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Breathing: A New High Efficient Ventilation Concept for Non-residential Buildings

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ABSTRACT

In order to reduce the primary energy consumption of buildings, highly efficient heat recovery of the HVAC system is indispensable. A reduction of the fresh air rate is not advisable; Indoor Air Quality (IAQ) is essential for the health and wellbeing of the user. In order to nullify the additional pressure loss of the heat recovery unit a mechanical ventilation system is needed. Central ventilation systems have to incorporate an oversized and space-consuming low-loss ductwork system, decentralized ventilation systems use multiple decentralized ventilation units at the facade. Both kinds of systems must have one fan each for supply air and return/exhaust air. An innovative decentralized ventilation solution is presented that uses only one fan for both supply and exhaust. Mirroring the principle of "breathing", this facade-mounted solution uses a damper system that ensures air reversal, while the direction and flow through the fan remain constant, minimizing power consumption. A unit provides high-efficiency heat recovery, in excess of 90%, based on the use of a regenerator. It also has to have a number of inbuilt control systems that react to the changes in the wind pressures on the façade, essential for use in multi-story buildings, and the ability to offer demand-based ventilation when the space is unoccupied. The first large-scale projects have shown that this ventilation technology is suitable to minimize the primary energy without compromising the IAQ, even in inner zones. Transient ventilation allows heat recovery without freezing even at very low outside temperatures, therefore no bypass is necessary, heat recovery is actively controlled through variations in the breathing cycle time and the air volume. The transient mode of the supply air has a positive influence on comfort in comparison with the steady-state mode achieved with constant or variable air supply.

INTRODUCTION

The global efforts made to reduce primary energy consumption and the analysis of the most important consumers are reflected in the many guidelines issued for minimizing the energy consumption of non-residential buildings. In Europe, the Energy Performance of Buildings Directive 2018/844/EU (EPBD) and the Energy Efficiency Directive 2012/27/EU are now shaping the future, since buildings account for approximately 40 percent of the EU's energy consumption and 36 percent of CO_2 emissions in Europe. According to these Directives, the Member States should strive to achieve a cost-efficient equilibrium between decarbonizing the energy supply and reducing final energy consumption. In particular, they are called upon to "encourage high-efficiency alternative solutions if technically, functionally and economically feasible, while also addressing the issues of healthy indoor climate conditions."

A "high-efficiency air-conditioning system that addresses the issues of healthy indoor climate conditions" must, on the one hand, transport a minimum quantity of outside air into users' indoor rooms while using as little energy as possible to do so. On the other, it must have good heat recovery capabilities in order to minimize the energy used to cover the ventilation heating requirement. The associated minimum requirements have been defined. In the EU regulation No. 1253/2014, thermal efficiency of the heat recovery system of non-residentual ventilation units, η_{t_nrvu}, therefore has to be 73% at a minimum. This heat recovery system has an air-side pressure loss which cannot be

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compensated for by natural ventilation. This will make fan-assisted mechanical ventilation indispensable in the future.

The well-known technical solution takes the form of a central ventilation and air-conditioning system which sucks in, filters and thermally post-processes the air before it is distributed through a system of ducts in the building. The used air is "collected" by means of a second system of ducts and is then conveyed out of the building by a second fan. A heat-exchanger located in each of the air routes makes it possible to transfer heat from one airstream to the other, thereby reducing the ventilation heat requirement.

In Germany, as of the year 2000, construction projects in the non-residential sector were undertaken in which the central ventilation system was replaced by small individual room-by-room ventilation units which, within certain limits (in particular without humidification), fulfill the same functions as a central system. The elimination of construction spaces for the high-volume system of ductwork, the reduction of costs for conveying the air and the possibilities of on-demand ventilation are major advantages of decentralized air conditioning. On the other hand, however, there are a large number of technical components such as fans, dampers or filters, all of which have to be serviced and maintained. These units have as yet been unable to meet the minimum heat recovery requirements currently placed on non-residential buildings.

