

# Can better indoor ventilation make schools safer during the COVID-19 pandemic?

---

## Introduction

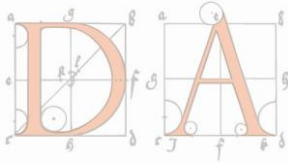
As children return to school this Fall, parents, teachers, school officials, and others may wonder how safe their school environments are from COVID-19. While, by now, most of us are quite familiar with the enhanced hygiene recommendations provided by health officials to limit the spread of COVID-19 (such as the mask wearing, social distancing, hand washing, and surface cleaning noted in [British Columbia, 2020](#); [British Columbia Ministry of Health, 2020](#); [Vancouver School Board, 2020](#)), not as much information is available related to preventing indoor airborne transmission over distances greater than two meters. Since this will be the first time in several months that local schools have assembled teachers and children together into classrooms, hallways, and other indoor spaces, it is useful to consider what researchers and industry professionals have documented that might inform how to do this with minimal risk of airborne disease transmission. Some of these considerations follow.

## Can children catch and spread COVID-19?

Young children seem to be much less likely than adults to catch COVID-19, and, when they do, they seem to react to it with moderate to no symptoms ([de Souza et al., 2020](#); [Escosa-García et al., 2020](#); [Hagmann, 2020](#); [Isaacs et al., 2020](#); [Kallem & Sharma, 2020](#); [Kevat, 2020](#); [Mallineni et al., 2020](#); [Ranabothu et al., 2020](#); [Ruggiero et al., 2020](#); [Yasuhara et al., 2020](#); [Davies et al., 2020](#)). It is not well known why this is so ([Yavuz, Kesici, & Bayrakci, 2020](#)), though research on the topic is growing ([She, Liu, & Liu, 2020](#)). Children's ability to spread the disease is not well known either ([de Niet, Waanders, & Walraven, 2020](#); [Munro & Faust, 2020](#); [Li et al., 2020](#)). While they seem to be less likely than adults to spread it, the evidence suggests that they can ([Li et al., 2020](#)).

## Can people without symptoms spread COVID-19?

In one study, He et al. ([2020](#)) found that 15.6% of adults with COVID-19 and 27.7% of children with COVID-19 were asymptomatic. Researchers generally agree that asymptomatic individuals with COVID-19 can spread the disease ([Abtahi-naeini & Saffaei, 2020](#); [Goyal et al., 2020](#); [Lango, 2020](#); [Lu et al., 2020](#); [Yu & Yang, 2020](#)), including asymptomatic children ([Ludvigsson, 2020](#)). In fact, several researchers claim that the viral load for asymptomatic persons is the same as it is for persons presenting symptoms ([Yang & Chen, 2020](#); [Huff & Singh, 2020](#); [Peng, Su, Zhang, & Wang, 2020](#)), though Luo et al. ([2020](#)) found the infection rate to be lower from asymptomatic persons.



## Can COVID-19 spread through the air?

While a lack of data ([Anderson et al., 2020](#)) has engendered some disagreement as to whether the SARS-CoV-2 virus can spread through airborne pathways ([Lewis, 2020](#); [Morawska & Cao, 2020](#)), consensus seems to be forming that it can ([Allen & Marr, 2020](#); [Christopherson et al., 2020](#); [Correia et al., 2020](#); [Gameiro da Silva, 2020](#); [Goyal et al., 2020](#); [Lu et al., 2020](#); [Lednicky, Lauzardo, et al., 2020](#); [Lednicky, Shankar, et al., 2020](#); [Morawska et al., 2020](#); [Nwanaji-enwerem, Allen, & Beamer, 2020](#); [REHVA, 2020](#); [Shen et al., 2020](#); [Somsen et al., 2020](#)). The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), a North American professional organization that is a preeminent authority on matters of building ventilation, has taken the position is that

*“Transmission of SARS-CoV-2 through the air is sufficiently likely that airborne exposure to the virus should be controlled. Changes to building operations, including the operation of heating, ventilating, and air-conditioning [HVAC] systems, can reduce airborne exposures.”* ([ASHRAE, 2020, p2](#))

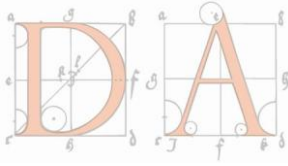
Thus, opinions from both academic and professional sources suggest that aerosolized (airborne) transmission of the SARS-CoV-2 virus is a concern.

