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The Impact of Infiltration on Heating Systems Dimensioning in Estonian Climate

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Abstract. In this study we analysed the climatic conditions for infiltration estimation, different calculation methods and infiltration impact on heat load for heating systems dimensioning. To determine the wind conditions at low air temperatures of the coastal- and inland climatic zones in Estonia, 42 years of climatic data for Tallinn and Tartu were investigated. Calculation models with detailed air leakages were constructed of a single and two-storey detached house using dynamic simulation software IDA ICE. Simulations were carried out with the constructed calculation models, simulating various wind and sheltering conditions to determine the heating load of the buildings under measured wind conditions at the design external air temperatures. The simulation results were compared with results calculated with European Standard EN 12831:2017, methodology given in the Estonian regulation for calculating energy performance of buildings and with simulations using the default settings in IDA ICE based on the ASHRAE design day conditions. The percentage of heat losses caused by infiltration was found as 13-16% of all heat losses for the studied buildings. Simulations with historical climate periods showed that even in windy weather conditions the heating system dimensioned by the methods analysed may not be able to provide the required indoor air temperature. Analysis using the coldest and windiest periods showed that when systems are dimensioned by the studied methods, the highest decline in indoor air temperature occurs on the windiest day and not on the coldest day. The impact of high wind speeds and low sheltering conditions resulted up to 50% of all heat losses.

1 Introduction

In cold climate countries, designing cost efficient low energy buildings requires careful optimisation of envelope elements as well as building systems [1,2]. As the thermal transmittance of building envelope elements decreases, the impact of thermal bridges and infiltration increases and constitutes for higher share of the total heat loss and becoming more important in the design process [3,4]. Thus, infiltration directly affects the heat load and heating system dimensioning. The usual practice before the focus on constructing low energy buildings a decade ago was to over-dimension the water-based room heating units at high supply water temperatures to compensate for higher heat losses and to account for ‘extreme’ outdoor conditions. This approach resulted usually in over-dimensioned heating systems which performed poorly in terms of energy efficiency. During a typical winter the heating system operates most of the time in reduced capacity under varying internal heat gain conditions. In contrast, the systems in low energy buildings are optimised and designed for such conditions to work effectively with low supply temperatures for energy efficient heat sources and provide stable indoor temperatures [5]. As the frequency of extreme weather events due to climate change is predicted to increase [6], building systems also need to be designed to withstand the future climatic conditions [7,8]. Therefore, it is important to accurately estimate infiltration heat losses in order to avoid under- or over-dimensioning the heating system.

There are several calculation methodologies used amongst heating systems designers to calculate infiltration heat losses, including both simplified approaches, such as rules-of-thumb and standard-based equations, but also sophisticated computer calculations. Building simulation software solutions are increasingly used for building design analysis, energy performance estimation and building systems load calculations [9]. Many such software solutions offer options for calculating infiltration airflow rates. Since nowadays building energy calculation models are generally needed, designers also have an interest in using the energy calculation model for dimensioning heating load. These simulation results depend highly on the input parameters and level of detail of the building model. To achieve sufficient accuracy requires precise air leakage modelling, accounting for wind effect and wind shielding. However, during the design phase, not all parameters and conditions for the building are known and such a thorough determination of the input parameters would make the design work unreasonably

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complicated and expensive. Because of the latter, usually the simplified models and calculation approaches are used.

In Estonia, the methodology for calculating the average annual infiltration is defined in the national regulation no. 58 'Methodology for calculating the energy performance of a building' [10]. However, this method is intended for whole year energy consumption calculations and not for heating system dimensioning.

The current European standard EN 12831:2017 [11], intended for heating systems dimensioning, outlines the methodology for calculating infiltrating outdoor air flow, but requires a national annex which is not implemented in the adapted Estonian version. In case the national annex is not provided, the standard gives default parameter values to be used for infiltration calculation.

Detached houses are generally up to three storeys high and therefore the infiltration calculations for sufficient accuracy can be simplified compared to calculations for high-rise buildings, since the wind pressure coefficients for low-rise buildings can be expressed as an average pressure coefficient for the façade of the building [12]. Also, in low-rise buildings, internal air movement due to stack effect usually has low impact and can be estimated with simpler approaches. For other building types and higher buildings, vertical air movement and pressure differences is important to be considered and analysed in detail [13].

