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NATURAL VENTILATION AND ENERGY EFFICIENCY IN NON-DOMESTIC BUILDINGS

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Abstract

Over the past 50 years the use of air conditioning in non-domestic buildings has become a norm and an indicator of status. Today the rediscovering of the natural ventilation is a part of rediscovering the buildings' energy efficiency, or maybe even a part of a wider approach, which is a desire to be closer to nature. The main task of all ventilation systems is to maintain an appropriate indoor air quality and to improve the indoor environment. Natural ventilation systems could do the above using less energy than mechanical systems. However, it requires also the implementation of other passive measures. The most important of them are: the reduction of the harmful air contaminants, the control of heat gains, the exposition of the building's thermal mass and utilisation of the night cooling. Because of energy efficiency and thermal comfort reasons, in temperate climate ventilation systems have to work according to at least three scenarios: spring/autumn, winter and summer. The thermal comfort parameters in naturally ventilated buildings are usually more variable than in air-conditioned ones, what does not mean that the occupants will experience thermal discomfort. Therefore, thermal comfort in passively ventilated buildings should be evaluated according to the adaptive comfort standard, appropriated for the naturally ventilated buildings. The natural ventilation has its limits and probably not all buildings can be ventilated naturally. From the energy efficiency and thermal comfort reasons, implementing the mixed mode systems is sometimes more feasible. However, the real reason why the full potential of natural ventilation could not be explored is very often the lack of confidence in relying exclusively on it.

Keywords: natural ventilation, adaptive thermal comfort, energy efficiency, air quality, passive cooling, risk of overheating, thermal mass

INTRODUCTION

The main task of all ventilation systems is to maintain an appropriate level of indoor air quality (IAQ). Another role of ventilation is, in combination with other measures, to improve the building's thermal comfort (CIBSE AM10 2005). Naturally driven ventilation, if done properly, can achieve the above aims with less energy than mechanical systems (Passe and Battaglia 2015).

"From an energy perspective, losses resulting, from ventilation and general air exchange can account for more than half of the primary energy used in building. These losses comprise space heating and refrigerative cooling losses as well as the electrical load associated with driving mechanical and cooling services" (CIBSE Guide A 2015). Better energy performance of natural than of mechanical ventilation systems, is one of the main reasons why investors decide for natural ventilation. Another important reason why naturally ventilated buildings are built is that simply the users prefer them. Occupants prefer naturally ventilated buildings even then they offer wider range of temperature and other thermal comfort parameters than the mechanical ventilated buildings. Passively ventilated buildings are preferred especially if the occupants can control the indoor climate parameters by themselves (Passe and Battaglia 2015).

REDISCOVERING THE NATURAL VENTILATION

"Natural ventilation is the process by which airflow is driven by the natural forces of wind (wind effect) and temperature difference (stack effect)" (CIBSE Guide A 2015). Till the mid of the 20th century most of the buildings all around the world were ventilated naturally. To utilise the natural forces, which drove the air stream through the buildings, their designers had to consider the passive measures and the local climate. Even the first sky skyscrapers, built in the first half of the 20th century, were ventilated naturally. Only around the 1950s the availability of cheap energy and the widespread use of air-conditioning, had changed this approach (Wood and Salib 2014). The dependence on very energy consuming air-conditioning and artificial light, allowed emergence of buildings' types which were disregarding the local conditions. They were deep-planned, transparent and very similar around the world. The transparency, lightness of the structure and lack of solar shading were causing the high solar and cooling loads.

The turning point in this approach was the oil crisis of 1973. As the result of this crisis the western countries started to think about saving energy. In the building industry the area, where the most savings could be found, was the energy consumption for heating, cooling and ventilation. Unfortunately, the main aim was only to reduce the energy consumption for heating, by increasing the insulation level of the building envelopes and reducing the air infiltration level by sealing the buildings. These measures even increased the dependence on mechanical ventilation and cooling, and often were reasons for the poor indoor air quality, which had a negative impact of occupants' health and comfort. In 1984 WHO published a report suggested that up to 30% of new and remodelled buildings worldwide could have poor indoor quality (Sick building syndrome (SBS) 2016)) and people started to relate the mechanically ventilated buildings with "sick building syndrome". "Sick building syndrome is a phenomenon affecting building occupants who claim to experience acute health and comfort effects that appear to be linked to time spent in a building, but no specific illness or cause can be identified. SBS is also used interchangeably with „building-related symptoms", which orients the name of the condition around patients rather than a „sick" building." (Sick building syndrome (SBS) 2016)).