## What research has been done on indoor airborne disease transmission?

Several studies have discussed the influence of building ventilation systems on airborne disease transmission ([Chung & Hsu, 2001](#); [Du et al., 2020](#); [Hobday & Dancer, 2013](#); [Kembel et al., 2012](#); [Li et al., 2007](#); [Memarzadeh & Xu, 2012](#); [Pantelic & Tham, 2013](#); [Pica & Bouvier, 2012](#); [Qian & Zheng, 2018](#); [Robinson, Stilianakis, & Drossinos, 2012](#); [Seppanen & Fisk, 2004](#); [Stewart et al., 2020](#); [Wan & Chao, 2007](#); [Yu et al., 2004](#)), with some studies focussing on hospital settings ([Aliabadi, Rogak, Bartlett, & Green, 2011](#); [Beggs, Kerr, Noakes, Hathway, & Sleigh, 2008](#); [Bolashikov, Melikov, Kierat, Popiolek, & Brand, 2012](#); [Li, Huang, Yu, Wong, & Qian, 2004](#); [Morawska et al., 2009](#); [Memarzadeh & Jiang, 2004](#); [Mousavi & Grosskopf, 2015](#); [Olmedo, Nielsen, Adana, Jensen, & Grzelecki, 2012](#); [Shajahan, Culp, & Williamson, 2019](#); [Tang, Li, Eames, Chan, & Ridgway, 2006](#); [Wan, Chao, Ng, To, & Yu, 2007](#)), on office environments ([Bagheri et al., 2014](#); [Chen et al., 2014](#); [Mendell et al., 2015](#); [Myatt et al., 2004](#)), or on school environments ([Kumar, 2019](#); [National Academies of Sciences, Engineering and Medicine, 2020](#); [Ridenhou et al., 2011](#); [Wang et al., 2014](#); [Rubin, 2020](#); [Zhang, 2020](#)). While most studies of indoor airborne disease transmission have focused on hospital settings, the indication that COVID-19 can spread through aerosolized transmission suggests that further research is needed on airborne disease prevention in other indoor environments, such as retail spaces, offices, and schools.

## How can the COVID-19 safety of a school ventilation system be evaluated?

There are two primary ways to evaluate the effectiveness of a building’s ventilation system—either by direct visual inspection and physical testing, or by computer



simulation. When inspecting and testing a ventilation system's potential to transmit infectious disease, several factors should be considered. Of course, air changes per hour is a primary concern, but there are many others. ASHRAE (2020) recommends the following measures to minimize the transmission of COVID-19:

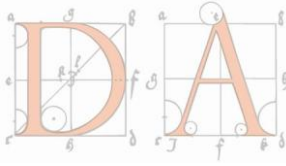
- *verify proper settings for indoor air temperature and relative humidity,*
- *verify proper separation of air intake and exhaust points,*
- *measure and balance building air pressures,*
- *evaluate potential for increased air changes per hour,*
- *verify positive pressure in all indoor spaces (relative to outdoors),*
- *verify airflow rates meet ASHRAE Standard 62.1,*
- *evaluate potential for MERV 13 (minimum) filtration,*
- *evaluate and adjust CO2 sensor levels as required.*

Such evaluations should be carried out by professionals with a background in mechanical systems and an understanding of infectious disease prevention.

Another means of understanding a building's ventilation system is by computer modeling. While building airflow can be modeled in various ways ([Ai, Huang, & Melikov, 2019](#); [Li, Duan, Yu, & Wong, 2004](#); [Pantelic & Tham, 2012](#); [To et al., 2008](#); [Zemouri et al., 2020](#)), a tool that is particularly well suited to this task is computer simulation software known as Computational Fluid Dynamics (CFD) ([Aliabadi, Faghani, Tjong, & Green, 2014](#); [Aliabadi, Green, Rogak, & Bartlett, 2010](#); [Bandhakavi, 2004](#); [Bustamante et al., 2013](#); [Cunha et al., 2019](#); [Deevy, Sinai, Everitt, Voigt, & Gobeau, 2008](#); [Gao & Niu, 2006](#); [Ivanov & Mijorski, 2017](#); [He et al., 2011](#); [Jiang et al., 2009](#); [King, Noakes, & Sleigh, 2015](#); [Lomax, Pulliam, & Zingg, 2001](#); [Pichurov, Stankov, & Markov, 2006](#); [Shen, Gao, & Wang, 2013](#); [Sekhar & Olesen, 2012](#); [Song & Li, 2010](#); [Tian, Tu, & Yeoh, 2007](#); [Tu, Yeoh, & Liu, 2018](#); [Villafruela, Olmedo, Adana, Méndez, & Nielsen, 2013](#); [Yam, Yuen, Yung, & Choy, 2020](#)). There are several makers of such software, including PALM, OpenFOAM, ExaFLOW, FDS, Fluent, and SimScale ([Fireman, 2016](#)). CFD simulations can be validated using experimental data ([Tu, Yeoh, & Liu, 2018](#)) such as smoke tracing ([Gao & Niu, 2006](#)) or CO2 tracing ([Chung & Hsu, 2001](#)). Recently, [Vuorinen et al. \(2020\)](#) used CFD simulation to model airborne transmission of the SARS-CoV-2 virus. While potentially able to provide better information about the airflow in a building space, CFD modeling may be time and cost prohibitive relative to a more basic building ventilation evaluation.

## Recommendations

While airborne transmission of SARS-CoV-2 is generally less of a hazard than direct transmission (by coughing or touching) or fomite (surface) transmission, it does present some level of risk. Although children are less likely to catch and spread COVID-19, they are able to do both to some degree. And, of course, every school has adults, who may transmit aerosolized SARS-CoV-2 even if they are asymptomatic. Therefore, health and school officials should consider evaluating whether the ventilation systems of schools under their jurisdictions are optimized to resist transmittance of aerosolized viruses such as the one that causes COVID-19.

