05/01/20

Visualization of Airborne Vapors and Interior Air Quality

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This letter provides a summary of technical papers and Association (ASHRAE, etc.) views on micron-sized particle movement in indoor environments. The purpose of this letter is to provide insight into the movement of these particles and to suggest visualization tools to further that understanding. The particles to which I am referring include organic materials like mold spores, pollen, aerosols from cooking, smoking, coughing, sneezing and normal breathing. It is this last group of aerosolized particles that can contain infectious biological agents that once airborne can alight on horizontal and vertical surfaces or remain suspended and pose an inhalation hazard.

As an engineer, I spent 35-years researching particle laden flows and how to redistribute gas and particulate fields to uniform distributions. The purpose of this effort was to improve availability for utility and industrial scale steam generators. In my research, field testing, and design activities, it was a matter of routine practice to use various types of flow visualization tools to reveal global and local flow patterns in large interior spaces. The most useful tool for these spaces was smoke generators (smoke bombs); same type used by firefighters in training exercises.

Recent discussions about business openings is being done by people that do not fully understand movement of airborne particulate and by extension aerosolized vapors. They are working around the margins and after the fact to put the brakes on the transmission mechanisms. Discussions about opening restaurants, patios first, indicates an innate understanding that outside is somehow safer than inside, and I believe that that is demonstrably correct.[1] Moving air, normally lots of this outside, dilutes and carries away the airborne spittle, vapor droplets (nuclei) that carry potentially infectious particles. We emit a range of vapor particles, typical from 0.1 – 100-microns depending on whether it is being released in conjunction with sneezing, coughing, talking, or breathing.

Particles at the large end of the distribution have enough mass to overcome drag forces and can fall quickly to horizontal surfaces nearby. This is thought to be one of the transmission

[1] *A guy walks into a bar, looks around and notices the other patrons are appropriately spaced so he sits on a stool. The bartender moves closer and asks, 'What'll you have Bud?' The guy points towards a patron at the other end of the bar and says, 'I'll have what he's having.'*

routes for infection, direct contact with formites[2], typically from the waist down to the floor. Smaller particles can remain suspended until they dry out and are carried away by the local air flow.

I have researched smoke particle behavior and its utility for visualizing the behavior of aerosols generated by coughing, sneezing, and breathing.[3] I believe that a compelling case can be made for this tool because smoke particles have similar physical characteristics: size, composition (water, organic and inorganic) and density. Therefore, human exhaled vapor particles could be visualized by someone smoking a cigarette. This is a useful tool because nearly everyone has experience with smoking and recently vaping. Before the indoor smoking ban, anyone that went to a bowling alley, bar or club remembers the smoky immersion into the second-hand smoke cloud. From that type of experience, most people have a visual understanding of smoke movement in inside spaces. Exhaled vapors are doing the same thing, only everyone in the space is breathing. In the old days, only a fraction of the people were smoking.

Indoor ventilation is designed for comfort and economy with a range of air exchange rates (ACH) deemed adequate for the expected number of people (spittle machines) that may gather. As an economy measure, some ventilation systems operate in a recirculation mode with varying amounts of exhaust and fresh air make-up. Whichever ventilation system is used, interior spaces are awash in vapor clouds of various types: baked goods, brewing coffee, frying bacon, fragrances, cigarette smoke, VOC's, etc., and of course spittle vapor from the people therein. Aerosolized vapors are most evident in cold weather due to their immediate condensation or if you put a mirror under your nose (to see if you are still alive) and when glasses get fogged while wearing ill-fitted masks. With every breath a vapor cloud is sent into the air.

The smoke visualization concept has the added benefit that in its diluted form, its presence can still be detected through the sense of smell. Humans can smell extremely low levels of airborne gases and vapors (several have already been mentioned). In fact, we can smell odors well after the source has been removed (thirdhand smoke) due to particle reintrainment. Small particles are attracted to proximate surfaces: walls, curtains, furniture, clothes, etc. Over time, they can become airborne as they lose their charge or are mechanically dislodged by nearby air currents.