In 1980s and 1990s designers were looking for the greater building energy efficiency and healthier indoor environment at the same time. They started to consider passive measures as less energy consuming and healthier, and the natural ventilation is a part of this approach (Wood and Salib 2014).

Researches show that people feel better in naturally ventilated buildings, especially if they have control over it (Passe and Battaglia 2015), which has a positive impact on employee productivity. Naturally ventilated buildings are also less often connected with SBS syndrome. Two American organisations the Advanced Building Systems Integration Consortium (ABSIC) and the Center for Building Performance and Diagnostics (CBPD) have created the Building Investment Decision Support (BIDS), which includes a cost-comparison of mechanical, mixed-mode and natural ventilation systems. This comparison shows that the savings in naturally ventilated or mixed mode buildings will be 47-79% on HVAC systems, a 0,8-1,3% savings in heath costs, and 3-18% gain in productivity.

However, it has to be mentioned that although the natural ventilation systems do not require technical equipment in such amount as the mechanical ones do, but to utilize the natural forces they require individual approach and special measures like: atriums, double-skin elevations, winter gardens, solar chimneys, chimneys, openable windows, wind catchers, massive construction and others, which could cause higher construction cost. European practice shows that already 30% of yearly occupational hours utilizing natural ventilation will justify the mixed-mode strategy economically (Gonçalves 2010), but for many investors this higher initial cost can be a difficult barrier to overcome. On the other hand, there are examples that show that the construction costs of the naturally ventilated buildings do not need to be higher than of the mechanically ventilated ones. One of these examples is the naturally ventilated Queens Building De Montfort University in Leicester. In this case it was a fundamental requirement of the Polytechnic and Colleges Funding Council that the construction process has to be no more costly than that of a conventional building. Cost comparison done by the quantity surveyor indicates that "the savings on mechanical and electrical services and finishes amount to approximately 9% of the total contract value, but that these were absorbed by higher superstructure costs" (New Practice Case Study 102 1997).

VENTILATION AND AIR QUALITY

The major role of all ventilation's systems is to secure optimal indoor air quality. In temperate climate, most people spend most of their time in buildings. Therefore, as it has been said already, indoor air quality has a big influence of people's health and well-being. Ventilations systems are diluting and removing from the indoor air:

- carbon dioxide,
- Volatile Organic Compound (VOC),
- odors,
- humidity,
- particle loads and other harmful air contaminants,
- heat gains,

and providing:

- oxygen dioxide.

The main health concerns related to poor indoor air quality include: asthma and cancer risk potentially caused by VOCs, radon, odors and chemicals, allergies, ozone irritation, and other respiratory problems (Passe and Battaglia 2015). Ventilation provides fresh air, dilutes and removes potentially harmful airborne contaminants. The amount of fresh air needed to dilute and remove the stale air depends on the amount of the airborne contaminants and heat gains. Usually the natural ventilation is less powerful than the mechanical one. Air movement, and connected with it efficiency of ventilation, is created by pressure difference, but in natural systems it is usually much smaller than in mechanical ones. It is usually less than 50Pa in natural, and 100-1000Pa in mechanical ventilation systems (Halliday 2008). Therefore, minimising the amount of harmful contaminants is the first rule by designing a naturally ventilated building. The small pressure is also the reason, why it is practically impossible to clean the outside air before taking it into the building. Therefore, naturally ventilated buildings can only be located in the places where clean air is available.

NATURAL VENTILATION AND THERMAL COMFORT

The second major goal of ventilation is an improvement, in combination with other measures, of the building's thermal comfort. Thermal comfort is a complex expression. According to the American ASHRAE standard 55-2013: "thermal comfort is the condition of mind that expresses satisfaction with the thermal environment, and is assessed by subjective evaluation" (Passe and Battaglia. 2015). A person's sensation of thermal comfort is influenced by the following main environmental parameters (CIBSE Guide A 2015):

- air temperature,
- mean radiant temperature,
- relative air speed,
- humidity.

