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Dynamic Insulation Systems to Control Airborne Transmission of Viruses in Classrooms: A Review of 'Airhouse' Concept

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ABSTRACT

The discovery of the Covid-19 virus in China at the end of 2019 has drastically altered the global landscape. The virus, which has now become a pandemic, has wrought devastation on the world, infecting over 500 million people and killing over 6 million. The virus's mutation into a few variations, however, has enabled the world's alarming situation to continue until now. Airborne particles and viruses including the new Covid-19 variant - Omricon, is not only extremely contagious but also can be transferred by airborne transmission, putting vulnerable people like children at risk, particularly in classrooms. Amongst the strategies to control airborne transmission of viruses and to improve indoor thermal and air quality is using ventilation strategies - such as dynamic insulation. Thus, this paper will review at how dynamic insulation systems in conventional farming and residential buildings, cleanrooms and other controlled environments work to reduce airborne viruses and particles in a room. An innovative "Airhouse" concept that combines with activated carbon has been researched and investigated with regard to the dynamic insulation systems.This system has a high potential to reduce the air temperature, humidity, and airborne viruses including Covid-19 whilst maintaining a steady airflow rate in a normal room. Therefore, it has a great deal of potential to decrease or eliminate concerns about the transmission of airborne viruses and adapt ventilation systems to new pandemic threats.

Keywords: Airborne viruses; indoor air quality; dynamic insulation; classrooms; airhouse

INTRODUCTION

A new virus known as Covid-19 was discovered in Wuhan, China, at the end of 2019. Within a few months, it had spread throughout Wuhan, forcing the Chinese government to isolate the city from the rest of the country. However, the highly contagious virus has spread to other countries in less than six months, with the United States of America and European countries bearing the brunt of the damage. Almost two years after its discovery, the virus has spread tremendously throughout the world, affecting over 600 million people and killing 1.3% of them (World Health Organisation, 2022). One of the options to reduce the fatality rate is using vaccine.

Vaccines are one of the methods of controlling many other viruses include polio, Hepatitis A, Hepatitis B, smallpox, measles, mumps, rubella, and rotavirus (REUTERS 2022). A highly effective vaccine, on the other hand, necessitates many years of research and a large number of animal and human trials. As the world is in a desperate situation, scientists from various countries have developed a number of vaccines that are being distributed and administered to a large portion of the world's population in a short period of time. However, the virus has mutated and evolved into a few new variants, the most recent and most contagious and dangerous of which are known as Delta and Omricon, putting the efficacy of vaccines, which is being debated by many scholars all over the world, in jeopardy.

The Delta variant was discovered in India, a developing country that has seen a significant increase in positive cases. Since its discovery in January 2021, the country's positive cases have quadrupled, rising from 3 million in January 2021 to 12 million in June 2021. Presently, this virus can be spread through the air, which necessitates adequate ventilation flow in an enclosed space. Meanwhile, Omricon - a heavily mutated variant, is more contagious than the previously dominating Delta variant. This variant of Covid-19 can circumvent vaccinated peoples' immunity than the Delta variant. Even though it is more contagious but the symptoms are milder than other variants. However, it can put pressure on the healthcare system, a sign that new variants of Covid-19 are predicted could emerge anytime (REUTERS 2022).

Schools as places of assembly for teaching and learning activities either outdoors or indoors including classrooms. Semi-outdoor classrooms promote cognitive, social-emotional, and physical motor skills (Mohamada et al. 2022). The ideal choice to think about ventilation is manipulating free resources like air flow and winds (Stoddart et al. 2022). One of the environmentally friendly methods for leveraging air flow to provide thermal comfort and good air quality is to use filtered apertures on building facades (Izahara et al. 2022). However, opened classrooms are very vulnerable to airborne transmission threats (from outside and inside); putting vulnerable people like toddlers, pupils and students at risk, particularly those who attend physical learning in classrooms. According to a report by Washington State Department of Health (2022), between August 1, 2021, and May 31, 2022, there were a total of 1,799 Covid-19 outbreaks in schools, and there were 11,823 Covid-19 cases connected to these outbreaks (Washington State Department of Health 2022). 89% of Covid-19 cases linked to outbreaks involved people under the age of 19 (Washington State Department of Health 2022). One of the causes of outbreaks is the traditional in-person settings of teaching and learning like classrooms (Hewson, 2021). Thus, this review of literature has been carried out to analyse dynamic insulation system as one of ventilation strategies to reduce airborne transmission in classrooms. This paper will investigate its efficiency on human health and comfort as well as ways to prevent viruses' spread in classrooms.

At the moment, most classrooms in tropical region are mostly ventilated using natural ventilation techniques (Sahabuddin et al. 2022). This scenario putting millions of children's health at stake. Many scholars agreed that an adequate ventilation is needed for comfort and health of the occupants (Sahabuddin et al. 2022; Willers et al. 1996). Thus, requiring a good ventilation flow is vital especially in the post-pandemic Covid-19 era. A number of academics have proposed using passive and active approaches to improve indoor air quality in naturally ventilated spaces such as classrooms (Mohd Sahabuddin & Gonzalez-Longo 2019, 2018; Tobin et al. 1993). As a result, the purpose of this paper is to examine a few conventional dynamic insulation systems in cleanrooms and residential buildings in reducing contaminants including Covid-19 and other airborne viruses and improving indoor thermal and air quality (IAQ) in classrooms. This paper will also review a few modern dynamic insulation techniques such as cleanroom ventilation and propose a new ventilation system that combines the vernacular and the new cleanroom techniques. This technique employs a hybrid ventilation system in conjunction with dynamic insulation to filter the supply air and implement unidirectional ventilation flow to ensure that the IAQ meets several established standards.