Secondhand and thirdhand smoke were studied extensively in the three decades prior to the turn of the century, so there is plenty of available literature. The solution to the secondhand and thirdhand smoke problem was to eliminate the source. The current solution to the spread of potentially infectious vapors has been the same – eliminate the source. While these actions

[2] Formite – An object or material that is likely to carry infection, such as clothes, utensils, and furniture.
[3] This connection is the subject of a separate abstract being prepared for submission to several technical conferences.

have been effective, for the present situation, it is not a viable long-term solution. The more difficult solution would have been to change ventilation practices to remove the secondhand smoke. The adequacy of this method would be evident if no odors were detected a few feet from their source. Current guidelines for distancing are based on the implicit understanding of the aerosolized transmission route: separation from exhaled vapors equals safety.

Separation may or may not be adequate, it's a matter of air flow and position relative to the source. For example, if you are outside and appropriately spaced from a person smoking a cigarette, eventually you would get a whiff of smoke. At some point, the person is going to be exhaling smoke, you will be directly downstream and breathing. So now it's a game of probabilities: if it's an infected person and neither are wearing masks, there is a high probability of inhaling a vapor particle at the whim of the wind. If you were both wearing masks, the probability has been diminished significantly as masks can absorb small particles at high efficiencies when properly fitted.[4] Interior spaces don't have the luxury of cleansing breezes typical of outdoors. Odors and vapors can remain in spaces with recirculating flow patterns, which is typical of standard ventilation patterns.

To put it bluntly, we are living in a cloud of each other's spittle. For interior spaces, increasing the refresh rates can reduce the amount of vapor present. Unfortunately, HVAC systems are not designed to purge room air in a uniform manner. Eventually, the 'old' air is replaced exponentially with the 'new' air depending on recirculation mode, rate, and flow patterns in the ventilated room. Consequently, it can take a long time to completely change the air in a room. If people remain in the room, an equilibrium level is achieved that is a mix of vapor and air (and all the other chemical compounds from the local environment).

The Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA)[5] updated their recommendations at the beginning of April with a list of sensible and clear recommendations to reduce airborne pathogens. The American Society of Heating, Refrigeration, and A/C Engineers (ASHRAE)[6] has posted a position document at their site that lists similar strategies. Their main recommendation is to operate in a 100-percent refresh mode, without recirculation. The National Institute of Health published a research report

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[4] ACS Publications: 'Aerosol Filtration Efficiency of Common Fabrics Used in Respiratory Cloth Masks', Abhiteja Kondo, et al, April 2020. https://pubs.acs.org/doi/10.1021/acsnano.0c03252. There are masks being used that have exhaust valves. Seems like that defeats the purpose of the mask, to capture some of the emitted (smoke) particles.

[5] See REHVA Guidance Document V2: https://www.rehva.eu/activities/covid-19-guidance

[6] ASHRAE Position Document: https://www.ashrae.org/file%20library/about/position%20documents/pd_infectiousaerosols_2020.pdf

indicating that Natural Ventilation was superior to Mechanical Ventilation in many indoor settings due to higher ACH.[7], [8]

There have been many studies that all come to the same conclusion – ventilation of interior spaces is an effective strategy for reducing suspended particles and vapors. One of the highest risk infection areas is **households** due to long exposure times and low ACH, typically **1-2**.[9] It's no wonder that Flu season is over the Winter months when everyone is huddled inside with the windows closed and leakage the main source of fresh. Opening windows in closed-up spaces can increase ACH to 5.[10] In our northern climate, this method is not that simple, but HVAC solutions are readily available.

