Impact of airtightness on the heat demand of passive houses in central European climate

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ABSTRACT

Excessive air leakage through the building envelope increases the infiltration heat loss and therefore lowers the energy efficiency. Therefore, very good airtightness is required in case of well insulated buildings equipped with a mechanical ventilation system with heat recovery (e.g. $n_{50} < 0.6$ h^{-1} for passive houses). Although the building industry has progressively adopted strategies to comply with such strict limits, it is still important to study how and how much the airtightness influences the energy efficiency of different types of buildings in different climatic conditions.

This study investigates the impact of building envelope airtightness on the heat demand of a single-family house and a multi-family residential building in the central European climate (Prague). Both model buildings are passive houses, equipped with a balanced mechanical ventilation system with heat recovery. Their heat demand was calculated in function of the envelope airtightness (n_{50} varying from 0 to 1 h^{-1}). Several combinations of leakage distribution over the building envelope and wind shielding conditions were considered. The single-family house was modelled as a single zone building. In the multi-family building, each flat and the staircase were considered as separate pressure zones. The heat demand was calculated considering the following alternatives of internal air leakage between the zones:

- no internal air leakage between zones
- each flat connected with the staircase (air leakage between flats not allowed)
- each flat connected with the staircase and neighbouring flats (air leakage between flats allowed)

The air leakage distribution over the residential building envelope and the characteristics of the internal leakage paths were estimated from results of airtightness tests of a real building. For the purpose of this study, transient thermal and air infiltration models were developed using Matlab – Simulink. Iterative approaches were adopted for a reliable coupling of the thermal and air infiltration models (differently in the single and multi-zone models).

The heat demand increases noticeably with the building envelope air permeability. The increase is more pronounced in case of the residential building (eg. 3 kWh/(m^2·a) per unit of n_{50} against 4 kWh/(m^2·a) for the single-family house under the same conditions). The wind shielding and the leakage distribution influence significantly the results. The highest heat demand was identified in cases with the air leakage paths distributed half and half at the bottom and on the top of the building. The internal air leakage does not affect significantly the heat demand of the residential building, which depends mostly on the envelope air leakage and its distribution. However, significant air flow rates were detected between the zones (up to 24 m^3/h between flats). The internal leakage may therefore cause an issue for IAQ, ventilation system function and fire safety.

KEYWORDS

Airtightness, air leakage, heat demand, thermal simulation, airflow simulation

1 INTRODUCTION

Excessive air leakage through the building envelope may substantially increase the infiltration heat loss. Consequently, the heat demand increases, which results into a lower energy efficiency of the building. This impact is particularly significant in case of well insulated buildings equipped with a mechanical ventilation system with heat recovery, where the transmission and ventilation heat losses were minimized. This is the reason why strict airtightness requirements were set for this category of buildings (e.g. $n_{50} < 0.6\ h^{-1}$ for passive houses).

Compliance with such a low limit value of n_{50} requires special design approaches during the planning phase, a particular care, systematic control and use of special products during the construction works. Although the building industry has progressively adopted suitable strategies to achieve very good airtightness, the building practitioners and investors still ask whether the strict requirements are justified and which effect would produce a deviation from them (both upwards and downwards) in terms of energy consumption. Therefore, it is still important to study, how and how much the airtightness influences the energy efficiency of different types of buildings in different climates.

Numerous studies were published during the last years which investigate the impact of airtightness on energy efficiency of buildings in different European countries. No similar study has been carried out in the Czech Republic until now. In pursuit of filling this gap, the authors present here a numerical investigation of the impact of building envelope airtightness on the heat demand of a single-family house and a multi-family residential building in the central European climate (Prague). Several combinations of leakage distribution over the building envelope and wind shielding conditions are considered. In case of the multi-family residential building, the impact of internal air leakage is studied as well. With regard to increasingly tighter energy efficiency policies, this work is focused on buildings with low energy consumption (passive houses) and very low airtightness levels.