Classrooms in tropical countries usually apply natural ventilation technique which is regarded as a sustainable solution for maintaining internal environments thermally comfortable with low energy consumption. However, adequate ventilation rates need to be maintained in order to keep the health and comfort of students are achieved in classrooms (Jayakumar 2019). According to United Kingdom Building Bulletin 101, all occupied areas within the school buildings including classrooms should provide at least 3 l/s in accordance with each person's maximum occupancy while all accommodation/medical/sleeping areas should provide at least 8 l/s when they are occupied. Moreover, all washrooms should be ventilated to provide 6 air changes per hour (Daniels 2018). Generally, it has been required by the established ASHRAE Standard 62.1 to provide mechanical systems in classrooms for the provision of fresh air ventilation (ASHRAE 2019). Moreover, this standard also recommends a ventilation rate of 15 cfm/p is required for children in classrooms aged 6 to 8 years while the recommended level is reduced to 13 cfm/p for children above 9 years (Raible & LaRowe, 2019).

A few studies have shown that natural ventilation plays an essential role in providing fresh air adequately and helps in maintaining thermal comfort and IAQ in internal learning environments under certain environmental conditions. A study conducted in United Kingdom by Angelopoulos et al. (2017) in which CFD simulation tool was used in order to study the thermal comfort metrics of naturally ventilated UK classrooms of different schools. The results revealed that with an average external temperature of 10°C and wind speed of 3.5 to 10 m/s, almost 80% of the school building's floors are likely to yield thermally comfortable conditions (Angelopoulos & Cook, 2017). Moreover, in another study conducted in Netherlands by Rosbach et al. (2010), ventilation rates in 84 schools have been investigated, the results revealed that all school buildings have a ventilation rate of 7 litters per second per person (Rosbach, et al., 2010).

A ventilation strategy like dynamic insulation can enhance both the thermal comfort and indoor air quality in a space. Thermal comfort as defined in ASHRAE 55 - a state of mind through which one can express satisfaction in accordance with the thermal environment (ASHRAE, 2020). According to the standard, people mostly feel comfortable when the temperature of the building lies in between 70°F and 79°F (21°C and 26°C) (Cena & De Dear 2001). However, the absence of a standard that deals with educational building's indoor thermal environment are compelling the architects and designers to use the existing standards i.e. CEN 15251; ASHRAE 55 and ISO-7730 (Singh, M. K., Ooka, R., & Rijal 2018). As a result, a number of studies have highlighted high levels of dissatisfaction towards prevailing thermal environments in classrooms (Puteh et al., 2012)

In the perspective of IAQ, when ventilation rate is inefficient, the presence of airborne viruses as well as moisture in buildings becomes significant. Moreover, the presence of excessive moisture would attract mould to grow and giving a threat to student's health in classrooms (Vereecken & Roels 2012). Essential factors that play an important role in influencing mould growth and poor IAQ in classrooms include temperature, moisture, exposure time, type of substrate while some less essential factors that influence mould growth in classrooms include pH, oxygen, light, availability of mould spores, and roughness of the surface (Vereecken & Roels, 2012). The extent of moisture damage has been investigated in a variety of research studies. These studies revealed that around 12-18% of school buildings in Finland have been affected by mould damage. Different scientific studies have emphasized that mould and moisture damage or signs of it were found in 19-80% of the school buildings of various countries around the world (Haverinen-Shaughnessy et al. 1998).

The exposure to viruses from mould in classrooms may go unnoticed for a few months but long-term exposure is reported commonly to be a cause of a variety of discomforts resulting in more serious conditions among students. Mould exposure among students in classrooms is common because they spend a large portion of their day in the rooms. Moreover, a study conducted by Simons et al. (2010) in which the concentrations and diversity of mould's pathogens have been investigated in inner-city schools which resulting a high incidence of asthma and different skin diseases among students (Simons et al. 2010). Furthermore, strong associations have been suggested between the incidence of moulds exposure in schools and students' absenteeism (Baxi et al. 2013). In addition to this, sick building syndrome (SBS) has been reported in numerous studies among school children. A research study conducted in Sweden revealed that from 21 schools, 11 schools showed a high prevalence of SBS among students and staff (Willers et al. 1996). Moreover, a number of similar studies have reported problems that exposure to pathogens from moulds resulted in the incidence of allergies, respiratory problems (new or worsening asthma), runny nose, coughing, nasal congestion, headaches, fatigue, irritated eyes. Some less common symptoms include nausea, fever, dizziness, diarrhea, constipation, nose bleeding, and changes in child behaviours (Awair, 2021).

According to the USA National Center of Environmental Health (2020), it is highly recommended to identify the source of high humidity as well as rectify the issue using a filtered ventilation system like dynamic insulation that can reduce the amount of moisture and viruses in air (USA National Center of Environmental Health, 2020). Furthermore, a study conducted by FSCEC Energy Research Center in Florida recommended that indoor humidity must be reduced by controlling the level of dampness and humidity by using dehumidifiers and air conditioners. Moreover, exhaust fans must be used in school kitchens and food service areas (USA National Center of Environmental Health 2020). However, these active systems are neither a cost-effective nor a low-carbon solution.

Additionally, using temporary humidity control equipment is advised especially in hot and humid environments (Ganser et al. 2012). Although there are no standards or federal codes for mould remediation for school and commercial buildings (MacPhaul & Etter 2016) but in most cases a normal mould count within a room is around two hundred to five hundred spores. However, it is also essential to package the mould contaminated materials using sealed bags prior to removing from the contaminated area in order to minimize mould dispersion spores throughout the building (IAQ). Openings like ventilation components, door fixtures must be sealed. Furthermore, investigations were carried out on the effectiveness of high efficient particulate air filters (also known as HEPA filters) to control mould growth. The results of the investigations suggested that HEPA filters do not allow mould growth to escape out of the contaminated classroom (Ganser et al. 2012).