The first and easiest strategy for reduction of airborne infection is to eliminate 'recirculation mode' and increase ACH, keeping in mind that it will take time to flush interior spaces. Heat recovery/shedding equipment, such as air-to-air heat exchangers, are readily available to maintain comfort and economy. I would not recommend heat recovery systems with seals or that have the potential to re-entrain condensate on the fresh air side. Distribution within spaces would require modeling (physical and/or computer) to identify methods to redistribute air to 'ideal' once-through patterns that carry away infectious vapor.[i]

Smoke is a useful method to visualize airborne micron-sized particle movement. A smoke generating device (cigarette, incense stick, smoke signals, etc.) would readily show flow patterns in, through and out of an interior space and most importantly reveal quiescent regions with long purge periods. Optionally, a fragrance atomizer would provide detectable and familiar scents. Quantifiable method can also be employed such as tracer gases: mercaptan or CO2 for example. The purpose of this activity would be to develop methods to remove odors and vapors on a continuous basis such that none of the interior has a detectable residuals.[11] With

[7] The World Health Organization has published guidance that make only brief mention of airborne transmission (probably because most of the world is natural ventilated), WHO: 'Modes of transmission of virus causing COVID-19 :implications for IPC precaution recommendations', https://www.who.int/publications-detail/modes-of-transmission-of-virus-causing-covid-19-implications-for-ipc-precaution-recommendations

[8] 'Natural Ventilation for the Prevention of Airborne Contagion', Escombe, A.R., et al., https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1808096/

[9] Excellent treatment of important factors for densely populated areas; a little heavy on the math in places, but well worth the slog. 'Building Ventilation as an Effective Disease Intervention Strategy in a Dense Indoor Contact Network in an Ideal City', Gao, X., et al., https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5017609/#pone.0162481.ref042.

[10] Ref. 9, Escombe, A.R., et al.

[11] If ventilation practices get to ideal once through flow, cigarette smokers no doubt would be clamoring for permission to smoke indoors as a means of confirming adequacy of air flow.

interior spaces uniformly purged, then the guy waiting outside the barber's door for his turn would be assured that he won't be walking into the previous customers spittle.[12]

The information presented here in no way diminishes the importance of other transmission methods.[13] There is a significant amount of discussion among and between academic and health organizations about routes of infection and their relative frequency. There is consensus, however, that airborne transmission is a concern and should be addressed. There are relatively simple measures that can be instituted to mitigate airborne transmission of infectious nuclei: opening windows would be the first and simplest method, especially for households and other comfortably ventilated spaces (like nursing homes, care facilities, offices, etc.) per current standards.

Flow visualization would provide insight into the complexities of air movement in interior spaces. This insight should identify deficiencies of present HVAC practices regarding the spread of infectious aerosols. Engineers and HVAC experts should be consulted to discuss the proposals presented in this summary. Then they should get to work designing and optimizing air flow distribution, heat recovery/shedding and supplemental cleaning methods using filtration, UV sterilizers, and electrostatic purifiers for the new normal.

Between better ventilation at home, work and play, and better designed restrooms, clean phones, and the canine patrol[14], Fall should be 'un-eventful', or should I say, 'full of events'? Eventually there will be a vaccine or treatment(s) to address and prevent this and future infections. Hopefully by that time a new ventilation mind-set will have render the current and next virus or flu impotent.

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[12] *A guy walks into a bar, looks around and notices the other patrons are appropriately spaced so he sits on a stool. The bartender moves closer and asks, 'What'll you have Bud?' The guy points towards a patron at the other end of the bar and says, 'I'll have what he's having.' The bartender retorts, 'It's your lucky day Bud, so breathe easy, you already got it, and it's on the house.'*

[13] See Addendum for more on this topic.
[14] See Addendum.

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i Modern computational modeling can be used to evaluate a broad range of complicated flow fields, in the present case air and aerosols in indoor spaces. Starting with the as-is flow pattern, methods to improve these patterns to the benefit of the occupants can be made in a fraction of the time needed for physical modeling or field testing. Physical models or field testing can be done thereafter to validate the computer model prior to implementation of the proposed solutions.