2 CALCULATION METHODS

In order to calculate the heat demand, a simplified transient model was developed in Matlab – Simulink. This model consists of two parts coupled to each other: thermal model and infiltration model. The calculation time step is one hour and the model uses hourly weather data. The model was first developed as single-zone and then adapted in order to allow for multi-zone simulations.

2.1 Thermal model

Fig. 1 shows the thermal model network (single-zone case). The model requires only limited amount of input data and its simplicity allows the coupling with the infiltration model to be handled easily. Based on the results of its validation, it is supposed to provide a reasonable accuracy for the purpose of this study (Kopecký 2016).

The thermal model calculates the internal air temperature, corresponding heat loss and heat demand. The heat capacity is calculated considering an effective thickness of 100 mm for all building components in contact with the internal air. The effect of heat recovery from the exhaust air is obtained by reducing the supply air flow rate by the factor $(1-\eta)$, where η is the efficiency of heat recovery. The supply air flow rate (as well as the internal heat gains) follows an occupancy schedule. The infiltration air flow rate is taken from the infiltration model.

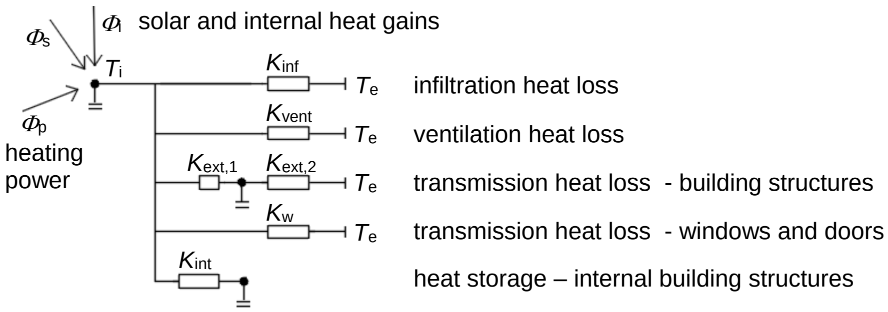

Figure 1: The thermal model network.

2.2 Infiltration model

The infiltration model calculates the infiltration air flow rate as a sum of air flow rates through the individual leakage paths. The air flow rate through the leakage paths is calculated using the power law equation in function of pressure difference, taking the air flow coefficient C and the air flow exponent n as leakage paths characteristics. The pressure differences are calculated with regard to wind pressure and stack effect. The pressure difference induced by the balanced ventilation system was supposed to be low in comparison with the wind and stack effect and therefore neglected in the calculation.

The pressure difference due to the stack effect is calculated from the leakage path position on the building envelope (height above the 1st floor) and the internal air temperature. Since the infiltration air flow rate and the internal temperature influence each other, the internal temperature is corrected by means of an iterative approach as explained in the next section.

The wind pressure is calculated in function of the wind speed at the building height and the wind direction. The wind speed taken from the weather data is corrected in order to account for the building height and the surrounding obstacles (wind shielding effect) according to (ASHRAE 2001). Wind pressure coefficients C_p for façades and roof in function of wind incidence angle are taken from (Orme 1998).

The infiltration model was validated with the computer program CONTAM. A single-zone model (the single-family house of this study) was modelled in CONTAM with the same settings. The difference between the results did not exceed 1.4 % for the air flow rate through the individual leakage paths and 0.3 % for the total air flow rate.

2.3 Coupling of the thermal and infiltration model

For each calculation time step, the infiltration model calculates the infiltration air flow rate based on an initial internal air temperature. The resulting infiltration air flow rate is transferred to the thermal model, which calculates the internal air temperature. Since the calculated internal air temperature may differ from the initial one, the calculated temperature is sent back to the infiltration model in order to adjust the stack effect pressure differences and recalculate the infiltration air flow rates. For each calculation time step, this iterative process is repeated until the difference between the internal air temperatures and infiltration air flow rates from two successive iterations is less than a pre-set limit.