In order to reduce indoor moisture from the building, air conditioning system or portable dehumidifiers can be considered. In addition to this, manual thermostat must be provided so that staff and students can easily activate HVAC system type and Carbon dioxide sensors should be considered in each zone for controlling outdoor air dampers especially in hot and humid weathers (United States Environmental Protection Agency, 2016). However, the active ventilation systems mentioned before are neither a cost-effective nor a low-carbon solution.

Based on the above review from literature, children are at high risk from exposure to airborne viruses, particles and pathogens from mould during schools' hours in their classrooms. The literature highlights the importance of optimizing filtered ventilation such as dynamic insulation for thermal comfort and IAQ in classrooms because it prevents the potential of spreading of the airborne viruses and moisture particles. In addition to these some health effects in children has been highlighted in literature studies along with some recommendations in order to prevent airborne viruses in classrooms especially located in hot and humid regions. Thus, this paper will review at how dynamic insulation systems in conventional farming and residential buildings, cleanrooms and other controlled environments work to reduce viruses, pathogens, and other airborne particles to a certain threshold set by several established standards in order to provide a safe and healthy environment in classrooms for young generations.

PRECEDENT STUDIES: FILTERED VENTILATION SYSTEM

In the 1960s, a type of filtered ventilation system - dynamic insulation, emerged as a building concept (Gonzalez-Longo & Mohd Sahabuddin, 2019; Halliday, 2000). The porosity element of materials was investigated and recommended as a positive attribute for application in buildings. Then in 1965, the concept's basic thermal principle and mathematical technique that can predict its effectiveness was published in 1965 (Gonzalez-Longo & Mohd Sahabuddin 2019; Halliday 2000). At that time, the application of dynamic insulation was only implemented in agricultural buildings especially in Austria, Canada, Norway and Sweden.

In the same period, Trygve Græe from the Norwegian University of Agriculture has developed dynamic insulation in ceiling compartment in farm buildings. His innovation works through airflow that was drawn naturally by stack ventilation under the eaves, pass through the loft that filled with hay layers. The air, then, preheated by the stored material before entering the ground floor (where the animals were kept) and to the lower level before drawn out through a sealed pipe which vented at a high level (Gonzalez-Longo & Mohd Sahabuddin 2019; Halliday 2000). This concept was largely used in Scandinavia countries especially in animal houses which need a high constant demand for ventilation combined with high moisture production. Later in Norway, the same principle was applied in schools, sports buildings and care buildings.

In the 1980s, Thoren – a Swedish researcher, published a work concerned with the effects of the air exchange and transmission of heat by convection and radiation on dynamic insulation surfaces. While in Austria within the same period, Batussek and Hausleitner studied the physics of air movement through materials and developed a concept called Solpor System. This system introduced the pre-heating mechanism to the incoming air intake. Through a series of tests using a test cell and physical model of two private houses, they found that this system could reduce energy consumption without loss of comfort (Halliday 2000).

In the 1990s, the dynamic insulation concept was widely accepted to be implemented in non-agricultural buildings. This includes a sports hall project in Rykkinnhallen, Norway that was completed in 1992. The basketball hall that has a 35m span of a curved roof, has applied the concept in its ceiling compartment and combined with roof-mounted fans to create pressurised-roof. The air that enters the hall is preheated through a 200 mm thick fibre insulation layer held by open-weave matting. The air is exhausted using grilles at 2.5m above floor level and then, the heat is collected using air-to-water heat pump for feeding the underfloor heating system. This technique has improved the indoor air quality and reduced the energy consumption of the building, where 50% of energy reduction is recorded over conventional buildings.

Baerum Nursing Home is another project located in Norway using the same principles as Rykkinnhallen but on a much smaller scale of an existing building. The building has a porous membrane located between the ceiling surface and pressurised loft compartment. Grilles are used to distribute the filtered air. This project uses the extraction point from the en-suite bathroom (directional airflow) – controlling and removing the moisture-laden air from the last point (Halliday 2000). A heat pump is used to recover heat from the extract air. This method has produced a subjective sense of freshness which is unusual in healthcare facilities and supports the theory of contaminant diffusion in the air.

Another project that implements dynamic insulation approach is Gullhaug Sheltered Housing in Baerum province in Norway. This project does not only apply the approach in loft compartment but also on the walls. Due to the unavailability of the ceiling compartment in the ground floor, this principle draws the air down from the upper floor to the ground floor through the cavity in the external walls. The air is preheated using a coil below the window sill and pre-cleaned using the insulation membrane before entering the habitable spaces. Similar to Baerum Nursing Home, the exhaust air is sucked out via the wet areas in the house such as kitchen and bathrooms and through an air-to-water heat pump. After three decades, the use of dynamic insulation in residential buildings and healthcare facilities in Scandinavia countries becomes common.

While in the UK, the first major building that uses this technique is the McLaren Community Leisure Centre (MCLC) – completed in 1998. The aim was to investigate the performance of the dynamic insulation in wet-side (swimming pool) and dry-side (bowling hall) environments of the sports complex. With the total area of approximately 3,591 m^2, this building introduces air into the swimming pool, wet changing, sports hall, squash courts and bowling areas using pressurised ceiling voids and through a dynamic insulation membrane. This layer consists of cellulose fibre, a layer of punctured ethylene and a visible layer of Heraklith ceiling tiles for the pool and bowling hall, while timber slats are used to replace Heraklith for the sports hall and squash courts (Halliday 2000).

As described earlier, the conventional dynamic insulation concept is widely used in domestic buildings. However, the application of the system in classrooms is not explored yet. Therefore, an improved version of dynamic insulation system will be used in tropical climate but instead of warming the air, the new system cools the air as well as reduces moisture and airborne viruses in classrooms.

