air constituent may totally change the perceived odor; and (3) measurements of concentrations are frequently undertaken to satisfy the regulator, yet investigation of warning signals is not regulated. In this paper the focus is on sensory measurements.

Odor measurements are made with panels of individuals. The olfactory system perceives over 4,000 different odors, yet the average individual can describe, name, only a small number of these odors, (Ruth,1986). Clearly, the complexity involved in the effort to measure odors is large; recall, the concept of accuracy is really not applicable in sensory measurement, but the precision of such measurements is quite good. Odor measurements use descriptive analysis techniques. Odor characterization involves the description of, and measurement in, a four dimensional space with detectability, intensity, character, and hedonics as axes. Detectability, or threshold measurements, determines the minimum concentration of an odorant or mixture of odorants that arouses a response to a certain, predetermined, segment of the population. Intensity is the strength of the odoriferous sensation. The third odor attribute is the odor character, it determines the aroma characteristics or what the odor smells like; fishy, fruity, flowery, and the like. Hedonics, or the hedonic scale, refer to the degree of acceptance (pleasant, neutral, unpleasant) of the perceived odor.

Odor Thresholds

There are two types of thresholds: the detection threshold, and the recognition threshold. Detection threshold is defined as the lowest odorant concentration that provokes a response by a segment of the population. If the segment that detects the odor is 50% of the population then the detection threshold is denoted by ED_{50}, which stands for effective dose at the 50% level. The recognition threshold is the lowest level at which 50% of the test population attributes a characteristic odor note to the test odorant, this threshold is denoted by RD_{50}, recognition dose at the 50% level. Threshold values are statistical measurements of best estimates and involve considerable uncertainty; the literature includes threshold values of the same odorant that vary by as much as two orders of magnitude. Detection threshold is also defined as the number of dilutions required to reduce the odor to levels that will be perceived by 50% of the population. Several olfactometers have been designed and are used to measure odor threshold values at the source of odoriferous emissions, and downwind from such sources, the American Society of Testing and Materials (ASTM) has approved the Forced Choice Dynamic Olfactometer method (ASTM, 1982) Such measurements of detection thresholds are most appropriate for studies of source and ambient odors, (O'Brien,1991). Additionally, these instruments have been used in controlled, laboratory experiments where the odor magnitude can be controlled, (Cain 1987, Moschandreas 1992, and others). However, olfactometers designed to measure outdoor odor threshold values do not appear to be sufficiently sensitive to study typical indoor odor levels (Moschandreas et al.1990, and Relwani et al., 1990). Consequently odor intensity appears to be the preferred odor quantity to measure in indoor odor application studies such as the study of the Sick Building Syndrome.

Odor Intensity

Several methods are used to measure odor intensity. The well known Steven's law: $S=kC^n$ relates the perceived odor magnitude, S, with the concentration, C; the factor that bridges these two quantities, the exponent n, depends on the odorant and varies between 0.2 to about 0.7 (Cain and Moskowitz, 1974) This law establishes that a change in the concentration of the odorant results in a relatively smaller change of the perceived odor intensity. Odor intensity can be expressed by the assignment of a value on a measurement scale. Odor intensity scales are either categorical, both number and/or word, or magnitude and estimation-ratio scales, (ASHRAE,1992; Cain and Mosckowitz, 1974; Meilgaard et al., 1988; and others) The Dynamic Dilution Binary Scale Olfactometer ,also known as the n-Butanol wheel, (Dravnieks, 1975) is an inexpensive measuring device that uses principles of matching intensities to measure the intensity of the test odoriferous air. A scale of odor intensity measurement used widely is the line scale, usually, a line of 10 cm in length. The subject is asked to indicate (mark) the perceived odor intensity on the line between two extremes of no odor, in the left end of the line, and very strong odor, in the right end of the line.

Odor Character and Hedonics

Odor character profiles help distinguish odors from different odoriferous air streams, in other words different odors result in different sets of odor notes or odor descriptors. An ASTM committee produced a list of 830 odor notes, but Amoore, 1962, generated a list with only seven notes. An Atlas of odor characters was published by ASTM, it contains 146 odor notes, it was used to characterize the odor of 180 chemicals, (ASTM,1985). One of the most telling odor attributes is its hedonic nature, odors that are unpleasant serve as warning agents of an unexpected event. An hedonic judgement may be expressed at once on a category scale (pleasant, neutral, unpleasant) and on a magnitude scale (very pleasant, slightly pleasant, unpleasant, unbearable, and the like. We may use similar techniques to measure odor hedonics and odor intensity, , but we measure different odor attributes or qualities. One of the interesting facts of odor perception is the relation between odor intensity and odor hedonic character: repeated increases of odor intensity of unpleasant odors result in monotonic increases of odor unpleasantness, but the hedonic magnitude of a pleasant odors does not necessarily increase with increasing odor intensity.

