Ing. Aleš VLK
Ing. Jiří NOVÁK, Ph.D.

CTU in Prague,
Faculty of Civil Engineering

Impact of Airtightness on the Heat Demand of Passive Houses in the Central European Climate

Vliv vzduchotěsnosti na potřebu tepla na vytápění pasivních domů v klimatických podmínkách střední Evropy

This calculation study investigates the impact of the airtightness of a building envelope 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. For the purpose of this study, transient thermal and air infiltration models were developed using Matlab – Simulink. 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. Iterative approaches were adopted for the reliable coupling of the thermal and air infiltration models (different in the single and multi-zone models). Their heat demand was calculated as a function of the envelope airtightness (n_{50} varying from 0 to 1 h^{-1}). Several combinations of leakage distribution over the building envelope, wind shielding and alternatives of the internal leakage paths between the zones were considered. The heat demand increases noticeably with the building envelope air permeability. The increase is more pronounced in the case of the residential building (e.g., 3 kWh/(m^2·a) per unit of n_{50} against 2 kWh/(m^2·a) for the single-family house under the same conditions). The wind shielding and the leakage distribution significantly influence the results. The internal air leakage does not significantly affect the heat demand of the residential building, which mostly depends on the air leakage of the envelope and its distribution. However, significant air flow rates were detected between the zones (up to 24 m^3/h between the flats). The internal leakage may, therefore, cause an issue for indoor air quality, ventilation system function and fire safety.

Keywords: *Airtightness, air leakage, heat demand, thermal simulation, airflow simulation, passive houses*

Tato výpočtová studie zkoumá vliv vzduchotěsnosti na potřebu tepla na vytápění rodinného a bytového domu v klimatických podmínkách střední Evropy (v Praze). Obě zkoumané budovy jsou pasivní domy, vybavené nuceným rovnotlakým větracím systémem se zpětným získáváním tepla. Pro obě budovy byl v prostředí Matlab – Simulink sestaven nestacionární tepelný model a model proudění vzduchu. Rodinný dům byl modelován jako jediná teplotní a tlaková zóna. V případě bytového domu bylo každé podlaží s byty a schodišťový prostor modelováno jako samostatná tlaková zóna. Vzájemné propojení tepelného modelu a modelu proudění využívá iterační postupy – odlišné v případě jednozónové a vícezónové budovy. Potřeba tepla na vytápění obou budov byla počítána opakovaně, v závislosti na vzduchotěsnosti obálky budovy (různé hodnoty n_{50} od 0 do 1 h^{-1}). Uvažovaly se různé kombinace rozložení netěsností po ploše obálky budovy, stínění budovy proti větru a vzduchotěsnosti vnitřních konstrukcí. Potřeba tepla na vytápění se znatelně zvyšuje s rostoucí průvzdušností obálky budovy. Nárůst je vyšší v případě bytového domu (o 3 kWh/(m^2a) při zvýšení n_{50} o 1 h^{-1} oproti 2 kWh/(m^2a) v případě rodinného domu za stejných podmínek). Stínění proti větru a rozložení netěsností po ploše obálky významně ovlivňuje výsledky. Netěsnosti ve vnitřních konstrukcích potřebu tepla na vytápění bytového domu příliš neovlivňují. Podstatná je velikost netěsností v obvodových konstrukcích a jejich rozdělení po ploše obálky budovy. Šíření vzduchu mezi jednotlivými zónami (průtok vzduchu mezi byty dosahoval až 24 m^3/h) by však mohlo negativně ovlivnit kvalitu vnitřního vzduchu, správnou funkci větracího systému a požární bezpečnost.

Klíčová slova: *Vzduchotěsnost, proudění vzduchu, potřeba tepla na vytápění, simulace tepelného chování budovy, simulace proudění vzduchu budovou, pasivní domy*

INTRODUCTION

Excessive air leakage through the building envelope may substantially increase the infiltration heat loss. Consequently, the heat demand increases, which results in a lower energy efficiency of the building. This impact is particularly significant in the case of well insulated buildings equipped with a mechanical ventilation system with heat recovery, where the transmission and ventilation heat losses are minimised. 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, particular care, systematic control and use of special products during construction. Although the building industry has progressively adopted suitable strategies to achieve very good airtightness, building practitioners and investors still ask whether strict requirements are justified and which effect would produce a deviation for 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 e.g. [7, 8] were published over the last several years which have investigated the impact of the airtightness on the energy efficiency of buildings in different European countries. A similar study has not been carried out in the Czech Republic until now. In pursuit of filling this gap, the authors present a numerical investigation of the impact of the airtightness of the building envelope on the heat demand of a single-family house and a multi-family residential building in a central European climate (Prague). Several combinations of leakage distribution over the building envelope and wind shielding conditions are considered. In the case of the multi-family residential building, the impact of the internal air leakage is studied as well. With regard to the increasingly tighter energy efficiency policies, this work is focused on buildings with low energy consumption (passive houses) and very low airtightness levels.