Therefore, to respond to the challenge of the EPBD, it is necessary to present a "high-efficiency alternative system" which is based on the decentralized ventilation concept and overcomes the main drawbacks of known systems. This innovative device concept, which makes use of a transient operating mode, is inspired by the breathing process. During test measurements, it was possible to identify energy consumption levels for air transportation and heat recovery values that have never before been observed at this order of magnitude. During the years 2015-2019, the technology was used in a number of construction undertakings and has proved its functional capabilities and energy efficiency in projects in which nearly 1000 decentralized ventilation units "breathe" on the building facade in transient mode.

TECHNICAL ADVANTAGES OF A TRANSIENT VENTILATION SYSTEM

As far as the arrangement of the ventilation components is concerned, the structure of decentralized ventilation units is very similar to that of central ventilation systems (Figure 1). Thus, two openings for outside air and exhaust air are required. These can both be hermetically closed by means of an adjustable motor-driven damper. A fan conveys the outside air through the ventilation unit into the room and a second fan conveys the extract air through the unit and out of the room to the exterior. Both fans must overcome the internal pressure loss of all the device components such as filter, heat recovery unit, sound absorber, dampers and so on in addition to external pressure losses. Heat recovery is performed by means of a recuperator. The recuperator is a counter-flow recovery heat exchanger positioned between the supply and extract air streams. It extracts heat from the exhaust air and preheats the outdoor air in winter. It can freeze in winter at high efficiency and that can be circumvented thanks to a bypass with an associated motor-actuated damper.

When the conventional system construction is transferred to decentralized ventilation units, the external pressure losses are greatly reduced due to the omission of the vertical and horizontal ducting system in the building, including fire dampers and air diffusers. This represents the great technical advantage of these systems. However, bringing together all the above-mentioned components in a small installation space, with the decentralized ventilation device being installed in the user space, results in increased internal pressure losses and, consequently, due to the adaptation to the fan speed, to an increased emitted acoustic power level.

It is possible to reduce the number of internal components if stationary device operation is replaced by transient operation, i.e. both directions of flow are conveyed by the same fan.

Alternating operation in small fans is known from the residential sector. Here, slide-in fans with downstream regenerators are inserted in a core drilled in the masonry in order to ensure a minimum level of ventilation in the living space. The direction of flow is reversed by the cyclical change of direction of rotation of the axial fan.

In the case under discussion here, namely the non-residential construction sector, this technology cannot be used in high-rise buildings which are subject to external pressure due to wind load on the facade and in which considerably

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higher volume flow rates are required. The efficiency of reversible fans is also lower, because the geometry of the blades can only be optimized for one direction of flow.

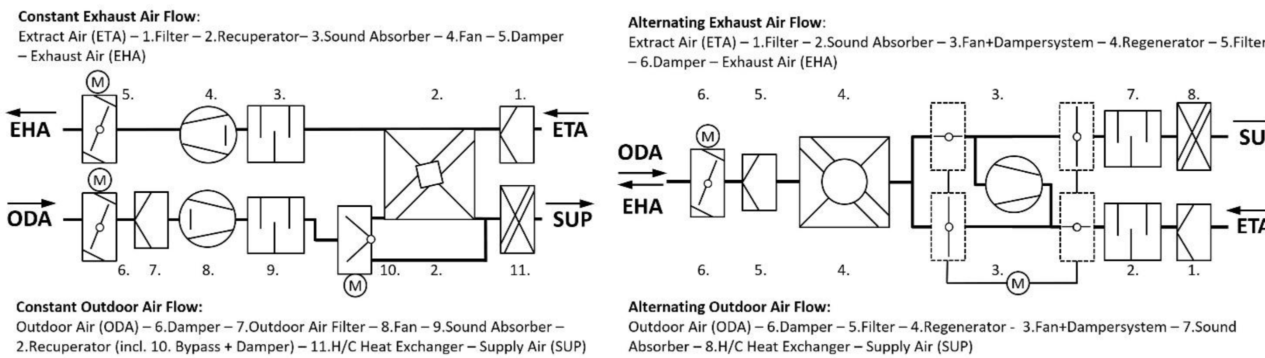

Figure 1 (left): Structure of known decentralized ventilation units with continuous functions: outside air feed, extract air removal, heating, cooling and heat recovery; (right): Structure of a decentralized ventilation unit with transient operating mode and with cyclically alternating functions: outside air feed, extract air removal, heating, cooling and heat recovery.

