E3S Web of Conferences **362**, 14003 (2022) https://doi.org/10.1051/e3sconf/202236214003
*BuildSim Nordic 2022*

# Simulation of modern passive stack ventilation in a retrofitted Nordic apartment building

*(leave this line blank)*

Ilia Kravchenko [1,*], Risto Kosonen [1,2,3], Juha Jokisalo [1,3] and Simo Kilpeläinen [1]
[1]Department of Mechanical Engineering, School of Engineering, Aalto University, Espoo, Finland;
[2]Department of HVAC, College of Urban Construction, Nanjing Tech University, Nanjing, China
[3]Smart City Center of Excellence, TalTech, Tallinn, Estonia
** corresponding author: ilia.kravchenko@aalto.fi*

## Abstract

Some heritage or protected residential buildings in Nordic conditions require retrofit; however, having limited or no access to the reconstruction of the ventilation system; thus, the native natural ventilation system must be preserved. Some retrofitted buildings are then equipped with modern passive stack ventilation systems implemented with self-regulated supply inlets. Although natural ventilation strongly depends on climate conditions, creating challenges in the design phase as the indoor air quality can not be guaranteed. In this study, such a building was modelled, and a novel self-regulated inlet component was created and applied to the simulation model of the multi-storey residential building with natural ventilation in the Nordic conditions. This IDA ICE model is implemented with a self-regulated inlet model with outdoor temperature control and simulates the yearly performance of a ventilation system, considering the effect of outdoor conditions, such as air temperature and wind direction. The self-regulated device is represented as a one-direction opening based on power-law with variable internal airflow resistance, calculated based on the outdoor simulation temperature. Several case scenarios of the multi-storey residential building with passive stack and windows opening ventilation were created for the analysis. The cases present possible maintenance issues, such as inlet device dirty filter and passive stack ducts, structural differences, such as envelope airtightness level and occupant behaviour, such as internal apartment doors and windows operation. The resulting CO2 concentration, indoor air temperature and air change rate were analysed and compared against indoor air standards. Overall, the building model simulation results coincide well with studies in comparable conditions; the novel self-regulated inlet device was simulated according to the manufacturer data. The resulting simulation model could be used to assess the performance of modern passive stack ventilation under different climatic conditions.

## Introduction

The ventilation of the residential buildings is designed to provide occupants with enough fresh air and ensure indoor air quality. The residential building stock is presented by 85% of all buildings in Finland (Rämö n.d.). The requirements for building stock ventilation construction and design are provided by the Ministry of Environment (Brelih and Seppanen 2011; 'The National Building Code of Finland' n.d.; 'Decree of the Ministry of the Environment on the Indoor Climate and Ventilation of New Buildings 1009/2017' 2017). The buildings constructed before 1950's are mostly equipped with natural passive stack ventilation. Some of these buildings are heritage or protected and have limited or no access for the envelope and buildings ventilation system reconstruction. These buildings operate in Nordic conditions and require retrofitting to meet current demands.

Natural ventilation usually utilises the wind and thermal buoyancy driving forces to provide airflow and, thus, strongly depends on the outdoor conditions and the indoor-outdoor temperature difference. Heritage or protected buildings retrofit in Finland preserves the initial natural ventilation system, consequently requiring design simulation to ensure indoor air quality. Also, to preserve a natural passive stack ventilation system, some retrofitted apartment multi-storey buildings are equipped with self-regulating inlets with outdoor temperature control. Previous studies created CFD models to investigate the performance of the self-regulated inlet devices in cold climates (Neve et al. 2005; Arendt and Krzaczek 2014); yet, no studies regarding the building ventilation system performance in Nordic climate were found.

The paper's novelty is the simulation model of a multi-store-store residential apartment building retrofitted with modern self-regulating air inlets concerning specific outdoor weather conditions. The model was created in IDA ICE with a custom component based on the manufacturing data to describe the temperature-dependent self-regulating inlet and evaluate the possible cases of poor maintenance, improved envelope airtightness and varying occupant behaviour.

