Box-Type Windows as Means for Better Air Quality and Acoustic Comfort in Urban Areas

David Offtermatt, Daniel Lust, and Tobias Erhart

Abstract

Controlled natural ventilation in office buildings can ensure the indoor thermal comfort while reducing the life cycle energy consumption for ventilation, compared to mechanical ventilation systems (e.g. HVAC). Natural ventilation is mostly used in moderate climate zones where air conditioning is not a standard. During intermediate seasons, buildings with HVAC systems can additionally use natural ventilation to reduce energy consumption. However, in dense urban areas, natural ventilation can be problematic in terms of acoustic comfort. Here, a box-type window can serve as a compromise between thermal and acoustic comfort. Due to the more complex handling of the box-type window, an automated (electric driven) novel box-type window approach was developed within the imaF project, a part of the iCity initiative. The following article describes the basics of automated natural ventilation, acoustic characterization as well as architectural integration of this window type and the optimization of the airflow through box-type windows. The results show that the proposed geometry can provide sound insulation while providing an appropriate air exchange rate.

Keywords

Box-type windows · Controlled natural ventilation · Noise protection · CFD
Nomenclature

ppm Parts per million  
CFD Computational fluid dynamics  
SST Shear stress transport  
Ma Mach number (Ma)  
STL STereoLithography file format  
HVAC Heating, ventilation, and air conditioning  
imaF intelligentes motorisch angetriebenes Fenster  
G_{FAC} Global irradiation on the facade plane (W/m²)  
ζ Pressure loss coefficient  
U_g U-value glass (W/(m²K))  
U_w U-value window (W/(m²K))  
N_x Mesh coordinate/number of cells x-direction  
N_y Mesh coordinate/number of cells y-direction  
L_x Channel dimension x-direction (m)  
L_y Channel dimension y-direction (m)  
k Turbulence kinetic energy (J/kg)  
ε Turbulent kinetic energy dissipation rate (J/(kgs))  
w Turbulence specific dissipation rate (1/s)  
u_ref Flow velocity (m/s)  
C_m Model coefficient for the turbulent viscosity (−)  
I Turbulence intensity (−)  
n Modified turbulence viscosity  
p Pressure (Pa)  
Δp Pressure difference (Pa)  
ρ Density (kg/m³)  
A Opening cross ion of windows (m²)  
A_1 Opening cross section 1 (m²)  
A_2 Opening cross section 2 (m²)  
A_{eff} Cross-sectional area (m)  
T_e Ambient temperature (°C)  
T_i Indoor temperature (°C)  
m Mass flow (kg/s)  
R_w Sound reduction index (dB)

21.1 Introduction

Along with higher energy building standards, the focus in energy saving has been shifting from heat losses by transmission more and more to ventilation heat losses. Whereas in old buildings classic windows naturally leak, the envelope’s air tightness increases the demand
of additional air delivered by ventilation systems. Furthermore, higher occupation rates in office rooms lead to a higher sensitivity for appropriate indoor air quality. In many climate zones, the comparably short hot periods do not justify the use of an HVAC system, in particular when the building has a considerable thermal mass. This is the case for most locations in Germany. Nevertheless, there is a worldwide trend towards more air conditioning in urban areas. In Europe alone, an increase of 45% in air conditioning units between 2020 and 2030 is expected (OECD/IEA, 2018).

Analyses within the KonLuft project (Schulze et al., 2016) have shown that life cycle costs (LCC) and life cycle energy consumption of a mechanical ventilation system consume approximately twice the power and resources compared to controlled natural ventilation. The maintenance costs and the complexity level of a building can be significantly reduced by using the natural ventilation principles. During the planning process, engineers must assure that the design of the ventilation concept meets the requirements of the building usage. Often, in commercial buildings, planners prefer mechanical ventilation or HVAC systems over natural ventilation to guarantee the demanded air exchange rates of (DIN EN 13779, 2007) and the former (DIN EN 15251, 2007) or its replacement (DIN EN 16798-3, 2017). The key to robust calculations is the availability of valid discharge coefficients (Gandhi et al., 2015) and the local wind situation (Maas et al., 1991).