In the concept described here (Figure 1 – right-hand side) a single radial fan continuously conveys air, but with double the transient volume flow rate. A damping system consisting of four dampers intermittently switches the airflow direction between outside air and exhaust air mode, while the fan's direction of rotation and transport direction remain unchanged. Seen from the outside, the unit reverses the flow direction. The bionic transfer of this intermittent ventilation concept from nature has its origins in the breathing process.

The airflow components are arranged in such a way that there is a single airflow path on the "facade side" of the group of dampers. This airflow path contains a single outside air damper, a fine filter, the heat recovery unit and an opening in the facade. This air route is intermittently exposed to outside air (ODA) and exhaust air (EHA). On the "room side" of the group of dampers, there are separate air routes for supply air (SUP) and extract air (ETA). This arrangement is of value because in the winter the extract air is not to be heated via the heat exchanger. The supply path on the room side contains a water-flow heat exchanger which also performs additional heating and cooling functions. The extract air path contains an extract air filter which protects the device against internal contamination. These two room-side flow paths are applied alternately in pulsed mode.

The internal device volume of an outside air path, from the opening in the facade through to the exit through the damper system, is also a dead volume which reduces the effective outside air volume conveyed into the room on each supply cycle. To avoid pressure differences between adjacent rooms caused by this transient ventilation system, two units were interconnected where one breathes in and the other one breathes out simultaneously. If only one unit is installed in a room, a transfer air device needs to be installed.

This transient flow concept is not used in centralized ventilation systems because the above-mentioned dead volume present in a connected single-channel system of ducts for the transportation of air into the individual rooms would be so great that the cycle times would have to be very long. The consequences this would have for the efficiency of the regenerator and the pressure ratios in the building make this approach unattractive for central ventilation systems.

Summing up, this new ventilation system provides lots of novellities such as the regenerative heat recovery, the transient air flow inside the room and hence the calculation of the thermal comfort in transient conditions and the design of the supply air temperature.

Compared with decentralized alternating units for residential buildings there are prejudices such as the higher efficiency of the fan, the better airtightness and the improved acoustic values.

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ELECTRICAL ENERGY CONSUMPTION

The electrical consumption required for transporting the air into and out of the building, including overcoming all the internal and external pressure losses, is a major consideration with regard to the aim of minimizing the primary energy requirement of buildings without reducing the Indoor Air Quality. In the case of a decentralized ventilation unit, this means minimizing the power consumption. A typical operating point for the economic operation of a decentralized ventilation unit corresponds to a supply air volume of 120 m³/h (33.3 l/s). At this level, the units in a building are operated at a statistical average value of 90m³/h (25 l/s) per decentralized ventilation unit.

The electrical energy required to transport this volume of air is evaluated and classified in dimensionless form by means of the SFP value, or Specific Fan Power.

$$SFP = \frac{P}{q} \tag{1}$$

European standards limit the permitted value for building ventilation in the new-build sector to the class SFP-4, i.e. a maximum of $SFP_{central}$= 2000 Ws/m³. Known decentralized ventilation units with a conventional design with two fans for outside air and exhaust air achieve considerably better values, irrespective of the acoustic emissions. Measurements show that, at a conveyed volume flow rate of 120 m³/h (33.3 l/s), each of the two radial fans has a power consumption of 16 W. The $SFP_{decentral}$-value is therefore $SFP_{decentral}$ = 480 Ws/m³. Replacing two fans with one fan that is operated with twice the volume flow rate, namely q=240 m³/h (66.6 l/s), leads to a higher power requirement in the first step. The fan power P is given by the product of the volume flow rate q and the static pressure increase Δp divided by the efficiency η of the fan.

$$P = \frac{q \cdot \Delta p}{\eta} \tag{2}$$

Because the pressure loss of a system characteristic increases almost quadratically with the volume flow rate, we expect:

$$P \sim q^3 \tag{3}$$

As a result, in the case of a single fan, an 8-fold increase in power consumption is expected when the volume flow rate doubles. This would correspond to an expected SFP=1920 Ws/m³. The value for comparison is the power consumption of two fans at half the volume flow rate, that is to say a 4-fold increase in power consumption.

