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Ventilation: finding a balance between a healthy building environment and energy consumption.

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Copyright Declaration

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Abstract

Governing bodies aim to implement zero energy building strategies to reduce the energy consumption and GHG emissions. However, the SARS-Cov-2 pandemic has shifted focus to creating a safe environment for occupants of buildings to prevent the spread of the virus, this is achieved by increasing ventilation rates, which ultimately increase the energy consumption of buildings. This study sets out to find a balance of the two. The study has used fresh air equations to determine the fresh air requirement for an office and compared it to the current literature on previous ACH and new ones suggested by guidance. Secondly, the study uses energy calculations to compare the energy consumption of the air change rates found in literature and the proposed ventilation strategy.

The study proposes a ventilation system on the basis of finding a balance between energy consumption and a healthy environment. The study concludes that a ventilation strategy that uses 50% RH and a variable ventilation rate isn't the silver bullet in stopping the spread of SARS-CoV-2, but it is a step in the right direction from current bad energy practice promoted by high ACH.

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Nomenclature

Symbol	**Description**	**Units**
ACH	Air change rate per hour	[m3 /hr]
Cp	Specific heat capacity	[kJ/kg.K]
h_{fg}	Specific enthalpy	[J/kg]
$\dot{m}$	Mass flow rate	[m^3/s][l/s]
P	Power	[kW]
RH	Relative Humidity	[%]
T	Temperature	[˚C]
ΔT	Change in temperature	[˚C]
V	Volume	[m^3]
$\dot{V}$	Volumetric flow rate	[kg/s]

1.0 Introduction

Since 2020, a global pandemic has restricted a large part of the population to their own homes and have forced them away from family, friends and colleagues. As of the 29th of November 2021, the death toll for the SARS-CoV-2 pandemic is 5.2 million (BBC, 2021). The virus responsible for this pandemic is called SARS-CoV-2, causing the illness COVID-19 (WHO, 2021). This pandemic has thrown up a large number of societal debates, including relating to the ways we live, work and travel (Mair, 2020). One major debate, in the area of building services, that has been intensified by the pandemic, surrounds the negative impacts that not-fit-for-purpose ventilation can have on human health (Fadaei, 2021). This was already being explored due to concerns about indoor pollution and spread of illnesses within buildings which did not provide adequate ventilation to offset these apprehensions. However, the severe impacts that the SARS-CoV-2 virus and subsequent illness, have had on human health has brought building ventilation to the forefront (Morawska et al., 2020) Simultaneously, the ongoing climate crisis has placed energy generation and demand firmly as another significant priority, especially since the Paris Agreement 2015, focusing on reducing greenhouse gas emissions (UN, 2016). Therefore, these two distinct narratives must be balanced, as whilst there is much alarm arising around how to protect human life during the pandemic and in its aftermath, such as by better ventilating our buildings, the precedence of making buildings more sustainable is also absolutely crucial (Dean, Dulac, Petrichenko and Graham, 2020). Given this context, the aims and objectives of this research are as follows:

- To study and analyse the new buildings regulations on saving energy to achieve zero carbon buildings.
- Analyse how buildings interact with human health.
- To assess diseases particles and their behaviour in building environments
- The study aims to contribute to literature of finding the balance between the energy consumption and a healthy internal environment.

2.0 Literature Review

The following section will explore literature on areas surrounding how the built environment is made and is changing and has had to adapt due to the ongoing climate crisis and pandemic. The section will also look at ventilation techniques and how they can be used within the current climate, A review of disease and how the SARs-Cov-2 is transmitted and IAQ measures that can help to mitigate the rate of infection.

2.1 Buildings and energy

The built environment consumes 40% of the energy converted worldwide, as well as being the culprit for 38% of the global greenhouse gas emissions (Dean, Dulac, Petrichenko and Graham, 2020). Buildings consume energy throughout their life span, through their construction, their maintenance and operation and their demolition (Ramesh, T., Prakash, R. and Shukla, K.K., 2010). This makes the built environment one of the biggest consumers of energy worldwide (Ramesh, T., Prakash, R. and Shukla, K.K., 2010). As countries around the world have committed to reducing their energy consumption and GHG emissions, the built environment has been targeted for development. The European Union implemented the European Union Energy Performance of Buildings Directive in 2010 (European Commission, 2010). This directive made all member states follow minimum energy requirements, that are outlined in the bill, for all existing buildings that are retrofitted or renovated. When the bill was brought into law, a change in policy could be seen in the member states, with the aim of creating low energy buildings reducing GHG emissions (Kiber & Fard, 2012). Numerous other countries have a similar directive, such as the United States of America with their Building Technology Program of the US Department of Energy, which fundamentally has the same purpose of creating Zero Energy Buildings (ZEB) (Energy.gov, 2021). The directive has pushed governments, such as the United Kingdom (UK), to create their own standards and pathways to reducing GHG and carbon emissions from buildings. The UK has created *The Future Homes Standard: consultation on changes to Part L (consultation of fuel and power) and Part F(ventilation) of the Building Regulation for new dwellings*, which sets a target for new homes that are built after 2025 to be future proofed by high levels of energy efficiency and low carbon heating. (Ministry of Housing, Communities & Local Government, 2021). Therefore, the climate crisis is worsening and has been pushed to the fore front of governing bodies thinking, leading to increased attempts to reduce the consumption of energy and production of GHG from different sectors. The evidence is pointing to the fact that buildings are a primary cause so are one core sector that are being targeted to reduce consumption. The next section will begin to delve deeper into one of the outcomes of the regulations in relation to provoking a greater focus on zero energy buildings.

2.1.1 Zero energy buildings

Zero energy Buildings often have two main characteristics. The first characteristic is reducing the requirement for energy within the building. This is often achieved by targeting heating and cooling of the building, enabling these processes to become more energy efficient. Secondly, renewable energy sources or other technology can be introduced to meet the energy demand (Torcellini, Pless, Deru, and Crawley, 2006). Building Energy Standards can differ from country to country due to such things as their level of development, the climate, their historical architectural design as well as the countries building standards (European Commission, 2010; Energy.gov, 2021; Lam, Wan, Tsang, and Yang, 2008). Architects and engineers create buildings or building service designs that are in line with the building standards requirements. The energy saving designs tend to encompass all of the building, but they can also be grouped into three subheadings, building envelope, internal conditions and building services systems.

2.1.1.1 Building envelopes

Back in 2007, the UK government first introduced the plan for all new homes built after 2016 to be zero carbon ready (Department for Communities and Local Government, 2007). The aim of this regulation was to introduce a fabric first approach which focused upon reducing the energy demand of homes through increasing the airtightness, improving insulation and reducing thermal bridging (Zero Carbon Hub, 2009). The fabric first approach has been continued into the Future Homes Standard, which has updated the aims of achieving zero carbon housing (Ministry of Housing, Communities & Local Government, 2021). Furthermore, the approach has also been adopted by the Royale Institute of British Architecture for office buildings in their RIBA 2030 Climate Challenge document (RIBA, 2021). Consequently, it would appear the “fabric first” approach will provide the basis for all new standards that will follow towards achieving zero carbon buildings in the UK, due to the fact it has been incorporated into each regulation released since its first adoption in 2007. The performance of the envelopes can be assessed through different techniques. One of these techniques is to use cost effectiveness (Dodoo, Gustavsson, and Tettey, 2019.) The aim for the building envelopes within zero energy buildings is to reduce heat gain in the summer months and heat loss in the winter months, which in turn reduces the amount of heating and cooling that is required (Lam, 1995; Lam, Tsang, Li and Cheung, 2005). Therefore, focusing on the efficiency of building can in turn reduce the energy consumption of the building. When targeting an improvement in energy efficiency of a building there are three main areas that are focussed upon for upgrade. The three areas are thermal insulation, glazing and windows and finally thermal mass.

There are three main points when implementing thermal insulation. First, insulation can be a cheap, energy efficient improvement to a building that doesn't have a large environmental impact (Gorgolewski, Grindley and Probert,1996). It is more efficient in colder climates where the energy for heating is larger than cooling. It is less efficient in warmer climates that require high levels of cooling. Therefore, whether insulation is efficient is contingent on the climate and the type of insulation installed. Second, insulation can see some differences in the theoretical side and practice side. In theoretical terms the increase of insulation would reduce the conduction heat gain/loss. There is a point where adding more insulation would have a detrimental effect on the energy consumed by the build, this point is called the "point of thermal inflexion" (Lam and Hui, 1996). If the building has more insulation than what is required, the heat loss during the cooling periods will be reduced. This can be seen in mid-season. This in turn increases the need for cooling which can heighten the overall energy demand of the building (Masoso and Grobler, 2008). Lastly, the size of the insulation can be determined through a process of life cycle analysis in throughout the design stage of a building (Thormark, 2002).