Coming together is a beginning,
Staying together is progress,
And working together is success.
Henry Ford

Kind Regards,

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Addendum

During this investigation I have come across several related topics that you may find interesting. Since I am not involved in any official group discussions related to the pandemic, I'm not sure if these items are already topics of discussed. Nevertheless…

A1. Contact transmission

The link below shows how far a 'virus' could spread among 10 people at a buffet using a fluorescent dye and UV light. I am sure there are groups (Health Dept, Restaurant Association, etc.) looking at transmission methods for different venues. Hopefully, there is or will be a coordinated effort to identify promising changes that can sever transmission routes in these settings. https://www.businessinsider.com/video-japan-nhk-uv-light-how-virus-spread-restaurant-2020-5

A2. Cell Phones and Networking

Robert Glass (Sr Scientist at Sandia, NM) studies complex systems and failure modes. His daughter's science experiment about social networking revealed a perfect method for disease transmission: schools and school buses. And what kid (adult?) doesn't like to find something silly on their smart phone and call their friends over in a huddle to share the experience? By the way, cell phones are typically the most contaminated surface that we handle. There are many papers and articles on this topic, so I am not including any references. Just keep in mind that if you dutifully wash your hands and then handle your cell phone, you just unwashed your hands.
https://medicalxpress.com/news/2006-05-virtual-city-flu-pandemic.html

A3. Splashback

Bathroom protocols – splashing and disinfecting. The WHO has yet to identify a fecal-oral transmission route for COVID-19; however, this route has been established for SARS-CoV-2. A British demonstration using fluorescent dyes shows how splashing distributes liquid droplets around the toilet. Should be similar w/ urinals. When these items are flushed, they typically generate a vapor cloud. Rest room etiquette and operation is going to require some serious rethinking other than 'wash your hands'. https://www.qssupplies.co.uk/splashback-study

And then there is the issue of *flatulence* that can spread a different kind of exhaust fume. Fortunately, the region of origin is typically masked. Gives new meaning to the phrase, 'silent but deadly'. https://www.news-medical.net/news/20200422/Lifting-the-lid-on-coronavirus-

flatulence.aspx

A4. Medical Ventilators

While I am not an expert in the design and use of these life saving devices, I have anecdotal evidence to suggest that they exhaust into the room where they are being used. From the discussion section of the referenced web site*; '*The other issue brought into stark relief by VOVID-19 is the safety of the surrounding treatment team with potential aerosol spread from the exhaust circuit*'.

* https://hackaday.com/2020/03/25/ventilators-101-what-they-do-and-how-they-work/

There seems to be a general awareness that this exhaust design is inadequate. ASHRAE offers a NEW! design course, '*Laboratory Exhaust Stacks: Safe and Energy-Efficient Design*'. Seems timely. https://www.ashrae.org/professional-development/all-instructor-led-training/online-instructor-led-training/laboratory-exhaust-stacks-safe-and-energy-efficient-design

A5. The Canine Patrol

Several organizations have been trying to train dogs to detect the Covid-19 virus or an infected person. It seems only a matter of time before they will have this in place. Other than some specialized chromatographic instrumentation, this could be the best method of rapid detection. It would be useful for large venues and transportation hubs. See Information sites listed here.

1. *University of Pennsylvania*
   https://www.washingtonpost.com/science/2020/04/29/coronavirus-detection-dogs/
   Eight Labrador retrievers… have been enlisted to help. The dogs are the first trainees in a … research project to determine whether canines can detect an odor associated with the virus that causes the disease covid-19.

2. *London School of Hygiene & Tropical Medicine*
   https://www.lshtm.ac.uk/newsevents/news/2020/dogs-could-join-fight-against-covid-19
   Researchers previously demonstrated that dogs could identify malaria infections in humans. In a statement, James Logan, head of the school's disease control department, called canines a "new diagnostic tool" that "could revolutionize our response to COVID-19."

3. *Manatee Nonprofit BioScent K9*
   <*https://www.bradenton.com/news/coronavirus/article242509151.html*>
   Junqueira, founder of BioScent K9, a Myakka City, FL. not-for-profit, is set to begin researching and training dogs to detect COVID-19.