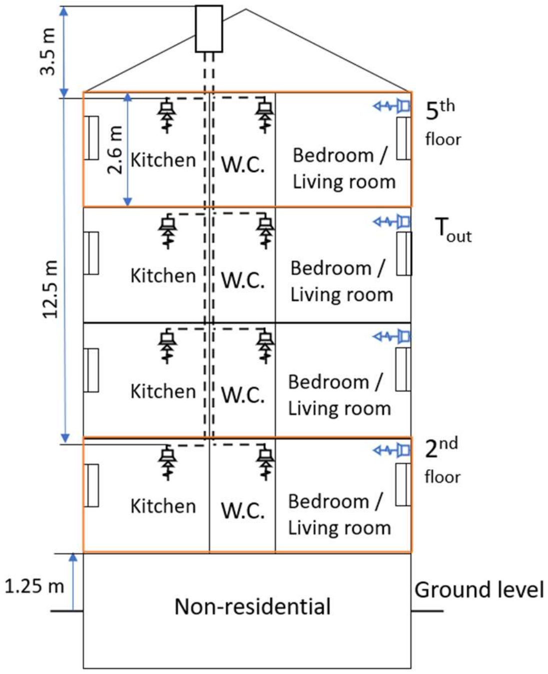
The comprehensive results of the study have been published in (Kravchenko et al. 2022), and this paper presents core findings.

## Materials and Methods

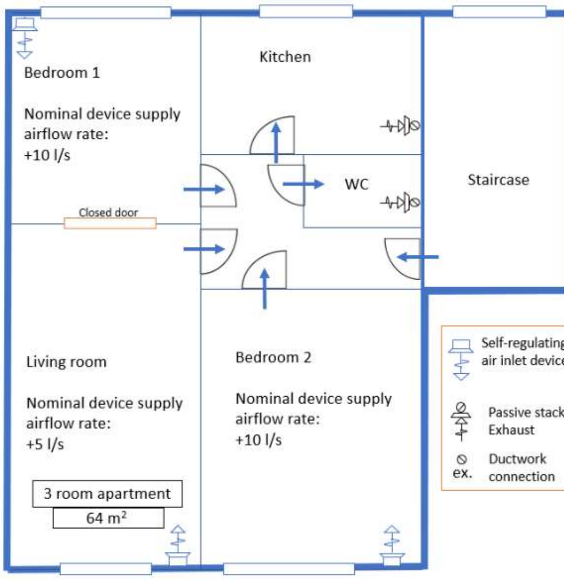
### Building description

The simulation building model (digital twin) is based on an apartment building in Southern Finland. It was built in 1951 and renovated in the 2016-2018 years, where the initial passive stack ventilation was implemented with self-regulating inlet devices with filters. The building is five-storey with the non-residential first floor as the ground floor, and the net area is 600 m$^2$. The residential floors have the same apartment and room layout, as shown in Figure 1. The three-room apartment, one on the second and the other on the fifth floor in one staircase, has been chosen for the simulation; the apartment layout is represented in Figure 1 (b).

The ventilation system is represented with passive stack ventilation with self-regulation inlet devices with filters; the living room, bedroom and kitchen windows are openable. Overall, the outdoor air is supplied into bedrooms and living rooms via the inlet devices and the envelope. The exhaust stack ventilation with separate ducts is located in the kitchen and WC. The ventilation design is represented in Figure 1.




(a)




(b)

*Figure 1: The building ventilation system design (a); The building apartment level ventilation system design (b).* (Kravchenko et al. 2022)

The envelope properties, window properties and other building structure properties are according to the construction year building code requirements. The building load-bearing structures are massive concrete; external walls are two rows of burnt bricks with insulation layers. The internal walls are two types: between the apartments are brick walls, and between rooms are lightweight structures with an air gap.

*Table 1: The structural building details and properties of windows.*

| Description | Building Details |
|---|---|
| Envelope airtightness, 1/h at 50 Pa | 2.4 |
| U-values, (W/m$^2$K) | |
| Roof | 0.5 |
| Floor | 0.5 |
| External walls | 0.5 |
| Entrance doors | 1.1 |
| Apartment doors | 2.2 |
| Windows properties | |
| U-value, (W/m$^2$K) | 2 |
| Total solar heat transmittance (g-value) | 0.44 |
| Direct solar transmittance (ST) | 0.72 |
| Integrated shading | Blinds |
| External shading | No |

The window blinds are simulated to be controlled according to the occupation profile and the intensity of solar radiation (>100 W/m$^2$). The window's openable area is 10% of a window.