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: the 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.

Thermal model

Fig. 1 shows the thermal model network (single-zone case). The model only requires a 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 reasonable accuracy for the purpose of this study [4].

The thermal model calculates the internal air temperature, the 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 a factor ($1-\eta$), where η is the heat recovery efficiency. 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.

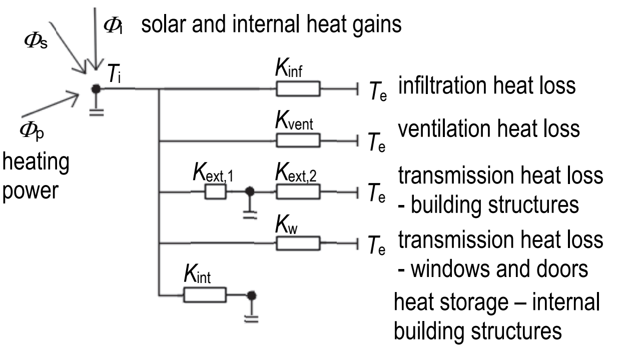

Figure 1 The thermal model network.

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 as a function of the pressure difference, taking the air flow coefficient C and the air flow exponent n as leakage path characteristics. The pressure differences are calculated with regard to the 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 section "Coupling of thermal and infiltration model".

The wind pressure is calculated as a function of the wind speed at the building's 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 [1]. Wind pressure coefficients C_p for the façades and the roof as a function of the wind incidence angle are taken from [6].

The infiltration model was validated with the computer programme CONTAM. A single-zone building 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.

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.

CASE 1 – A SINGLE-FAMILY HOUSE

Building description

The size, the thermal performance and building services of the studied building (Fig. 2) are representative for a typical single-family passive house recently built in the Czech Republic. The building has two storeys and it is intended for a four member 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 a 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 heat recovery efficiency is η = 75 %.

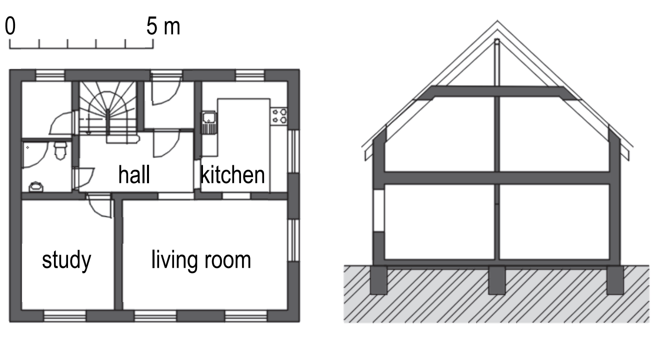

Figure 2 The studied single-family house. Left - first floor plan. Right - cross section.

Simulated alternatives
The objective of this work is the evaluation of the impact 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 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 energy efficient buildings equipped with the ventilation system in question. For example, the Czech technical standard [2] recommends one to fulfil the limit value of n_{50} = 1.0 h^{-1} in the case when buildings are equipped with a mechanical ventilation system with heat recovery and n_{50} = 0.6 h^{-1} in the case when buildings with very low heat demand are 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 an open terrain).

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

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

- the 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),
- the 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 on the 2nd floor, penetrations of structural elements – joists, etc.),
- the 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 on the 2nd floor, penetrations of structural elements of the roof truss),
- the 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.

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

In all the studied alternatives, the building was modelled as a single zone. The reasons are that the internal doors commonly remain 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.

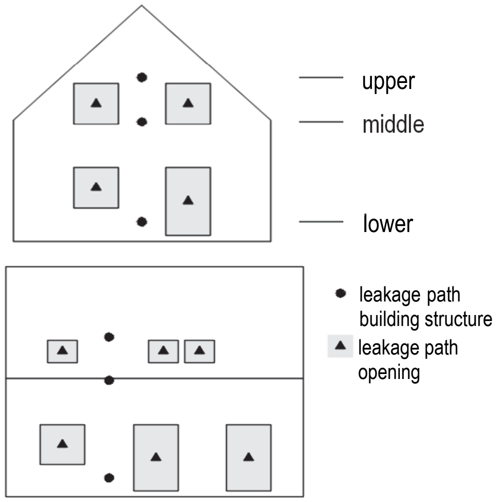

Figure 3 The position of the leakage paths.