3 CASE 1 – A SINGLE-FAMILY HOUSE

3.1 Building description

The size, thermal performance and building services of the studied building (fig. 2) are representative for a typical single-family passive house built recently in the Czech Republic. The building has two storeys and it is intended for a four member's family. The floor area is 132 m^2 and internal air volume is 352 m^3. The mean thermal transmittance of the building envelope is U_{em} = 0.21 W/(m^2·K) and the heat demand calculated by means of monthly method according to (EN ISO 13790) is 16.1 kWh/(m^2·a). The building is equipped with a balanced mechanical ventilation system with heat recovery. The efficiency of the heat recovery is η = 75 %.

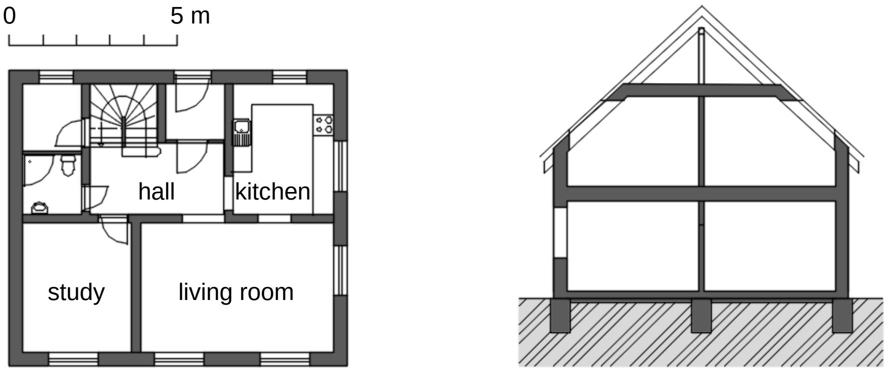

Figure 2: The studied single-family house. Left - first floor plan. Right - cross section.

3.2 Simulated alternatives

The objective of this work is evaluation of the building airtightness on the heat demand. In this study, the building airtightness is expressed in terms of the air change rate at 50 Pa, n_{50} [h^{-1}]. The heat demand of the building was calculated several times with the n_{50} varying stepwise from 0 to 1.0 h^{-1} with an increment of 0.1 h^{-1}. This range was supposed as typical for the energy efficient buildings equipped with the ventilation system in question. For example, the Czech technical standard (CSN 73 0540-2: 2011) recommends to fulfil the limit value of n_{50} = 1.0 h^{-1} in case of buildings equipped with mechanical ventilation system with heat recovery and n_{50} = 0.6 h^{-1} in case of buildings with very low heat demand equipped with the same ventilation system (typically passive houses).

Since the wind can significantly influence the infiltration, the study of the airtightness impact on the heat demand as described above was repeated three times, considering the following wind shielding conditions:

- no wind (hypothetical case, the infiltration is driven by the stack effect only)
- heavy shielding (buildings in city centres)
- moderate shielding (buildings in suburban or wooded areas)
- no shielding (buildings in open terrain)

The single-family houses are usually built in suburban areas of larger towns or in smaller villages surrounded by the buildings and trees of similar height. The villages are rarely situated in completely open country exposed to undisturbed wind. Therefore, the moderate shielding can be considered as typical for this category of buildings.

For the case of moderate shielding, the impact of leakage distribution over the building envelope was studied. On each of the building faces, the air leakage was concentrated into leakage paths (spots) located at different heights (fig. 3):

- lower leakage path 0.5 m above the 1st floor – representing the leakage through the external wall/slab on the ground interface and other leakages in the lower part of the external wall (e.g. electrical boxes)
- middle leakage path 4.05 m above the 1st floor – representing the leakage through the external wall/pitched roof interface and other leakages in the upper part of the external wall (e.g. electrical boxes in the 2nd floor, penetrations of structural elements – joists etc.)
- upper leakage path 5.82 m above the 1st floor – representing the leakage through the pitched roof /ceiling interface and other leakages in the upper part of the external wall (e.g. electrical boxes in the 2nd floor, penetrations of structural elements of the roof truss)
- leakage paths in the middle-height of the building openings (windows, doors) - representing the leakage through the window or door/external wall interface and the leakage of the element itself