All of the above factors are influenced by ventilation. Besides the environmental factors, there are also personal factors that affect thermal comfort:

- metabolic heat production, depending mostly on a person's activity, and
- clothing.

In Poland and the other EU countries, thermal comfort considerations are regulated by ISO 7730. However, the asse are primary intended as an aid for designing HVAC installations (Hegger 2008). Research done by de Dear and Brager in the USA and Nicol and Humphrey in the UK shows, that for understanding of thermal comfort in naturally ventilated buildings, this model is not dynamic enough and, as a result, gives too narrow range of temperatures and air speeds considered as comfortable by users (Passe and Battaglia 2015). Therefore, recently the American organisation ASHRAE (the American Society of Heating, Refrigerating and Air-Conditioning Engineers) and the British organization CIBSE (the Chartered Institution of Building Services Engineers) published the guidance for thermal comfort values in naturally ventilated public buildings. The guidance is provided by ASHRAE standard 55-2013 and the "Environmental design CIBSE Guide A". It is based on field studies of people in daily life under ordinary living conditions and is called an "adaptive model" or an "adaptive approach to thermal comfort". By the ASHRAE standard 55-2013 adaptive comfort model is defined as "a model that relates indoor design temperatures or acceptable temperature ranges to outdoor metrological or climatological parameters" (Passe and Battaglia 2015). According to CIBSE Guide A (2015): "It is a behavioural approach, and rests on the observation that people in daily life are not passive in relation to their environment, but tend to make themselves comfortable, given time and opportunity. They do this by making adjustments (adaptations) to their clothing, activity and posture, as well as to their thermal environment". It is a new approach, which is of high value for natural ventilation and passive cooling concepts.

In temperate climate, the ways in which the natural ventilation can influence the thermal comfort depend on season. The systems of natural ventilation work the best in spring/autumn seasons. During these periods the outside temperatures are usually lower than the inside ones, and the resulting pressure difference can create the sufficient air movement to ventilate the building.

As it has been already said in Chapter "Ventilation and Air Quality", one of the main ventilation's tasks is to remove heat gains, and this is the major task during the cooling season. The excessive heat gains could contribute to potential building overheating, what in changing climate could be a serious and potentially increasing problem. Depending on standard used, there are different criteria for term "overheating". CIBSE TM52 (2013) sets tree criteria by which a naturally ventilated building could be classified as overheated. The first criterion sets a limit of 3% for the number of occupied hours when the indoor operative temperature can exceed T_{max}. The T_{max} is calculated from the mean outdoor temperature according to the following equation:

$$T_{max} = T_{com} + 3 \tag{1}$$

where:
$T_{com} = 0{,}33\, T_{rm} + 18{,}8$, and T_{rm} is the running mean outdoor air temperature (CIBSE Guide A 2015).

The second criterion is the severity of overheating within one day and the third an absolute maximum acceptable temperature for a room.

The heat gains which could be removed by the natural ventilation are limited. According to CIBSE publication (CIBSE AM10 2005), natural ventilation system can meet total heat loads (external and internal) averaged over the day of around 30-40 Wm^{-2}. Therefore, the main rule to keep the comfortable indoor climate in naturally ventilated buildings is minimising the internal and external heat gains during cooling season. The main sources of internal heat gains are occupants, equipment and lighting, and the external heat gains come from solar radiation and ventilation (hot incoming air).

Achieving acceptable level of thermal comfort in naturally ventilated buildings in summer, in most cases depends on many measures implemented simultaneously (CIBSE AM10 2005):

- good solar control to prevent excessive solar gains,

- minimizing the internal heat gains by using energy effective equipment and lighting, and occupant density smaller than for mechanical ventilated buildings,
- control of the amount of fresh air entering the building, in case that the air is not passively precooled before, and during the high outside temperatures keeping the air change rate only on the minimum needed to assure the proper indoor air quality,
- increased thermal capacity of a building combined with night cooling,
- acceptance that during peak summer conditions, indoor temperatures will exceed 25°C for some periods of time, but this does not automatically mean that the occupants will experience thermal discomfort, because the higher air temperature could be offset by cooler mean radiant temperature and enhanced air speed.