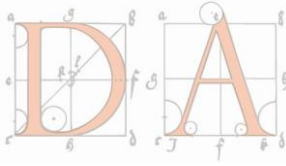


© Eric Douglas, 2020

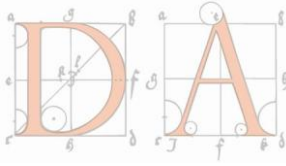
## References

- Abtahi-naeini, B., & Saffaei, A. (2020). COVID-19 and elective cosmetic procedures: Asymptomatic transmission in epidemic area and subsequent burdens. *Journal of Cosmetic Dermatology*, 19(May), 1838–1839. <http://doi.org/10.1111/jocd.13535>
- Ai, Z. T., Huang, T., & Melikov, A. K. (2019). Airborne transmission of exhaled droplet nuclei between occupants in a room with horizontal air distribution. *Building and Environment*, 163. <http://doi.org/10.1016/j.buildenv.2019.106328>
- Aliabadi, A. A., Faghani, E., Tjong, H. A. R., & Green, S. I. (2014). Hybrid Ventilation Design for a dining hall using computational fluid dynamics (CFD). In *Proceedings of The Canadian Society for Mechanical Engineering International Congress 2014 CSME*. <http://doi.org/10.13140/2.1.3784.1608>
- Aliabadi, A. A., Green, S., Rogak, S., & Bartlett, K. H. (2010). CFD Simulation of Human Coughs and Sneezes: A Study in Droplet Dispersion, Heat, and Mass Transfer. In *Proceedings of ASME International Mechanical Engineering Congress & Exposition*. <http://doi.org/10.1115/IMECE2010-37331>
- Aliabadi, A. A., Rogak, S. N., Bartlett, K. H., & Green, S. I. (2011). Preventing Airborne Disease Transmission: Review of Methods for Ventilation Design in Health Care Facilities. *Advances in Preventive Medicine*. <http://doi.org/10.4061/2011/124064>
- Allen, J. G., & Marr, L. C. (2020). Recognizing and controlling airborne transmission of SARS-CoV-2 in indoor environments. *Indoor Air*, 30, 557–558. <http://doi.org/10.1111/ina.12697>
- Anderson, E. L., Turnham, P., Griffin, J. R., & Clarke, C. C. (2020). Consideration of the Aerosol Transmission for COVID-19 and Public Health. *Risk Analysis*, 40(5). <http://doi.org/10.1111/risa.13500>
- ASHRAE. (2020). *ASHRAE Epidemic Task Force - Schools & Universities*.
- Bagheriadi, M., Trevan, P., Globan, M., Tay, E., Stephens, N., & Athan, E. (2014). Transmission of tuberculosis infection in a commercial office. *The Medical Journal of Australia*, 200(3), 177–179. <http://doi.org/10.5694/mja12.11750>
- Bandhakavi, B. R. (2004). *Application of computational fluid dynamics for high energy efficiency design with human comfort of CAD - VAV and UFAD systems*. Acharya Nagarjuna University, Guntur, India.
- Beggs, C. B., Kerr, K. G., Noakes, C. J., Hathway, E. A., & Sleigh, P. A. (2008). The ventilation of multiple-bed hospital wards: Review and analysis. *American Journal of Infection Control*, 250–259. <http://doi.org/10.1016/j.ajic.2007.07.012>
- Bolashikov, Z. D., Melikov, A. K., Kierat, W., Popiolek, Z., & Brand, M. (2012). Exposure of health care workers and occupants to coughed airborne pathogens in a double-bed hospital patient room with overhead mixing ventilation Exposure of health care workers and occupants to coughed airborne pathogens in a double-bed hospital patient. *HVAC&R Research*, 602–615. <http://doi.org/10.1080/10789669.2012.682692>
- British Columbia. (2020). *Provincial COVID-19 Health & Safety Guidelines for K-12 Settings*.
- British Columbia Ministry of Health. (2020). *COVID-19 Public Health Guidance for K-12 School Settings*.
- Bustamante, E., Garcia-Diego, F.-J., Calvet, S., Estellés, F., Beltrán, P., Hospitaler, A., & Torres, A. G. (2013). Exploring Ventilation Efficiency in Poultry Buildings: The Validation of Computational Fluid Dynamics (CFD) in a Cross-Mechanically Ventilated Broiler Farm. *Energies*, 6, 2605–2623. <http://doi.org/10.3390/en6052605>
- Chen, C., Zhu, J., Qu, Z., Lin, C., Jiang, Z., & Chen, Q. (2014). Systematic study of person-to-person contaminant transport in mechanically ventilated spaces (RP-1458). *HVAC&R Research*, 20, 80–91. <http://doi.org/10.1080/10789669.2013.834778>
- Christopherson, D. A., Yao, W. C., Lu, M., Vijayakumar, R., & Sedaghat, A. R. (2020). High-Efficiency Particulate Air Filters in the Era of COVID-19: Function and Efficacy. *American Academy of Otolaryngology-Head and Neck Surgery*, 1–3. <http://doi.org/10.1177/0194599820941838>