Factors Affecting Odor Measurements

Measurement of odor qualities is affected by several factors such as temperature, relative humidity and the general comfort of the indoor environment, by the frequency and length of exposure to the odorant, by the education/culture of the receptor, and by the biological needs of the receptor. Additionally, odor perception is affected by the olfactory acuity of the subject, olfactory acuity is defined as the ability , keeness, of an individual to detect and discriminate odors.

Given the expected variation in odor perception, the size and the quality of the panels are most important in determining the value of odor data generated by panels. Clearly, a small panel represents itself, and conclusions reached by such panel can not be generalized, yet a very large panel presents practical problems. For outdoor studies, panels of nine to ten properly selected panelists appear to generate statistically robust data. For indoor studies large panels are necessary: Fanger and his associates use large panels, about fifty members; Moschandreas used 200 panelists for a laboratory experiment, (Moschandreas and Relwani, 1992) and a minimum of 15% of occupants in studies of potentially sick buildings, (Moschandreas and Relwani, 1990 and 1992). Note, ASHRAE requires responses to an odor questionnaire from at least twenty potential occupants of the building under investigation to determine whether the indoor air is acceptable.

MILESTONE STUDIES OF INDOOR ODORS

Historically, indoor environments with odors were considered dangerous places, places associated with unsanitary conditions, illness, hospitals, and generally places to be avoided, if possible. Even though urban disagreeable odors have been mostly brought under control, the perception of "evil smells" persists in many developing countries. There is little doubt that odors or their absence are poor indexes of toxicity. Yet, odors in indoor environments are unwanted, because odors may be indices for (1)irritation of the exposed occupants, (2) for low air exchange with fresh outdoor air, (3) for indoor emissions of VOCs and other odoriferous gases, and (4) for any combination of the above.

In indoor environments, the effort to control odors is closely related with the effort to characterize odors, i.e. the effort to formulate indoor odor profiles. Dilution by ventilation air is the conventional, indeed the preferred, strategy for controlling indoor residential odors; additional control systems may be used to control odors in large non-industrial environments, such as offices, theaters, sport arenas , and the like. Two hundred years ago, Benjamin Franklin provided the first odor control strategy. Writing in defense of the Franklin stoves, he pointed out that the odor, "the smell",attributed to the stove is not emitted from the iron, rather it is the product of the "general uncleanly manner" of using the stove.

Body and Tobacco Odors

Undoubtedly, good housekeeping remains the best known means of reducing odors indoors. However in 1936 Yaglou and his associates (1936) began to study odors systematically, body odor control was the strategy they used to determine minimum ventilation requirements. Using a room sized chamber, these investigators determined a ventilation rate range that would cause a visitor to perceive a neither pleasant nor disagreeable odor. They concluded that the range depends on the occupancy density, it varied between 7 to 25 cfm per occupant. A few years later, Yaglou concluded that control of tobacco smoke would require 40 cfm per smoker, this rate it was concluded did not depend on the number of smokers, (Yaglou, 1955)

In 1981 the American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) published its standard on Ventilation for Acceptable Indoor Air Quality, (ASHRAE Standard 62-1981). ASHRAE defines acceptable air as the air with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction. The ventilation rate for environments with non-smoking occupants was 7 cfm per occupant, for environment occupied by smokers the rate was set at 35 cfm per smoker. In a classic study of body and tobacco odors, Cain et al (1983) generated odor descriptive data for periods of smoking and non-smoking inside a room sized chamber. Cain and his associates showed that only 71% and 75% of visitors to the indoor environment with non smoking and smoking occupants, respectively, would be satisfied with the ASHRAE ventilation requirement. Cain and his colleagues at the John B. Pierce Foundation Laboratory have studied extensively these discrepancies and related issues of odor perception. In 1989 ASHRAE issued a new standard for "Ventilation for Acceptable Indoor Air Quality" (ASHRAE Standard 62-1989). This standard does not set two distinct requirements for indoor environments with smoking and non-smoking occupants, rather it sets one ventilation requirement for most all indoor spaces. The prevailing rate of the ASHRAE Standard is 15 cfm per person, but a large number of specific indoor environments require higher rates, frequently 20 cfm per person. The required ventilation rate for smoking lounges is set at 60 cfm per person.

