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Retaining a healthy indoor environment in on-demand mixed-mode classrooms

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ABSTRACT

A global pandemic has increased focus on indoor air quality and fresh air exchange in mixed-mode buildings where the transition between modes often requires human intervention. A study to measure energy performance and CO_2 concentrations was conducted in two Hawai'i classrooms to determine the impact of user decision-making on adequacy of fresh air. Using CO_2 as a marker for indoor air quality and fresh air exchange, significantly different CO_2 concentrations were observed in the two identical classrooms. This study complements the findings by others who showed classroom ventilation was frequently inadequate, but illuminates the importance of user familiarity with building operation in order to maintain a healthy indoor environment. In the Hawai'i mixed-mode classrooms, ventilation and CO_2 levels were dependent upon: user awareness of how fresh air was introduced; user training; availability of operable windows; and outside fresh air supply from the air-conditioning unit.

1. Introduction

Climate change, population growth, building efficiency and indoor air quality are conflicting drivers in the effort to meet aggressive carbon emission goals being imposed by several U.S. states and European countries (Darby, 2019). Global air-conditioning energy use more than doubled from 2000 to 2016, and at this rate is estimated to triple by 2050, mostly driven by population and economic growth in the hottest parts of the world (IEA, 2018). The potential impacts of climate change on building performance include: energy use; emissions; and system failures by operating in conditions outside of their design specifications (de Wilde and Coley, 2012). Moreover, research shows that future generations will likely own more appliances including air-conditioners due to economic growth in developing countries (Wolfram et al., 2012). Thus, buildings built today need to be designed to work successfully in both the current and future warmer climates (de Wilde and Coley, 2012). A building design response to these challenges is a mixed-mode building: a hybrid energy design that is either naturally ventilated or mechanically heated/cooled as conditions demand, minimizes the operating hours of air-conditioning, and maximizes energy efficiency.

Air-conditioned classrooms, including mixed-mode, and retrofits in particular, often do not meet ventilation requirements through heating, ventilation and air-conditioning (HVAC) operation alone (Chan et al., 2020) when using the types of HVAC units often found in classrooms. Mini-split air-conditioning units do not provide outside fresh air while window air-conditioning units can commonly provide inadequate ventilation (SMACNA, 2019). High levels of CO_2 resulting from insufficient ventilation rates can lead to lethargy and lower productivity when the concentration exceeds the acceptable threshold (Allen et al., 2016). Inadequate air exchange may also result in a subsequent buildup of indoor pollutants including carbon monoxide, volatile organic compounds, biological and other contaminants (USEPA, 2019; Deuble and de Dear, 2012). The ability to improve ventilation is becoming more acute and desirable in the current viral pandemic situation (Morawska and Cao, 2020; Correia et al., 2020).

Mixed-mode buildings rely on operable windows, skylights, clerestories and other apertures to create natural ventilation opportunities. Apertures may be manually operated by occupants or automatically controlled by sensors, controls and actuators. An unintended consequence of manually controlled mixed-mode classrooms can be poor fresh air exchange due to lack of awareness or training of the user. During mild weather, interior conditions may not demand that windows be opened in order to maintain thermal comfort and thus the user may not be cued to open the windows or turn on the HVAC to provide ventilation. As such,

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while the windows are closed and the HVAC system remains off, CO_2 levels rise. While clearly problematic, these under-ventilated conditions are not necessarily obvious to the user as demonstrated by high CO_2 concentrations measured in this study and by others. Chan et al. (2020) evaluated 104 classrooms in California to confirm inadequate ventilation and determine the root causes. Fisk's comprehensive literature search found that "Based on a review of literature published in refereed archival journals, ventilation rates in classrooms often fall far short of the minimum ventilation rates specified in standards" (Fisk, 2017).

This study describes two mixed-mode classroom buildings in Honolulu, Hawai'i (USA), located in International Energy Conservation Code climate zone 1. University of Hawai'i at Manoa (UHM) researchers monitored the two classrooms to evaluate the energy savings of a unique and dedicated *on-demand HVAC* thermostat while monitoring CO_2 levels and other indoor variables.

2. Case study – UHM FROG buildings – investigation of CO_2 concentration

The two identical 134 m^2 (1440 ft^2) classroom buildings named the FROGs (Fig. 1) were constructed on the UHM campus in 2015–2016 to test building design and fabrication strategies, and research new technologies and energy control systems. These single-room classroom buildings were equipped with split-system air-conditioning units with an outside air supply. Monitoring and data collection systems were installed during construction to measure: temperature; humidity; light; CO_2; energy flows; and outdoor conditions. Two calendar years of outdoor temperature data showed the average monthly temperature ranged from 21.5 °C to 27.8 °C and average monthly humidity ranged from 65.3% to 75.5%. Hourly outdoor temperatures complied with the ASHRAE 55-2017 adaptive comfort standard for 80% satisfaction for 87% of hours of the year (only 2.5% of hours were too hot) which makes the buildings suitable for mixed-mode (ASHRAE, 2017). These buildings were not designed with automated window actuators or HVAC interlocks. Ceiling fans, with seven variable speeds, increase the air movement inside the buildings. Previous studies in the tropics showed that air movement increases the range of temperatures in which people feel comfortable (Mallick, 1996; Nicol, 2004; Zhai et al., 2015). The interior conditions of the FROGs were highly dependent upon the knowledge and preference of the user to choose between using natural ventilation or activating the on-demand air-conditioning unit.