Multiple studies in the past reported that natural ventilation can be a reliable and cost-effective alternative. However, in an urban environment, noise pollution causes severe discomfort when windows on street facing facades are opened. During night-time, controlled natural ventilation can reduce the temperature of the room and the building components. For moderate middle European climates, up to \(-5^\circ\)C (Erhart et al., 2015) can be achieved. In hot dry climates, natural ventilation achieves up to \(-3^\circ\)K to \(-6^\circ\)K during one night (Shaviv et al., 2001).

Figure 21.1 shows various influencing factors that need to be taken into account during the planning process. It also shows architectural design guidelines to consider in the first steps of the planning process. The key factors that influence the thermal comfort (see Fig. 21.2) can be assured by rather low-tech approaches through controlled natural ventilation.

The article is divided into the following chapters:

- Controlled Natural Ventilation.
- Box-Type Windows.
- Laboratory Set-Up.
- Airflow Through Box-Type Windows.
- Architectural Integration.
- Acoustic Comfort.
- Conclusion and Outlook.
- Nomenclature
Fig. 21.1 (a) Parameters that influence ventilation planning. Design. (b, c, d): Design recommendations. Reduction of the window camber. Height instead of width. Position of the opening wing.
21.2 Controlled Natural Ventilation

For every orifice in a building and each prevailing ambient condition, an associated airflow, or air exchange, can be calculated. The pressure differences between the two sides of the orifice cause an airflow. Differences in temperature, and therefore in density of air, cause the pressure difference through the buoyancy effect. In addition, the wind induces a difference in pressure (Fig. 21.3). Especially in cross-ventilation situations, this case results in significantly higher air exchange rates. However, in urban areas statistically, the thermal regime (temperature difference between internal $T_i$ and ambient $T_e$) clearly dominates over the wind regime (tangential flow $U_{\text{Wind}}$). Consequently, in order to assure the desired air exchange rate, one should configure the windows according to thermal regime properties. While classic natural ventilation depends on the occupants opening the windows, controlled natural ventilation comes with a control system and window drives. The drives today are mainly electric, whereas pneumatic drives have become rare nowadays.

Control Strategies

One can implement various control strategies for the automation of opening and closing windows. Each of the following strategies can contribute to thermal comfort as a passive solution. The following strategies can be combined or work independently.

- Hysteresis CO$_2$: If the CO$_2$ concentration rises above 1000 ppm, the window opens until the CO$_2$ concentration drops below 600 ppm.
– Hysteresis CO₂ + manual override: A manual mode supplements the described hysteresis CO₂ strategy. This mode allows an interruption by the occupant. During the manual mode, the window is opened or closed via a wall-mounted switch.
– Night cooling: If the ambient temperature ($T_e$) at night is lower than the indoor temperature while the day meets the criteria of a summer day (24-h mean $T_e \geq 15$ °C), night cooling mode is enabled.
– A typical combination is night cooling + hysteresis CO₂ + manual mode. This strategy is the best choice to increase hygienic properties of chose as basis.
– Increased daytime cooling: If the criterion of a summer day at daytime is met and the inside temperature is higher than the ambient temperature, the window will open.

### 21.3 Box-Type Windows

The historical box-type window consists of two single glazed windows connected with a fix case (box) to one element. It aims to achieve a better heat resistance and an improvement of the sound insulation. In the case at hand, two windows with a size of 1.28 m by 1.45 m and an $U_w$-value of 1.6 Wm⁻² K⁻¹ and $U_g$-value of 1.1 Wm⁻² K⁻¹ (glass 6|12|14|12|14) were arranged successively. Two thirds of each window are fixed and one third is an opening segment. The air gap between the windows has a depth of 0.28 m and it has an air volume of 0.52 m³. Figures 21.4a, b show a scheme of the evaluated box-type window and its dimension.
21.4 Laboratory Set-up

Within the project, an occupied office serves as in situ laboratory. The room measures 4.67 m by 6.47 m, with a height of 3.39 m. The gross volume is 102.4 m$^3$; subtracting furniture it results in a ventilated net volume of 98.58 m$^3$. The data acquisition system records the following outdoor and indoor thermal properties as well as comfort parameters:
– Indoor air temperature, five sensors equally distributed along the height of the room.
– Indoor radiation temperature at average office clerk head level (sitting position).
– CO₂ measured at the pole in the centre of the room and near to the window.
– Indoor relative humidity.
– Outdoor air temperature (radiation shielded).
– Outdoor relative humidity.
– Wind speed and direction (3D).
– Global irradiation on the outer wall plane.
– Absolute air pressure.