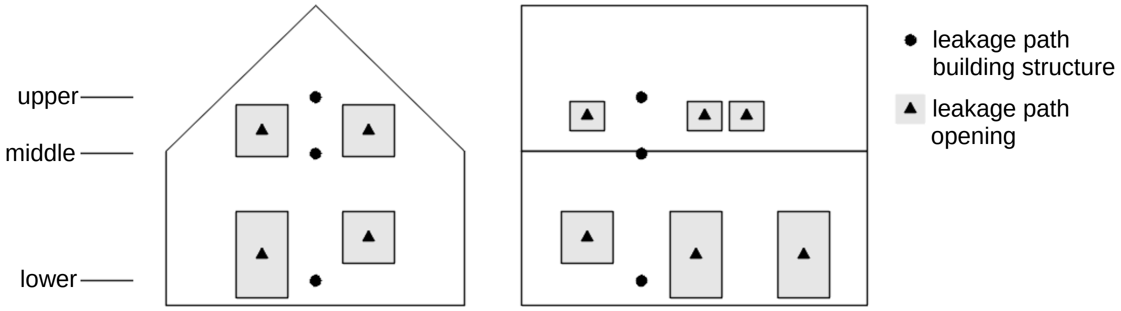

Figure 3: The position of the leakage paths.

Note that the horizontal position of the leakage paths has no significance for infiltration calculations, since average wind pressure coefficients C_p apply for whole area of each building face. Tab. 1 shows the five studied alternatives of the overall building envelope leakage distribution.

Table 1: Overview of the studied alternatives of the leakage distribution over the building envelope

leakage path	**share of the leakage path on the overall envelope air leakage**				
	alt. 1	**alt. 2**	**alt. 3**	**alt. 4**	**alt. 5**
lower leakage paths	30 %	70 %	10 %	40 %	50 %
middle leakage paths	30 %	10 %	10 %	10 %	0 %
upper leakage paths	30 %	10 %	70 %	40 %	50 %
openings leakage paths	10 %	10 %	10 %	10 %	0 %

In all the studied alternatives, the building was modelled as a single zone. The reasons are that the internal doors remain commonly open in a single-family house and the ventilation system considered in this study requires interconnections allowing for air flow between the rooms. The same time schedules (tab. 2) and the same weather data (test reference year for Prague) were used in all simulations.

Table 2: Time schedules for single-family house simulations

		0:00 ÷ 8:00	**8:00 ÷ 16:00**	**16:00 ÷ 0:00**
number of persons	[-]	4	0	4
ventilation air flow rate	[m^3/h]	100	35 (n = 0.1 h^{-1})	100
internal heat gains	[W]	500	100	500

3.3 Results

In all the studied alternatives, the heat demand increases linearly with the air change rate at 50 Pa, n_{50} (fig. 4). The increase of the heat demand may range from approx. 2 to 4 kWh/(m^2·a) per unit of n_{50}, depending on the wind shielding and the leakage distribution. For the likely most common case, i.e. almost uniform distribution of the air leakage (alt.1 in tab. 1) and moderate wind shielding, the heat demand corresponding to the building with n_{50} = 0.6 h^{-1} is about 8 % higher than the heat demand of an ideally airtight building. In case of a building with n_{50} = 1 h^{-1}, the increase of the heat demand reaches 14 %.