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 %
leakage paths of openings	10 %	10%	10 %	10%	10 %

Table 2 Time schedules for single-family house simulations

		0:00 ÷ 8:00	8:00 ÷ 16:00	16:00 ÷ 0:00
Number of people	[-]	4	0	4
Ventilation air flow rate	[m^3/h]	100	35*)	100
Internal heat gains	[W]	500	100	500

*) *corresponds to an air change rate n = 0.1 h^{-1}*

Results
In all the studied alternatives, the heat demand increases linearly with the air change rate at 50 Pa, n_{50} (Fig. 4 and Fig. 5). The increase in 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 a uniform distribution of 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 the case of a building with n_{50} = 1 h^{-1}, the increase in the heat demand reaches 14 %.

Unfavourable shielding conditions can significantly strengthen the impact of the airtightness on the heat demand. Considering the same level of airtightness, the increase in the heat demand of the studied house would be approx. 50 % higher in the case of "no shielding" compared to the case of “moderate shielding”. On the other hand, the difference in 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.

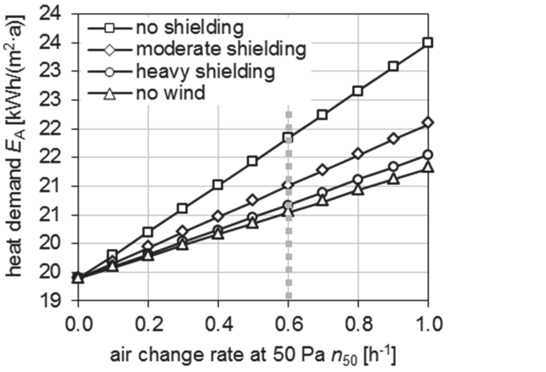

Figure 4 Simulation results for the single-family house. Influence of wind shielding, the leakage distribution corresponds to Alt. 1 in Table 1.

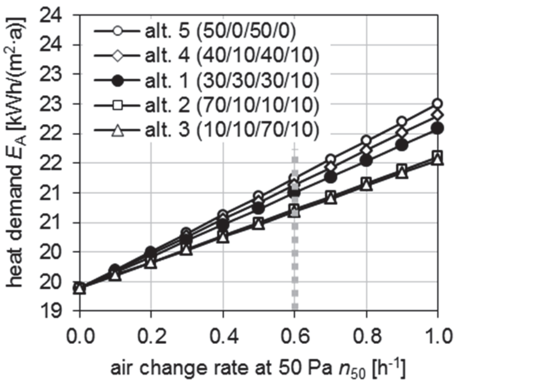

Figure 5 Simulation results for the single-family house. Influence of leakage distribution, moderate shielding

The influence of the leakage distribution is noticeable, but seems to be not 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 Alt. 3 in Tab. 1). Splitting the air leakage half on the top and half on the bottom of the building with no or a small leakage in the middle height of the building leads to the highest heat demand (Alt. 4 and Alt. 5). The uniform leakage distribution leads to the heat demand being rather closer to the unfavourable cases.

CASE 2 – A MULTI-FAMILY RESIDENTIAL BUILDING

Building description

The studied building (Fig. 6 and Fig. 7) 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 [5]. Therefore, data concerning the envelope airtightness, the leakage distribution and data concerning the airtightness of the internal partitions are available.

The building has 4 residential floors above the ground level and a parking area 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 1173 m² and its internal volume is 3933 m³. The mean thermal transmittance of the building envelope (heated zone) is U_{em} = 0.3 W/(m²·K) and the heat demand calculated by means of a monthly method according to [3] is 14.1 kWh/(m²·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 the overall airtightness test carried out at the time the building was commissioned is n_{50} = 0.48 h⁻¹.

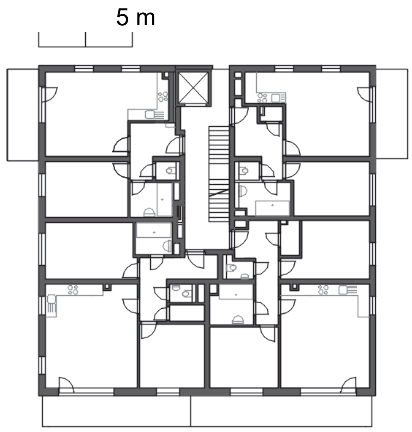

Figure 6 The studied multi-family residential building. 3rd floor plan.