When designing building windows, the tendency is to reduce the size of windows to increase the size of walls and install low emissivity double or triple glazing with the cavity within filled with an inert gas to reduce the heat loss or heat gain (Weir and Muneer, 1998). However, the windows also need to be chosen for their appropriate climate. For example, double or triple glazing can be detrimental to cooling in a warmer climate where the internal heat loads are high. For these climates, single glazing with reflective glass is more effective to reduce the solar heat gain. Alternatively double or triple glazing is appropriate for colder climates to reduce heat loss (Lam and Li, 1998; Loutzenhiser, Maxwell and Manz 2007). The reduction of window size and using reflective glass can also have adverse effects on the energy demand of the building. These changes will reduce the daylight that enters the building (Wilkinson, M.A., 1992). Research suggests daylighting designs when applied can reduce the overall energy demand as there is a reduced need for lighting which in turn reduces the need for cooling as the lighting doesn't emit heat. Research also suggests that good daylighting design can have health benefits such as improved mood, alertness and behaviour (Lockley, 2010; Hraska, 2015). Thus, there are a multitude of factors to consider in terms of building windows, including certain characteristics relating to which climate the building is situated in and wider considerations beyond energy reduction, such as the impacts of smaller windows on human health.

Thermal mass is a design technique used to reduce the internal temperature of a building (Kammerud, Ceballos, Curtis, Place, and Andersson, 1984). This is achieved as thick exterior walls retard the transfer of heat from the exterior to the internal space. This coupled with internal mass such as building furniture, further reduces the rise in internal temperature. These culminate in a slow heating of the internal space in the summer. The reduced heat transfer means the building reaches a peak temperature late in the day when the outside temperature has dropped. The heat that is transferred into the building can be removed through good ventilation throughout the day or at night (Karlsson, Wadsö, and Öberg, 2013). There is a belief that thermal mass should be controlled through the use of night-time ventilation to reduce the need for cooling throughout the day and limit overheating in summertime. This technique reduces the energy demand of the building, which in turn reduces the impact of global warming from the building as the energy required is reduced. (Shaviv and Shaviv, 1978). Therefore, the internal temperature of the building can be controlled through the use of the building envelope and mitigate overheating through ventilation strategies.

2.1.1.2 Internal conditions

There are numerous variables that have an influence on the required heating and cooling of a building (Hestnes, and Kofoed, 2002). Some of these are the maximum and minimum internal temperature set points, the internal electrical equipment heat generation and heat generated from the occupants (Mazzeo, Oliveti and Arcuri, 2016). A study focusing on the *impact of climate change on the energy use in the built environment* showed that adjusting the internal temperatures in certain climates can be an efficient energy saving method. The study also found that reducing the lighting load density can have a large effect on the energy savings of non-domestic buildings (Li, Yang and Lam, 2012). Consequently, the energy saving of reducing the lighting density is in line with promoting good daylighting schemes. Changing the internal temperatures of buildings is therefore a good energy saving method that can be applied to new builds and existing building. Changing the lighting density load, however, can be more difficult as existing buildings may need to renovate to allow for the correct amount of light infiltration to not affect the building occupants or the air conditioning system (Ibid). There are building energy management systems (BEMS), which is a type of system that can monitor and control internal temperatures and lighting levels among other things, the aim is to manage the energy consumption of the building. These BEMS systems allow for optimisation in real time of buildings to create a good internal environment and promote energy saving (Clarke, Cockroft, Conner, Hand, Kelly, Moore, O'Brien and Strachan, 2002; Doukas, Patlitzianas, Iatropoulos, and Psarras, 2007; Lowry, 2002). Thus, this development has facilitated more accurate monitoring of internal environments, essential in improving the ability to enable more sustainable buildings. Internal building conditions can be further broken down into two categories of internal design conditions and internal heat loads.

Research into the internal design has shown that decreasing and increasing internal temperatures during the winter and in summer has shown to greatly decrease the cooling and heating requirements (Chidiac, Catania, Morofsky, and Foo, 2011). Studies have shown there are a variety of temperatures utilised in homes due to personal preference. Due to this variance, there is scope to reduce the heating used in the high usage homes (Peffer, Pritoni, Meier, Aragon and Perry, 2011). As thermal comfort is personal preference, it is hard to determine a universal set point which is acceptable for all, which leads to a range of temperature set points (Nicol and Humphreys, 2002). The adoption of widening temperature set points may not work in the long term as it is uncertain how acceptable this will be to the occupants. This has been noted in newer green buildings with occupants feeling the environment is too cool or too warm. (Leaman, Thomas Vandenberg, 2007). Thus, there are a wider range of thermal comfort set points that are personal to each individual and not one set point will appease all occupants. The result of this is to establish a temperature set point that is guided by principles around what will be beneficial to energy consumption and at the same time provide some thermal comfort.

Concerning internal heat loads, a study on the impacts of climate change on building performance, carried out in New Zealand, showed around a 1˚C reduction in overheating during the summer months can be achieved if the internal heat loads are reduced by 10W/m^2. Consequently, the reduction in heat loads would reduce the need for cooling or air conditioning (Camilleri, Jaques and Isaacs, 2001). The electric lighting load density of a building has shown to have a large impact on the energy and thermal performance in varying climates. It is seen as a key design component when considering energy efficiency (Lam, Tsang and Yang, 2006). With the advancements of controls and lighting equipment, this has allowed there to be more energy efficient practices in lighting designs. Further advancements in technology aimed at increasing energy efficiency would in turn help to achieve energy efficient buildings.

2.1.1.3 Building services systems

Within building services, there are multiple energy consumers and their consumption can be interlinked. Two of the largest consumers are HVAC and lighting. In the UK, 62% of energy end use in domestic buildings is attributed to space conditioning, with lighting accounting for 16% of this (Pérez-Lombard, Ortiz and Pout, 2008). There are many different variables that influence a buildings consumption, such as the type, the local climate and how the building is used. The type of building, when broken down, shows domestic buildings consume 28% of the 39% total final consumption of buildings in the UK. The remaining 11% is attributed to non-domestic (Pérez-Lombard, Ortiz and Pout, 2008). The other influences, such as internal heat fluxes from appliances or occupants, can require the HVAC system to consume energy to correct the internal condition (Korolija, Marjanovic-Halburd, Zhang, and Hanby, 2011). There are ways to decrease the energy consumed by the lighting. One method, that has been around since the 1990s, is daylighting systems. This method uses solar shading to block direct sunlight and diffuse light. The method aims to reduce the heat from the sun and prevent glare for occupants. The outcome achieves a bright space that requires little artificial lighting, reducing the heat flux from the penetrating sun and artificial lighting (Kischkoweit-Lopin, 2002). When assessing energy efficiency measures, it is optimal taken into account different approaches to building services and different designs of envelopes that occur in the built environment in addition to the internal and outdoor conditions (Chidiac, Catania, Morofsky, and Foo, 2011; Bain, 2015). Hence, good envelope design incorporating daylighting schemes through solar shading can limit the energy requirements of HVAC systems as internal and external heat fluxes are reduced.

The main aims for HVAC in a building are to provide a comfortable and healthy environment within the building. Ventilation in buildings aims to reduce indoor emitted pollutants, odours and potential chemicals that can cause illness or irritation. Low ventilation rates are linked to an increase in illness, higher chance of sick building syndrome and reduced performance of occupants (Mendell, and Heath, 2005; Wargocki, and Wyon, 2006). With the increase in focus on reducing the energy usage of buildings, through reducing air leaks with improvements to the building's envelope, there is an importance being placed on ventilation to ensure these buildings are healthy spaces for their inhabitants (Ren, and Cao, 2019). This next section will delve deeper into the role of ventilation within buildings.

2.1.2 Ventilation

The exchange of air inside a building, with air from outside, can be allocated into two wide ranging categories: ventilation and infiltration. Ventilation can be further broken down into two categories: natural ventilation and mechanical ventilation (Brumbaugh, 2004).