In addition to building air leaks and building location, infiltration is highly dependent on the climatic conditions, i.e. outdoor air temperature, wind speed and direction [14]. The current Estonian standard for the design of heating of buildings EVS 844:2016 [15] gives design outdoor air temperature values for different regions of Estonia, but does not include parameters for wind conditions to be used for heating load dimensioning. The American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) [13] has provided climate data for several regions of Estonia, including wind speeds and direction at different ambient temperatures for heating power dimensioning. However, ASHRAE database includes only average values for wind data corresponding to the design outdoor temperatures which are not compatible with outdoor temperatures given in EVS 844:2016.

The aim of the study is to compare different infiltration calculation methods to determine the impact of infiltration induced heat loss in case of low energy buildings on heating system dimensioning and the effect on building internal temperatures at the occurring outdoor temperatures, taking into account the climatic wind conditions at the design temperatures. We have analysed the Estonian climate conditions and infiltration calculation according to the Estonian energy performance calculation methodology, the methodology of EVS-EN 12831:2017, simulations with simplified leakage modelling and ASHRAE climate data calculations. As a reference, a detailed infiltration leakage model for single and two-storey low energy detached house was constructed using IDA ICE simulation software. To determine the wind conditions prevailing in Estonia at low temperatures, 42 years of climate data were analysed.

2 Methods

The study consisted of the following steps: historic weather data analysis to define wind conditions at low ambient temperatures and the occurrence frequencies, analysis of typical building envelope air leaks and its distribution, calculation of infiltration air flow rates using different methodologies, modelling of two detached houses and simulation of building heat load and indoor temperatures, analysis of the simulation results.

2.1 Wind and ambient temperature conditions in Estonia

Estonia lies in the northern part of the temperate climate zone and in the transition zone between maritime and continental climate, characterised by warm summers and fairly severe winters. In cold periods, mostly in January and February, wind speeds can reach relatively high values and last several hours, even during extreme outdoor temperatures (Fig. **1**). The analysis of recorded historic wind and temperature data from 1970 to 2012 shows also, that high wind speeds at low temperatures are quite characteristic in Estonian climate (Fig. **2**).

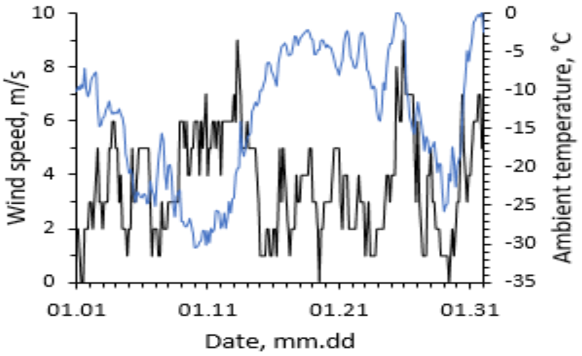

Fig. 1. Hourly-average wind speed (black line) and ambient temperature (blue line) during January 1987 (weather data acquired from the Estonian weather service (EMHI) [16]).

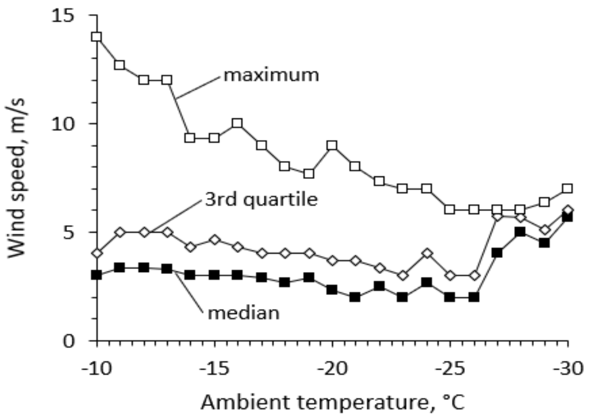

Fig. 2. Hourly-average wind speeds at low ambient temperatures in Tallinn, Estonia. Based on historic weather data (1970-2012) acquired from EMHI [16].