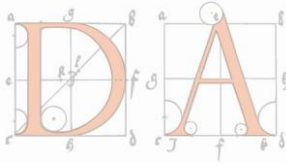




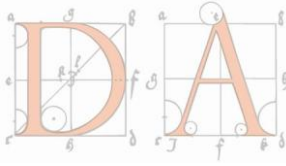
- Chung, K., & Hsu, S. (2001). Effect of ventilation pattern on room air and contaminant distribution. *Building and Environment*, 36, 989–998.
- Correia, G., Rodrigues, L., Gameiro, M., & Gonçalves, T. (2020). Airborne route and bad use of ventilation systems as non-negligible factors in SARS-CoV-2 transmission. *Medical Hypotheses*, 141. <http://doi.org/10.1016/j.mehy.2020.109781>
- Cunha, G. C. D. A., Neto, J. P. L., Furtado, D. A., Borges, V. P., Freire, E. A., & Nascimento, J. W. B. (2019). Diagnosis and validation by computational fluid dynamics of poultry house with negative pressure ventilation. *Revista Brasileira de Engenharia Agrícola E Ambiental*, 23(10), 761–767.
- Davies, N. G., Klepac, P., Liu, Y., Prem, K., Jit, M., & Eggo, R. M. (2020). Age-dependent effects in the transmission and control of COVID-19 epidemics. *Nature Medicine*, 26. <http://doi.org/10.1038/s41591-020-0962-9>
- de Niet, A., Waanders, B. L., & Walraven, I. (2020). The role of children in the transmission of mild SARS-CoV-2 infection. *ACTA Paediatrica*, 109, 1687. <http://doi.org/10.1111/apa.15310>
- de Souza, T. H., Nadal, J. A., Nogueira, R. J. N., Pereira, R. M., & Brandão, M. B. (2020). Clinical manifestations of children with COVID-19: A systematic review. *Pediatric Pulmonology*, 55, 1892–1899. <http://doi.org/10.1002/ppul.24885>
- Deevy, M., Sinai, Y., Everitt, P., Voigt, L., & Gobeau, N. (2008). Modelling the effect of an occupant on displacement ventilation with computational fluid dynamics. *Energy and Buildings*, 40, 255–264. <http://doi.org/10.1016/j.enbuild.2007.02.021>
- Du, C.-R., Wang, S.-C., Yu, M.-C., Chiu, T.-F., Wang, J.-Y., Chuang, P.-C., ... Fang, C.-T. (2020). Effect of ventilation improvement during a tuberculosis outbreak in underventilated university buildings. *Indoor Air*, 30, 422–432. <http://doi.org/10.1111/ina.12639>
- Escosa-García, L., Aguilera-Alonso, D., Calvo, C., Mellado, M. J., & Baquero-Artigao, F. (2020). Ten key points about COVID-19 in children: The shadows on the wall. *Pediatric Pulmonology*, 1–11. <http://doi.org/10.1002/ppul.25025>
- Fireman, J. (2016). *Improve Energy Efficiency, Thermal Comfort, and Performance of HVAC Systems with CFD in the Cloud*.
- Gameiro da Silva, M. (2020). *An analysis of the transmission modes of COVID-19 in light of the concepts of door Air Quality*.
- Gao, N., & Niu, J. (2006). Transient CFD simulation of the respiration process and inter-person exposure assessment. *Building and Environment*, 41, 1214–1222. <http://doi.org/10.1016/j.buildenv.2005.05.014>
- Goyal, A., Reeves, D. B., Cardozo-ojeda, E. F., Schiffer, J. T., & Mayer, B. T. (2020). *Wrong person, place and time: viral load and contact network structure predict SARS-CoV-2 transmission and super-spreading events*.
- Hagmann, S. H. F. (2020). COVID-19 in children: More than meets the eye. *Travel Medicine and Infectious Disease*, 34. <http://doi.org/10.1016/j.tmaid.2020.101649>
- He, J., Yifei, G., Mao, R., & Zhang, J. (2020). Proportion of asymptomatic coronavirus disease 2019: A systematic review and meta-analysis. *Journal of Medical Virology*, (July), 1–11. <http://doi.org/10.1002/jmv.26326>
- He, Q., Niu, J., Gao, N., Zhu, T., & Wu, J. (2011). CFD study of exhaled droplet transmission between occupants under different ventilation strategies in a typical office room. *Building and Environment*, 46, 397–408. <http://doi.org/10.1016/j.buildenv.2010.08.003>
- Hobday, R. A., & Dancer, S. J. (2013). Roles of sunlight and natural ventilation for controlling infection: historical and current perspectives. *Journal of Hospital Infection*, 84.
- Huff, H. V., & Singh, A. (2020). Asymptomatic Transmission During the Coronavirus Disease 2019 Pandemic and Implications for Public Health Strategies. *Clinical Infectious Diseases*, 1–5. <http://doi.org/10.1093/cid/ciaa654>
- Ivanov, M., & Mijorski, S. (2017). CFD modelling of flow interaction in the breathing zone of a virtual thermal manikin. *Energy Procedia*, 112, 240–251.
- Jiang, Y., Zhao, B., Li, X., Yang, X., Zhang, Z., & Zhang, Y. (2009). Investigating a safe ventilation rate for the prevention of indoor SARS transmission: An attempt based on a simulation approach. *Building*