Usually the naturally ventilated buildings will deliver more variable temperature than the air conditioned ones, but as a person's sensation of thermal comfort depends on many parameters, it does not necessarily mean that their occupants will experience discomfort.

The temperature which a person perceives is a combined temperature of air and mean radiant temperature (Hegger 2008). Therefore, the building's components cooler than the indoor air (e.g. the structure element of the high thermal mass cooled in summer by the night ventilation) will lower the temperature a person really experience, which could have a positive effect during peak summer outdoor temperatures and is used in night cooling systems. A thermally massive construction with high nigh-ventilation reduces the peak internal temperature by nearly 5K. Also the air speed has an effect on the experienced temperature. Elevated air speeds are considered as unpleasant during heating season but could have a positively cooling effect in summer. Air speed of about $0{,}25 m \cdot s^{-1}$ is sufficient to give a cooling effect equivalent to a 1K reduction in dry resultant temperature and a speed of about $0{,}6 m \cdot s^{-1}$ gives a cooling effect of about 2K (CIBSE AM10 2005). The moving air cools the occupant directly through convection and evaporation. It happens because air at the relatively high speed, e.g.$1 m \cdot s^{-1}$, increases the rate of sweat evaporation from the skin and in this way minimizes occupants' discomfort when their skin perspires, besides of this the elevated air movement also "determines the convective heat and mass exchange of human body with the surrounding air, which affects thermal comfort" (Wood and Salib 2013). Such high air speeds acceptable in the context of summer cooling are allowed according to the adaptive standard. According to ISO 7730 standard, the regarded as comfortable air velocity should not exceed $0{,}5 m \cdot s^{-1}$ by the interior air temperature of 26°C (Hegger 2008).

During the periods when the outdoors temperatures are higher than indoor temperatures, it could be difficult to keep the natural ventilation continuously running. This is one of the main reasons why investors often opt for mixed mode systems (systems, which use both the natural and the mechanical ventilation).

In heating season, the ventilation system has to remove internal heat gains only in the buildings, where they are very big. In winter, the high temperatures differences between outdoor and indoor air result in big pressures differences and consequently possibly high air exchange rates and elevated speed of cold air, what could negatively influence the thermal comfort. With the indoor air temperature of 20°C comfortable air velocity should not exceed 0,5 – 1,5 $m \cdot s^{-1}$, depending on standard (0,5 $m \cdot s^{-1}$ according to ASHRAE 55-2013 and 1,5 $m \cdot s^{-1}$ according to ISO 7733).

There are two possible solutions for these problems:

- passively preheating the supply air (e.g. in solar buffer zones like atriums or double skin elevations),
- minimising the amount of the supply air to the amount needed only to keep the appropriate air quality, as removing the internal heat gains is usually not a problem at that time.

NATURAL VENTILATION AND ENERGY EFFICIENCY

Apart from providing both good indoor air quality and acceptable thermal comfort, natural ventilation can also contribute to improve a building's energy efficiency. Use of natural ventilation potentially reduces the operational and the maintenance cost needed for mechanical system, the space needed to accommodate it and the embodied energy. Although, it should be mentioned that the mixed mode systems will still require the mechanical equipment and the place for it.

The Carbon Trust states that "average overall energy consumption of air conditioned buildings is approximately twice that of similar sized naturally ventilated buildings" and that making the most of natural ventilation is a simple and cost-effective way of achieving big savings" (CIBSE Guide A 2015). "The Carbon Trust is a not-for-dividend company that helps organizations and companies reduce their carbon emissions and become more resource efficient. Its stated mission is to accelerate the move to a sustainable, low carbon economy" (Carbon Trust 2013). Also the carbon reduction strategy of UK National Health Service states that: "Buildings designed with passive ventilation have improved resilience to energy supply failure and are more energy efficient than mechanically ventilated buildings" (CIBSE Guide A 2015).