Inspired by the prevailing, but never verified, assertion that visual contact with an odor source is likely to affect the perceived odor intensity, Moschandreas and Relwani (1992a) used a room sized chamber, a panel of 200 randomly selected subjects, and an experimental design of two stages (contact-no contact) to test the impact of visual contact on perceived odors. They concluded that at least one in three subjects who can see the smoker will perceive stronger odor intensity, more unpleasant odors, and more odors that are characterized as tobacco odors than if they were exposed to the same air but had no visual contact with the emitting source, the smoker. If true in public indoor environments, eliminating visual contact between smoking and non smoking sections may provide a third control strategy for establishments that wish to provide space for customers who smoke.

Odors, Irritation and Indoor VOC Exposures

Occupants of non-industrial indoor environments are likely to be exposed to low levels of as many as 300 Volatile Organic Compounds (VOC). Individual compounds rarely exceed the corresponding threshold Limit Value (TLV), yet in a mixture exposure to indoor VOCs is suspected of causing odor, irritation and neurobehavioral effects. Molhave et al. (1986) studied effects on the air quality, odor, irritation and ability to concentrate of individuals exposed to a mixture of 22 VOCs commonly found in indoor environments. They performed a series of controlled experiments by exposing 62 individuals to three levels of concentration: 0, 5, and 25 mg/m^3. The effect on odor perception was significant, as was the nonaceptability of odor intensity when the subjects were exposed to 5 and 25 mg/m^3. In a related study by Bach et al. 1984, significant decreases of scores of (1) memory, (2) ability to concentrate, and (3) irritation were measured as a function of exposure to VOC concentrations. Finally, Molhave and his associates suggest that the mucous irritation threshold for total organic vapors is in the range of 0.16 to 5.0 mg/m^3. Using this and related work, Tucker (1990) recommends that a single indoor source should not add to the indoor environment more than 0.5 mg/m^3 of organic vapors, one assumes that this guideline will affect occupant odor perception.

The approach of using of low emitting indoor materials and products, leads to a fourth odor control strategy: material selection. These control strategies, and others, have been employed by indoor and odor scientists to resolve the increasing number of complaints registered by occupants of indoor non-industrial environments. These complaints have led to an area of specialized inquiry known as the Sick Building Syndrome (SBS)

SICK BUILDING SYNDROME

The term sick building syndrome is often used incorrectly, The World Health Organization defined the SBS as an inclusive term describing the following : the majority of the occupants register complaints, specific cause of the complaints and symptoms is not identified, but bad engineering, design and practice is not included in the syndrome, symptoms fall in four classes sensory, odor, general symptoms of fatigue, dizziness and nausea, and lower airway and gastrointestinal symptoms, (WHO, 1984). Dry mucous membrane sensation is noticeable in buildings with SBS, the onset of the symptom is gradual, and the duration long. Molhave uses a more extensive definition of the SBS concept in his effort to provide an etiology for the symptom and to identify questions to be addressed in planning research protocols for subjective symptom and IAQ studies, (Molhave, 1992). SBS buildings are studied by a combination of air sampling and analysis, and survey questionnaires. Odor quantity magnitudes are usually obtained from responses to a questionnaire that uses either pictures or word descriptors, or the line scale.

Moschandreas and Relwani (1990) studied, among other quantities, the odor perception of visitors and occupants of two buildings, one with a SBS, the other a Healthy building, i.e. no registered complaints. Odor levels were measured with a questionnaire and by analyzing air samples using a dynamic olfactometer and panels of ten. A minimum of thirty occupants (about 25% of the total number of occupants responded to the questionnaire in each of the buildings. The questionnaire was administered every day for twenty work days. The conclusions reached are as illuminating as any in the literature: (1) odor analysis of indoor air using an olfactometer and panels is not sufficiently sensitive to quantify indoor odor thresholds and the levels of odor intensity indicated by the occupants on the scale line; (2) Indoor pollutant concentrations of total volatile organic compounds did not correlate well with occupant perceived odor intensity levels; (3) odor intensity levels, marked by the occupants, varied markedly from day to day; and (4) the building symptom index, the average number of symptoms indicated by occupants per day, (Burge, 1990) did not correlate well with the measured indoor pollution levels, or the building ventilation levels. These conclusions are applicable to both the sick building with a large number of complaints and to the healthy building with no complaints. Since the literature includes a few episodic studies that have been successful in reducing indoor odors, these conclusions are not universal, but they describe the fundamental difficulties encountered in efforts designed to research the SBS.