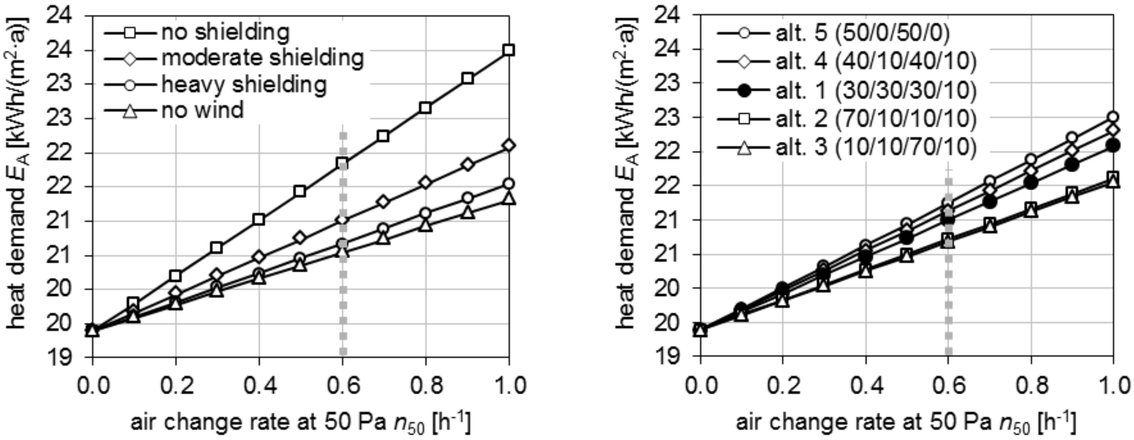

Figure 4: Simulation results for single-family house. Left – influence of wind shielding, the leakage distribution corresponds to alt. 1 in table 1. Right – influence of leakage distribution, moderate shielding

Unfavourable shielding conditions can significantly strengthen the impact of airtightness on heat demand. Considering the same level of airtightness, the increase of the heat demand of the studied house would be approx. 50 % higher in case of "no shielding" compared to the case of "moderate shielding". On the other hand, the difference of the heat demand between the cases "moderate shielding" and "heavy shielding" is rather small. Under moderate and heavy shielding (usual conditions) the stack effect is the dominant driving force of air infiltration.

The influence of the leakage distribution is noticeable, but seems not to be really significant in comparison with the impact of the wind shielding. The lowest heat demand is obtained if the air leakage is concentrated either on the top or on the bottom of the building envelope (alt. 2 and 3 in tab. 1). Splitting the air leakage half on the top and half on the bottom of the building with no or small leakage in the middle height of the building leads to the highest heat demand (alt. 4 and 5). The uniform leakage distribution leads to heat demand rather closer to the unfavourable cases.

4 CASE 2 – A MULTI-FAMILY RESIDENTIAL BUILDING

4.1 Building description

The studied building (fig. 5) represents an example of a real multi-family residential passive house. The building was built in a suburb of Prague in 2012. Its airtightness was tested and studied in detail (Novák 2013). Therefore, data concerning the envelope airtightness, the leakage distribution and data concerning airtightness of internal partitions are available.

The building has 4 residential floors above the ground level and a parking in the underground. In the residential part, 14 flats are spread around the central staircase including an elevator shaft. The flats are of different sizes, the expected number of inhabitants is 40. The buildings height above the ground is 12.3 m. The floor area of the heated residential part is 1 173 m^2 and its internal volume 3 933 m^3. The mean thermal transmittance of the building envelope (heated zone) is U_{em} = 0.3 W/(m^2·K) and the heat demand calculated by means of monthly method according to (EN ISO 13790) is 14.1 kWh/(m^2·a). The building is equipped with a decentralised balanced mechanical ventilation system with heat recovery (the efficiency is η = 75 %.). Each flat has its own air handling unit. The air change rate at 50 Pa, resulting from an overall airtightness test carried out at commissioning of the building is n_{50} = 0.48 h^{-1}.

Figure 5: The studied multi-family residential building. Left – 3rd floor plan. Right – completed building

4.2 Simulated alternatives

The heat demand of the multi-family residential building was calculated in function of the n_{50} value ranging from 0 to 1 h^{-1} with an increment of 0.2 h^{-1}. In such a markedly compartmented building, the use of the single-zone model is not suitable. Therefore, the original thermal and infiltration models were adapted, including their coupling, in order to allow for multi-zone simulations.