Depending on the building location, thermal capacity and time constant the typical design outdoor temperature for heating systems dimensioning is between -21°C and -25°C. The typical weather is mostly dominated by south-west blowing winds but at low temperatures, the wind direction can vary from east to west with highest frequencies (15 to 20%) from south and west directions.

2.2 Description of studied building

We analysed the performance of two detached houses: a wood frame single storey building and a two-storey concrete structured building. The analysed buildings are designed as nearly Zero Energy Buildings (nZEB) according to the Estonian building code requirements for energy performance. The thermal transmittances of building envelope elements are presented in Table 1. The single storey house is designed with un-heated attic and relatively small windows whereas the two-storey building represents more modern architectural style with larger windows, characteristic to typical passive house design. The buildings were designed with central mechanical supply and exhaust ventilation with heat recovery of 80% and average airflow rate of 0.5 l/(s·m^2) in the heated spaces.

Table 1. Characteristics of building envelope.

	Single storey house	Two-storey house
Airtightness q_{50}, m^3/h·m^2)	1.5	1.5
Thermal transmittance, W/(m^2·K)		
- External wall	0.12	0.12
- Roof	0.10	0.10
- Floor on ground	0.12	0.12
- External door	0.90	0.90
Windows (incl. frame)	0.90	0.90
Thermal bridges, W/(m·K)		
- Ext. wall – ext. wall	0.04	0.06
- Ext. wall – int. wall	0.01	0.01
- Ext. wall - slab	-	0.01
- Ext. wall - roof	0.04	0.07
- Ext. wall - floor	0.23	0.18
- Floor – int. wall	0.01	0.01
- Roof – int. wall	0.01	0.01
- Window perimeter	0.04	0.04
- Door perimeter	0.05	0.04

2.3 Building modelling and simulations

For detailed analysis of the buildings we used indoor climate and energy simulation software IDA Indoor Climate and Energy (IDA ICE) version 4.8 SP1 [17,18]. This well-validated tool allows detailed and dynamic whole-year multi-zone building simulations of indoor climate, energy consumption and building systems performance.

The thermal properties of external boundaries of the buildings were calculated automatically in IDA ICE by defining the material layers with specific parameters values for each layer, which included properties for thermal conductivity, specific heat capacity and density for accurate calculation of thermal mass of the building and heat fluxes through the structures.

Internal heat gains with daily load profiles for dwellings were used according to the national building code regulation: 42.8 m^2 and 28.3 m^2 floor area per occupant for single and two-storey buildings respectively with occupant heat emission of 125W, including 85W sensible heat. The maximum load for equipment in case of single storey building was 3 W/m^2, for two-storey building 2 W/m^2 and lighting for both cases 6 W/m^2.

The leaks between exterior wall and roof joints for the zones were divided according to the roof perimeter distribution, the exterior wall and floor leaks according to the floor perimeter distribution and the exterior wall and internal wall joints according to the ceiling perimeter distribution, equally on both floors. Window and door leaks were distributed according to the element perimeter distribution. Window leaks were split between the top and bottom of the window (Fig. 3). The leakage distribution by percentages are presented in Table 2.

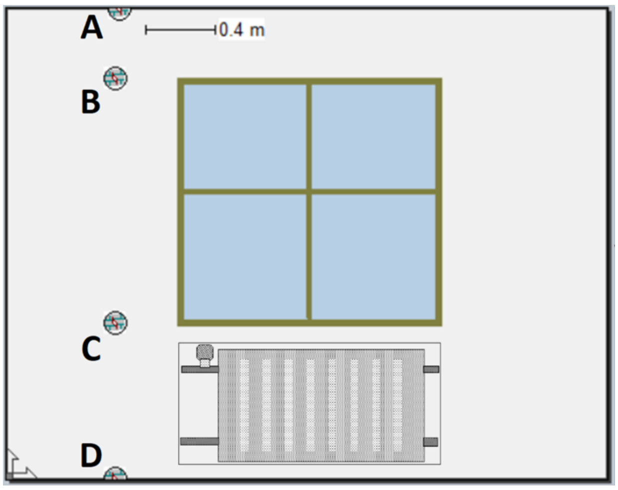

Fig. 3. Modelled detailed leakage distribution in IDA ICE wall element: wall - slab/roof joints (A), upper edge (B) and lower edge (C) of windows and wall - floor joints (D).