The simulated apartment heating design power is 100 W/floor-m$^2$ on the top floor and 60 W/floor-m$^2$ on the middle floor, with the temperature setpoint of heating being 21 ˚C in the apartments. The setpoint of space heating in the staircase and basement floor is 17 ˚C.

**The building usage**

Household equipment's total annual electricity consumption, the total annual electricity consumption of indoor lighting and usage time of the lights are according (Kravchenko et al. 2022). The apartments' occupant activity level is 1.2 MET.

- The windows opening schedule is set, that the windows are closed during the cold period (September to April). The windows are opened from May to August if the outdoor temperature exceeds 12 ˚C, and the indoor temperature exceeds 22 ˚C.
- The bathrooms or WCs are always closed, but the other internal doors inside the apartments are opened according to the cases (shown in Table 3).

**IDA ICE simulation building model**

The building model was created with the IDA ICE, a dynamic building simulation tool ('Validation & Certifications - Simulation Software | EQUA' n.d.; Kontonasiou, n.d.). The software is created and verified to model multi-zone buildings and provides simultaneous dynamic simulation of heat transfer and airflows. The resulting simulation model considers flows between zones, building envelope and windows, calculating the interactions between building structures, HVAC systems, operational and occupancy schedules of the building, and outdoor climate conditions. The infiltration airflows are calculated by wind pressure on each façade combined with zone stack effects.

**Façade pressure calculation**

Wind pressure distribution around the house is simulated, assuming the wind flow is horizontal, and an atmospheric boundary layer is neutral without vertical airflow. The wind conditions of the environment were approximated using the wind profile equation. The model considers wind pressure and thermal buoyancy, and the calculation details are accordingly (Jokisalo et al. 2009).

**Internal flows calculation**

IDA ICE calculates the internal building flows for each separate zone, where large vertical openings such as an open door between the zones are simulated as bi-directional flows. In the case of a flat velocity profile, the air mass flow between the zones is calculated with the standard orifice flow equation:

$$Q = C_d \cdot A\sqrt{2\rho \cdot \Delta P}, \qquad (1)$$

where $C_d$ is a discharge coefficient and $A$ is the opening area (m2). In the case of a slanted profile, the airflow between the zones is simultaneously bi-directional.

- The windows are also represented with the bi-directional flow with 0.65 discharge coefficient and 10% of the openable area for calculation.
- The envelope cracks (leakage) are represented as external area infiltration distributed based on the power law, and the exfiltration and infiltration are separated.
- The apartment entrance door has a mail slot, a crack with a k coefficient of $9.3\times10^4$ and a power-law exponent of 0.7 (Jokisalo et al. 2003).
- The model for the internal nodes of the simulation model is fully mixed for the concentration calculation, such as $CO_2$ level.

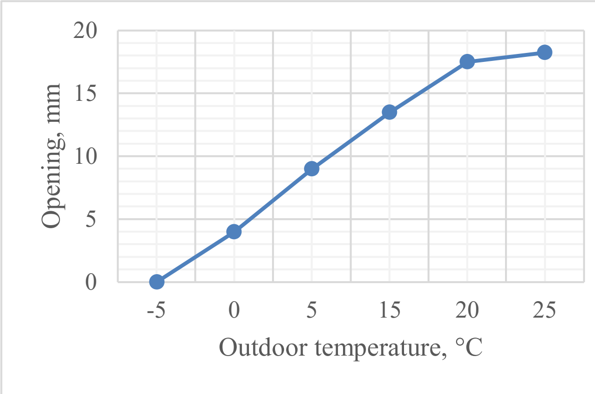
**Passive stack ventilation system model**

The passive stack ventilation is introduced with the standard IDA ICE bi-directional chimney model with stacks of different heights according to the floor. The chimney model considers the inlet and outlet loss coefficient, duct roughness, shape, and height.