In the thermal model, the heated space consists of two zones: one zone representing all the flats and a second zone representing the staircase. The infiltration model consists of five pressure zones. The flats of each floor are grouped into one zone (four zones, referred to as flats hereafter). The staircase is considered as a separate zone. Following alternatives of connection between the pressure zones were considered (fig. 6):

- alt. 1 no internal air leakage between zones (airtight internal partitions)
- alt. 2 each flat connected with the staircase (air leakage between flats not allowed)
- alt. 3 each flat connected with the staircase and neighbouring flats (air leakage between flats allowed)

The characteristics of the internal leakage paths were estimated from the results of the airtightness tests (Novák 2013). These characteristics were kept constant in all simulations, regardless the airtightness level of the building envelope.

In case of the residential building, a more detailed distribution of the wind pressure coefficients C_p over the envelope was considered. Each face of the building was divided into several regions with characteristic C_p values for high-rise buildings (Orme 1998).

Identical air leakage distribution was considered in all simulations (i.e. unlike in the single-family house study, the effect of leakage distribution over the building envelope was not studied here). The total air leakage through the building envelope was distributed between the envelope area enclosing the flats (61 % of the total air leakage) and the envelope area enclosing the staircase (39%). This proportion reflects real leakage distribution deduced from the results of airtightness testing. The air leakage proper to each of these two areas was equally divided among the four floors (25 % each). In case of flats, this "floor leakage" was equally divided between two leakage paths: one at the top and one at the bottom of the zone height, as shown on fig. 6. In case of staircase, the "floor leakage" was concentrated into one leakage path in the mid-height of the floor (fig. 6).

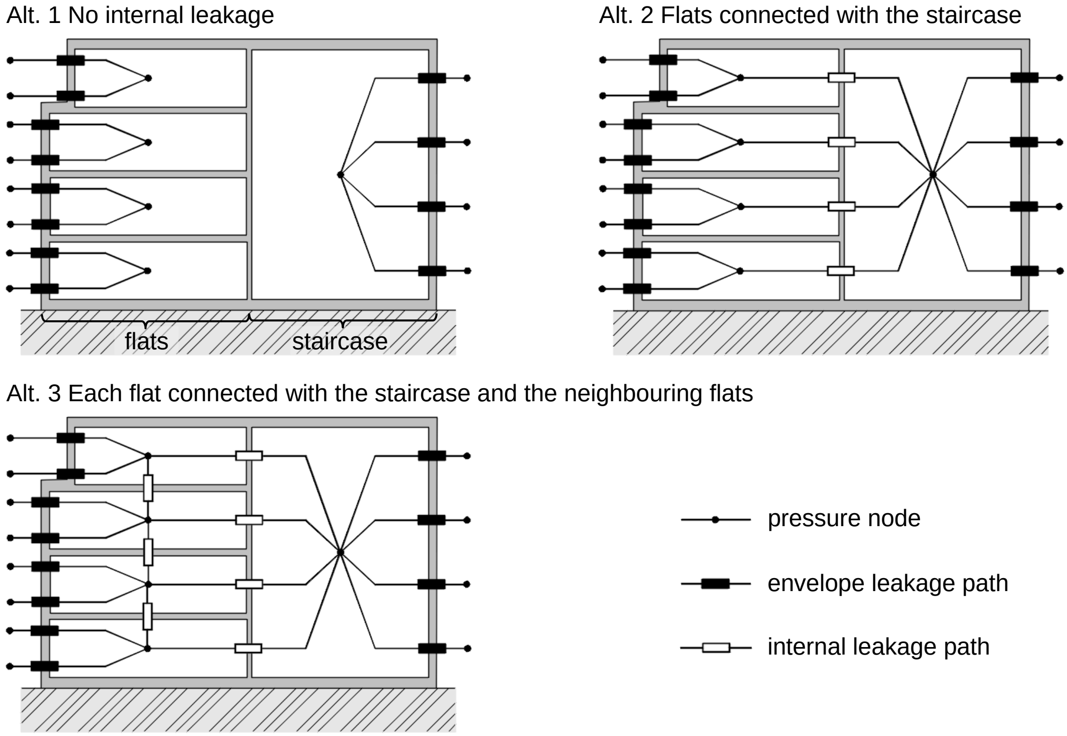

Figure 6: Infiltration model networks for the multi-family residential building. Schematic cross section.