The Olf Concept

Motivated by the inability of the indoor air sciences community to establish a cause and effect relationship between indoor contaminant levels and complaints of occupants, Fanger and associates changed the focus from chemical analysis to sensory analysis. They defined the olf, a new measurement unit, as the emission rate of air pollutants (bioeffluents) from a standard person, and determined the segment of people dissatisfied when exposed to emissions from one person as a function of ventilation rate by fresh air. In essence the olf is an odor measuring unit, it is used with an experimental design of multiple visits to the subject building that allows the researcher to measure emission rates, olfs. from the building itself, the occupants and the ventilation system, and a combination of the above (Fanger, 1987, 1988, and others). In addition Fanger and associates defined the decipol unit as the pollution caused by a standard, an olf, ventilated by 10 l/s of unpolluted air, (Fanger, 1988). Using these units and several designs, the Danish investigators were able to correlate perceived air quality,as judged by a trained panel, with prevalence of complaints, mucosal irritation, and general symptoms in schools, (Thorstensen et al. 1990)

The DEM Index

The Olf approach is a powerful tool that determines whether a building requires further investigation of its indoor air quality, and the specific, but generic, source of the building that should be controlled. This approach requires repeated visits to the building by a large and trained panel. Preliminary results from a recent study by Moschandreas and Relwani (1992b) indicate an alternative approach that uses occupants as the panelists, and leads to the Degree of Effluvium Measurement Index (DEMI). A characterization study was performed in five office buildings occupied by a minimum of 80 individuals. Among the many instruments of inquiry used, these investigators administered a symptoms/comfort questionnaire that requested the occupants to rate indoor air odor intensity and to mark health symptoms as they were perceived at the time of responding to the questionnaire. The number scale used varied from no odor, from 1 on the line scale,to bad odor, 7 on the scale.

The DEM index corresponds to the concept of percent applicability employed by Dravnieks in his odor studies (see ASTM 1985) The index was calculated using three statistical measures: (1) percent usage, that is the segment of subject occupants who rate the indoor odors as bad odors, i.e. greater than four; (2) score level, the maximum score sum is the number of subject occupants multiplied by seven. The sum of the scores higher than four given by subject occupants is then divided by the maximum score to calculate the percentage of maximum score level in odor perception; (3) the geometric mean of percent usage and percentage of maximum score is the DEM index. This statistical approach is a noise reducing method that reduces time, space, and acuity variation in odor perception by the occupants. The DEM index was calculated after pooling responses from at least three days.

The difference between DEM index value of the sick buildings minus the value of the healthy buildings is statistically significant. More importantly, there is a good correlation between the index and the number of complaints register that day as well as before the commencement of the study. The database is currently analyzed to determine if this approach will help isolate areas, within a building, where the cause of the complaints may be found. The data are not as revealing toward this objective, but the experimental design of the study did not seek to isolate the sources of the complaints, a revised design and further research is needed to investigate if the DEM index will isolate the source of the complaints.

If successful, this index has many advantages over more conventional odor perception approaches: it uses the occupants' nose and sensory perception of symptoms and odors, it requires short periods of time, it does not require trained panelists, nor experienced analysts. If applicable to buildings, it can be administered intermittently and will provide information that can be used to avoid conditions that lead to large number complaints. Clearly, more research is needed to determine the practical implications of the index.

Indoor Odor Models

Deterministic models use fundamental mathematical equations of indoor processes to relate the effect, odor perception , with the cause, odor source emission. Statistical models use semiemperical statistical relations between the effect, complaints regarding the indoor environment, and the measurements of odor perception. Deterministic models relating indoor odor quantities with emission rates of odorant sources, temperature, relative humidity, occupant density, and other factors that affect odor perception are not available in the literature. Although the concepts are not brought forward as modelling efforts, both the olf concept and the DEM index may be considered as statistical models for determining if the source of the indoor air pollution is the occupant, the furnishings or the HVAC system, or for determining if an indoor environment is a building with SBS.