Figure 7 The studied multi-family residential building. Completed building

Simulated alternatives

The heat demand of the multi-family residential building was calculated as a 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. The following alternatives of connection between the pressure zones were considered (Fig. 8):

- Alt. 1 no internal air leakage between the zones (airtight internal partitions),

- Alt. 2 each flat connected with the staircase (air leakage between the flats is not allowed),
- Alt. 3 each flat connected with the staircase and neighbouring flats (air leakage between the flats is allowed).

The characteristics of the internal leakage paths were estimated from the results of the airtightness tests [5]. These characteristics were kept constant in all simulations, regardless of the airtightness level of the building envelope.

In the case of the residential building, a more detailed distribution of the wind pressure coefficient 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 [6].

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 the real leakage distribution deduced from the results of the airtightness testing. The proper air leakage of each of these two areas was equally divided among the four floors (25 % each). In the case of the flats, this “floor leakage” was equally divided between the two leakage paths: one at the top and one at the bottom of the zone height, as shown in Fig. 6. In the case of the staircase, the “floor leakage” was concentrated into one leakage path in the mid-height of the floor (Fig. 7).

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

			0:00 ÷ 8:00	8:00 ÷ 16:00	16:00 ÷ 0:00
Flats (total figures)	Number of people	[-]	40	0	40
	Vent. air flow rate	[m³/h	1000	230*)	1000
	Internal heat gains	[W]	5400	1400	5400
Staircase	Number of people	[-]	0	0	0
	Vent. air flow rate	[m³/h	34	34	34
	Internal heat gains	[W]	0	0	0

**) corresponds to an air change rate n = 0.1 h^{-1}*

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

Results

The increase in 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 the case of the single-family house showing a more significant impact of the airtightness on the heat demand in the case of residential buildings (compare Fig. 4, Fig. 5 and Fig. 9, Fig. 10, respectively). Since the residential buildings are higher, they suffer from stronger wind pressure than low-rise single-family houses (higher C_p values).

Different alternatives of the connections between the pressure zones led to very similar results in terms of heat demand (Fig. 9). However, the airtightness of the 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. 11).

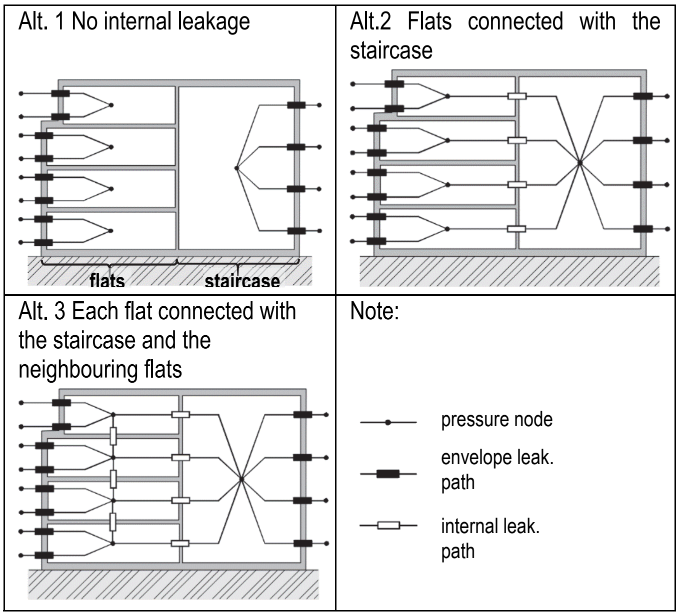

Figure 8 Infiltration model networks for the multi-family residential building - schematic cross sections

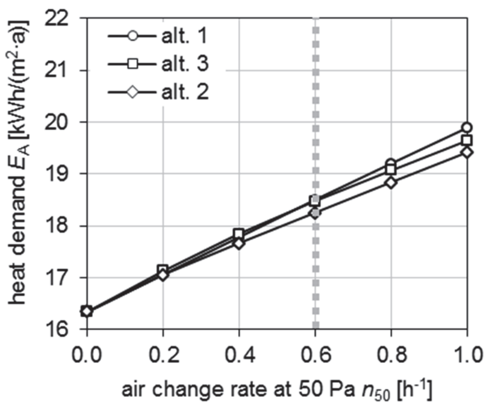

Figure 9 Simulation results for the multi-family residential building. Influence of internal leakage, moderate shielding.