Table 2. Distribution of air leakages [19].

	Air leakage distribution, %	
	Single storey building	**Two storey building**
Penetrations through the envelope air barrier	10	7
Ext. wall – floor on ground	9	5
Ext. wall – int. slab joints	0	16
Ext. wall – roof joints	47	34
Ext. wall – ext. wall joints	1	7
Windows and doors	32	31

The default zone model in IDA ICE intended mainly for energy performance estimation uses simplified distribution of envelope leaks by accounting for average leaks with the height of 1m on every façade. This approach requires average pressure coefficients for façades with different orientations to calculate the wind driven infiltration. We used experimentally defined values depending on the wind sheltering conditions, based on previous studies [12], presented in Table 3. However, in the methodology used for energy performance calculations according to Estonian building code, wind driven air flows through the building envelope are defined with a constant value for the whole building and divided between zones proportionally to the envelope area. The infiltration air flow q_i (l/s) in this case is calculated using the following equation:

$$q_i = q_{env,50} \cdot A_{env}/(3.6 \cdot z) \qquad (2)$$

where A_{env} is the total envelope surface of the building; z is building height factor: 35 for one, 24 for two, 20 for three and four and 15 for five and higher story buildings. This simplified methodology does not account for wind driven infiltration air flows.

Table 3. Average façade pressure coefficients for different levels shielding conditions [12].

Façade azimuth	**Wind angle**							
	0°	45°	90°	135°	180°	225°	270°	315°
Sheltered								
0°	0.1	-0.1	-0.2	-0.4	-0.3	-0.4	-0.2	-0.1
90°	0.2	0.2	-0.3	-0.3	-0.2	-0.3	-0.3	0.2
180°	0.1	-0.1	-0.2	-0.4	-0.3	-0.4	-0.2	-0.1
270°	0.2	0.15	-0.3	-0.3	-0.2	-0.3	-0.3	0.2
Semi-exposed								
0°	0.3	0.1	-0.4	-0.6	-0.5	-0.6	-0.4	0.1
90°	0.4	0.2	-0.6	-0.5	-0.3	-0.5	-0.6	0.2
180°	0.3	0.1	-0.4	-0.6	-0.5	-0.6	-0.4	0.1
270°	0.4	0.2	-0.6	-0.5	-0.3	-0.5	-0.6	0.2
Exposed								
0°	0.5	0.3	-0.5	-0.8	-0.7	-0.8	-0.5	0.3
90°	0.6	0.2	-0.9	-0.6	-0.4	-0.6	-0.9	0.2
180°	0.5	0.3	-0.5	-0.8	-0.7	-0.8	-0.5	0.3
270°	0.6	0.2	-0.9	-0.6	-0.4	-0.6	-0.9	0.2

The heat loss from infiltration according to the standard EVS-EN 12831:2017 for rooms in one or two storey detached houses can be simplified and expressed as:

$$\Phi_{V,i} = \rho \cdot c_p \cdot q_{env,50} \cdot f_{qv,z} \cdot A_{env,i} \cdot f_{dir} \cdot \left(\theta_{int,i} - \theta_e\right) \qquad (1)$$

where $\Phi_{V,i}$ is infiltration heat loss of the zone, W; ρ is density of air at internal design temperature $\theta_{int,i}$, kg/m^3; c_p is specific heat capacity of air at internal design temperature $\theta_{int,i}$, Wh/(kg·K); $q_{v,env,50}$ is specific air permeability of the envelope at 50Pa , m^3/(m^2·h); $f_{qv,z}$ is volume flow factor (-); $A_{env,i}$ is envelope surface of the zone, m^2; f_{dir} is the façade orientation factor; $\theta_{int,i}$ is internal design temperature of the zone, °C; θ_e is external design temperature, °C. The volume flow factor is defined according to the zone height, number of façades with different orientations, zone height from the ground and wind shielding. The factor value varies between 0.03 and 0.11. The orientation factor is usually defined in the national supplement of the standard. In case the supplement is not provided, the default value 2.0 is to be used.