In addition to serving as research platforms, the FROGs are used as individual classrooms for middle school students in the morning and university students in the afternoon and evening. They generally operate in change-over mode, when natural ventilation and HVAC operation are mutually exclusive. Because they are manually controlled they may be alternatively run in a concurrent mode, when HVAC and natural ventilation occur simultaneously. The mode is chosen by user preference.

The classrooms were monitored over three calendar years (two school years) to measure thermal comfort, CO_2 concentrations, and energy performance. The schedules of the classrooms are dynamic with user group and class size that vary broadly by hour and day: while the buildings are fully occupied during the mornings (8:00 a.m.–1:00 p.m.) by several groups of middle school students (45-min classes); during the 2-1/2 to 3-h afternoon and evening sessions the buildings are not at full capacity. This type of intermittent scheduling is not limited to educational buildings but can also reflect other types of end-uses with irregular occupancy such as offices, business incubators, or meeting rooms.

2.1. On-demand mechanical cooling and ventilation

Other researchers have found that the more engaged the users are in the operation of their space, the more adaptive and tolerant they are of higher and lower temperatures (Pigman et al., 2018; Brager et al., 2004). Both FROG classrooms are designed to actively engage users, while at the same time utilizing some degree of automated controls. In particular, the HVAC systems were outfitted with an on-demand thermostat control, a manually-activated control that allows the HVAC to run for 60 min. This requires user engagement and awareness to optimize comfort while reducing energy use by limiting the run-time during unoccupied periods. The on-demand control is estimated to save up to 84% energy per year compared to a system running on a fixed 7:00 a.m. and 7:00 p.m. schedule (Maskrey et al., 2018).

The two adjacent buildings experience the same outdoor conditions, have the same equipment, and on average have the same number of occupants with similar activities; however, the users operated the HVAC, lighting, ceiling fans and windows quite differently. During the first school year of investigation, the users of FROG 1 frequently engaged the HVAC upon arrival in the morning without opening windows while users of FROG 2 primarily relied on natural ventilation. When the FROG 1 users relied on HVAC only, the average hourly CO_2 concentration frequently exceeded the 1100 ppm acceptable maximum (ANSI/ASHRAE, 2013) and occasionally reached the sensor's upper range limit of 2000 ppm (Fig. 2). This was despite the HVAC systems passing the testing, adjusting and balancing commissioning tests. During a period when both HVAC systems were simultaneously down for repair and maintenance in October 2018, the users had to rely upon open windows and ceiling fans for thermal comfort and ventilation resulting in far lower CO_2 concentrations (Fig. 3).

3. Impact of occupant awareness, training and engagement

UHM researchers provided initial instructions to users with the intention of fostering an understanding of building operation and instill more energy-conscious behavior. To provide visual feedback, the buildings' performance was displayed on a wall-mounted dashboard in each classroom that graphically rendered the energy consumption, energy generation, CO_2, and environmental conditions in both buildings. Even with initial training, data showed that during the first calendar year of study (2017) many of the instructors ran the HVAC unit frequently and seldom opened windows.

After two years of data collection it became apparent that a more focused training was required in order to optimize building operation and maintain a healthy indoor environment. Trainings at the beginning

Fig. 1. FROGs 1 and 2 at the University of Hawai'i at Manoa. Photos by University of Hawai'i.

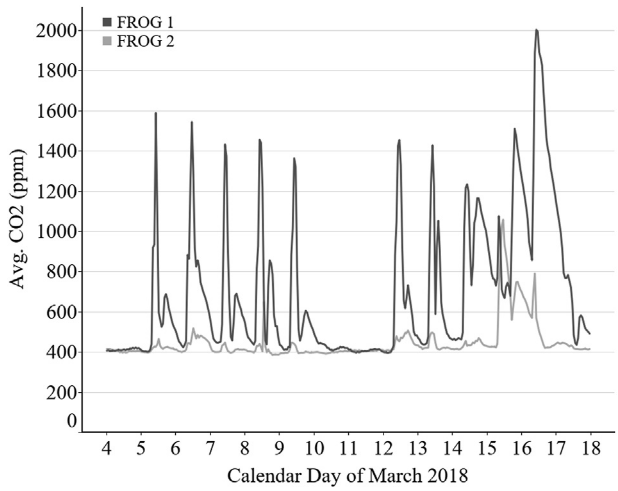

Fig. 2. Two weeks of hourly average CO_2 data in March 2018. FROG 1 HVAC on daily resulting in higher CO_2 concentrations. FROG 2, HVAC used only on one day (Mar. 16, 2018) resulting in lower overall CO_2 levels.