- Simulation*, 2, 281–289. <http://doi.org/10.1007/s12273-009-9325-7>
- Kallem, V. R., & Sharma, D. (2020). COVID 19 in neonates. *The Journal of Maternal-Fetal & Neonatal Medicine*, 1–9. <http://doi.org/10.1080/14767058.2020.1759542>
- Kemmel, S. W., Jones, E., Kline, J., Northcutt, D., Stenson, J., Womack, A. M., ... Green, J. L. (2012). Architectural design influences the diversity and structure of the built environment microbiome. *The ISME Journal*, 6, 1469–1479. <http://doi.org/10.1038/ismej.2011.211>
- Kevat, A. (2020). Children may be less affected than adults by novel coronavirus (COVID-19). *Journal of Paediatrics and Child Health*, 56, 657. <http://doi.org/10.1111/jpc.14876>
- King, M.-F., Noakes, C. J., & Sleight, P. A. (2015). Modeling environmental contamination in hospital single- and four-bed rooms. *Indoor Air*, 25, 694–707. <http://doi.org/10.1111/ina.12186>
- Kumar, S. (2019). *A Simulation Framework to Characterize the Effect of Ventilation Control on Airborne Infectious Disease Transmission in Schools*. University of Texas at Austin.
- Lango, M. N. (2020). How did we get here? Short history of COVID-19 and other coronavirus-related epidemics. *Head & Neck*, 42, 1535–1538. <http://doi.org/10.1002/hed.26275>
- Lednicky, J. A., Lauzardo, M., Fan, Z. H., Jutla, A., Tilly, T. B., Gangwar, M., ... Wu, C.-Y. (2020). *Viable SARS-CoV-2 in the air of a hospital room with COVID-19 patients*.
- Lednicky, J. A., Shankar, S. N., Elbadry, M. A., Gibson, J. C., Alam, M., Stephenson, C. J., ... Wu, C. (2020). Collection of SARS-CoV-2 Virus from the Air of a Clinic within a University Student Health Care Center and Analyses of the Viral Genomic Sequence. *Aerosol and Air Quality Research*, 20, 1167–1171.
- Lewis, D. (2020). Is the coronavirus airborne? Experts can't agree. *Nature*, 580, 175.
- Li, X., Xu, W., Dozier, M., He, Y., Kirolos, A., & Theodoratou, E. (2020). The role of children in transmission of SARS-CoV-2: A rapid review. *Journal of Global Health*, 10(1), 1–10. <http://doi.org/10.7189/jogh.10.011101>
- Li, Y., Duan, S., Yu, I. T. S., & Wong, T. W. (2004). Multi-zone modeling of probable SARS virus transmission by airflow between flats in Block E , Amoy Gardens. *Indoor Air*, 15, 96–111. <http://doi.org/10.1111/j.1600-0668.2004.00318.x>
- Li, Y., Huang, X., Yu, I. T. S., Wong, T. W., & Qian, H. (2004). Role of air distribution in SARS transmission during the largest nosocomial outbreak in Hong Kong. *Indoor Air*, 15, 83–95. <http://doi.org/10.1111/j.1600-0668.2004.00317.x>
- Li, Y., Leung, G. M., Tang, J. W., Yang, X., Chao, C. Y. H., Lin, J. Z., ... Yuen, P. L. (2007). Review Article Role of ventilation in airborne transmission of infectious agents in the built environment – a multidisciplinary systematic review. *Indoor Air*, 17(March 2006), 2–18. <http://doi.org/10.1111/j.1600-0668.2006.00445.x>
- Lomax, H., Pulliam, T. H., & Zingg, D. W. (2001). *Fundamentals of Computational Fluid Dynamics*. Berlin: Springer-Verlag.
- Lu, J., Gu, J., Li, K., Xu, C., Su, W., Lai, Z., ... Yang, Z. (2020). COVID-19 Outbreak Associated with Air Conditioning in Restaurant, Guangzhou, China, 2020. *Emerging Infectious Diseases*, 26(7), 1628–1631.
- Lu, S., Lin, J., Zhang, Z., Xiao, L., Jiang, Z., Chen, J., ... Luo, S. (2020). *Alert for non-respiratory symptoms of Coronavirus Disease 2019 (COVID-19) patients in epidemic period: A case report of familial cluster with three asymptomatic COVID-19 patients*.
- Ludvigsson, J. F. (2020). Children are unlikely to be the main drivers of the COVID-19 pandemic – A systematic review. *ACTA Paediatrica*, 1525–1530. <http://doi.org/10.1111/apa.15371>
- Luo, L., Liu, D., Liao, X., Wu, X., Jing, Q., Zheng, J., ... Cai, M. (2020). Contact Settings and Risk for Transmission in 3410 Close Contacts of Patients With COVID-19 in Guangzhou, China. <http://doi.org/10.7326/M20-2671>
- Mallineni, S. K., Innes, N. P., Raggio, D. P., Araujo, M. P., Robertson, M. D., & Jayaraman, J. (2020). Coronavirus disease (COVID-19): Characteristics in children and considerations for dentists providing their care. *International Journal of Paediatric Dentistry*, 30, 245–250. <http://doi.org/10.1111/ipd.12653>
- Memarzadeh, F., & Jiang, Z. (2004). Effect of Operation Room Geometry and Ventilation System