Natural ventilation comprises of thermal, wind or diffusion effects that passes through opened vents, doors, windows or other modes of ventilation added to the building's envelope. The air passes through these openings due to pressure differences in the outdoor and indoor environments (Emmerich, Dols, and Axley, 2001).

Mechanical ventilation, is the deliberate introduction of air into the building or removing air by a mechanical device. Mechanical ventilation is necessary when natural ventilation cannot deliver the required ventilation rates a space requires. This can be due to the size of the space or the number of people inside. This form of ventilation commonly uses fans to introduce air and force air out through exhausts (Brumbaugh, 2004).

Infiltration is the unplanned flow of air into the building through the use of doors, cracks or unintended gaps. Exfiltration is the unintentional leakage of internal air to the outside environment in the winter months can cause mould growth within the building. The air passes through these areas due to pressure differences. (Sherman, M., 2008). The reduction of infiltration increases the air tightness of the building which is desirable to reduce energy consumption (Ibid). However, infiltration can beneficial in buildings with poor ventilation strategies to improve IAQ.

Both means of ventilation are used widely in the Built environment. However, certain modes are used more widely in certain circumstances. Mechanical ventilation tends to be installed in commercial buildings (Op't Veld, 2008). This allows for the air exchange to be controlled and these systems tend to be pressurised to reduce infiltration. Mechanical ventilation allows the building to have a comfortable environment with good air quality. Whilst natural ventilation has many benefits, including the reduction of energy consumption and emitting less CO_2 and not desirable under certain circumstances due to the heat being lost and lack of control over IAQ (Lomas and Ji, 2009).

Natural ventilation and infiltration are widely used in a residential setting. This can however be unreliable, as they require weather conditions and specific envelope designs (Yao, Li, Steemers, and Short, 2009). However, natural ventilation in residential buildings can be useful in improving the IAQ and to regulate temperature. Mechanical ventilation requires energy to run the fans and ducts and a poorly designed mechanical system can incur large energy demands (Emmerich, Dols, and Axley, 2001)

Natural ventilation also has drawbacks when implementing it into a building, especially a commercial building. Noise pollution can be a major drawback in both residential and commercial buildings, if these are situated close to busy streets in terms of traffic, or venues that open late or have outside areas. The noise can be a nuisance to people working in a commercial building in an urban area (Ghiaus et al., 2006). However, mechanical ventilation is also a noise polluter, as the running of the equipment can produce a noise (Ligang, 2010). As a result, both methods of ventilation have draw backs relating to noise.

Another drawback of natural ventilation is the consequential draughts. In office spaces these can make workers uncomfortable. It has also the possibility of been disruptive objects within the office setting. However mechanical ventilation can suffer from similar problems with increase ventilation rates (Heiselberg, 2004). Thirdly, air pollutants from external air can be a problem, especially buildings in urban areas that are close to busy roads. Dangerous pollutants in cities/urban areas can reach unacceptable levels throughout the day, these pollutants can lead to poor IAQ and be harmful to occupants (Tong et al., 2016).

Ultimately both modes of ventilation have their benefits and drawbacks. However, their main purposes are similar as bother methods want to provide oxygen to the occupants for breathing, dilute gaseous contaminants, control the humidity of the building, control aerosols inside the building and provide thermal comfort to occupants (Awbi, 2002).

2.1.2.1 Ventilation rates

Air ventilation requirements in buildings represent how often the air is required to be changed in a space in an hour which is called an air change rate (ACH). The rates are affected by the size of the space, its occupants and their activity (Brumbaugh, 2004). The ventilation rates have a large effect on the buildings internal conditions, indoor air quality (IAQ) and energy demand. External air that is brought into buildings through mechanical ventilation is cooled or heated, or in some circumstances humidified or dehumidified (Ibid). These actions change the demand for energy of the building which is directly linked to the ventilation rate, the outdoor and indoor temperature, the humidity difference and the design of the building (Ibid). The type of building can change the requirement of ventilation such as offices require an air change rate of 3 per hour (Brumbaugh, 2004; Engineering toolbox, 2021). However, during the pandemic the advice has been to open windows to let as much fresh air in as possible (World Health Organisation, 2021). This has been studied and is shown to generate a number as high as 22.39 air changes per hour (Park, et. Al, 2021). Therefore, the advice has been given to promote good health in building environments and to educe the risk of the being effected by harmful indoor pollutants or diseases. However as seen in sections above the increase in ventilation can result in a magnitude of issues including a rise in energy consumption and a decrease in thermal comfort. The next section present the difficulty of achieving good thermal comfort in a building.

2.1.2.2 Thermal Comfort Metrics

Temperatures in buildings can be difficult to get right, shown in a recent report by Karmann et al. (2017), which stated around 30% of occupants from 3892 respondents were unhappy with the temperature within their office. How comfortable a person within a building, concerning the temperature and ventilation, is personal to them and the environment and is referred to as thermal comfort. Thermal comfort is hard to outline, this is because there are different factors to consider such as: environmental elements, including the outside temperature and air conditioning, personal factors, such as sex, age and health and the occupant’s activity and clothing worn also affects the comfort (Carlucci and Pagliano, 2012). The Health and Safety Executive (1999) suggests workplaces should satisfy the ‘majority’ of the people that occupy the space, as it is difficult to satisfy all the occupants.

2.2 IAQ

The world health organisation (WHO) has their own IAQ guidelines that set out limits for carbon monoxide, formaldehyde and other chemicals based on the time of exposure (World Health Organization, 2010). IAQ has a large effect on the occupant’s health within a building, which is also liked to the probability of infection of COVID-19. Studies have shown a higher rate of infection within cities with poor air quality (Barcelo, 2020; Hassan et al., 2020; Liu et al., 2020)

As a species humans tend to live in heavily populated areas, where air quality levels can be poor. Thus, increasing their likely hood of coming across an infected individual in the case of this pandemic. Governing bodies have realised the possibility of transmission in these areas, so to limit the health and economic impact, guidance on improved ventilation, social distancing, isolation, mask wearing and disinfection (Shakil et al., 2020; Nishiura et al., 2020; Amoatey et al., 2020). The next section proceeds to look further into IAQ in terms of humidity and how the diseases are spread.

2.2.1 Humidity

Humidity is part of the IAQ of a building. The outside climate directly impacts the indoor environment. In cold climates, during the winter months, people spend more than 87% of their time in buildings (Klepeis, et al, 2001). With that taken into consideration it's understandable that the indoor environment has a large impact on the occupants. Existing guidance put out by ASHARE promotes occupant comfort as a main reason to control the internal environment. New studies suggest that occupant health is more important than comfort (Taylor and Tasi, 2018.) The findings in this research have been founded because of the priorities of basic health and well being takes over a person's comfort level. Despite this, it will be important that a person at least receives a basic level of comfort highlighting this as still an important consideration.

During winter months in cold climates, RH can be reduced when cold air is brought in and heated to a comfortable temperature. Low humidity can cause dry skin, difficulty breathing and other issues (Sterling, Arundel, and Sterling, 1985).

The natural immunological defences of the airways, skin and eyes can be impaired when RH is less that 40% (Kudo et al., 2019). The reduced moisture content can lead to occupants being more susceptible to allergic diseases, inflammation and infections (Kudo et al., 2019). Infectious bioaerosols are more prevalent in dry air environments than in hydrated air. In dry atmospheres, airborne pathogens stay buoyant and viable for a prolonged period and are shown to spread more easily in internal breathing zones (Reiman et al., 2018). Humidity in buildings also effects human function. Human bodies can lose water to the environment through sweat glands even when the temperature is low (Hancock, Whitehouse and Haldane, 1929). This water loss can cause mild dehydration which can cause numerous issues, some being concentration, mood and it can also stress brain function (Lieberman, 2007; Ganio, 2011). It can overstimulate blood clotting which can be associated with heart attacks and strokes (Galson, 2008). Humidity can also affect wound healing and skin health, with higher humidity healing wounds at a greater rate (Kruse et al., 2015; Altaf et al., 2021). Low humidity also affects natural immunity in the respiratory tract. As stated above dry air can be harmful to the occupant's health, including the transmission of pathogens, and their brain capacity. Therefore, this means that ventilation can be directly linked to a wide variety of health complications for occupants within the built environment.