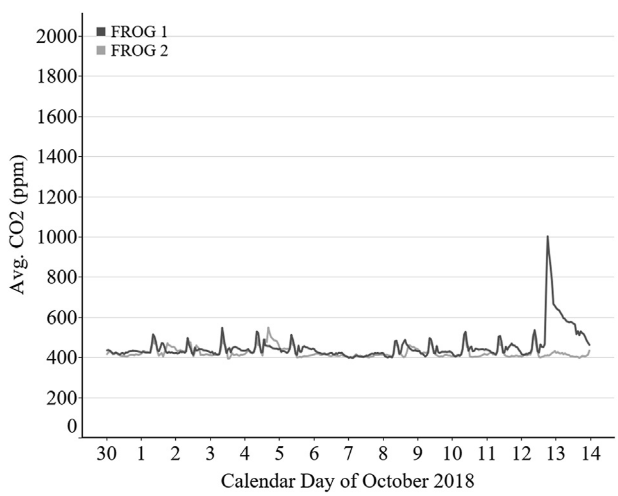

Fig. 3. Two weeks of hourly average CO_2 data in October 2018 when both HVAC units were under repair and not operational, which resulted in open windows and use of ceiling fans for comfort. The spike on Oct. 13, 2018 is likely due to windows not being opened.

of the third calendar year (January 2019) focused on ensuring that the instructors understood the importance of providing ventilation by opening windows when HVAC was not in use. Concurrent use of HVAC and natural ventilation was also suggested. The 2019 results showed that training and awareness on the CO_2 issue significantly impacted how occupants operated the buildings. Fig. 4 shows how the number of CO_2 readings exceeding 1000 ppm (up to the sensor limit of 2000 ppm) was reduced in 2019.

During the first two calendar years, the CO_2 levels occasionally spiked after the HVAC automatically turned off, suggesting that the occupants had not left the building or opened windows. The dashboard display was not effective in cuing the users to the increasing CO_2 levels. In the third calendar year, an LED CO_2 indicator light was installed in a conspicuous location in line of sight of the instructor as a visual cue. This multi-LED indicator displayed the current status of CO_2: green ($<$1000 ppm); yellow ($>$1000 ppm); and red ($>$1750 ppm). This provided instructors with additional information to determine if a manual intervention was necessary, such as opening windows. Through these human-driven interventions and manual control of the indoor space and ceiling fans they were able to maintain a healthy and comfortable learning environment.

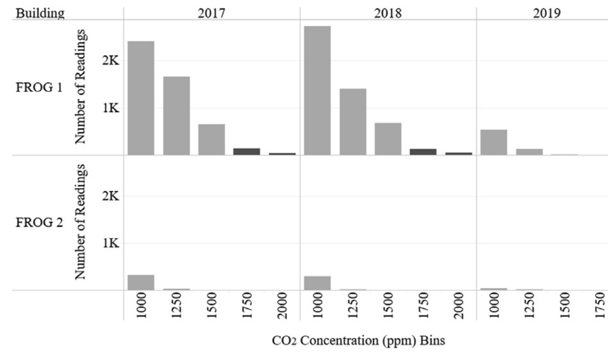

Fig. 4. Histogram of the number of 5-min CO_2 readings that exceeded 1000 ppm on weekdays between 7:00 a.m. and 8:00 p.m. for three calendar years of monitoring.

4. Conclusion

As a response to environmental and indoor public health challenges, mixed-mode buildings provide an opportunity for users in tropical, cooling-only climates to control their indoor environment at a lower energy cost. On one hand, mixed-mode allows users to choose to open windows to increase ventilation rates. Conversely, mixed-mode can provide a false sense of well-being when the user feels that the choice between natural ventilation and air-conditioning is a binary decision and that either one will provide adequate ventilation. In many cases, because air-conditioning may not provide adequate fresh air, CO_2 concentrations are likely to increase without the user recognizing it. Repeated training, and conspicuous visual cues such as LED CO_2 indicators assist the users in understanding the appropriate operating protocols for the building and the effect on decision-making. An energy saving, on-demand thermostat that automatically turns off the HVAC after 1 h might leave an untrained occupant without adequate ventilation if they did not re-activate the HVAC or open the windows. This on-demand timer/controller requires more training of users than a conventional thermostat. As a result of the potential weaknesses in classroom HVAC systems to provide adequate fresh air, as well as fallible human decision-making, automated systems activated by temperature, humidity and CO_2 sensors are a healthier solution to ensure mixed-mode classrooms remain healthy, vibrant learning environments in a tropical environment.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Allen, J.G., MacNaughton, P., Satish, U., Santanam, S., Vallarino, J., Spengler, J.D., 2016. Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: a controlled exposure study of green and conventional office environments. Environ. Health Perspect. 124 (6), 805–812. https://doi.org/10.1289/ehp.1510037.