RECENT APPLICATION: ADVANCED FILTERED VENTILATION SYSTEM

In advance application using directional airflow, dynamic insulation has been implemented in healthcare and electronic facilities known as 'cleanrooms'. As defined in the International Organization for Standardization (ISO) 14644-1: Cleanrooms and Associated Controlled Environments – Part 1, a cleanroom is defined as a 'room in which the concentration of airborne particles is controlled, and which is constructed and used in a manner to minimise the introduction, generation, and retention of particles inside the room' and in which other relevant parameters, e.g. temperature, humidity, pressure, vibration and electrostatic are controlled as necessary (Standard & ISO 2015).

In the industry, these rooms are provided in the manufacturing of electronic hardware and in biotechnology and medicine, these rooms are used when it is necessary to ensure an environment that is free from bacteria, viruses, or other pathogens (Bhatia 2012). The basic rules for cleanrooms are contaminants must not be introduced into the controlled rooms, the materials or equipment within the controlled rooms must not generate contaminants,

contaminants must not be allowed to accumulate in the controlled rooms and existing contaminants must be eliminated from the controlled rooms.

However, the integrity of the cleanrooms is totally created by the heating, ventilation and air-conditioning (HVAC) system which controls the required limits of contaminants (Bhatia 2012). This HVAC system requires supplying airflow in sufficient volume and cleanliness with introducing constant air movement to prevent stagnant areas, filtering the outside air across high-efficiency particulate air (HEPA) filter, conditioning the air to meet the required temperature and humidity limits, as well as ensuring enough air to maintain positive pressurisation.

On the other hand, the cleanroom HVAC system is more or less similar to the conventional HVAC system except three main differences that differentiate these two systems (Bhatia, 2012) as follows: (1). Increased air supply – a normal HVAC system requires 2-10 air change rate/ hour (ach), while a typical cleanroom would require 20-60 ach. (2). The use of high-efficiency filters – the use of HEPA filters in ceiling area is a key element of cleanrooms. This filter can eliminate 99.9% of particles and in most cases provide 100% ceiling coverage. (3). Room pressurisation – cleanrooms are positively pressurised. It is done by supplying more air and extracting less air from the controlled rooms.

In principle, cleanrooms apply three basic elements in its design – a blower or supply fan, a high-efficiency air filter and a plenum or space (Bhatia 2012). With the same basics, larger space requires more fans and filters. Typically, three airflow options are usually used in cleanrooms – unidirectional flow or laminar flow, non-unidirectional flow or turbulent flow, and mixed flow. The selection of the cleanroom criteria has to first identify the level of cleanliness. It shows the maximum permitted concentration of particles for each considered particle size. Unidirectional flow is typically assigned to ISO 4 and ISO 5 classes of cleanrooms that need stringent control of environment. For intermediate and less stringent environments, non-unidirectional flow or mixed flow are preferred.

For example, cleanrooms with classes 10 (ISO 4) to 100 (ISO 5) will use unidirectional flow and cleanrooms classes more than 1,000 (ISO 6) to 100,000 (ISO 8) will use a non-unidirectional flow or mixed flow (Standard & ISO, 2015). The cleanrooms with classes of 10 to 100 require high air velocity and air change rate between 50 fpm to 110 fpm and 300 ach to 600 ach respectively (Standard & ISO, 2015), whereas the cleanrooms with classes of 1,000 to 100,000 require lower air velocity and ach between 10 fpm to 90 fpm and 10 ach to 250 ach respectively (Standard & ISO 2015).

The unidirectional flow pattern where air moves vertically downward from the ceiling to a return air plenum on a raised floor or wall. To ensure its efficiency, 100% of ceiling or wall coverage is recommended. It is designed for air velocity of 60 fpm to 90 fpm to keep the contaminants directed downward or sideward before they settle onto surfaces (Bhatia 2012).

The method of non-unidirectional flow is often used in cleanrooms with the classification of 1,000 and above where intermediate control environment is needed. Due to the random pattern of air streamlines, pockets of air with high particle concentrations will occur. However, these pockets could only persist for a short period of time before disappearing through the random nature of the downward airflow (Bhatia 2012b). Typically, sidewall return arrangement is used with non-unidirectional flow.

The mixed flow technique is used when there are critical and non-critical processes in the same space. These activities are divided by creating different zones in the space. More filters are installed in the ceiling of the zone that needs stringent control. For less stringent zone, fewer filters are installed. Return air arrangements are adjusted by locating sidewall grilles. For more effective results, raised floor could be used (Bhatia 2012).

In a normal application, cleanrooms require air temperature and humidity conditions to be set at 20°C and 45% to 50% Relative Humidity (RH) respectively (Bhatia 2012). Thus, to achieve these conditions constantly, cleanrooms are usually associated with HVAC systems (Bhatia 2012). With these stringent conditions, the concept of dynamic insulation in cleanrooms demands high energy consumption (Bhatia 2012) to condition the air with the right air change rate, air temperature (20°C) and humidity (45% to 50% RH). Undoubtedly, the combination of cleanrooms and HVAC system is highly energy-intensive, and the use of efficient HVAC have largely been ignored by the large profit companies. Considering that this system could control indoor spaces to be in good thermal and air quality environments, it is a necessary to re-evaluate the basic methods of cleanrooms and re-consider it in domestic buildings. As the application of these kind of systems in classrooms are still undiscovered, this paper investigates the potential of dynamic insulation using cleanroom rules in providing health and comfort in classrooms in hot-humid climate.