Introducing humidity to a building has health benefits for its occupants but there are issues for the building itself. Older buildings tend to be poorly insulated and inadequately ventilated, so when water is introduced into the environment, this allows for condensation to occur. This condensation can promote mould growth within buildings (Lopez-Arce, 2020; Small, 2003).

2.2.2 Disease

In 2020, a novel virus named Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) spread throughout the world causing the global COVID-19 pandemic. At the outbreak there was an understanding that large droplets produced when coughing or sneezing, from an infected individual, would settle on surfaces and be passed on when another individual touched the infected surface and subsequently touched their face. This was thought to be the main mode of transmission. As time passed this mode was deemed to not be the main transmission pathway by the Centres for Disease Controls and Prevention (CDC, 2020).

The focus was then on another mode of transmission. As the pandemic progressed, there was an increase in events that were named 'superspreader' events. These events were indoors and resulted in multiple people being infected from a single source (Li et al., 2020; Hijnen et al., 2020; Kong et al., 2020). These events showed the prevalence of aerosol airborne transmission as a major mode of transmission for the virus. Tests of SARS-CoV-2 have shown that the virus can remain infectious for up to 16 hours in airborne aerosols and have a half-life of over one hour (Fears et al., 2020; Van Doremalen et al., 2020). Research is still on going as to which aerosols and droplets carry the virus, although samples of exhaled droplets from breathing has shown evidence that SAR-CoV-2 is present in small and large aerosol droplets (Ma et al., 2020). Studies into the exhaled breath of influenza and seasonal coronavirus have also shown that the virus is present in small and large aerosol droplets (Leung et al., 2020).

As the evidence grew for aerosol airborne transmission and the prevalence of 'superspreader' events, guidance from international groups that are responsible for building services recommended that all indoor areas should be ventilated as much as possible. The ventilation would allow outdoor air into the building which in turn would dilute the infectious aerosols. (CIBSE, 2021; ASHARE, 2020). The guidance has been generalised to increase ventilation as much as possible without major detrimental effect to energy demand or thermal comfort. Due to this, there is no set guidance per person due to the lack of understanding of the virus.

2.2.2.1 Droplets

Aerosols are produced from the respiratory system and form during different respiratory activities such as talking, shouting, coughing, laughing and breathing. The aerosols are expelled as droplets. The size of droplets can range from 1um to 100um and their size changes for different activities (Duguid, 1946). These droplets are a potential host for pathogens that can transmit airborne viruses. The size of the droplet has an impact on the probability of transmission. Large droplets of over 200um only suspend in the air for seconds and fall to the floor under gravity, a lot of the pathogens can be found in the large droplets. Smaller droplets under 20um evaporate quickly and become droplet nuclei, which can be suspended in the air for hours and be circulated over large areas through airflows. The inhalation of these pathogen carrying droplets is called airborne transmission. (Chao et al., 2009). Although larger droplets have a higher ability to carry a pathogen, smaller droplets can have a higher infectivity, due to them being able to infiltrate the lower respiratory tract, which is the prevalent infection site for diseases, such as tuberculosis (Nicas et al., 2005). Therefore, the size of the droplets is a key factor for the transmission of the disease and the area of effect.

As shown above, the droplet size has a huge importance in disease transmission. This has resulted in numerous studies on the size of the droplets expelled during different respiratory activities. Studies carried out in the early 1900s showed that droplets expelled during respiratory activities were in the submicrometric size (Duguid,1945; Jennison,1942; Wells, 1934). These results were mainly due to the techniques and technology that was available at that time, meaning smaller droplets were difficult to measure. The studies consisted of examining droplet sizes from slides that were placed in front of the mouth during the different respiratory activities. Due to the environment and distance from the mouth, it is possible that droplets could have reduced in size due to evaporation. Duguid (1945) stated that 95% of the droplets exhaled were smaller that 100um and the highest number of droplets ranged from 4 – 8um. Consequently, as technology has improved so has the understanding of droplet size exhalation. Early studies set the basis of understanding of disease and pathogen transmission.

Newer studies have been carried out with a more modern approach using optical particle detection technology. This has allowed for detection of smaller droplets down to submicrometere range (Papineni and Rosenthal,1997; Fairchild and Stamper, 1987). The Papineni and Rosenthal study (1997) used particle detection counters that had a range of 0.3 – 10um, along side electron microscopy to detect the droplets. This study showed that the majority as high as 80-90% of expelled droplets during respiratory activities are smaller than 1um (Ibid). The study also showed that the lowest concentration of droplets was expelled during breathing through the nose and the highest concentration was generated during coughing. However, the results were not the same for each person involved in the experiment. Coughing for four of the participants expelled the larger concentration of droplets compared to brought through the mouth but this was not true for one participant. The participant expelled a larger concentration of droplets, larger than 1um when breathing compared to coughing (Ibid). This shows the nonlinear fashion of expelled droplets. There can be large variances in concentrations from person to person. A more recent study conducted by Yang et al. (2007) showed a range from 0.6 – 16 um and an 8.35 um average for cough droplets that have not dried. Yang et al. (2007) also used optical particle counters but utilised a different technique; the participants were asked to cough into bag. Although the previous studies used modern techniques, they still suffered from the same problems the initial studies suffered as the droplets were not instantly captured and can be affected by their environment.

The studies carried out by Morawska et al. (2009) and Papineni and Rosnthal (1997) both concluded that most of the droplets were found in the submicrometer and low micrometer range, during human respiratory activities. Morawska et al. (2009) found that the average diameters of droplets were the following sizes for these activities: breathing = $\leq$0.8um, coughing = 1.8um and speech = 3.5-5.5um.

The evaporation rate of droplets is dependent on the temperature and humidity of the environment. Evaporation causes the droplet to reduce mass and their terminal velocity. The size of droplets can be reduced by the relative humidity (Su et al., 2018; Lu et al., 2019) As a result, the droplets that can carry a virus can be reduced through careful humidity set points. The next section will look at the effect RH can have on infection rates.

2.2.2.2 Humidity effects on viruses

The environment of a space can have a large influence in the reduction in size of a droplet. Humidity is said to have a large effect on the control of transmission for a virus (ASHARE, 2020). A study by Taylor and Hugentober (2016) showed that having internal humidity between 40-60% can reduce healthcare-associated infections (HAI). The study was carried out in a hospital in the United States of America over a year. The temperature, absolute and relative humidity (RH), CO2 levels, occupants coming and going, external air fractions and the lighting was tracked throughout. The RH had a range between 32 to 42%, the results in Figure 1 show that as the humidity rose closer to 42% the rate of HAI decreased.

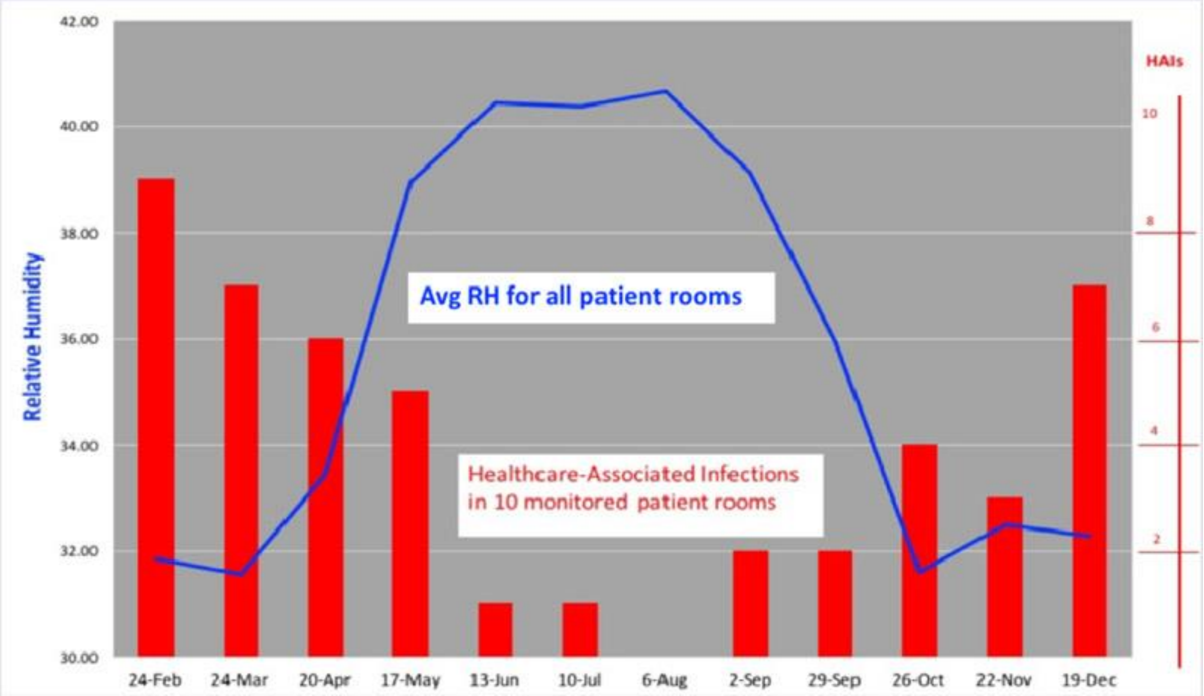

Figure 1: RH effect on the rate of infection

Derby et al. (2018) also studied the effects of RH on patient infections in a long-term care facility. The study was conducted over 4 years, the results showed that low indoor RH increased the infections within patients especially respiratory infections. The study also found the ideal RH for the indoor environment to prevent infections was between 40-60%. Hence, the studies have found a range of humidity's within a building setting that can reduce the risk of infection.