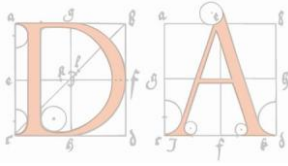


- Parameter Variations on the Protection of the Surgical Site. *ASHRAE Transactions*.
- Memarzadeh, F., & Xu, W. (2012). Role of air changes per hour (ACH) in possible transmission of airborne infections. *Building Simulation*, 5(1), 15–28. <http://doi.org/10.1007/s12273-011-0053-4>
- Mendell, M. J., Eliseeva, E. A., Spears, M., Chan, W. R., Cohn, S., Sullivan, D. P., & Fisk, W. J. (2015). A longitudinal study of ventilation rates in California office buildings and self-reported occupant outcomes including respiratory illness absence. *Building and Environment*, 92, 292–304. <http://doi.org/10.1016/j.buildenv.2015.05.002>
- Morawska, L., & Cao, J. (2020). Airborne transmission of SARS-CoV-2: The world should face the reality. *Environment International*, 139(April). <http://doi.org/10.1016/j.envint.2020.105730>
- Morawska, L., Johnson, G. R., Ristovski, Z. D., Hargreaves, M., Mengersen, K., Corbett, S., ... Katoshevski, D. (2009). Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities. *Aerosol Science*, 40, 256–269. <http://doi.org/10.1016/j.jaerosci.2008.11.002>
- Morawska, L., Tangb, J. W., Bahnfleth, W., Bluysend, P. M., Boerstra, A., Buonanno, G., ... Yao, M. (2020). How can airborne transmission of COVID-19 indoors be minimised? *Environment International*, 142. <http://doi.org/10.1016/j.envint.2020.105832>
- Mousavi, E. S., & Grosskopf, K. R. (2015). Ventilation Rates and Airflow Pathways in Patient Rooms: A Case Study of Bioaerosol Containment and Removal. *Annals of Occupational Hygiene*, 59(9), 1190–1199. <http://doi.org/10.1093/annhyg/mev048>
- Munro, A. P. S., & Faust, S. N. (2020). Children are not COVID-19 super spreaders: time to go back to school. *Archives of Disease in Childhood*, 105(7), 618–619. <http://doi.org/10.1101/2>
- Myatt, T. A., Johnston, S. L., Zuo, Z., Wand, M., Keadze, T., Rudnick, S., & Milton, D. K. (2004). Detection of Airborne Rhinovirus and Its Relation to Outdoor Air Supply in Office Environments. *American Journal of Respiratory and Critical Care Medicine*, 169. <http://doi.org/10.1164/rccm.200306-760OC>
- National Academies of Sciences, Engineering and Medicine. (2020). *Reopening K-12 Schools During the COVID-19 Pandemic: Prioritizing Health, Equity, and Communities*. National Academies Press.
- Nwanaji-enwerem, J. C., Allen, J. G., & Beamer, P. I. (2020). Another invisible enemy indoors: COVID-19, human health, the home, and United States indoor air policy. *Journal of Exposure Science & Environmental Epidemiology*, 10–12. <http://doi.org/10.1038/s41370-020-0247-x>
- Olmedo, I., Nielsen, P. V., Adana, M. R. de, Jensen, R. L., & Grzelecki, P. (2012). Distribution of exhaled contaminants and personal exposure in a room using three different air distribution strategies. *Indoor Air*, 22, 64–76. <http://doi.org/10.1111/j.1600-0668.2011.00736.x>
- Pantelic, J., & Tham, K. W. (2012). Assessment of the mixing air delivery system ability to protect occupants from the airborne infectious disease transmission using Wells – Riley approach. *HVAC&R Research*, 18(4), 562–574. <http://doi.org/10.1080/10789669.2012.647230>
- Pantelic, J., & Tham, K. W. (2013). Adequacy of air change rate as the sole indicator of an air distribution system's effectiveness to mitigate airborne infectious disease transmission caused by a cough release in the room with overhead mixing ventilation: A case study. *HVAC&R Research*, 19, 947–961. <http://doi.org/10.1080/10789669.2013.842447>
- Peng, J., Su, D., Zhang, Z., & Wang, M. (2020). Identification and management of asymptomatic carriers of coronavirus disease 2019 (COVID-19) in China. *Influenza and Other Respiratory Viruses*, 14, 599–600. <http://doi.org/10.1111/irv.12768>
- Pica, N., & Bouvier, N. M. (2012). Environmental factors affecting the transmission of respiratory viruses. *Current Opinion in Virology*, 2(1), 90–95. <http://doi.org/10.1016/j.coviro.2011.12.003>
- Pichurov, G., Stankov, P., & Markov, D. (2006). HVAC control based on CFD analysis of room airflow. In *Energy saving control in plants and buildings* (Vol. 39, pp. 213–218). IFAC. <http://doi.org/10.3182/20061002-4-BG-4905.00036>
- Qian, H., & Zheng, X. (2018). Ventilation control for airborne transmission of human exhaled bio-aerosols in buildings. *Journal of Thoracic Disease*, 10(Suppl 19), 2295–2304. <http://doi.org/10.21037/jtd.2018.01.24>
- Ranabothu, S., Onteddu, S., Nalleballe, K., Dandu, V., Veerapaneni, K., & Veerapandiyani, A. (2020).