‘AIRHOUSE’ CONCEPT FOR REDUCING AIRBORNE VIRUSES TRANSMISSION

A few studies mentioned that dynamic insulation can achieve the right indoor comfort and air quality conditions as set by several established international and local standards (Dabbagh & Krarti 2020; Fantucci et al. 2015; Imbabi 2012; Mohd Sahabuddin & Gonzalez-Longo 2019, 2018). The system reduces the heat and moisture circa 16% while the airborne particles and toxicant gases circa 90% (Mohd Sahabuddin & Gonzalez-Longo 2019). A study done by Mohd Sahabuddin & Gonzalez-Longo (2019) found that dynamic insulation in tandem with activated carbon (AC) could further improve the thermal conditions (temperature and humidity) performance up to another 10% to 20% (Figure 1). A study has found out that for better air circulation in schools, exhaust fans can be employed to push indoor air out of atriums between classrooms (Jessiea et al. 2022).

In detail, the studies have tested four ventilation protocols; fully passive (B-B), hybrid-positive (B-F), hybrid-negative (F-B) and fully active (F-F). Their finding has suggested that the concept works well with the hybrid ventilation protocols – hybrid-positive (B-F) and hybrid-negative (F-B) (Figure 2). The hybrid-positive protocol has consistently produced better results than the hybrid-negative protocol, especially for air quality (particulate matter reductions – circa 15%) but for thermal comfort criteria (temperature and humidity) both protocols achieved almost similar performance. Given the above findings, the hybrid-positive protocol has a slight advantage, however, in a larger space like classroom, the hybrid-negative protocol is also needed. Especially for sucking indoor contaminants out from the classrooms.

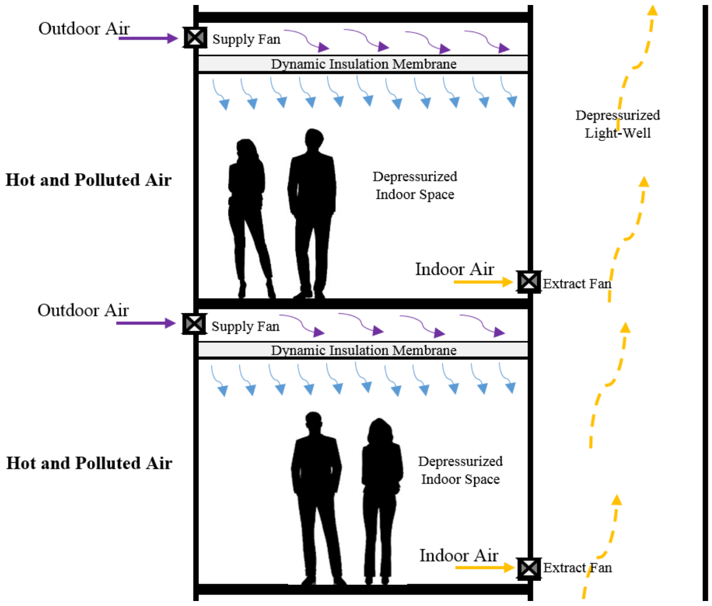

FIGURE 1. Schematic design concept of the Airhouse system

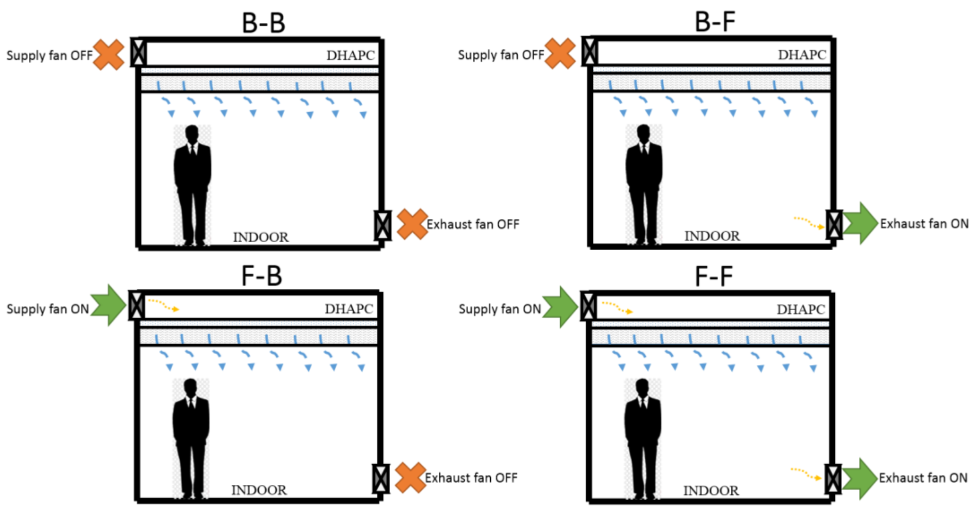

FIGURE 2. Four ventilation protocols

Therefore, these ventilation protocols are designed to have a certain level of controls by the end-users according to their needs. Meaning that the ventilation protocols can be activated and deactivated at any time as required by the occupants. It is suggested that every classroom should be equipped with a device that can monitor the actual thermal and air quality conditions. As technologies in these areas are actively developing in many countries, the availability of such reliable devices at affordable prices is considerably high.

Another study has found that recycled materials such as plastic, wool and glass, have achieved excellent results in filtering the airborne particulate matter (Sahabuddin & Howieson 2020). The reduction rates were circa 55%, 65% and 80% for recycled plastic, recycled wool and recycled glass respectively. It means that recycled glass has significantly achieved optimum result in reducing airborne viruses.

The conventional HVAC approaches – such as air conditioning systems, can improve thermal comfort in tropical countries. However, they create high energy demand, produce high carbon emissions and require high maintenance. As tested in several methodologies in a research by the authors, the new dynamic insulation concept called 'Airhouse' could successfully addressed the thermal comfort and air quality issues as well as excessive moisture and airborne viruses with low energy consumption and low carbon emissions. This system can be widely implemented not only for classrooms in tropical countries but also in other different climatic contexts.