**Inlet device model**

The self-regulating inlet devices regulate airflow based on the outdoor temperature in the reference case. The simulation model was created according to the manufacturer data, and the setpoints between values were interpolated linearly. The bedrooms are modelled with a 160 mm diameter inlet device with a nominal setting of 9.3 l/s at a pressure difference of 5 Pa, according to the reference building. The living rooms are modelled with 100 mm diameter inlet devices with a nominal setting of 5.1 l/s at a pressure difference of 5 Pa. The flow characteristics are presented in Table 1. The inlet device flow characteristics and design are shown in Figure  and Table 2.


**(a)**




**(b)**

*Figure 2: The inlet device product scheme (a); The inlet device opening as a function of outdoor temperature (b).*

*Table 2: The inlet device airflow rate at different pressure differences and opening degrees. Nominal conditions 5 Pa, 15 ˚C outdoor air temperature.*

| Opening, b, mm | Airflow rate, l/s | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Living room device | | | | Bedroom device | | | |
| | Pressure difference, Pa | | | | | | | |
| | 5 | 10 | 20 | 30 | 5 | 10 | 20 | 30 |
| 4 | 3.2 | 2.9 | 7.5 | 9.5 | 4.5 | 6.6 | 9.5 | 13 |
| 8 | 4.5 | 6.9 | 11 | 13 | 7 | 11 | 16 | 21 |
| 12 | 4.9 | 7.5 | 12 | 14 | 8.5 | 13 | 20 | 25 |
| 16 | 5.1* | 7.8 | 12 | 15 | 9.3* | 14 | 22 | 28 |

*nominal conditions 5 Pa, 15 ˚C outdoor air temperature

The self-regulating inlet device was created as a custom model (user-specified) based on the infiltration model with temperature-dependent power-law k-factor and exponent equal to 0.5. The model has a simultaneous single-direction flow.

The k-values for the inlet device and filter were calculated according to the manufacturer's product data. The following equation was used for the volumetric airflow rate:

$$q_v = k \cdot \sqrt{\Delta p}, \qquad (2)$$

where $q_v$ is volumetric airflow rate, and $\Delta p$ is component pressure drop.

The k-value has been calculated for the given inlet device characteristic data points and linearly interpolated. The k-value was coupled with outdoor temperature and presented as a function in Figure 3.

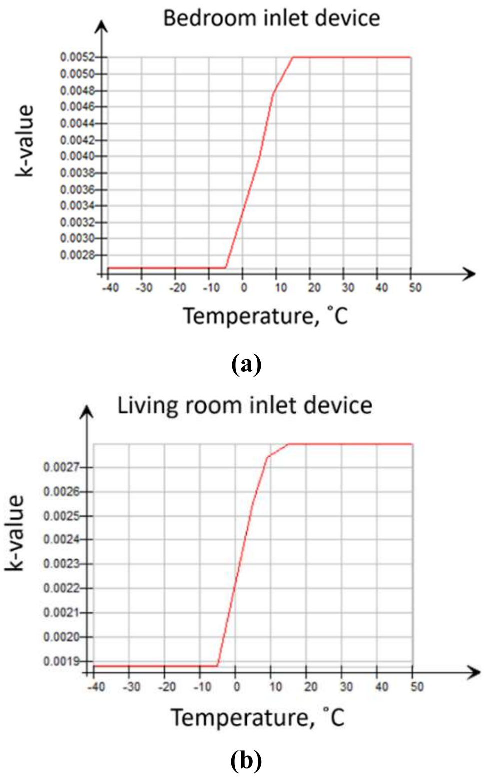



*Figure 3: The inlet device flow characteristics via k-value against outdoor temperature: (a) bedroom inlet device; (b) living room inlet device.*

The function of the bedroom and living room inlet devices was used in the simulation model to calculate the airflow considering pressure difference and outdoor temperature. Dirty inlet device filters were simulated, assuming they were not being cleaned for more than 1 year, resulting in k-values twice lower than in nominal operation. The loaded filter is described with half the standard k-value. The stack ductwork has the total pressure loss coefficient of the passive stack increased to 40 ('REHVA Guidebook 29' n.d.).

**Weather data**

The weather data is presented with climatological conditions at the Helsinki-Vantaa weather station in southern Finland for the 2012 reference year ('Validation & Certifications - Simulation Software | EQUA' n.d.; Kalamees et al. 2012). The data consists of hourly mean outdoor air temperature, relative humidity, direct and diffused insolation, wind speed and direction.