For the infiltration analysis of the studied buildings we created multi-zone models with every room as a separate zone. The 3D visualisation of the buildings is shown in Fig. 4 and Fig. 5. For the internal temperature simulation analysis, the reference case was simulated without infiltration heat loss. In all cases the room heating units' power is calculated for design conditions according to the methodology. In the simulations, internal heat gains were included beside the room heating unit.

Fig. 4. Building model of analysed single storey detached house.

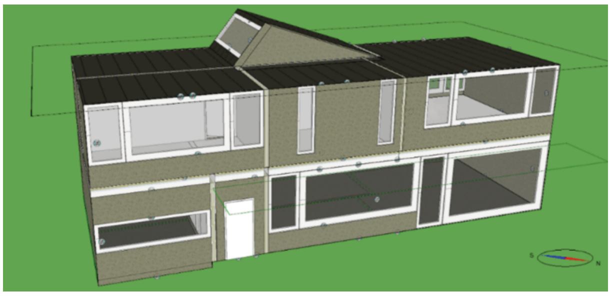

Fig. 5. Building model of analysed two-storey detached house.

3 Results

The calculated heat losses using different methodologies for infiltration estimation for the analysed buildings are presented in Fig. 6. The heat load of the analysed, the modern well-insulated and airtight detached houses was found to be roughly 30-45W/m^2 depending on the calculation methodology. In case of the single storey building, with the different methods and wind sheltering options the infiltration heat losses vary between 3% and 26% from the total heat loss. Highest fraction for infiltration losses gives the standard-based calculation method and the lowest value the simplified leaks model with ASHRAE design weather data.

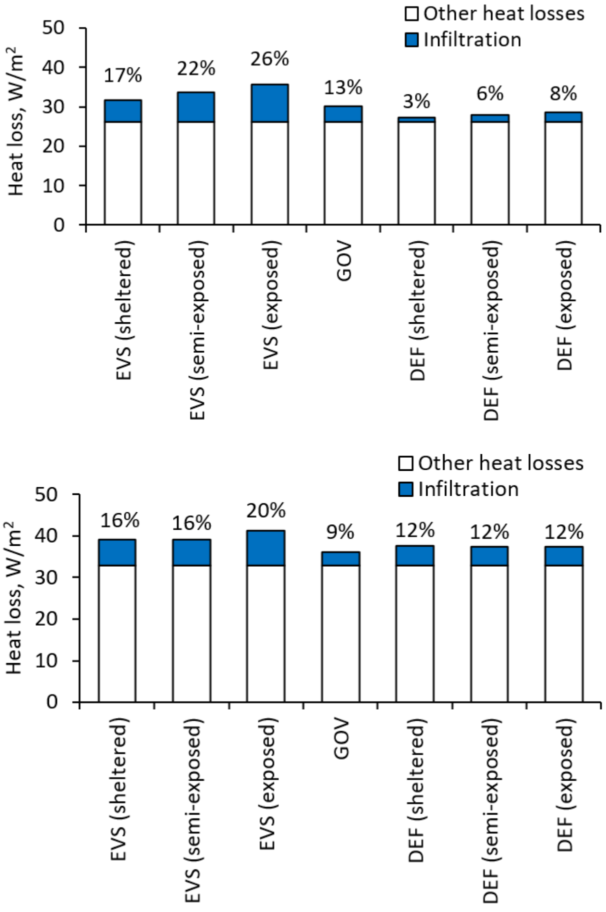

Fig. 6. Comparison of calculated heat losses of single storey (top) and two-storey (bottom) buildings using different calculation methods. Code: REF – reference case without infiltration; EVS – standard based calculation; GOV – national regulation-based calculation; DEF – simplified leaks, ASHRAE weather data (default settings in IDA ICE).