Based on the above findings, another detailed experiments of 'Airhouse' system have been performed but this time to filter substances from petrol and diesel engines using additional absorbance material called activated carbon (AC). Several substances similar like airborne viruses such as carbon monoxide (CO), benzene, sulphur dioxide (SO_2), PM1, PM2.5 and PM10 were selected and tested. These experiments sought for improvement on the performance of AC in filtering the substances using two different applications – AC in a cartridge and AC loose-fill. Among the key findings that could be deduced from the tests are explained below:

1. The application of AC cartridge in the 'Airhouse' system could produce better reduction rates on gases than particles. This scenario happened due to the compact amount of AC that could adsorb more gases from both petrol and diesel engines (Figure 3).
2. However, the AC loose-fill approach could efficiently reduce particles than gases. It suggested that more particles were 'adsorbed' on the AC molecules and also 'absorbed' in the 'Airhouse' insulation membrane (Figure 3).
3. Ventilation protocols gave different effects in reducing air pollution from petrol and diesel engines. The F-B protocol, for instance, significantly produced higher reduction rates on particles. This was due to the repulsion force that made more 'larger' airborne particles trapped inside the membrane (Figure 4).
4. While the B-F protocol that was dominantly powered by suction pressure had dragged and released more particles from the insulation membrane, but not gases. It seems that more adsorption process occurred when B-F protocol was in use (Figure 4).
5. According to this test, filtering gases from petrol and diesel engines using 'Airhouse' and AC applications met a new barrier. After a certain period, the amount of gases in the indoor space of the test model gradually increased. A mechanism that could suck and channel out the gases (in the 'Airhouse' compartment) before it permeates the indoor space should be studied in the future.

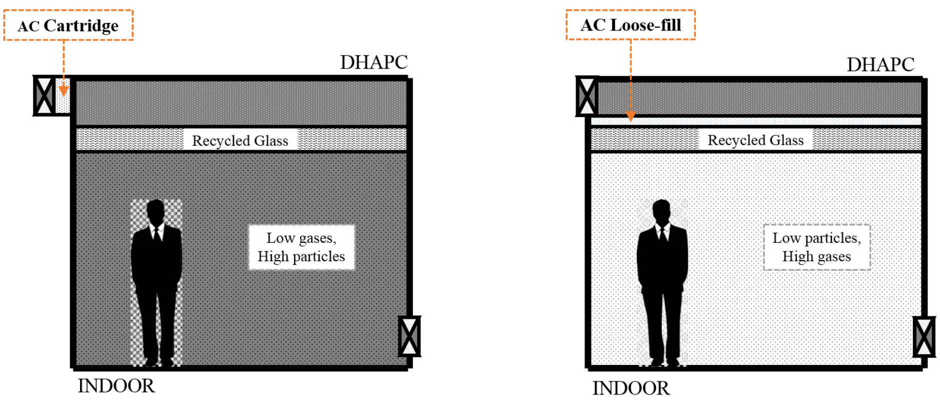

FIGURE 3. AC Cartridge vs AC Loose-fill

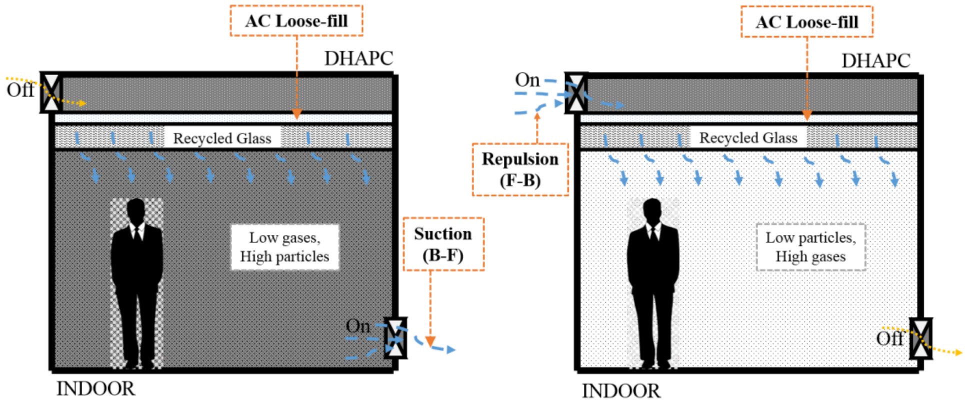

FIGURE 4. Suction (B-F) vs Repulsion (F-B)

It could be concluded that 'Airhouse' system with AC applications (AC cartridge or AC loose-fill) and hybrid ventilation protocols (F-B and B-F) have a great potential to be developed in a full-scale classroom as a solution for filtering heat, excessive moisture and airborne viruses as well as providing constant and adequate airflow.

DISCUSSIONS

In this paper, two dynamic insulation techniques - the hybrid-positive (F-B) configuration and the hybrid-negative (B-F) configuration have significantly given different effects in reducing airborne particles like viruses. The F-B configuration, for instance, produced higher reduction rates on particles. This was due to the repulsion force that makes more 'larger' airborne particles trapped inside the membrane. While the B-F configuration which dominantly powered by suction pressure, dragged and released more particles from insulation membrane but not gaseous molecules. It seems that more adsorption process occurred when B-F was used. For example, F-B configuration recorded circa 15% more reduction on airborne particles than B-F configuration. Whereas, B-F configuration filtered circa 15% more gaseous molecules than F-B configuration. These scenarios need to be further studied by a physicist to explain why such conditions could happen.