From the energy efficiency perspective it is necessary, that in the temperate climate ventilation systems work at least according to the three scenarios: spring/autumn, winter and summer. As it already has been mentioned above, the natural ventilation systems work the best in spring/autumn seasons and mixed-mode buildings usually are ventilated naturally during these periods of time.

In winter scenarios, it is important to prevent the ventilation heat loss, which can account for 50% or more of the total heat loss from a well-insulated building (CIBSE Guide A 2015). Unnecessary heat loss could be minimised by:

- preventing overventilation but maintaining minimum really needed air exchange rate,
- preventing uncontrolled heat losses due to air infiltration,
- matching heat losses with heat gains (internal from occupants, lighting and equipment and external solar heat gains),
- preheating of ventilation supply air (in buffer zones like atriums, winter gardens, double elevations or in buried pipes, taking advantage of the relative stability of underground temperature throughout the year).

In winter scenario, some of the measures needed to prevent the unnecessary heat loss and to prevent the reduction of thermal comfort level are similar: minimising the amount of the supply air or preheating it. However, there can be a conflict between meeting ventilation needs and reducing energy consumption by minimising the air exchange rate. This conflict does not occur when the incoming air is passively preheated.

On the other hand, the efficiency of heat recovery, used in mechanical systems, is high during low external temperatures. Therefore, in mechanical systems part of energy used for heating could be reused, which is very difficult to achieve in natural systems, and could be a reason why some investors decided for the mixed mode systems in winter.

Summertime temperatures are probably the single biggest issue that influences technical viability of natural ventilation (CIBSE AM10 2005). At the same time utilising of passive cooling and resignation from energy and cost consuming air conditioning, could give a potential for both energy and cost savings. The passive methods used by natural systems to keep a comfortable indoor environment in summer and to avoid the risk of overheating have been described in Chapter Natural Ventilation and Thermal Comfort.

CASE STUDIES

KfW Westarkade in Frankfurt, Germany – administration building in Frankfurt

The completed in 2010, KfW's Westarkade is a part of the KfW banking group head office complex. The KfW banking group is Germany's most important financier and funding provider, among the other things, for environmental projects. The KfW had a big influence on establishing the newest German standards for the buildings' energy efficiency, and the new bank's head office is the highlight of investor's energy efficiency strategy and should set new energy standards for high-rise office buildings (Detail Green 2011). To comply with the guidelines for administrative buildings formulated by programme "SolarBau", the building's primary energy usage, estimated according to the "SolarBau" standard, should be less than 100 kWh$(m^2a)^{-1}$. The estimated value could be as low as 82 kWh$(m^2a)^{-1}$, what is significantly below "SolarBau's" limit (Auer and Sauerbruch 2011). Primary energy is the final energy multiplied by renewable energy factor, which according to the "SolarBau" standard amounts 3 (Auer and Sauerbruch 2011). Therefore, reduction of the electrical energy needed for running the mechanical systems is crucial for reducing the primary energy usage. The utilisation of natural ventilation is especially energy efficient, because it makes possible to reduce the electrical energy needed for running the mechanical ventilation. Other passive design elements helping to reach such low energy usage are: the use of daylight, exposition of the thermal mass of the building and venetian blinds with a light redirection feature for controlling solar heat gains (Wood and Salib 2013).

The KfW Westarkade accommodates approx. 700 office workspaces and additional conference rooms. The building consists of a four storey plinth and a high-rise tower. The office tower has an aero-dynamic shape positioned towards the prevailing west-wind. The cellular offices are located along the perimeter of the building and are naturally ventilated via a double-skin façade. The unique feature of the double-skin façade is the air cavity, so called "pressure ring", which maintains a ring of consistent positive pressure around the building. The "pressure ring" protects the office rooms against undesirable effects of high wind speeds and ensures a constant regulated flow of air into the interior. Additionally, the façade's double skin acts as a solar thermal collector, where the supply air is preheated before entering the office space. The implementation of pressure ring allows occupants to open the windows all year round without causing drafts or heat loss (Wood and Salib 2013). In order to avoid overheating in the summer, the façade may be completely opened. The mechanical ventilation is only activated when temperatures drop below 10°C or rise above 25°C. As a result, the office rooms are naturally ventilated during about 65% of the year (Auer and Sauerbruch 2011). The passive preheating the supply air allows the reduction of the heat loss caused by the ventilation and improves the thermal comfort. Consequently, the estimated annual energy savings for heating and cooling amount 84% compared to a fully air-conditioned German office building (Wood and Salib 2013).