However, the measurements of the electrical power consumption of the prototype as well as the series device in the test laboratory only resulted in an SFP value of SFPtransient = 345 Ws/m³ at 240 m³/h (66.6 l/s).

The reason for this lies in the internal air supply and the choice of heat recovery unit. The transient operating mode makes it possible to eliminate intersecting air routes, e.g. in a recuperator. This makes it possible to reduce internal pressure losses. At the same time, almost the entire volume of the unit is available for a single airflow path. This prevents the unnecessary acceleration of the air in its path through the unit together with the associated friction losses and turbulences. This effect leads to a considerable reduction in internal pressure losses and a shift of the system characteristic. This results in minimum electrical power consumption at the fan.

In a building in which the units are operated at an average of 90 m³/h (25 l/s), this means power consumption per fan of < 10 W for each unit. The corresponding SFP value is 194 Ws/m³. To show the resulting energy saving potential for air transport, a comparison of the SFP values is useful. For non-residential buildings, for example, the law in Germany "Gesetz zur Vereinheitlichung des Energieeinsparrechts für Gebäude" requires a minimum SFP of 1500 Ws/m³ for supply air and 1000 Ws/m³ for exhaust air. The average value of 1250 Ws/m³ can now be compared with the SFP value of the described transient system at an average volume flow of 90 m³/h (25 l/s). The power requirement for the air transport through the building is therefore only 15.52 % of the required minimum value.

REGENERATIVE HEAT RECOVERY

A second aspect in minimizing the primary energy requirement consists in efficient heat recovery, thanks to which energy costs can be reduced by minimizing the ventilation heating requirement during the winter. In the case of

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continuous operation, heat recovery is performed using a recuperator. Two spatially separated material flows pass over a membrane and heat is transferred from the warm to the cold liquid. By contrast, in the case of regenerative heat recovery, the material flows are not spatially but temporally separate. The regenerator acts as a heat store and is alternately loaded and unloaded. Temperature ratios of up to 90 % can be reached with system (Kaup, Mathis). Dimensioning of the switchover heat recovery unit is an optimization process in which heat storage capacity, heat transfer coefficient and thermal diffusivity have to be maximized at a limited volume without increasing pressure loss and the associated acoustic emissions from the fan. Figure 2 (left) shows the air temperatures of a decentralized ventilation unit with integrated regenerator, measured using thermocouples with a very short response time of t_{90}=15 seconds. The thermocouples are placed both in the opening of the ventilation unit and next to the heat regenerator. Variations of the volume flow rate and the cycle time take place.

Each cycle is subdivided into the subcycles “breathing in” and “breathing out”. On the “breathing in” subcycle, fresh air is conveyed into the room, and on the “breathing out” subcycle, used air is conveyed out of it. As can be seen in Figure 2, more heat from the extract air is stored in the regenerator at the start than at the end of the 20-second subcycle. This is because the potential difference for heat transfer - the temperature difference - falls. The diagram makes it clear that the temperature ratio has to decline as the cycle time increases because the average temperature difference between extract air and exhaust air defines this value. By adjusting the length of the cycle from 10 to 80 seconds, it is therefore easy to control the average temperature ratio. Increasing the volume flow rate causes higher velocities on the surface of the heat regenerator and therefore a reduction of the temperature ratio.