A review of indoor odor studies can not be comprehensive without mentioning the extensive and high quality work done in Sweden by B. Berglund, T. Lindvall and their associates. In an excellent review on measurement and control of annoyance, Berglund et al., 1987, refer to a series of investigations that may fall under the umbrella of statistical models for matching procedures, undimensional and multidimensional scaling. These authors have constructed a master scale with references that can be used as common calibration of judgements of sensory stimuli independent of peculiarities of individual subjects serving in a particular experiment. A method such as the Master Scale has great potential value for assessing odors in indoor environments where physical measures have not proven sufficiently sensitive to measure odor intensity, unfortunately this scale has not been used extensively indoors.

CONCLUDING REMARKS

A recent report from the Commission of the European Community (CEC) addressed the connection between Indoor environment and sensory effects. CEC defines sensory effects as "the perceptual response to environmental exposures". Clearly sensory effects include more than odor perception, yet the four reasons brought forward in this report for investigating sensory effects in indoor environment are most revealing. The first reason suggests that sensory effects indicate health effects that demonstrate themselves as sensory disfunction. Annoyance, an environmentally perceived sensory response, may be an unwanted effect or it may be a warning for a disease. The third reason refers to odors explicitly, and reason that odors and mucosal irritation may indicate exposures to toxic air pollutants. Lastly, belief that sensory effects may be used as sensory bioassays. The last reason for including the study of sensory effects in indoor investigations reflects the growing An illustration of this concept that has found great application in indoor studies is the use of odor criteria for establishing ventilation requirements. Additionally, there is a growing belief among indoor air quality researchers that sensory effects can be utilized to screen indoor pollution sources, i.e. building materials, furnishings and others, to provide a perceived measurement of VOC emissions from such sources.

A four odor attribute construct determines the odor profile. Of the four attributes, odor threshold measuring devices do not appear to be sufficiently sensitive to measure either recognition or detection threshold values of typical indoor odors in non-industrial environments. For application measurements of indoor odors, the measurement of odor intensity is the most useful odor quality. Sensory tools used for measuring odor intensity include estimation-ratio scales, the line scale, the n-butanol binary olfactometer, and Steven's law. The Olf unit, and to a lesser extent, the DEM index may be also thought of as statistical indicators for odor intensity measurements. Odor hedonics, and odor characterization notes are also used to characterize indoor odors. Odor perception is affected by a large number of physical and chemical factors, by the olfactory acuity of the exposed subjects, by the frequency and duration of the exposures, and by the ethnic and education of the exposed. The multitude of factors that potentially affect odor perception requires that investigations of indoor air odors use large panels. The need for large panels constraints the measurement of indoor odors, yet the use of occupants as panelists provide a powerful, inexpensive, and continuous sensor.

As we have seen, sources of indoor odors in non-industrial environments include occupants (body odors), building materials (several odors related to VOCs), indoor furnishings (formaldehyde, carpet odors, ozone, others) and occupant activity (cooking odors, tobacco odors, hobbies, cleaning solvent odors, and others). Good housekeeping, dilution by ventilation, and reduction of odor emissions by selecting low emitting products for use indoors are control strategies used to reduce odors indoors. A strategy not addressed in this paper is the use of control systems to absorb odoriferous gases. Several limitations are associated with this strategy: (1) it is mostly applicable in large non-industrial environments and rarely in residential environments, (2) their effectiveness in reducing indoor odors is commercially claimed but it has not been documented in the scientific literature, and (3) the possibility of re emitting the absorbed gases, specially from the stand alone room air cleaners that claim to reduce odors associated with tobacco smoke, is quite strong and may defeat the very purpose of using such cleaners.

Exposure to hydrogen sulfide causes adverse health effects, but these effects are caused by the gas which is toxic, and not by the odor that is perceived by the receptor. This may be obvious, what is not as clear is whether odor-related health effects constitute a public health problem. Discussion of this issue revealed a schism in the scientific community of public health and odor experts (NAS,1979). Independently of ones alliance with respect to this controversial issue, odor perception in indoor environment should be considered as warning of indoor sources of unwanted emissions, and as a potential surrogate for problems associated with indoor air pollution. Elimination, or substantial reduction of a persistently perceived indoor odor is a robust indicator for improved indoor air quality.

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