**The simulation case description**

The developed building model was used to simulate the one-year performance of the ventilation system and indoor air quality (IAQ). The $CO_2$ level and indoor air temperature have been chosen to assess the IAQ during the summer. The $CO_2$ level is an indirect indicator for the room airflow rate and was compared against standards ('National Building Code of Finland. Part D2. Indoor Climate and Ventilation of Buildings Regulations and Guidelines.' 2012; 'Decree of the Ministry of the Environment on the Indoor Climate and Ventilation of New Buildings 1009/2017' 2017). The indoor air temperature assesses the influence of the airflow rate in apartments and occupant personal conditions.

The three-room apartments on the second and fifth floors were chosen to show the influence of the height difference of passive stack ventilation ductwork. For each, a range of cases was created to assess the effect of the ventilation system condition, improved envelope airtightness, occupant behaviour, and doors and windows operations, see Table 3.

The reference case represents standard performance with no maintenance issues, changes to building envelope or building operation. In the best-case scenario, occupants are assumed to keep all the doors open, possibly affecting the passive stack ventilation performance.

The cases with dirty inlet device filters (M1) and passive stack ducts (M2) represent poor maintenance cases. The case with improved airtightness (M3) represents a building with more efficient envelope insulation, thus higher airtightness of 1.5 1/h. The case with no windows shading (M4) represents the influence of the insolation. The cases with non-openable windows (M5) represent the ventilation only via infiltration and inlet devices and the scenario where windows are not operated for some reason, such as occupant inability to do it.