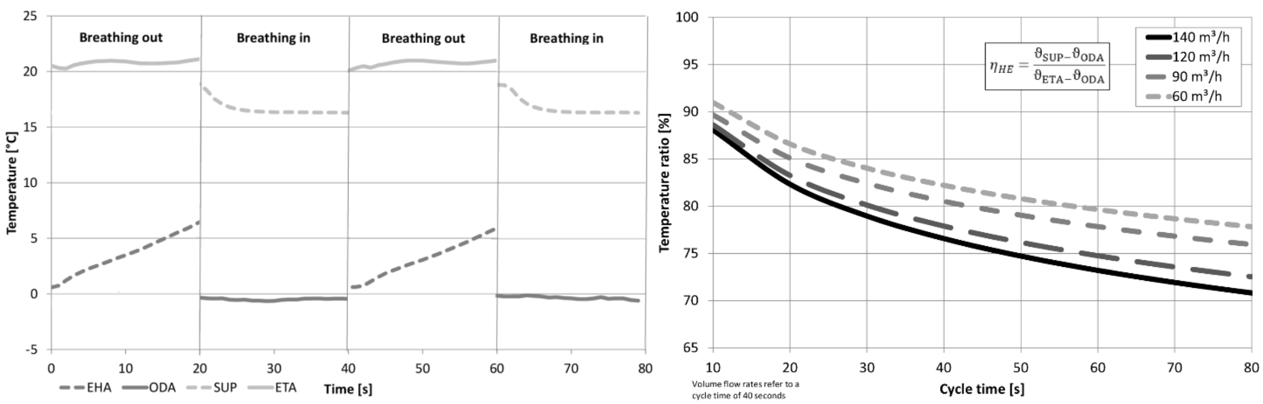

Figure 2 (left): Temperature curves in a unit with regenerative heat recovery and a cycle time of 40 seconds; the interval between the extract and exhaust air temperature on “breathing out” and the supply and outside air temperature on “breathing in” is proportional to the amount of heat transferred. (right): Temperature ratio in a regeneratively operated heat recovery unit, measured based on DIN EN 308 (1997). The size of the temperature ratio increases as the cycle time becomes shorter and the volume flow.

The optimum temperature ratio can therefore be set continuously at every operating point without the additional integration of a bypass being necessary. The temperature ratios that arise in a decentralized ventilation unit can reach up to 90 % and depend on both the cycle time and the size of the volume flow rate (Figure 2 right).

THERMAL COMFORT

The international standards ISO 7726 (1998) and 7730 (2006) have become established for the measurement, recording, judgment and evaluation of thermal comfort. However, the above-mentioned standards implicitly assume steady flow conditions. Strictly speaking, therefore, they cannot be applied to the evaluation of cyclical, transient flows. Research work that has examined the influence of cyclical, transient air flows on the feeling of comfort in test subjects (Ring, Dear, Melikov 1993), (Melikov 2010), shows a negative influence, albeit coupled with a significant dependence

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on frequency (see Figure 3, left). Consequently, it can be assumed that the greatest negative impact on thermal comfort is felt at frequencies of around 0.4 Hz (which corresponds to a period of length 2.5 s). Clearly, the skin, as the most important sensory organ for discomfort, no longer temporally resolves high frequencies. In the case of long periods (=low frequencies), the negative influence falls rapidly and is negligible as of a period length of 40 s (0.025 Hz).

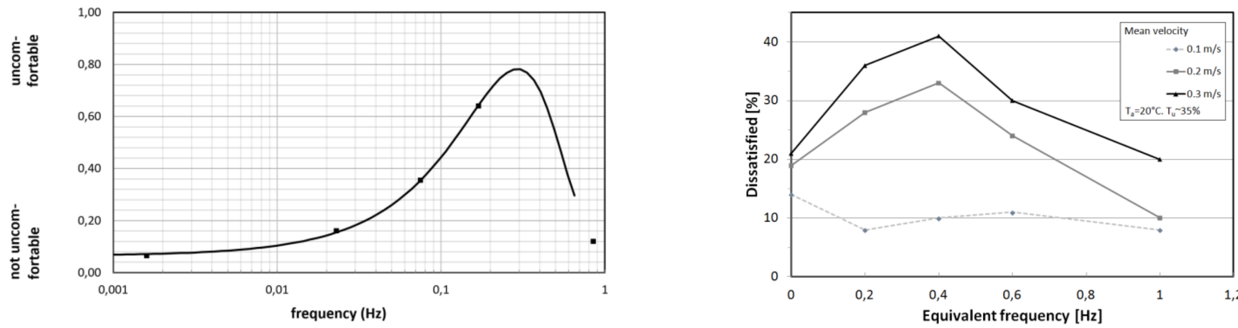

Figure 3 (left): Impact of velocity fluctuations on draft discomfort (Ring, Dear, Melikov 1993); (right): of equivalent frequency draft discomfort, depending on mean velocity (Melikov 2010).