- Spectrum of COVID-19 in children. *ACTA Paediatrica*, 109, 1899–1900.  
<http://doi.org/10.1111/apa.15412>
- REHVA. (2020). *How to operate and use building services in order to prevent the spread of the coronavirus disease (COVID-19) virus (SARS-CoV-2) in workplaces.*
- Ridenhour, B. J., Braun, A., Teyrasse, T., & Goldsman, D. (2011). Controlling the Spread of Disease in Schools. *PLOS ONE*, 6(12), 1–7. <http://doi.org/10.1371/journal.pone.0029640>
- Robinson, M., Stilianakis, N. I., & Drossinos, Y. (2012). Spatial dynamics of airborne infectious diseases. *Journal of Theoretical Biology*, 297, 116–126. <http://doi.org/10.1016/j.jtbi.2011.12.015>
- Rubin, R. (2020). School Superintendents Confront COVID-19—“There Are No Good Options for Next Year.” *Journal of the American Medical Association*, 324(6), 534–536.
- Ruggiero, A., Sanguinetti, M., Gatto, A., Attinà, G., & Chiaretti, A. (2020). Diagnosis of COVID-19 infection in children: Less nasopharyngeal swabs, more saliva. *ACTA Paediatrica*, 109, 1913–1914. <http://doi.org/10.1111/apa.15397>
- Sekhar, C., & Olesen, B. (2012). ASHRAE IAQ 2010: Airborne Infection Control — Ventilation, IAQ & Energy. *HVAC&R Research*, 18(4), 549–551. <http://doi.org/10.1080/10789669.2012.700601>
- Seppanen, O. A., & Fisk, W. J. (2004). Summary of human responses to ventilation. *Indoor Air*, 14, 102–118.
- Shajahan, A., Culp, C. H., & Williamson, B. (2019). Effects of indoor environmental parameters related to building heating, ventilation, and air conditioning systems on patients' medical outcomes: A review of scientific research on hospital buildings. *Indoor Air*, 29, 161–176. <http://doi.org/10.1111/ina.12531>
- She, J., Liu, L., & Liu, W. (2020). COVID-19 epidemic: Disease characteristics in children. *Journal of Medical Virology*, 92, 747–754. <http://doi.org/10.1002/jmv.25807>
- Shen, C., Gao, N., & Wang, T. (2013). CFD study on the transmission of indoor pollutants under personalized ventilation. *Building and Environment*, 63, 69–78. <http://doi.org/10.1016/j.buildenv.2013.02.003>
- Shen, Y., Li, C., Dong, H., Wang, Z., Martinez, L., Sun, Z., ... Xu, G. (2020). Community Outbreak Investigation of SARS-CoV-2 Transmission Among Bus Riders in Eastern China. *JAMA Internal Medicine*, 1–7. <http://doi.org/10.1001/jamainternmed.2020.5225>
- Somsen, G. A., Rijn, C. Van, Kooij, S., Bem, R. A., & Bonn, D. (2020). Small droplet aerosols in poorly ventilated spaces and SARS-CoV-2 transmission. *The Lancet*, 8, 658–659. [http://doi.org/10.1016/S2213-2600\(20\)30245-9](http://doi.org/10.1016/S2213-2600(20)30245-9)
- Song, J., & Li, X. (2010). The Application of Computational Fluid Dynamics (CFD) in HVAC Education. In *2010 International Conference on Life System Modeling and Simulation & International Conference on Intelligent Computing for Sustainable Energy and Environment* (pp. 238–239).
- Stewart, E. J., Mead, K., Olmsted, R. N., Pantelic, J., Schoen, L. J., Sekhar, C., ... Conlan, W. (2020). *ASHRAE Position Document on Infectious Aerosols.*
- Tang, J. W., Li, Y., Eames, I., Chan, P. K. S., & Ridgway, G. L. (2006). Factors involved in the aerosol transmission of infection and control of ventilation in healthcare premises. *Journal of Hospital Infection*, 64, 100–114. <http://doi.org/10.1016/j.jhin.2006.05.022>
- Tian, Z. F., Tu, J. Y., & Yeoh, G. H. (2007). CFD Studies of Indoor Airflow and Contaminant Particle Transportation. *Particulate Science and Technology*. <http://doi.org/10.1080/02726350701492728>
- To, G. S., Wan, M. P., Chao, C. Y. H., Wei, F., Yu, S. C. T., & Kwan, J. K. C. (2008). A methodology for estimating airborne virus exposures in indoor environments using the spatial distribution of expiratory aerosols and virus viability characteristics. *Indoor Air*, 18, 425–438. <http://doi.org/10.1111/j.1600-0668.2008.00544.x>
- Tu, J., Yeoh, G.-H., & Liu, C. (2018). *Computational Fluid Dynamics - A Practical Approach*. Oxford: Butterworth-Heinemann. <http://doi.org/10.1016/B978-0-08-101127-0.09982-7>
- Vancouver School Board. (2020). *COVID-19 Safety Plan, Safe Work Instruction, and Protocols.*
- Villafruela, J. M., Olmedo, I., Adana, M. R. De, Méndez, C., & Nielsen, P. V. (2013). CFD analysis of the human exhalation flow using different boundary conditions and ventilation strategies. *Building and Environment*, 62, 191–200. <http://doi.org/10.1016/j.buildenv.2013.01.022>
- Vuorinen, V., Aarnio, M., Alava, M., Alopaeus, V., Atanasova, N., Auvinen, M., ... Österberg, M. (2020).