The same time schedules (tab. 3) and the same weather data (test reference year for Prague) were used in all simulations.

Table 3: Time schedules for multi-family residential building simulations

			0:00 ÷ 8:00	**8:00 ÷ 16:00**	**16:00 ÷ 0:00**
flats	number of persons	[-]	40	0	40
(total figures)	ventilation air flow rate	[m^3/h]	1000	230 (n = 0.1 h^{-1})	1000
	internal heat gains	[W]	5400	1400	5400
staircase	number of persons	[-]	0	0	0
	ventilation air flow rate	[m^3/h]	34	34	34
	internal heat gains	[W]	0	0	0

4.3 Results

The increase of the heat demand ranges from approx. 3 to 5 kWh/(m^2·a) per unit of n_{50}, depending on the wind shielding. Under moderate wind shielding, the heat demand corresponding to the building with n_{50} = 0.6 h^{-1} is about 13 % higher than the heat demand of an ideally airtight building. These figures are markedly higher than in case of the single-family house showing a more significant impact of airtightness on the heat demand in case of residential buildings (compare fig. 4 and fig. 7). Since the residential buildings are higher, they suffer from stronger wind pressure than low-rise single-family houses (higher C_p values).

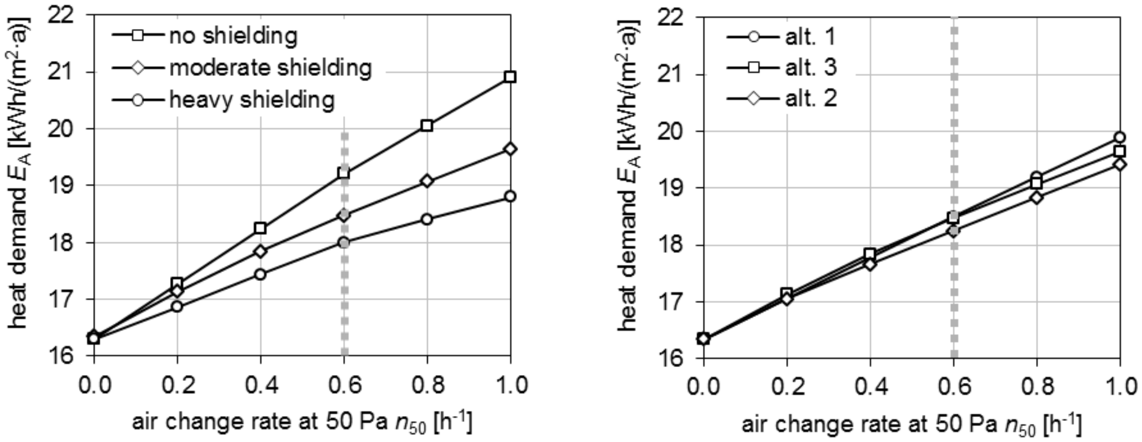

Figure 7: Simulation results for multi-family residential building. Left – influence of wind shielding, no internal leakage (airtight internal partitions). Right – influence of the internal leakage, moderate shielding.

Different alternatives of connections between the pressure zones led to very similar results in terms of heat demand (fig. 7, right). However, the airtightness of internal partitions strongly affects the distribution and magnitude of the internal air leakage. Significant air flow rates were identified from the staircase to adjacent flats and between neighbouring flats (fig. 8).