In this paper, two activated carbon (AC) approaches were tested – AC cartridge and AC loose-fill. The first option had a compressed box while the second option had an uncompressed surface. Polluted air was introduced and passed through the compressed box and the uncompressed surface. It was observed that different profiles of air quality variables (CO, benzene and SO_2, PM1, PM2.5 and PM10) were observed when AC cartridge and AC loose-fill were applied. AC cartridge produced better results for filtering gaseous molecules while AC loose-fill filtered airborne particles better than AC cartridge. For example, AC cartridge filtered almost 35% more carbon monoxide than AC loose-fill but AC loose-fill filtered almost 25% more particulate matter than AC cartridge.

From the experiments, it could be deduced that airborne particles in classrooms like moisture drops and viruses can be significantly reduced using dynamic insulation technique combined with AC in the form of loose-fill and hybrid-positive (F-B) ventilation configuration.

CONCLUSIONS

The spread of airborne viruses like Covid-19 have serious impacts on children in many countries. Classrooms, particularly for its ventilation system, are not addressing these issues in full. Many classrooms are turning to wall-mounted split air conditioners as a quick fix, but this is neither a cost-effective nor a low-carbon solution. These buildings' high air temperatures and humidity levels are a result of both internal and exterior elements, including plan layout, human behaviour, and ventilation strategy, as well as local climate, urban fabric, and building envelope materials. The use of this dynamic insulation system in classrooms will lessen the need for high energy-use appliances like air conditioners, resulting in lower electricity costs as well as reduced carbon emissions and the urban heat island effect. When this dynamic insulation system is extensively used, the current situation in classrooms, which is vulnerable to airborne viruses, could be improved.

This paper discusses the first commencement in looking for solutions to produce more sustainable buildings that respond to airborne viruses like Covid-19 virus. The proposal of dynamic insulation combining activated carbon proposed here is only an initial evaluation of its potential to reduce the air temperature, humidity and airborne viruses such as Covid-19 as well as to provide a constant airflow rate in a typical classroom. More research need to be carried out. There are still other factors that should be focused in the future to implement the system in more practical and realistic situations. Even though this article has explained results from the physical experiments, the validation of the system should be done using a full-scale prototype in existing and new type of classrooms in different climatic contexts. In dealing with the effects of climate change, urbanisation and Covid-19 endemic, classrooms have to apply more explicit ventilation approaches in reducing both thermal discomfort and airborne viruses' contagion for the betterment of our future generations.

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DECLARATION OF COMPETING INTEREST

None

REFERENCES

Angelopoulos, C. & Cook, M. J. C. I. 2017. Evaluation of thermal comfort in naturally ventilated school classrooms using CFD. *Researchgate.Net*, *15th Conference of Inter*.

ASHRAE. 2019. *ANSI/ASHRAE Standard 62.1-2019 Ventilation for Acceptable Indoor Air Quality*.

ASHRAE. 2020. *Standard 55-2020 - Thermal Environmental Conditions for Human Occupancy (ANSI Approved*.

Awair. 2021. *Mold in Schools Harms Kids: How to Improve Classroom Air*.

Baxi, S. N., Muilenberg, M. L., Rogers, C. A., Sheehan, W. J., Gaffin, J., Permaul, P., Kopel, L. S., Lai, P. S., Lane, J. P., Bailey, A., Petty, C. R., Fu, C., Gold, D. R. & Phipatanakul, W. 2013. Exposures to molds in school classrooms of children with asthma. *Pediatric Allergy and Immunology* 24(7): 697–703. https://doi. org/10.1111/pai.12127

Bhatia, A. 2012. *HVAC Design for Cleanroom Facilities*. Continuing Education and Development Inc.

Cena, K., & De Dear, R. 2001. Thermal comfort and behavioural strategies in office buildings located in a hot-arid climate. *Journal of Thermal Biology* 26(4-5): 409-414.

Dabbagh, M., & Krarti, M. 2020. Evaluation of the performance for a dynamic insulation system suitable for switchable building envelope. *Energy and Buildings* 222: 110025.

Daniels, R. 2018. *BB 101: Ventilation, Thermal Comfort and Indoor Air Quality 2018*.

Fantucci, S., Serra, V., & Perino, M. 2015. Dynamic insulation systems: experimental analysis on a parietodynamic wall. *Energy Procedia* 78: 549–554.

Ganser, J., Kanwal, R., Kreiss, K., Martin, M., & Sahakian, N. 2012. Preventing occupational respiratory disease from exposures caused by dampness in office buildings, schools, and other nonindustrial buildings. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

Gonzalez-Longo, C. & Mohd Sahabuddin, M. F. 2019. High-rise social housing in hot-humid climates: Towards an "Airhouse" standard for comfort. *Applied Sciences* 9(23). https://doi.org/10.3390/app9234985

Halliday, S. 2000. *Dynamic Insulation Guidance Note*.

Haverinen-Shaughnessy, U., Borras-Santos, A., Turunen, M., Zock, J.-P., Jacobs, J., Krop, E. J. M., Casas, L., Shaughnessy, R., Täubel, M., Heederik, D., Hyvärinen, A., Pekkanen, J., Nevalainen, A. & HITEA Study Group. 2012. Occurrence of moisture problems in schools in three countries from different climatic regions of Europe based on questionnaires and building inspections–the HITEA. *Indoor Air* 22(6): 457–466. https://doi.org/10.1111/j.1600-0668.2012.00780.x

Hewson, K. 2021. *COVID-19 Outbreaks in Washington State K-12 Schools: Time to First COVID-19 School Outbreak Characterized by Learning Modality and Community Transmission*. University of Washington.

Imbabi, M. S.-E. 2012. A passive–active dynamic insulation system for all climates. *International Journal of Sustainable Built Environment* 1(2): 247–258.