## Douglas Architecture

Eric Douglas, Architect AIBC

eric@douglasarchitecture.ca

douglasarchitecture.ca

604-283-7560

- Modelling aerosol transport and virus exposure with numerical simulations in relation to SARS-CoV-2 transmission by inhalation indoors. *Safety Science*, 130. <http://doi.org/10.1016/j.ssci.2020.104866>
- Wan, M. P., & Chao, C. Y. H. (2007). Transport Characteristics of Expiratory Droplets and Droplet Nuclei in Indoor Environments With Different Ventilation Airflow Patterns. *Journal of Biomechanical Engineering*, 129(June), 341–353. <http://doi.org/10.1115/1.2720911>
- Wan, M. P., Chao, C. Y. H., Ng, Y. D., To, G. N. S., & Yu, W. C. (2007). Dispersion of Expiratory Droplets in a General Hospital Ward with Ceiling Mixing Type Mechanical Ventilation System. *Aerosol Science and Technology*. <http://doi.org/10.1080/02786820601146985>
- Wang, L., Chu, C., Yang, G., Hao, R., Li, Z., Cao, Z., ... Song, H. (2014). Transmission Characteristics of Different Students during a School Outbreak of (H1N1) pdm09 Influenza in China, 2009. *Nature*, 4, 1–8. <http://doi.org/10.1038/srep05982>
- Yam, R., Yuen, P. L., Yung, R., & Choy, T. (2020). Rethinking hospital general ward ventilation design using computational fluid dynamics. *Journal of Hospital Infection*, 77(1), 31–36. <http://doi.org/10.1016/j.jhin.2010.08.010>
- Yang, X., & Chen, F. (2020). Letter to the Editor: “Asymptomatic Carrier Transmission of Coronavirus Disease 2019 (COVID-19) and Multipoint Aerosol Sampling to Assess Risks in the Operating Room During a Pandemic.” *World Neurosurgery*. <http://doi.org/10.1016/j.wneu.2020.07.144>
- Yasuhara, J., Kuno, T., Takagi, H., & Sumitomo, N. (2020). Clinical characteristics of COVID-19 in children: A systematic review. *Pediatric Pulmonology*, 1–11. <http://doi.org/10.1002/ppul.24991>
- Yavuz, S., Kesici, S., & Bayrakci, B. (2020). Physiological advantages of children against COVID-19. *ACTA Paediatrica*, 109, 1691. <http://doi.org/10.1111/apa.15410>
- Yu, I. T. S., Li, Y., Wong, T. W., Tam, W., Chan, A. T., Lee, J. H. W., ... Ho, T. (2004). Evidence of Airborne Transmission of the Severe Acute Respiratory Syndrome Virus. *The New England Journal of Medicine*, 1731–1739.
- Yu, X., & Yang, R. (2020). COVID-19 transmission through asymptomatic carriers is a challenge to containment. *Influenza and Other Respiratory Viruses*, 14, 474–475. <http://doi.org/10.1111/irv.12743>
- Zemouri, C., Awad, S. F., Volgenant, C. M. C., Crielaard, W., Laheij, A. M. G. A., & de Soet, J. J. (2020). Modeling of the Transmission of Coronaviruses, Measles Virus, Influenza Virus, Mycobacterium tuberculosis, and Legionella pneumophila in Dental Clinics. *Journal of Dental Research*. <http://doi.org/10.1177/0022034520940288>
- Zhang, J. J. (2020). Integrating IAQ control strategies to reduce the risk of asymptomatic SARS CoV-2 infections in classrooms and open plan offices. *Science and Technology for the Built Environment*, 26, 1013–1018. <http://doi.org/10.1080/23744731.2020.1794499>