In order to obtain accurate values for the air exchange, multiple tracer gas campaigns were undertaken in the test office using both decay and constant concentration methods with hydrofluorocarbon (HFC) 1,1,1,2-tetrafluoroethane (R134a).

Throughout the measurements, the inside and outside air temperatures and pressures were logged in order to characterize the flow with regard to thermal-induced pressure differences. The experiment was executed with the reference window (opening angle of 15°) and inserted acoustic foam (20 mm).

**Decay Method**
The decay method starts with a manually initiated constant tracer gas concentration; the room is sealed and the tracer gas is applied. Then, the concentration is measured for approximately 1 h. The event changing the gas equilibrium inside the room, that is, opening the window, is triggered. The latter method is more reliable under the given laboratory set-up as the dosing error for the tracer gas does not go into consideration. More samples can be obtained per time, as the device requires no time for dosing. A downside is the relatively short measuring period. After the tracer gas is below the detection limit, the experiment needs to be paused for the reapplication of tracer gas.

**The Constant Concentration Method (CC Method)**
The CC method is favourable when data over a long period are needed, for instance, under changing ambient conditions, or to record a full set of day and night data. A dosing unit applies tracer gas according to a control algorithm. The obtained values undergo a Kalman filter.

### 21.5 Airflow Through Box-Type Windows

**Governing Equations**
The airflow through windows (if wind influences are negligible) is driven by temperature differences between the inside air and the ambient conditions. The pressure resulting from the temperature difference \( \Delta p \) can be approximated according to Eq. (21.1) (with the density \( \rho \), the free fall acceleration \( g \) and the opening height \( H \))
\[
\Delta p = \rho \cdot \left(1 - \frac{T_i}{T_e}\right) \cdot g \cdot H
\]  

(21.1)  

If the pressure loss coefficient \( \zeta \) is known, e.g. from wind channel experiments or from CFD simulations, the corresponding airflow velocity \( u \) can be determined with Eq. (21.2).\(^1\)

\[
u = \sqrt{\frac{2 \cdot \Delta p}{\rho \cdot \zeta}}
\]

(21.2)  

The volume flow \( \dot{V} \) could be calculated with the area on which \( \zeta \) refers to (e.g. effective opening area or inlet area of a wind channel) and results as.

\[
\dot{V} = u \cdot A
\]

(21.3)  

The actual air exchange rate (ACH) is then defined as shown in Eq. (21.4) with the volume of the investigated room \( V_{\text{room}} \).

\[
\text{ACH} = \frac{\dot{V}}{V_{\text{room}}} \cdot 3600 \frac{s}{h}
\]

(21.4)  

ACH is given in changes per hour \( h^{-1} \).

21.5.1 Airflow Through Box-Type Windows Compared to a Single Window

Compared to single windows with the same opening area, box-type windows show comparably higher pressure losses and hence a lower volume flow at the same inflow conditions (see Fig. 21.5).  

With the same boundary conditions, the pressure at windward site of the window more than doubles from 4.67 Pa for the single window to 13.7 Pa for the box-type window. This results from the two sharp airflow deflection at the two opening edges of the box-type window. This effect finally limits the achievable air exchange rates of this window type.  

Another limiting factor is the small opening areas resulting from the geometry with the outer window opening to the inside of the encasement. These areas depend on the opening angle (see Fig. 21.6 areas A, A\(_1\) and A\(_2\)). From the characteristic arises an optimal opening angle for every box-type window configuration (see Fig. 21.7).