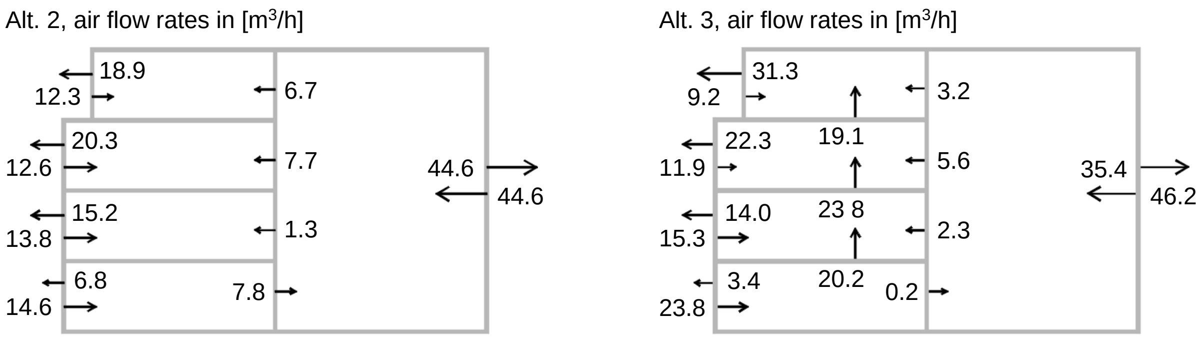

Figure 8: Average air flow rates between the pressure zones for January (schematic cross section). Left – alt. 2, flats connected with the staircase. Right – alt. 3, each flat connected with the staircase and neighbouring flats.

5 DISCUSSION AND CONCLUSIONS

This study confirms a significant impact of air leakage through the building envelope on the heat demand of passive houses in Central European climate. This impact is more pronounced in case of higher residential building. Exposure to the wind considerably amplifies the impact of air leakage. Even under typical wind exposure (moderate shielding), the air leakage corresponding to $n_{50} = 1\ h^{-1}$ can increase the heat demand of about 14 % (single-family house) or 20 % (residential building), with reference to an ideally airtight building. Hence, seeking for even better airtightness remains a meaningful challenge.

Despite simplifications and limited extent of this study, one can try, based on its results, to estimate approximately an appropriate level of airtightness requirements for passive houses in Central European climate. Generally, a factor causing an increase of heat demand higher than 10 % can be perceived as a critical threat for energy efficiency targets. On the other hand, a factor causing an increase lower that 5 % would obviously be of minor significance (e.g. due to uncertainties in determination of the factor itself and in the calculation method). Therefore, let us set lower and upper limits of acceptable increase of heat demand due to the air leakage to 5 and 10 % respectively with reference to an ideally airtight building. Then, we can find a corresponding range of n_{50} being about 0.4 ÷ 0.7 h^{-1} for single-family houses and 0.2 ÷ 0.5 h^{-1} for residential buildings. From this point of view, the commonly accepted limit value of n_{50} = 0.6 h^{-1} seems to be appropriate for single-family houses, but could be further reduced for residential buildings. Achievement of n_{50} values ranging from 0.2 to 0.5 h^{-1} should not represent an issue in case of residential buildings due to usually favourable envelope area to volume ratio (A/V). Moreover, field experience proves that such values can be achieved in practice, in particular if systematic control is required (mandatory airtightness testing).

An unfavourable distribution of the air leakage over the building envelope can strengthen the increase of the heat demand. The worst case occurs if the air leakage paths are concentrated at the bottom and at the top of the height of a pressure zone. Therefore, the design and construction of connections between the building elements in these locations merit a particular attention.

The influence of internal air leakage on the heat demand was found negligible. However, leaky internal partitions result into significant air exchange between adjacent pressure zones causing potential interference with the ventilation system. Transport of contaminants (or fumes in case of fire) due to the internal air leakage represents a potential IAQ issue and fire safety risk. Further investigation is needed in order to decide whether and to what degree the airtightness of internal partitions should be required.

6 ACKNOWLEDGEMENTS

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