Example of calculated cumulative heat loss occurrence frequency of a west facing room to maintain the design indoor temperature of 21°C during a relatively cold and windy January month is presented in

Fig. 7. It can be seen that 90% of the time the heat loss is roughly 45 W/m^2 which is roughly the standard-based design heat load calculation value. However, when low temperatures and strong winds persist for longer periods, the heat loss can reach values as high as 110 W/m^2.

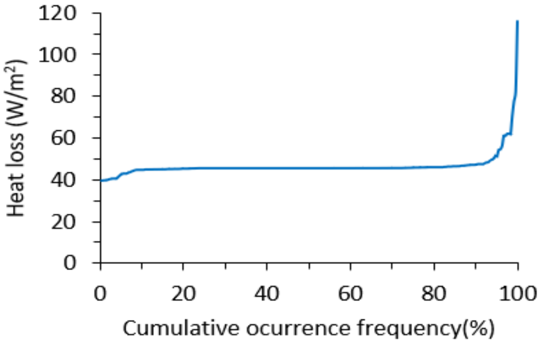

Fig. 7. Simulated heat loss in west facing room.

Fig. 8 illustrates the effect of exposure value to the infiltrating air flow rate. It can be seen that at higher wind speeds the exposed condition gives up to four times higher air flow rates compared with the sheltered option. When modelling the building air leaks the detailed air leakage model with sheltered wind condition gives mostly higher infiltration flow rates compared to the simplified model case (Fig. 9).

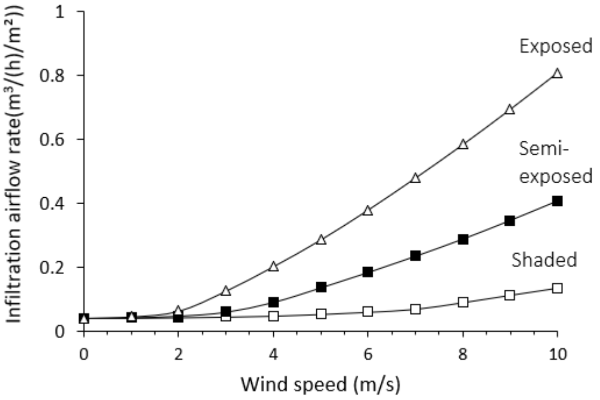

Fig. 8. Simulated infiltration air flow rate dependence on wind speed under exposed, semi-exposed and sheltered wind conditions. Simulated with detailed zone model.

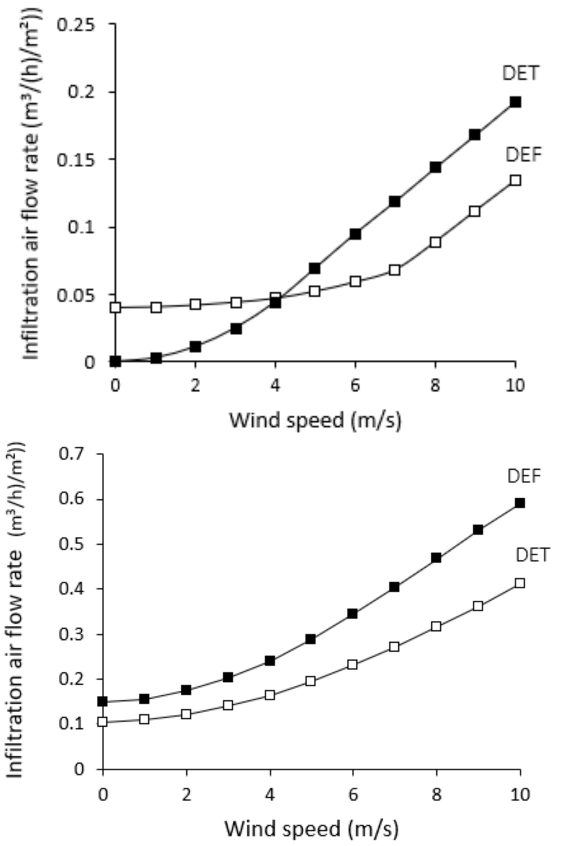

Fig. 9. Comparison of simulated infiltration air flow for simplified (DEF) and detailed (DET) zone models in case for single storey house (top) and for first floor zone of the two-storey house (bottom) in sheltered conditions.