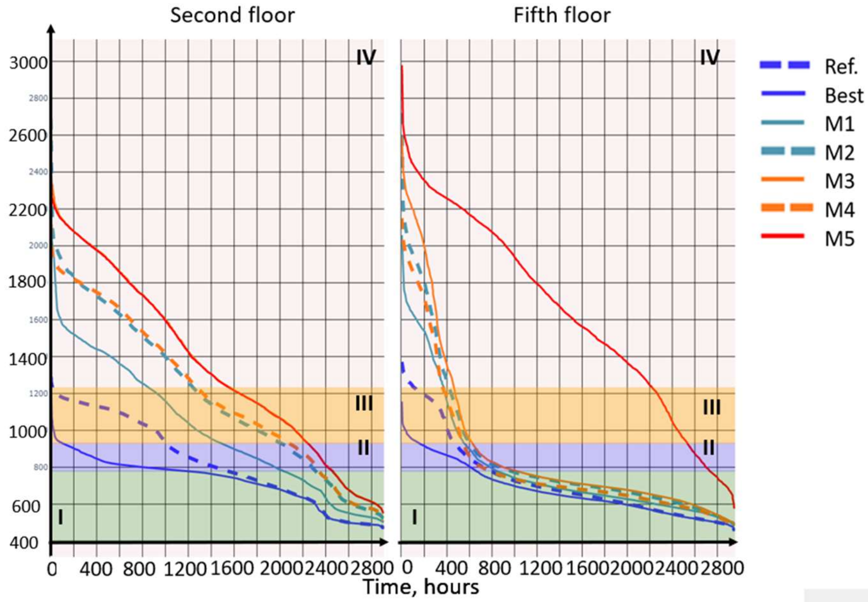
# Results

## Apartment indoor temperature and $CO_2$ analysis results

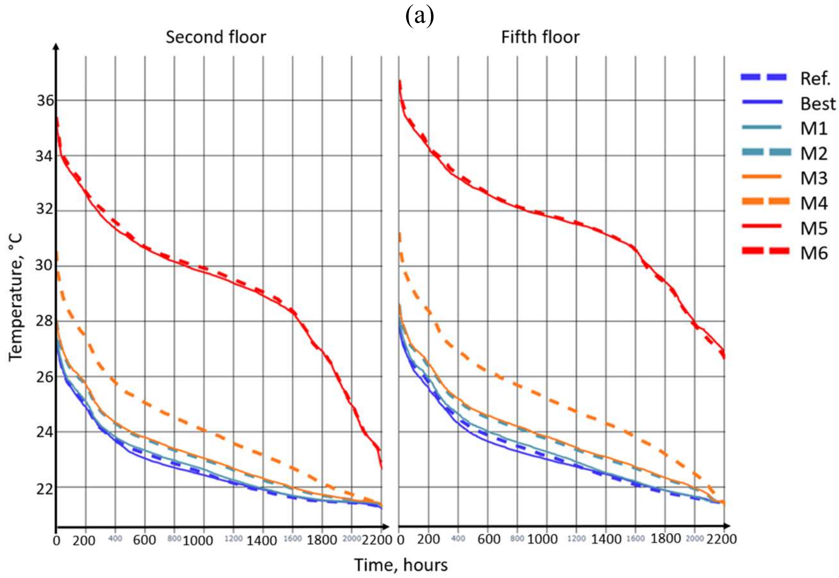
The apartment indoor air temperature results were analysed to represent the overheating during the summer. The $CO_2$ results are represented for summer (May to August) period, making the results comparable to the overheating analysis. The colours for the figures are used consistently to represent the correlations.

The indoor air temperatures simulation results in the three-room apartments on the second and fifth floors are represented in Figure 4 and cases Table 3. The results show the indoor air overheating trend in the cases with no windows shading (M4) and non-openable windows (M5), where the temperature on the fifth floor is significantly higher due to insolation and pressure conditions. A significant amount of time spent above 32 °C is an overall health indicator and 30 °C - is for vulnerable groups of people. The window shading has less influence than additional airflow through the windows, if they are operated, see M4 vs M5.

The $CO_2$ level in the three-room apartments on the second floor is shown in Figure 4. In reference and best-scenario cases, occupants spend most of the time in I to II category. However, the maintenance issues (M1 and M2) show significant influence, with a dirty passive stack system decreasing performance to the IV category. The apartment on the fifth floor shows higher maximum $CO_2$ and lower overall levels. It might occur due to the additional façade wind pressure, thus more effective windows operation. Improved airtightness (M3) is insignificant due to the low stack effect. It is consequently shown in M5 case with no additional window ventilation, which results in most of the time spent in III and IV categories. However, the stack effect on the second floor can still provide better occupational conditions due to the more substantial stack effect and reacts on the internal door operating (closing of all doors), rapidly decreasing the IAQ.




(a)




(b)

*Figure 4: The indoor air temperature (a) and $CO_2$ level (b) duration curves for the three-room apartments on the second and fifth floors from June to August and from May to August, respectively.*

*Table 3: The building simulation case scenarios.*

| Case Scenario | Bedroom Door | Bathroom Door | Inlet Device | Stack Duct | Airtightness $n_{50}$, 1/h | Windows Shading | Windows Opening | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Summer | Winter |
| Ref. | Closed, Night | Opened | Clean | Clean | 2.4 | Yes | Always, if >12 °C | 30 min. before sleep |
| Best | Opened | Opened | Clean | Clean | 2.4 | Yes | Same | Same |
| M1 | Closed, Night | Closed | Dirty | Clean | 2.4 | Yes | Same | Same |
| M2 | Closed, Night | Closed | Dirty | Dirty | 2.4 | Yes | Same | Same |
| M3 | Closed, Night | Closed | Dirty | Dirty | 1.5 | Yes | Same | Same |
| M4 | Closed, Night | Closed | Dirty | Dirty | 1.5 | No | Same | Same |
| M5 | Closed, Night | Closed | Dirty | Dirty | 1.5 | No | No | Same |
| M6 | Closed | Closed | Dirty | Dirty | 1.5 | No | No | No |

## Conclusions

The paper introduces the building simulation model of a retrofitted five-storey apartment building equipped with modern passive stack ventilation in Nordic conditions. The model was created with IDA ICE software, where the novel self-regulating inlet custom model was developed for this study. The resulting simulation model considers internal flows, building envelope and windows airtightness, operational and occupancy schedules of the building, and specific outdoor weather conditions. The infiltration airflows are taken into account by wind pressure on each building façade combined with zones stack effects. The case scenarios were created to assess the possible effect of poor maintenance, improved airtightness, and window opening on the system performance. The results are represented for the two and fifth floors' three-room apartments. The $CO_2$ levels and indoor air temperature were compared against the EN 16798-1 to assess the IAQ. The simulation building model results correlate well with comparable previous studies. The results clearly show that poor maintenance significantly contributes to the low IAQ, thus should be carefully planned to prevent its clogging. Openable windows are essential to provide an additional airflow rate, especially in the cases of a group of vulnerable people who may struggle to operate openable windows. Otherwise, the apartment temperature exceeds 30 °C, or even 32 °C in some cases, which is a health limit.