In addition, experiments with test subjects have shown that the negative influence on thermal comfort depends not only on the frequency of the cyclically varying air flow but also on the amplitude of the air speed (Figure 3, right). If the supply air flowing into the room is cyclically pulsed then the random turbulence effects that occur are overlaid by large-scale speed fluctuations. The temperature values therefore also vary cyclically. In this case, the fluctuation range falls off with increasing distance from the air diffuser.

A research project (Kriegel et al.) assessed the impact of unsteady air supply in displacement ventilation. For unsteady conditions a higher tolerance to low supply temperature was found and therefore a reduction of the volume flow rate is possible.

Measurements of thermal comfort according to ISO 7730 were performed in a test chamber with typical office layout, where internal heat gains and a heated façade were used to build up a steady state for a cooling case. The parameters to calculate thermal comfort were logged vertically and parallel to the façade for different cycle times, temperature differences between supply and extracted air and volume flow rates. In comparison to the transient experiment, tests with steady flow conditions were executed (Geiger).

The extent of this attenuation depends on the area of deployment. If the air is introduced below the ceiling at a large distance from the frequented space then it is advisable for the speed to fall only just before the occupied area. If the air is blown in close to the floor then a highly inductive air diffuser can reduce both speed and temperature gradients within just a small space. Figure 4 (left) shows the risk of drafts that occurs in the case of floor-level air inflow by means of an underfloor unit. The Figure shows a vertical section perpendicular to the facade through an office space. Even at a distance of only 20 cm from the diffusion grille, category B of ISO 7730 is adhered to.

Thanks to the highly inductive transient air inflow, the local undertemperature of the supply air entering the frequented area is reduced and hence the vertical temperature gradient. The air is now warmer and forms layers up to a greater height in the room. Instead of a lower pool of fresh air that is typical of the displacement air, a larger volume is now supplied with cool, fresh air. The height of the cooled air volume in case of a steady experiment and a supply air volume of 120 m^3/h is 0.5 m, in a transient trail 0.9 m can be measured for cycle times of 40, 60 and 80 seconds.

As can be seen in Figure 4 (right), almost the entire space taken up by a sitting person is covered. As a result, a smaller vertical temperature gradient occurs in the frequented area (Figure 5). This more uniform temperature distribution makes it possible to allow greater room set temperature tolerances in the control system. In addition, the effectiveness of the way the supply air is mixed with the room air means that it is possible to introduce supply air with a greater undertemperature into the room when compared to a displacement air system.

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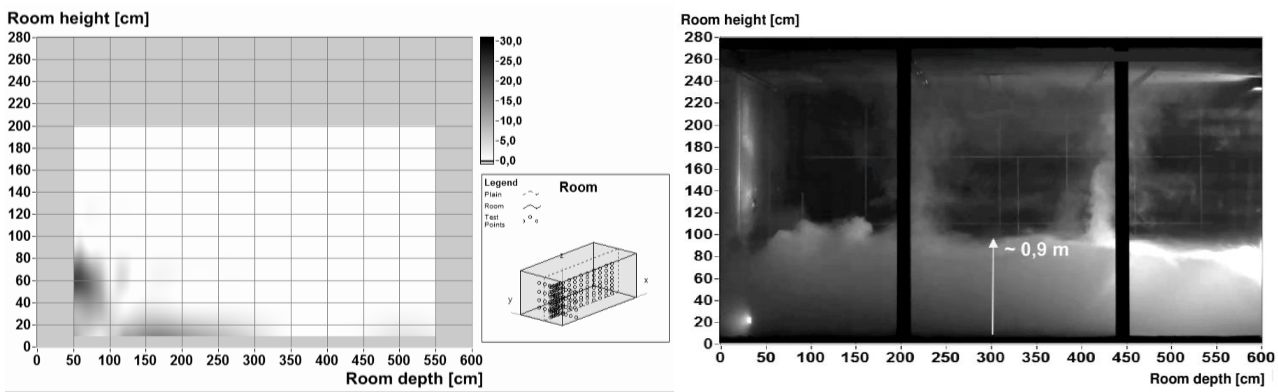

Figure 4 (left): Distribution of the local risk of draft; facade at x=0; risk of draft as per ISO 7730 in the case of cooling; comfort criteria for a sitting person with light summer clothing; humidity= 70 %; undertemperature of the supply air compared to the room air = 8 K; cycle time 40s. (right): Visualization of the airflow pattern: The height of the cooled air volume is approximately 0.9 m at a supply air undertemperature of 8 K.