2.3Conclusion

To conclude, the review of literature has uncovered the aims governing bodies have for the built environment and how this can be achieved through zero energy buildings. However, it has also shown that certain aspects such as the IAQ can be neglected if energy consumption can benefit. As seen in the literature the governing bodies have adjusted their focus on the health aspects of occupants within a building setting, to achieve this they have advised to increase the amount of fresh air allowed into the building. The review has also shown a short coming in terms of research into the transmission of diseases within buildings. New research has outlined the benefits of having better controlled spaces in terms of ventilation rates and humidity. The literature shows that virus transmission pathways are well founded however droplets for diseases is of less knowledge. The review showed a hole in terms of a definitive conclusion to what droplet sizes carry pathogen and how many need to be inhaled to infect a host.

Therefore, the literature review has steered this study to look at the requirements for fresh air in a building environment and analyse the air change rates the new guidance set by governing bodies has promoted. The study will also compare the energy consumption of said guidance and subsequent air changes the guidance has promoted with a ventilation strategy that aims to bring balance to energy consumption and a healthy built environment.

3.0 Methods

As airborne water droplets are thought to be the main mode of transfer of SARS-CoV-2 and other respiratory infections. It is unknown exactly what size of droplets carry the diseases with studies finding it can be all sizes. This methodology will set out the calculations and assumptions made when finding the fresh air requirement set by WHO, how much fresh air is delivered by air change rates and their subsequent energy consumption. Finally, a proposal will be made that refers to literature to find a balance between energy consumption and a healthy environment in a winter day in the United Kingdom. The models will be created in excel and the data will be extracted in a presentable format.

The research will use assumptions for the base values for the calculations. The first assumption is that the building type is an office, these effect the ventilation rate and subsequently is a basis for the occupancy levels and volumes of the space. The second assumption was for the occupancy, it is assumed 25 people would occupy the space for the initial equations. The volume of the office was determined by using an average from literature of 25.7m^3 per person (Saari, 2006). This resulted in a volume of 642.5m^3.

The first calculation will be to determine the requirement of fresh air required for the 25 occupants for the building. The rate per person of 10 l/s per person for this equation has come from WHO guidance (World Health Organisation, 2021). The proceeding formula is used to calculate fresh air requirement when the number of occupants is known (Commonwealth of Australia, 2012):

$$Quantity\ of\ air = Number\ of\ occupants\ x\ rate\ per\ person$$

The result from the above equation will then be compared to the results of different air change rates found in literature. The air changes that will used 0.06 h^{-1} (Ng, Persily, and Emmerich, 2015), 0.55 h^{-1} (Gładyszewska-Fiedoruk and Krawczyk, 2014), which both represent low infiltration rates for buildings. The new two set of numbers are seen as guidance for an office space 3 h^{-1} (Engineering toolbox, 2021) and a hospital 6 h^{-1} (Engineering toolbox, 2021). Final the last group is made up of recommended air change rates for office with wearing a mask 18 h^{-1} (Dai and Zhao, 2020) and without wearing a mask 80 h^{-1} (Dai and Zhao, 2020). The last number is from a study that analysed what the air change rates would be at different levels of opened windows, the 100% opened was subsequently chosen as it is in line with guidance to open windows, the air change rate is 22.39 h^{-1} (Park, et. Al, 2021). The equation requires two variables in this case the air change rate and the volume of the space, which has already been obtained. The proceeding formula is used to calculate fresh air requirement when the air change rate is provided (Commonwealth of Australia, 2012):

$$Quantity\ of\ fresh\ air\ required = \frac{Air\ change\ rate\ x\ volume\ x\ 1000}{3600}$$

Once the quantity of the fresh air received from the air change rates has been calculated and discussed the next step will be to calculate the air change rates energy consumption. To calculate this the heat transfer equation is used. For this equation to be used the quantity of fresh air generated from the previous equation must be changed from l/s to the mass flow rate. There is one other variable for this equation, which is the change in temperature (ΔT). To determine this an assumption of the temperature must be made for the model. The temperature of the external environment effects the internal conditions as seen in the literature. This study will use set points for the external weather that can be seen in the United Kingdom winter to determine the energy used in the conditioning of the environment. For the winter a temperature 0°C and a humidity of 60% was assumed this can be seen in the United Kingdom during the peak of the summer and with the increase volatility of weather it could be seen more regularly. The other seasons aren't covered winter is the extreme case for cooling heating within the cold climate.

In this case the starting temperature is 0°C and the ending temperature is 20°C therefore the change in temperature equals 20. The specific heat capacity of air was taken as 1 kJ/kg.K (Kluitenberg, 2002). The heat transfer equation (Brumbaugh, 2004):

$$Q = \dot{m}c_p\Delta T$$

After analysing the results of the calculation, the next stage will be to generate a ventilation strategy that can be compared to the existing options.

To calculate the energy consumption for the mechanical ventilation system the heat balance equation will be used. The first internal condition that will be used for the model is 20°C and a RH of 20%. From there the humidity will be increase to 40% which is in line with the literature that shows the health benefits of keeping a 40-60% RH in a building and then the RH will be increase by 10% for the subsequent two results finishing within the range of RH health benefits.

The values to work out energy consumption for the ventilation system such as the specific enthalpy and temperatures were obtained through the psychrometric charts, like the one seen in Figure 2.

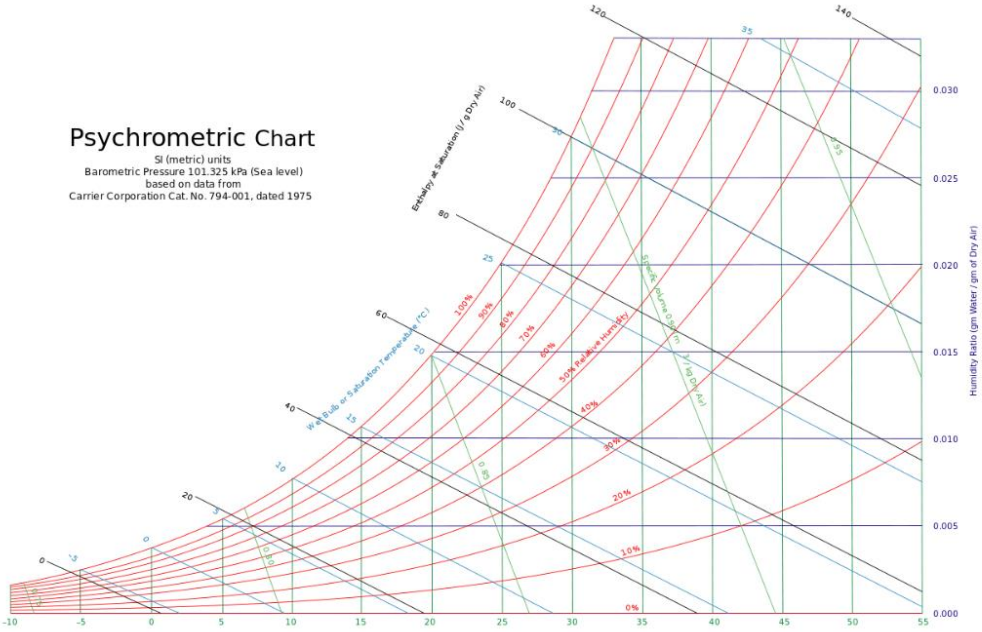

Figure 2: Psychrometric chart (Designing Buildings, 2020)

The specific heat capacity of air will remain the same as the previous equation. Lastly the occupants and the ventilation rate of 10 l/s per person will be used to create a mass flow rate. The heat balance equation (Brumbaugh, 2004):

$$Q = \left(\dot{Q}_c + \dot{Q}_a\right) = \dot{m}_w c_{pw}(T_{wo} - T_{wi}) = \dot{m}_a c_{pa}(T_{ai} - T_{ao}) + \dot{m}_c h_{fg}$$

For the final results, the heat balance equation will be used again with only the ventilation rates and the number of occupants changing. The final results will use ventilation rates of 10 l/s, 12 l/s, 14 l/s and 16 l/s. The number of occupants will decrease to 18 people.