In Fig. 10 it is shown the simulated indoor temperatures for different wind sheltering conditions for the analysed infiltration calculation methods. During strong winds and exposed condition, hourly-average indoor temperatures can drop up to 8K from the design indoor temperature of 21°C due to infiltration if calculated with simplified leaks model according to ASHRAE design weather data. The national energy performance formula-based infiltration gives similar temperature decrease and the standard based calculation 6K decrease for the exposed wind condition. When considering sheltered and semi-exposed conditions, the different methods give maximum indoor temperature drop from 1K to 4K.

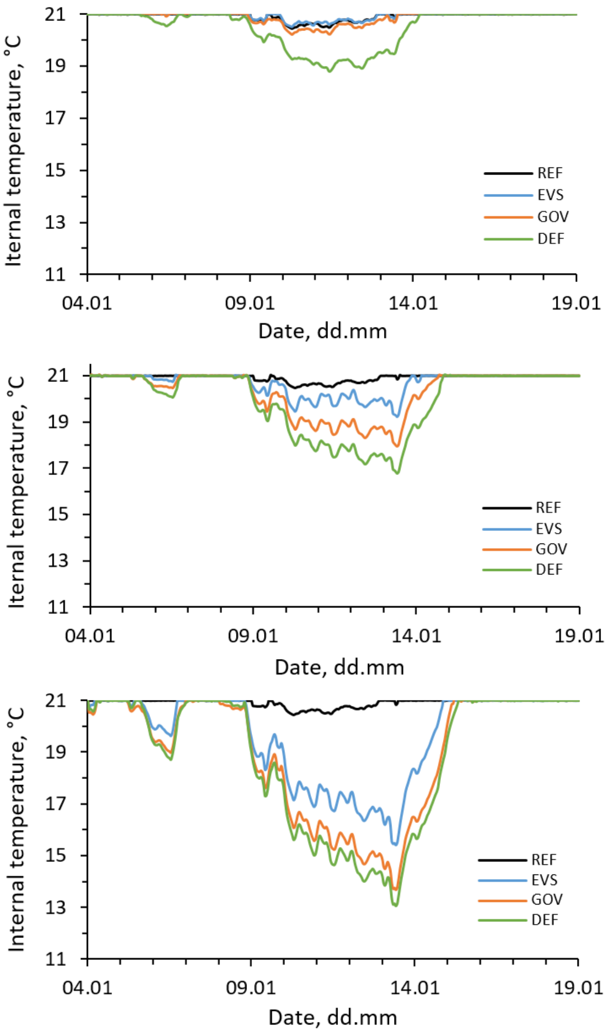

Fig. 10. Comparison of simulated internal temperatures of the single storey building with internal heat gains for different wind conditions during cold and windy period: sheltered (top), semi-exposed (middle) and exposed (bottom) using different methodology to dimension room unit heat power. Code: REF – reference case without infiltration; EVS – standard based calculation; GOV – national regulation-based calculation; DEF – simplified leaks, ASHRAE weather data (default settings in IDA ICE).

Fig. 11 shows the same comparison in case of the two-storey detached house. In this case the infiltration effect is lower compared to the single-story case. The maximum temperature decrease is 6K for exposed wind conditions. For sheltered conditions, the temperature decrease is minimal, even in cold outdoor temperatures and high winds.