**Acknowledgement**

The authors would like to acknowledge Mika Vuolle from Equa Simulation Finland Ltd. for developing the inlet device model, IDA ICE software support and cooperation.

## References

Arendt, K., and M. Krzaczek. 2014. ‘Co-Simulation Strategy of Transient CFD and Heat Transfer in Building Thermal Envelope Based on Calibrated Heat Transfer Coefficients’. *International Journal of Thermal Sciences* 85 (November): 1–11. https://doi.org/10.1016/j.ijthermalsci.2014.06.011.

Brelih, Nejc, and Olli Seppanen. 2011. ‘Ventilation Rates and IAQ in European Standards and National Regulations’. *Proceedings of the 32nd AIVC Conference and 1st TightVent Conference in Brussels*, January.

6. Ministry of Environment Decree (1010/2017) on the Energy Performance of the New Building; Ministry of the Environment: Helsinki, Finland, 2018.

Jokisalo, Juha, Jarek Kurnitski, Minna Korpi, Targo Kalamees, and Juha Vinha. 2009. ‘Building Leakage, Infiltration, and Energy Performance Analyses for Finnish Detached Houses’. *Building and Environment* 44 (2): 377–87. https://doi.org/10.1016/j.buildenv.2008.03.014.

Jokisalo, Juha, Jarek Kurnitski, Mika Vuolle, and Antti Torkki. 2003. ‘Performance of Balanced Ventilation with Heat Recovery in Residential Buildings in a Cold Climate’. *International Journal of Ventilation* 2 (3): 223–36. https://doi.org/10.1080/14733315.2003.11683667.

Kalamees, Targo, Kirsti Jylhä, Hanna Tietäväinen, Juha Jokisalo, Simo Ilomets, Reijo Hyvönen, and Seppo Saku. 2012. ‘Development of Weighting Factors for Climate Variables for Selecting the Energy Reference Year According to the EN ISO 15927-4 Standard’. *Energy and Buildings* 47 (April): 53–60. https://doi.org/10.1016/j.enbuild.2011.11.031.

Kontonasiou, Eleni. n.d. ‘Analysis of Indoor Air Quality & Thermal Comfort Parameters in Building Regulations in 8 Member States’, 10.

Kravchenko, Ilia, Risto Kosonen, Juha Jokisalo, and Simo Kilpeläinen. 2022. ‘Performance of Modern Passive Stack Ventilation in a Retrofitted Nordic Apartment Building’. *Buildings* 12 (January): 96. https://doi.org/10.3390/buildings12020096.

‘National Building Code of Finland. Part D2. Indoor Climate and Ventilation of Buildings Regulations and Guidelines.’ 2012. Ministry of the Environment, Finland.

Neve, J De, S Denys, J G Pieters, I Pollet, and J Denul. 2005. ‘CFD Analysis of the Effect of Self-Regulating Devices on the Distribution of Naturally Supplied Air’. *26th AIVC Conference: Ventilation in Relation to the Energy Performance of Buildings*, 6.

Rämö, Anu. n.d. ‘Statistics Finland - Building Stock 2019’. Statistics Finland. Accessed 5 November 2020. http://www.stat.fi/til/rakke/2019/rakke_2019_2020-05-27_kat_002_en.html.

‘REHVA Guidebook 29’. n.d. REHVA. Accessed 7 July 2021. https://www.rehva.eu/hvac-guidebook-repository/rehva-guidebook-29.

‘The National Building Code of Finland’. n.d. Ympäristöministeriö. Accessed 11 November 2020. https://ym.fi/en/the-national-building-code-of-finland.

‘Validation & Certifications - Simulation Software | EQUA’. n.d. Accessed 22 June 2021. https://www.equa.se/en/ida-ice/validation-certifications.