4.0 Results

The following section will present the results found in the calculations that have been set out in the methodology section. The results for energy loss through the higher air change rates in buildings will be analysed. An option to reduce the energy loss will then be set out and analysed. The energy demand of the heating, cooling which both include humidifying, and dehumidifying and reheating outside air that is brought into an indoor environment, in this case an office. The results will be analysed with each change in humidity, change in ventilation rate and occupancy. The benefits and downsides of the outcomes will be discussed.

4.1 IAQ

The results set out in this section will show the level of fresh air required for a small office of the volume 642.5m³ with 25 staff members. The section will then present the varying level of fresh air brought into the created building through the different air change rates found in literature or guidance.

Table 1: Fresh air requirement for office building

Number of occupants	Fresh air requirements per person	Total fresh air required (l/s)
25	10 (World Health Organisation, 2021)	250

As seen in Table 1 the ventilation required for the office is 250 l/s to achieve the minimum recommended ventilation rate for a safe space set out by WHO (World Health Organisation, 2021).

Table 2 Fresh air delivered dependent on air change rate

Air change rate (h^{-1})	Ventilation delivered (m³/s)	Ventilation delivered (l/s)
0.06 (Ng, Persily, and Emmerich, 2015).	0.01	10.42
0.55 (Gładyszewska-Fiedoruk and Krawczyk, 2014).	0.10	95.49
3 (Engineering toolbox, 2021).	0.52	520.83
6 (Engineering toolbox, 2021).	1.04	1041.67
18 (Dai and Zhao, 2020).	3.13	3125.00
22.39 (Park, et. Al, 2021).	3.89	3887.15
80 (Dai and Zhao, 2020).	13.89	13888.89

The varying air change rate in Table 2 represent air change rates found in literature and what they would deliver in terms of fresh air into the assumed building. The first value of 0.06 h^{-1} is from air infiltration rates of a high-quality insulated building, which delivers a small amount of fresh air by design which ultimately is significantly smaller than the minimum recommended for the office space. The second air change rate of 0.55 h^{-1} is from research of doctor's offices. This number represented an office with windows and doors closed (Gładyszewska-Fiedoruk and Krawczyk, 2014). Again, this doesn't meet the required fresh air for the office. The subsequent two numbers are the recommended air change rates, 3 is the recommended for an office space and 6 is recommended for a hospital room (Engineering toolbox, 2021). These rates both give able amount of fresh air to the office space with 520.83 l/s and 1041.67 l/s respectively. Therefore, the recommended set point for offices of 3 air changes per hour results in more than double the required fresh air for the occupants. The proceeding numbers are in reaction to the SARS-COV-2 pandemic, the air change rate of 18 h^{-1} is recommended though testing undertaken in a study by Dai and Zhao (2020). The number is recommended to reduce the probability of infection to 1% in an office space over an exposure time of 8 hours if all occupants wear a mask. This results in a number 12.5 times greater than the minimum requirement in Table 1. The final number comes is also from Dai and Zhao's 2020 study. This number is recommended if the occupants are not wearing a mask. The air change rate is drastically increased when masks are not being worn in the space, resulting in an increase of over 344.44% from the non-mask wearing recommendation. Lastly the 22.39 h^{-1} air change rate is from a study by Park, et, al. (2021) using opened windows as a strategy to prevent transmission of COVID-19. The study found that when the windows are open fully there is an air change rate of 22.39 h^{-1} producing 15.55 times the minimum requirement for buildings. Although the higher rates deliver more fresh air than recommended, thus reducing the probability of infection, this will result in significant energy loss.

4.2 Energy loss

The following section will present the results from the energy consumption equations set out in the methodology. The air change rates in the previous section have been used to determine the energy used to heat the office from 0˚C to 20 ˚C, this was assumed for a cold winters day in the UK.

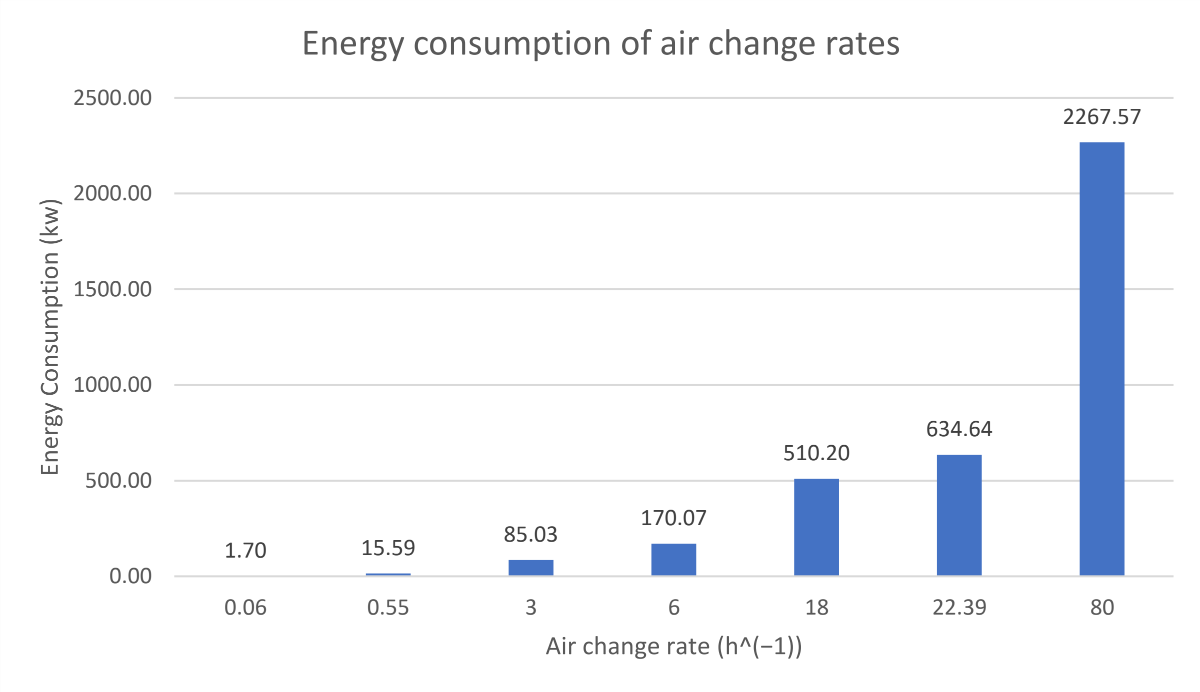

Figure 3: Energy consumptions of air change rates

Figure 3 shows the results from the calculations undertaken; the order of the air change rates is the same as seen in Table 2. The first air change rate shows little energy is needed to heat the office, this shows that the design of having high thermal efficiency allows for lower energy consumption. However as seen in the previous section the fresh air supplied does not meet minimum requirements. The second air change rate also has the same benefits and negatives as the previous, they allow for good energy efficiency but ultimately, they produce an unhealthy building which would lead to occupant sickness. The next two results show an increase in energy which is to be expected. They also allow for the minimum recommended fresh air requirement. The next group of results have a drastic rise in energy consumption which ultimately would be loss of energy. Each air change rate is assumed to be achievable through opening the windows fully and allowing natural ventilation to supply the fresh air. However, with the outside temperature being at 0˚C the space will have to be heated to allow for thermal comfort of the occupant. In the case of the air change rate of 22.39 (h^{-1}), 634.64 kW would be consumed in one day with almost all of it leaving the building. The continuous air change rate would bring in cold air into the building resulting in a temperature being somewhat lower than 20 ˚C. This level of energy loss cannot be sustained in winter months. It is the polar opposite of the high thermal efficiencies and low energy consumption of zero carbon buildings (Torcellini, Pless, Deru, and Crawley, 2006).