ANSI/ASHRAE Standard 62.1-201, 2013. Ventilation for acceptable indoor air quality, Atlanta, GA. https://www.ashrae.org/technical-resources/bookstore/standards-62-1-62-2.

ASHRAE Standard 55, 2017. Thermal Environmental Conditions for Human Occupancy. Refrigerating and Air-Conditioning Engineers, Atlanta, GA, USA.

Brager, G.S., Paliaga, G., de Dear, R., 2004. Operable windows, personal control and occupant comfort. AHRAE Transactions 110 (2).

Chan, W.R., Li, X., Singer, B.C., Pistochini, T., Vernon, D., Outcault, S., Sanguinetti, A., Modera, M., 2020. Ventilation rates in California classrooms: why many recent HVAC retrofits are not delivering sufficient ventilation. Build. Environ. 167, 106426. https://doi.org/10.1016/j.buildenv.2019.106426.

Correia, G., Rodrigues, L., Gameiro da Silva, M., Gonçalves, T., 2020. Airborne route and bad use of ventilation systems as non-negligible factors in SARS-CoV-2 transmission. Med. Hypotheses 141, 109781. https://doi.org/10.1016/j.mehy.2020.109781.

Darby, M., 2019. Which countries have a net zero carbon goal? Clim. Home News. https://www.climatechangenews.com/2019/06/14/countries-net-zero-climate-goal/ Accessed on June 23.

de Wilde, P., Coley, D., 2012. The implications of a changing climate for buildings. Build. Environ. 55, 1–7. https://doi.org/10.1016/j.buildenv.2012.03.014.

Deuble, M.P., de Dear, R., 2012. Green occupants for green buildings: the missing link? Build. Environ. 5, 21–27. https://doi.org/10.1016/j.buildenv.2012.02.029.

Fisk, W.J., 2017. The ventilation problem in schools: literature review. Indoor Air 27, 1039–1051. https://doi.org/10.1111/ina.12403.

International Energy Agency, 2018. The future of cooling, Paris, France. Paris, France. https://www.iea.org/reports/the-future-of-cooling.

Mallick, F.H., 1996. Thermal comfort and building design in the tropical climates. En. Build. 23 (3), 161–167. https://doi.org/10.1016/0378-7788(95)00940-X.

Maskrey, A.J., Cerri, S., Peppard, E., 2018. Second generation ZNE: inheriting the good genes. In: Proceedings of the American Council for an Energy-Efficient Economy (ACEEE). Summer Study Conference, Pacific Grove, CA. , August 2018. http://www.aceee.org/files/proceedings/2018/index.html#/paper/event-data/p309.

Morawska, L., Cao, J., 2020. Airborne transmission of SARS-CoV-2: the world should face the reality. Env. Int. 139, 105730. https://doi.org/10.1016/j.envint.2020.105730.

Nicol, F., 2004. Adaptive thermal comfort standards in the hot-humid tropics. Build. Environ. 36 (7), 628–637. https://doi.org/10.1016/j.enbuild.2004.01.016.

Pigman, M., Brager, G.S., Zhang, H., 2018. Personal control: windows, fans, and occupant satisfaction. In: Proceedings of the Windsor Conference: Rethinking Comfort, pp. 210–226. In: http://www.nceub.org.uk/W2018/W18_PROCEEDINGS.pdf.

Sheet Metal and Air-Conditioning Contractors National Association, 2019. Mini-split systems in residential retrofit applications. https://www.smacna.org/docs/default-source/market-sector-residential/mini-split-systems-residential-retrofit-applications-2019.pdf?sfvrsn=b9ebcaa5_4.

U.S. Environmental Protection Agency, 2019. Indoor air quality. EPA Website. https://www.epa.gov/indoor-air-quality-iaq/introduction-indoor-air-quality. Accessed on June 23.

Wolfram, C., Shelef, O., Gertler, P., 2012. How will energy demand develop in the developing world? J. Econ. Perspect. 26, 119–138. https://doi.org/10.1257/jep.26.1.119.

Zhai, Y., Zhang, Y., Zhang, H., Pasut, W., Arens, E., Meng, Q., 2015. Human comfort and perceive air quality in warm and humid environments with ceiling fans. Build. Environ. 90, 175–185. https://doi.org/10.1016/j.buildenv.2015.04.003.