Izahara, M. N., Mohameda, M. F., & Yusoffa, W. F. M. 2022. Pendekatan lestari masjid-masjid lama di Bandar Melaka. *Jurnal Kejuruteraan (Journal of Engineering) Special Issue* 5(1).

Jayakumar, S. 2019. Estimation and analysis of ventilation rates in schools in Indian context: IAQ and Indoor Environmental Quality. *Materials, MG Apte - IOP Conference Series: Materials Science and Engineering*. https://doi.org/10.1088/1757-899X/609/3/032046

Jessiea, F., Yusoff, W. F. M., & Amirb, A. 2022. Kriteria reka bentuk atrium dalam aspek sosial dan persekitaran bangunan komersial di Lembah Klang. *Jurnal Kejuruteraan (Journal of Engineering) Special Issue* 5(1).

Lawton, M. D., Dales, R. E., & White, J. 1998. The influence of house characteristics in a canadian community on microbiological contamination. *Indoor Air* 8(1): 2–11. https://doi.org/10.1111/J.1600-0668.1998.T01-3-00002.X

MacPhaul, D., & Etter, C. 2016. *Mold Remediation Guidelines*. Whole Building Design Guide. https://www.wbdg.org/resources/mold-remediation-guidelines

Mohamada, N., Affandi, H. M., Saaric, M., Kamald, M. F. M., & Noore, M. S. M. 2022. The impact of preschool outdoor environment on children's socio-emotional development. *Jurnal Kejuruteraan (Journal of Engineering) Special Issue* 5(1).

Mohd Sahabuddin, M. F. Bin, & Gonzalez-Longo, C. 2019. Balancing comfort and indoor air quality in high-riser buildings for social housing in Kuala Lumpur: from regulations to construction. *51th AiCARR International Conference Venice*, 286–300.

Mohd Sahabuddin, M. F., & Gonzalez-Longo, C. 2018. Assessing the indoor comfort and carbon dioxide concentration in high-rise residential buildings in Kuala Lumpur: the people's housing programme. *CIBSE Technical Symposium 2018*.

Puteh, M., Ibrahim, M. H., Adnan, M., Che'Ahmad, C. N., & Noh, N. M. 2012. Thermal comfort in classroom: constraints and issues. *Procedia-Social and Behavioral Sciences* 46: 1834-1838.

Raible, M. & LaRowe, A. 2019. *FRESH AIR: The Impact of HVAC Systems on Indoor Air Quality*. https://spaces4learning.com/articles/2019/01/01/hvac-iaq.aspx. Retrieved: 8 April 2022.

REUTERS. 2022. *Fact check: Vaccines do protect against viral infection*. https://www.reuters.com/article/uk-fact-check-vaccines-protect-against-v-idUSKBN25O20E

Rosbach, J., Vonk, M., Duijm, F., van Ginkel, J., Brunekreef, B., Groningen, G. G. D., & IJsselland, G. G. D. 2010. FRESH: Effects of a ventilation intervention in classrooms upon cognitive performance and respiratory health of primary school pupils. *Environment*. 43: 362-367.

Sahabuddin, M. F. M., Aminuddin, A., Muhammad-Sukki, F., & Shukri, S. M. 2022. Indoor and outdoor air quality in densely populated areas: Case studies of high-rise social housing in Kuala Lumpur. *Pertanika Journal of Science & Technology* 30(2).

Sahabuddin, M. F. M., & Howieson, S. 2020. Improving indoor air quality using dynamic insulation and activated carbon in an air permeable ceiling. *Building Services Engineering Research and Technology* 41(4): 441–453.

Simons, E., Hwang, S.-A., Fitzgerald, E. F., Kielb, C., & Lin, S. 2010. The impact of school building conditions on student absenteeism in upstate New York. American Public Health Association (APHA) 100(9): 1679–1686. https://doi.org/10.2105/AJPH.2009.165324

Singh, M. K., Ooka, R., & Rijal, H. B. 2018. Thermal comfort in Classrooms: A critical review. *In Proceedings of the 10th Windsor Conference-Rethinking Comfort, Windsor, UK 12-15*

Standard, B., & ISO, B. 2015. *Cleanrooms and associated controlled environments—*.

Stoddart, C., Muhammad-Sukki, F., Anderson, M., Ardila-Rey, J. A., Ayub, A. S., Mohd Sahabuddin, M. F., Rahmat, M. K., Muhtazaruddin, M. N., & Zulkipli, M. 2022. A study of zero bid wind farm for future Scotland's energy demands—A new approach. *Applied Sciences* 12(7): 3326.

Tobin, R. S., Bourgeau, M., Otson, R., & Wood, G. C. 1993. Residential indoor air quality guidelines. *Indoor Environment* 2(5–6): 267–275. https://doi.org/10.1177/1420326X9300200503

United States Environmental Protection Agency. 2016.

USA National Center of Environmental Health. 2020.

Vereecken, E., & Roels, S. 2012. Review of Mould Prediction Models and Their Influence on Mould Risk Evaluation. *Building and Environment*, 51, 296–310. https://doi.org/ https://doi.org/10.1016/j.buildenv.2011.11.003

Washington State Department of Health. 2022. *COVID-19 Outbreaks in Washington State K-12 Schools*.

Willers, S., Andersson, S., Andersson, R., Grantén, J., Sverdrup, C., & Rosell, L. 1996. Sick building syndrome symptoms among the staff in schools and kindergartens: Are the levels of volatile organic compounds and carbon dioxide responsible? *Indoor and Built Environment* 5(4): 232–235. https://doi.org/10.1177/1420326X9600500406

World Health Organisation. 2022. *WHO Coronavirus (COVID-19) Dashboard*. https://covid19.who.int/