4.3 Ventilation

Following on from the energy loss for the air change rates in the previous section the energy consumption for conditioning the air for the space is set out in this section. The equations have a basis of taking outside air at a temperature of 0˚C at a humidity of 60% RH which can be typical of a winter's day in the UK. The outside air is then heated to 20 ˚C which reduces the humidity of 15% RH. Moisture is then added to the air to increase the humidity. The ventilation rate for this result was set as the minimum recommended of 10 l/s per person by the World Health Organisation (2021).

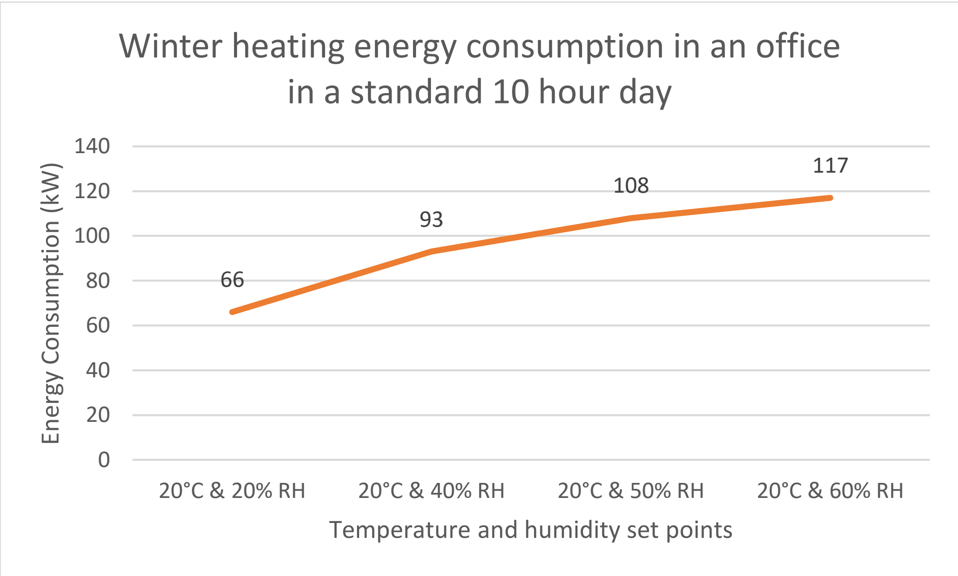

Figure 4: Winter heating energy consumption in an office in a standard 10-hour day

As stated above in figure 4, the process bringing in outside air and heating it to a set temperature decreases the humidity found in the air. Due to this, humidity needs to be added to the air to bring it to an acceptable level for health purposes. However, a set point of 20% RH was shown to compare the energy consumption increase when adding moisture to air. The second set point represents the energy consumption to bring the humidity from 15% to 40% at 20 ˚C. The 40% RH set point is from literature which shows the minimum humidity for healthy buildings is 40% (Derby et al., 2018; Taylor and Hugentober, 2016). The energy consumption for the set point 40% RH represents a 27 kW increase in consumption from the 20% RH set point. This demonstrates that increasing the humidity can be an energy intensive process. The next set point increases the relative humidity to 50% (Cortiços, and Duarte, 2021). The increase represents the middle of the minimum and maximum recommended relative humidity set points. The increase in humidity subsequently increases the energy consumption, the consumption grew by 13.9%. The final set point is 60% RH. This represents the highest recommendation for a healthy building. The energy consumption increases again but at a smaller rate of 7.7%.

The energy consumption result for the mechanical ventilation at 20˚C at 50% is an 87.06% reduction from the energy consumption from the air change rate of 22.39 replicating open windows.

The pandemic has allowed for new flexible working schemes, such as working from home. If buildings are able to predict the number of occupants that will be in the office per day. There is an opportunity to adapt the ventilation scheme. This in turn can help the overall ventilation schemes for offices, the reduced number of staff members in the office can reduce the fresh air requirement and ultimately reduce the energy consumed. The reduced members of staff can also offer an opportunity to increase the ventilation per person to create a healthier environment. In the case of the office modelled if the members of staff were reduced to 18, the increased ventilation rates have been modelled in Figure 5.

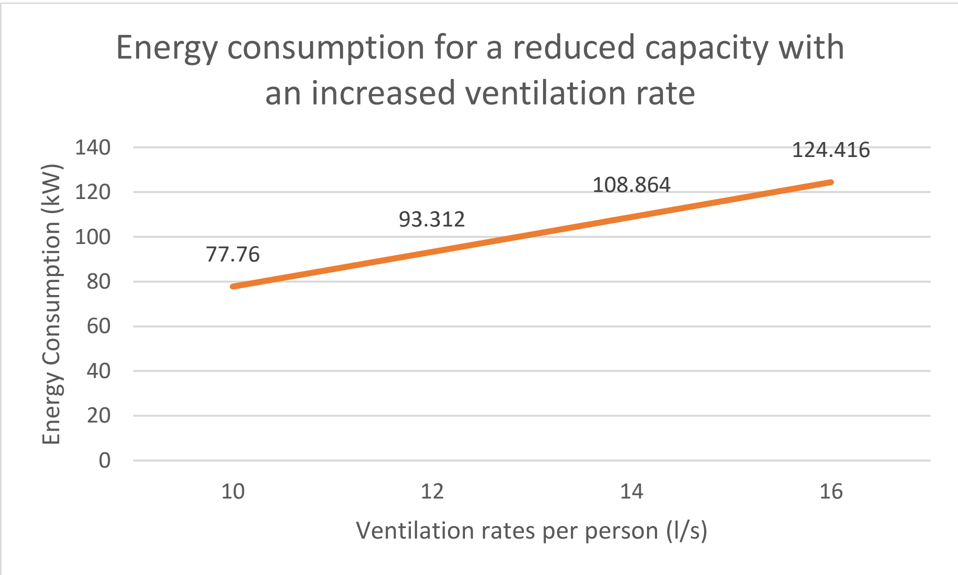

Figure 5: Energy consumption for a reduced capacity with an increased ventilation rate

The energy consumption of ventilating the room can be seen in Figure 5 For this test the humidity set point of 50% was deemed the appropriate number to take forward and compare.

If the ventilation rate stayed at 10 l/s and the capacity was adjusted, a saving of 30.24 kW could be made on this day. However, due to the on-going pandemic guidance it is advised to increase the ventilation rate to as much as possible. In this case a ventilation rate of 14 l/s would only incur an increase of energy demand of 0.8% while subsequently allowing a further 4 l/s of fresh air per occupant.

5.0 Discussion

Since February 2020, the global SARS-CoV-19 pandemic has restricted most people to their homes and away from friends, family and work. This has pushed transmission modes to the forefront of research of disease. The research has shown in the case of SARS-CoV-19 aerosol transmission is the main mode of the spread of the virus which was evident through super spreader events. Other diseases like the common cold or the flu have a similar primary transmission. For instance, the flu results in deaths, serious illness and is expensive to businesses with staff being off due to sickness.

This posed a problem, as seen in literature, since the introduction of the European Union Energy Performance of Buildings Directive in 2010 where the overall aim for the built environment is to become more energy efficient. To achieve this, a “fabric first” approach, as seen in the future home standard guidance, has been adopted in the UK (Ministry of Housing, Communities & Local Government, 2021). This is achieved by increasing the thermal performance of the building, ultimately reducing the air infiltration rate (Ng, Persily, and Emmerich, 2015). The reduction in air change rate, achieves a low energy consumption, seen in Figure 3, but in doing so it allows a small amount of fresh air into the building, seen in Table 2. The air change rate would only allow fresh air of 10.42 l/s into the room. The air change rate of 0.55 h^{-1} from an office that had the door and window closed also produces lower fresh air than what is required (Gładyszewska-Fiedoruk and Krawczyk, 2014). Therefore, with human behaviour tendencies to close windows in the winter these values would create an unhealthy environment (Langevin, Gurian, and Wen, 2013). The results would not only increase the probability of catching COVID-19 and other seasonal virus but expose the occupants to high levels of CO2 and other harmful pollutants. In response to this WHO advised that open windows would help prevent the spread of the virus in buildings (World Health Organisation, 2021).