The cooling capacity that is introduced in a thermally comfortable way into the frequented area increases. An indication for the additional induction is the mixing of the cold supply air with the warm air in a larger volume and hence the reduction of the temperature gradient (in Figure 5). In this transient case, the cycle time is varied with the other performance data held constant and the temperature gradient is plotted against the distance to the facade.

It is found that, starting with a steady experiment with a period of infinite length, the temperature gradient in the entire frequented area falls off continuously as the length of the period becomes shorter (Figure 5). It can be seen that through the period length factor, the transient operating mode creates an additional degree of freedom for controlling the mixing of the supply air and room air.

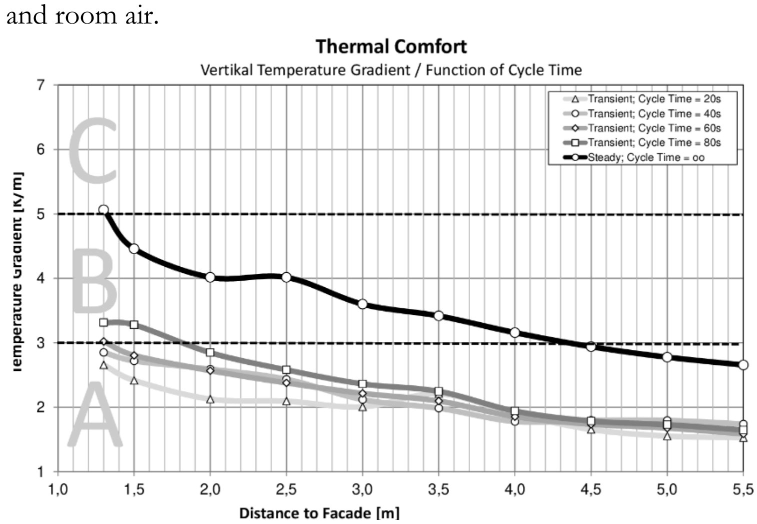

Figure 5: vertical temperature gradient according to ISO 7730 (1.1 m – 0.1 m) as a function of the cycle time and the distance to the facade and ventilation unit. The volume flow rate is 120 m³/h, the undertemperature of the supply air against the extracted air is -6.5K

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CONCLUSION

It has been shown that the ventilation and air conditioning of non-residential buildings using decentralized room-by-room ventilation units offers great potential in terms of reducing the primary energy requirement. A transient operating principle improves energy efficiency by minimizing power consumption for conveying the air and, by using a regenerator, makes it possible to minimize the ventilation heat requirement thanks to the controllable heat recovery with temperature ratios of up to 90%. Thermal comfort in the frequented area is ensured thanks to the high level of inductivity of the supply air jets. The suitability of these "breathing" devices has been shown in real operation through the simple implementation of operating modes which, for their part, offer considerable potential for energy savings: demand controlled ventilation, night-time ventilation, cross-ventilation or hybrid operating modes in which the extract air escapes through the open window, while the unit permanently operates in supply air mode to convey twice the quantity of outdoor air.

SYMBOLS

ε_v	=	ventilation effectiveness [ ]
c	=	gas concentration [ppm]
SFP	=	specific fan power [Ws/m³]
p	=	power [W]
q	=	volume flow rate [m³/h]
η	=	efficiency [ ]
η_{t_nrvu}	=	minimum thermal efficiency [ ]

SUBSCRIPTS

ODA	=	outdoor air
SUP	=	supply air
IDA	=	indoor air
ETA	=	extract air
EHA	=	exhaust air
IAQ	=	Indoor Air Quality

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