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\(^1\)Note that the velocity calculated with that approach is not necessarily the velocity at the window itself. It depends on which velocity \( \zeta \) refers to. This could be the velocity at the effective opening area, or the inlet velocity of an (artificial) wind channel.
In this specific case \((d = 0.28 \text{ m}, \ w = 0.424 \text{ m}, \ F_w = 0.037 \text{ m})\), the ideal opening angle \((\alpha)\) is 27.5°. Up to this angle, the smallest opening area is \(A_2\). By exceeding an opening angle of 27.5°, surface \(A_1\) becomes the smallest area.

If the inside surfaces of the window box are faced with materials to increase the absorption of sound, these areas may further diminish. Hence, the planning of box-type windows requires a balancing of the acoustic comfort and the ventilation ability.

### 21.5.2 Measurements of the Volume Flow

Figure 21.8 shows the results from tracer gas measurements. The measured air exchange rates over the temperature difference are plotted. This window configuration achieves an ACH up to about 0.5 (shown in Fig. 21.4). Although a trend that ACH increases with rising temperature difference is visible, the measurement points in Fig. 21.8 fluctuate around the
same temperature differences. This effect might be caused by pressure fluctuations at the building facade due to wind effects like occurring gusts.

Figure 21.9 shows the measured volume flow in comparison to the calculated volume flow (Eqs. 21.1, 21.2 and 21.3) with $\zeta$ from CFD results versus temperature difference. It is clear from this figure that the calculated volume flow is overestimated compared to the measurement results. This could be caused by several reasons:

- As the window is installed in an occupied office, the measurements were not executed under laboratory conditions. Influences of wind or infiltration could lead to divergent results.
- The pressure loss caused by an installed insect protection mesh was not considered in the CFD calculations.
- Three-dimensional (thermal) airflow effects may be not sufficiently represented in the 2D CFD simulations.
Further experiments must be executed to calibrate the CFD model to the measurement results.

### 21.5.3 Measures to Increase Air Exchange Rates

To increase the volume flow rates through box-type windows, some modifications on the window design are possible. The impact on the actual pressure loss coefficient of three different variants (see Table 21.1; all variants without acoustic foam inlet) is investigated using computational fluid dynamics (CFD\(^2\)).

Table 21.2 shows the resulting pressure loss coefficients for every window variant. Compared to the reference window, the optimization of the opening angle (variant 1) leads to half of the pressure losses. Rounding the corners (variant 2) shows higher pressure losses.

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\(^2\)OpenFOAM, solver: simpleFoam, turbulence model: k-\(\omega\)-SST.
than variant 1, due to the decreased effective opening area (see Table 21.1). By far, variant 3 achieves the highest improvement. The airflow guidance reduces the flow separation at the inner window edge and consequently decreases the occurring velocity significantly. Figure 21.10 depicts this effect, visualizing the flow for every investigated variant.

**21.6 Architectural Integration**

A modular system design supports the construction process and achieves a high degree of prefabrication. To improve the acoustic properties when the windows are closed, two different types of windows have been chosen. Triple glazing in the outer part of the box-type window provides thermal and weather protection. Double glazing with laminated glass serves as basis for the inner part of the box-type window. A surrounding aluminium profile offers space for the control system, cabling and sound absorbing material.
Table 21.1  Box-type window optimization variants ($A_{\text{eff}} = \text{effective opening area}$)

<table>
<thead>
<tr>
<th>Variant</th>
<th>Description</th>
<th>$A_{\text{eff}}$ (m$^2$)</th>
<th>Sketch</th>
</tr>
</thead>
</table>
| Reference | Geometry as installed in the ventilation lab  
Opening angle: 15° | 0.07                     | ![Sketch](image1) |
| 1       | Optimized opening angle (according to Fig. 21.6)  
Opening angle: 27° | 0.12                     | ![Sketch](image2) |
| 2       | Opening angle: 27°  
Rounded corners | 0.099                    | ![Sketch](image3) |
| 3       | Opening angle: 27°  
Airflow guidance within box | 0.12                     | ![Sketch](image4) |

Table 21.2  Resulting pressure loss coefficients for each window variant

<table>
<thead>
<tr>
<th>Variant</th>
<th>$\Delta p$ (Pa)</th>
<th>$\zeta$</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>13.65</td>
<td>2236</td>
<td>–</td>
</tr>
<tr>
<td>1</td>
<td>6.75</td>
<td>1107</td>
<td>−50.0%</td>
</tr>
<tr>
<td>2</td>
<td>7.05</td>
<td>1156</td>
<td>−48.0%</td>
</tr>
<tr>
<td>3</td>
<td>3.30</td>
<td>541</td>
<td>−75.8%</td>
</tr>
</tbody>
</table>
Furthermore, the profile supports the element mounting and assures a better construction process. The isometric drawing in Fig. 21.11 depicts the components.