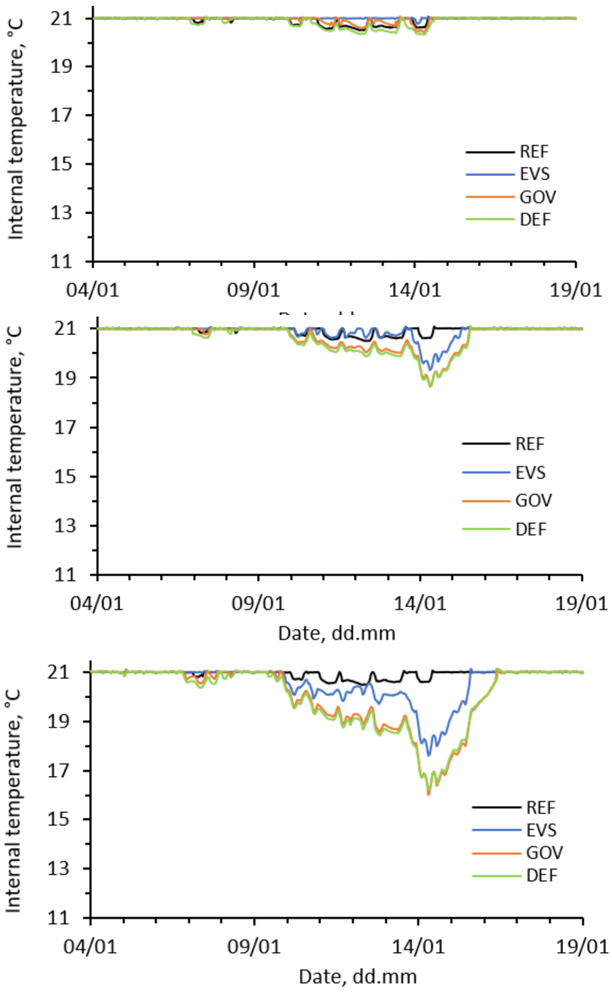

Fig. 11. Comparison of simulated internal temperatures of the two-storey building with internal heat gains for different wind conditions during cold and windy period: sheltered (top), semi-exposed (middle) and exposed (bottom) using different methodology to dimension room unit heat power. Code: REF – reference case without infiltration; EVS – standard based calculation; GOV – national regulation-based calculation; DEF – simplified leaks, ASHRAE weather data (default settings in IDA ICE).

4 Discussion and conclusions

In most cases the wind speeds at the design ambient temperature are low and the infiltration heat losses of an airtight low energy detached house constitute about 13-16% of the total building heat losses. As wind speeds increase the infiltration heat losses increase rapidly. At the highest wind speeds measured at the design ambient temperature the infiltration heat losses constitute roughly 50% of the building total heat loss. The calculation methods analysed underestimate the infiltration heat loss and thus can result in under-dimensioned heating system. In cases when high wind speeds dominate for longer periods, indoor air temperatures may drop by several degrees. Simulations with climate conditions which have occurred in Estonia, specifically periods with strong winds, show that even with temperatures higher than the design ambient temperature, infiltration can cause a substantial decrease in the indoor temperatures. Simulations with the coldest and windiest periods show, that indoor temperatures can drop from the typical design temperature of 21°C to as low as 12°C even with the addition of internal heat gains, when standardised infiltration calculations are used. As ASHRAE design day data uses average wind speeds, it is found to be not suitable for heating systems dimensioning.

In sheltered conditions, most methods studied give relatively similar results. However, with the decrease in sheltering, the difference increases. In exposed conditions, infiltration has very high impact on heating systems dimensioning because of the large difference in the infiltrating airflows between prevailing low wind speeds and rarely occurring higher wind speeds. The results show that the infiltration calculation according to the Estonian building code is in close correlation with the reference model results if the effects of wind induced infiltration are low. Comparison of the detailed simulation results and heat loads calculated according to the standard EVS-EN 12831:2017 show that the required heat load would be met with at least 90% of the time under cold and windy weather even with exposed conditions.

Simulation results, using the simplified leakage distribution (energy model with default parameter values in IDA ICE) and ASHRAE design day data for wind parameters, underestimate the heat load for the single-storey building. Using the wind speed according to ASHRAE proves also to be problematic because of the wind speeds which are significantly lower than historic data presents. In case of a two-storey house, the correlation of the simplified IDA ICE calculation is significantly higher, because the leaks are then divided into different heights and stack effect is accounted for.

When using IDA ICE to calculate heating load, fixed infiltration is usually sufficiently accurate for a single storey detached house in all sheltering conditions. The wind driven option can only be used for a multi-storey detached house at sheltered conditions, in less sheltered conditions fixed infiltration must be used.

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