Faculty of Architecture in Innsbruck, Austria – refurbishment of existing building

The building is a part of the technology campus at the University of Innsbruck, which was constructed in 1969 and refurbished in 2014. It should be a pilot project for highly energy-efficient refurbishment (Detail 2015).The aim was to reach the EnerPHit Standart developed by the Passive House Institute – a Passive House Standard for refurbishments, which has slightly lower requirements than those for new buildings. During the refurbishment of the Faculty of Architecture, the second elevation was added. The elevation consists of the maintenance balconies and frameless second glass fins. Its primary role is protection against rain and sun. The building is ventilated by a mixed mode system. The system works according to summer, winter and spring/autumn scenarios. In the winter the building is ventilated mechanically with heat recovery. In the summer there usually works mechanical system during the day and passive night cooling via openable windows at nights. In spring and autumn the building is mostly naturally ventilated. Other design element which plays important role in passive ventilation system is the exposed concrete structure, with its high thermal mass.

After the energy upgrade the estimated primary energy usage, estimated according to the Passive House Standard, should be 20 kWh$(m^2a)^{-1}$ in comparison to 180 kWh$(m^2a)^{-1}$ before the upgrade. A part of these energy savings is the exploitation of the natural ventilation and night cooling. The Passive House Institute conducted for the building a cost comparison between the passive cooling and the standard air-condition. The period of 40 years was considered for the purpose of this cost simulation. The results show that the initial construction costs were five times higher in case of the natural cooling. However, the energy savings caused by passive cooling were so high that the total cost of natural system was only 40% of the cost of mechanical cooling.

CONCLUSION

At present, rediscovering natural ventilation is a part of rediscovering the buildings' energy efficiency, or maybe even a part of a wider approach, which is a desire to be closer to the nature. Natural ventilation systems can contribute to the better energy performance of a building but this should not happen on the expense of a comfortable and heathy indoor environment. Therefore, it is important to find the balance between the optimum indoor quality, ventilation effectiveness, energy use and thermal comfort. Effectiveness of a natural ventilation system depends on the implementation of the other passive measures at the same time. The most important of them are: minimising the amount of the harmful air contaminants, control of the heat gains, exposition of the building thermal mass and the utilization of the night cooling. But even then the thermal comfort parameters would be probably more variable in naturally than in mechanically ventilated buildings. This does not automatically mean that the occupants will experience thermal discomfort; however it requires implementation of the adaptive thermal comfort standard, which is appropriated for the naturally ventilated buildings.

Both from the energy efficiency and the thermal comfort reasons, in a temperate climate, natural ventilation systems have to work according to at least three scenarios: spring/autumn, winter and summer.

Adopting natural ventilation systems in non-domestic buildings could cause the higher construction cost, and although they can be compensated by the future profits, this is one of the reasons why the investors very often do not decide for naturally systems. The future profits include not only energy savings but also a positive impact on employee health and well-being, and the resulting growth in productivity.

However, natural ventilation has also its limits and probably couldn't be implemented in buildings:

- with high heat gains,
- without access to clean outdoor air, or
- where the parameters of thermal comfort have to be constant or of very narrow range.

Because of the energy effectiveness and thermal comfort issues, the mixed mode systems are sometimes more feasible. However, investors very often decide for mechanical systems mostly for the psychological reasons. Over the past 50 years the use of air conditioning has become a norm and an indicator of status in many non-domestic buildings all over the world. The resulting very narrow and all year around the same, range of thermal comfort parameters is today a standard. Therefore, many investors do not want to take a risk of more variable indoor climate, which usually occurs in naturally ventilated buildings. The solution they choose very often for this problem is a mixed mode system, however "hybrid buildings reduce operating energy for a portion of the year, but do not eliminate the embodied energy that resides in the mechanical plant, nor the space needed to house such equipment" (Wood and Salib 2013). So the full potential of natural ventilation could be explore only after the investors feel confident in relying exclusively on it.

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