Figure 21.12 shows the architectural integration of the investigated box-type window. With this set-up, only a narrow window frame is visible from the inside. However, with the fixed glazing, maintenance will be more difficult. Figure 21.13 shows a more suitable solution for architectural design and maintenance. A casement window is used as a template. The outer part of the surrounding aluminium profile is enlarged. This offers flexibility in usage of other window types and offers more space for the integrated control as well as sound-absorbing material. To increase air exchange, it also allows the window to be fully opened. Note that the sound insulation is thereby reduced immensely. One can expect a negative effect for the daylight efficiency due to the smaller outer window (see Fig. 21.12). Due to the box principle, the window reveal can be very small despite higher insulation standards from the outside.
21.7 Acoustic Comfort

By using a box-type window, the weighted sound reduction index $R_w$ can be increased around 5 dB in opened and closed states compared to a single window. If the box-type window is additionally equipped with acoustic foam (basotect 20 mm), the sound insulation in closed state again increases by 2 dB.

Without absorbing foam, opening the single and box-type windows 5 cm and 10 cm reduces the weighted sound reduction index by approximately 20 dB to 25 dB, respectively. However, with absorbing foam, the reduction is only 5 dB to 16 dB. Generally, the box-type window without foam has weighted sound reduction index that is 5 dB higher than that of the single window. The box-type window with foam with an opening of 5 cm even outperforms the closed single window by 3 dB and is only 3 dB under the closed box-type window without foam. This option gives the best acoustic results while allowing some sort of natural ventilation (Table 21.3).

21.8 Conclusions

The findings of this work conclude as follows:
Fig. 21.12 Architectural integration of the investigated box-type window
Fig. 21.13 Alternative for the investigated box-type window, friendly for maintenance and service
Table 21.3  Expected weighted sound reduction index $R_w$ of the investigated box-type window

<table>
<thead>
<tr>
<th></th>
<th>Single window (dB)</th>
<th>Box-type window (dB)</th>
<th>Box-type window with acoustic foam (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window closed</td>
<td>34</td>
<td>40</td>
<td>42</td>
</tr>
<tr>
<td>Window opened (5 cm)</td>
<td>15</td>
<td>20</td>
<td>37</td>
</tr>
<tr>
<td>Window opened (10 cm)</td>
<td>10</td>
<td>16</td>
<td>26</td>
</tr>
</tbody>
</table>

Comparison of a single window, box-type window and the box-type window with acoustic foam

- CFD calculations show that the pressure losses are reduced by approximately 50% by simply optimizing the opening angles of the casements. Further reductions are achievable by guiding the airflow inside the window box.
- The resulting air exchange rate under a mean temperature difference of 3.4 K was around 0.4 l/h (with an infiltration of about 0.14 l/h).
- Despite the relatively small flow cross section, the system provides appropriate air exchange rates. The very low width-to-height-ratio of the window gap (0.0385 m/m) supports higher pressure differences.
- The weighted sound reduction index of an opened box-type window equipped with acoustic foam is around 22 dB higher than an open single window.

21.9  Outlook

- The 2D CFD simulations will be transferred to 3D simulations which may take buoyancy effects into account better, but come with higher computation costs.
- More detailed calculation approaches must be found and applied to be able to better simulate real airflow conditions, e.g. mounting conditions and wind influences.
- In the future, the more suitable architectural design window will be studied in the laboratory and with CFD simulations.
- Implementation of the algorithm to control the increase of air exchange during the day and subsequent evaluation of the impact on thermal comfort.
- Installation and evaluation of the active noise control in the box-type window.

References

DIN EN 15251:2012-12; Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics; German version EN 15251:2007, 2007.


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