The pandemic has shone a light on IAQ of buildings and their role in spreading diseases (Dai and Zhao, 2020) (Park, et. Al, 2021). In response to the outbreak the advice was to open windows to allow as much fresh air to flow into areas to reduce the risk of infection (World Health Organisation, 2021). This in turn would increase the IAQ of the building by diluting the virus if it is present in the air and allowing for more fresh air per person in the building. This can be seen in Table 2. The 22.39 h^{-1} air change rate produces an 3887.15% increase in required air quality from the recommended guidelines. However, this doesn’t come without its drawbacks. These measures have a high energy consumption seen in Figure 3 The study by Park, et. al (2021), showed fully opening the windows as advised by WHO results in 22.39 h^{-1} which would result in a 634.64 kW energy loss in one 10 hour day. The energy consumption results of the study show that reducing the risk of outbreaks in work settings can be an extremely energy intensive operation and it is not achievable for all buildings. The energy consumption is due to the thermal comfort of the people occupying the space. In winter months, having the windows open throughout the day would result in a cold office space and draughts. One issue with this is as stated above heating would need to be used to heat the space to a set point. Although the room wouldn't reach that set point due to the cold air coming in, meaning heat will escape resulting in energy loss throughout the day. This leads on to the second issue. Due to people being uncomfortable with the low temperature in the office, they will close the windows, resulting in increased bad pollutants and increasing the probability of infection from COVID-19 or other seasonal viruses.

When comparing the 10 l/s at 50% Rh, the recommended set point for an office space of 3 air changes per hour, does achieve an increase of 108.33% in fresh air required and a reduction in energy consumption a day of 21.27%. However as seen in literature IAQ especially RH within a building can be hard to achieve in naturally ventilated buildings (Lomas and Ji, 2009). As literature shows the control of RH within a building space can be beneficial to the health of the occupant (Derby et al., 2018).

As shown above both approaches of having energy efficient buildings with poor ventilation, or lowering the risk of transmission through open windows, can have a similar outcome. Even if they succeed in their main goal, the other side can suffer. Therefore, a solution must be found to find a balance between health and energy consumption. This is a multifaceted problem which will need an adaptable solution. Different climates and different seasons require measured responses. For instance, in winter months, during colder climates, as seen above, the response is to close the windows. This could mean spikes in infection cases in winter months. As shown in the literature and confirmed by this study, there is no definitive safe option, and it is about reducing the risk rather than being able to eradicate the risk. With SARS-CoV-2 and other respiratory infections the main transmission mode is airborne droplets. It is hard to determine the exact number of droplets that is needed to infect people and what droplets are infectious. Also, some could be infectious to one person but not another. Due to the wide unknowns about the transmissions of diseases, it is hard to determine a risk-free indoor environment. However, through guidance from governing bodies and through literature of humidity levels an option has been proposed in Figure 4.

Literature of disease infection rates (Derby et al., 2018; Taylor and Hugentober, 2016) showed a reduction in infection rates of patients in medical facilities when the relative humidity was kept between 40-60%. Also seen in literature the immunological defences of the airways, skin and eyes can be weakened when Rh is below 40%. As RH cannot be set in naturally ventilated buildings, this is an aspect that can be harmful to the occupants in winter months, as the RH could conceivably go below 40%. This was the basis of the proposal for the ventilation results set out in Figure 4. The ventilation rate of 10 l/s was taken from the WHO, as the minimum guidance for emerging from lock down (World Health Organisation, 2021). The ventilation rate can also have a role to play in forcing larger droplets to the ground (Duguid, 1946). The temperature set point of 20˚C for the office was deemed to be just under the 80% acceptable range (De Dear and Brager, 1998). It was assumed the occupants could wear better thermally insulated clothing as an offset of saving energy.

Therefore, the proposal found in Figure 4 was based on the above literature. The outcome showed a range of results from 93 – 117 kW. These results are larger than the lower air change rates which are to be expected, especially the 0.06 h^{-1} air change as this is created to be low energy consuming. When comparing the results to the ASHRAE suggestions for offices and hospitals consumption the upper range of the results 117 kW has lower energy consumption than the hospital set point of 170.07 kW but greater than the office set point. These two set points deliver a far greater volume of fresh air than required. Finally, the energy consumed for air change rates when the window is open to the proposed system at the highest consumption of 117 kW has a difference of 517.64 kW per working day. Other than the high air change rates, another reason why the energy is so high is the air change is for the full volume of the office, whereas the ventilation system proposed is ventilating the room according to each occupant. Therefore, a reduced energy consumption is seen.

Having a controlled ventilation system that ventilates per person allows for a greater amount of freedom when aiming to reduce the energy consumed but maintain a healthy environment. The SARS-CoV-2 pandemic has changed working for some people, working from home became a new normal for people and has allowed people to a have a hybrid work scheme of working at home on certain days and within the office others. This can be beneficial to a controlled ventilation system, which is proposed in Figure 5 For this result it was assumed only 18 staff members were in the office that day, with 7 working from home. The RH was taken as 50% this allowed for the increase in ventilation rates to create what would subsequently be a healthier building environment. One issue with increasing the ventilation rate can be the presence of draughts for the occupants. The results in Figure 5 show that a reduced occupancy can reduce the energy consumption 28% for a day if the ventilation rate of 10 l/s is maintained. However, if the ventilation rate is increased to 14 l/s it is a small increase of 0.8% in the energy consumption from the 108 kW result at 10 l/s but with 25 occupants. The final result of 124.42 kW shows a 14.29% increase from the 14 l/s at 50% set point however it is still a saving of 510.22 kW a day from the recommendation of opening windows and the subsequent air change rate for buildings energy consumption.

Therefore, the proposed solution that could potentially find a balance between health and energy consumption is a ventilation rate of 10 l/s per person at a set point of 20˚C and 50% humidity if the office is fully staffed. However, if the work tracks what days people will be at home and what days they are in, a tailor-made ventilation rate can be set, which increases the IAQ and maintain a steady energy consumption.

6.0 Conclusions

In conclusion, the guidelines set out by WHO to alleviate the probability of infection in building areas has allowed for more fresh air to be brought into spaces, if the open windows guidelines are adhered to. However, as shown in the results, the high air change rate of opening windows can lead to an increased level of energy consumption within buildings. Although this is due to unforeseen circumstances regarding the pandemic meaning the reaction is more than reasonable, this is the antithesis of what the aims are for the built environment and its role in tackling climate change. The pandemic has shone a light on unhealthy buildings and their detrimental effect on human health, which has allowed research to refocus on health and wellbeing in the built environment. As shown in the literature and the results there is no silver bullet in terms of zero energy consumption and a good healthy environment. There may never be a time when that is possible, considering the fact that often when trying to achieve either one of the aims, the other has been shown to be somewhat compromised. However, developing ventilation strategies that can find a balance to allow people to populate buildings with a reduced risk of catching a virus and not waste a high amount of energy consumption, such as having opened windows, can be achieved. From the study a set point of 50% RH with a 10 l/s ventilation rate if fully occupied, however a variable ventilation rate corresponding to occupants with 50% RH could be desirable. The prevalence of seasonal virus and COVID-19 spread in the winter months means this should be a priority to mitigate. This report sets out a possibility for a ventilation scheme in a small office, that achieves the balance of providing a healthy environment in terms of humidity and ventilation rates at an energy consumption below the perceived amount currently advised.

There is more work to be done in this field, firstly a study into the probability of infection at 50% RH and ventilation set points of 10 l/s, 12 l/s, 14 l/s and 16 l/s which are outlined in the study could be undertaken. To further the previous study the droplet sizing and how the set points affect them could improve the study. A study that uses real weather set points that are adjusted for future global warming outcomes could be analysed, this would create a more accurate model in terms of energy consumption of the building. Further work into this study could be further enhancement of the model with the incorporation of ventilation heat recovery. Also, another addition to the ventilation system could be technologies such as UVC or other sterilisation ventilation units. Finally, as this study only targets the winter cooling period a hybrid system could be incorporated for the summer months. Despite the fact that there is still ample room for further research in this area, this study has moved the literature on and contributed to the idea that some sort of a balance is achievable without overly compromising either the energy consumption or health risks.

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