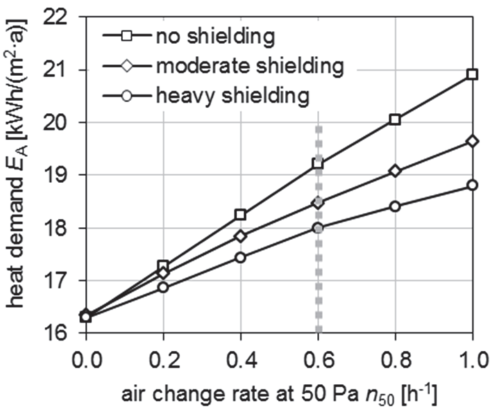

Figure 10 Simulation results for the multi-family residential building. Influence of wind shielding, no internal leakage (airtight internal partitions).

Alt. 2, flats connected with the staircase, air flow rates in [m³/h]

Alt. 3, each flat connected with the staircase and neighbouring flat, air flow rates in [m³/h]

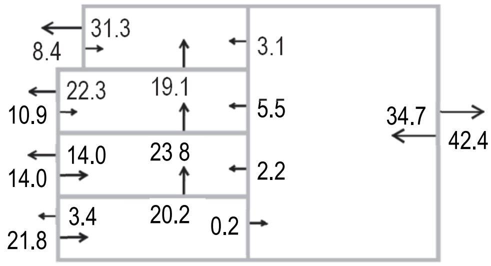

Figure 11 Average air flow rates between the pressure zones for January (schematic cross section).

DISCUSSION AND CONCLUSIONS

This study confirms the significant impact of air leakage through the building envelope on the heat demand of passive houses in the Central European climate. This impact is more pronounced in the case of taller residential buildings. Exposure to the wind considerably amplifies the impact of the 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 an even better airtightness remains a meaningful challenge.

Despite the simplifications and limited extent of this study, one can try, based on the results, to estimate approximately an appropriate level of airtightness requirements for passive houses in the Central European climate. Generally, a factor causing an increase in the 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 the uncertainties in the determination of the factor itself and in the calculation method). Therefore, let us set lower and upper limits of an acceptable increase in the 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. The achievement of n_{50} values ranging from 0.2 to 0.5 h^{-1} should not represent an issue in the case of residential buildings due to the usually favourable envelope area to the volume ratio (*A/V*). Moreover, field experience proves that such values can be achieved in practice, in particular, if a systematic control is required (mandatory airtightness testing).

An unfavourable distribution of the air leakage over the building envelope can strengthen the increase on 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 the connections between the building elements in these locations merit particular attention.

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

Authors contact: ales.vlk@fsv.cvut.cz, jiri.novak.4@fsv.cvut.cz

ACKNOWLEDGEMENTS

This work has been supported by the Ministry of Education, Youth and Sports within the National Sustainability Programme I, project No. LO1605. This paper has been published in the Proceedings of the 38th AIVC Conference, Nottingham, September 2017.

REFERENCES

[1] ASHRAE (2001). 2001 ASHRAE Handbook - Fundamentals, American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc. Atlanta. ISBN 1-883413-88-5

[2] ČSN 730540-2: 2011. Thermal performance of buildings – Part 2: Requirements. Czech office for standards, metrology and testing.

[3] EN ISO 13790:2008. Energy performance of buildings – Calculation of energy use for space heating and cooling. European Committee for Standardisation

[4] KOPECKÝ, P. (2016). Comparative testing of simplified lumped parameter building thermal models. Proceedings of conference CESB 16 - Central Europe towards sustainable building 2016, 22nd – 24th June 2016, 789 – 796. Grada Publishing a.s. ISBN 978-80-271-0248-8

[5] NOVÁK, J. (2013). Airtightness of a multi-family passive residential building in the Czech Republic. Proceedings of the 8th International BUILDAIR-symposium 2013, Hannover

[6] ORME, M., LIDDAMENT, M., WILSON, A. (1998). Numerical Data for Air Infiltration and Ventilation Calculations. Coventry: AIVC. ISBN 1 946075 97 2.

[7] RICHIERI, F. et al. (2008). Numerical evaluation of the airtightness impact on energy needs in mechanically ventilated dwellings. Proceedings of the 8th International BUILDAIR-symposium 2013, Hannover.

[8] JOKISALO, J., KURNITSKI, J., VINHA, J. (2007) Building leakage, infiltration and energy performance analyses for Finnish detached houses. Building and Environment, Volume 44, Issue 2, February 2009, Pages 377-387.