Building leakage, infiltration and energy performance analyses for Finnish detached houses

Juha Jokisalo[1], Jarek Kurnitski[1] and Juha Vinha[2]

[1]Helsinki University of Technology, HVAC Laboratory, Finland
[2]Tampere University of Technology, Structural Engineering Laboratory, Finland

Corresponding email: juha.jokisalo@tkk.fi

SUMMARY

This study focuses on the correlation between the airtightness of a building envelope and the average infiltration and energy consumption of a typical modern Finnish detached house. The correlation between tightness and infiltration was determined using an empirically validated dynamic IDA-ICE simulation model of a two-storey detached house. The effect of wind conditions, Finnish climate conditions, balance of ventilation system and leakage distribution on infiltration were studied with the simulation model. According to the results, the average infiltration rate and heat energy consumption increase almost linearly with the building leakage rate n_{50} of the building envelope. Resulting from the linear dependence, the annual average infiltration rate of the detached house in a sheltered suburban area can be approximated with the simple equation $n_{50}/31$. If the average infiltration rate is applied to heat energy calculations, the simple equation is $n_{50}/25$.

INTRODUCTION

This study is part of the cooperation project *Tightness, indoor air and energy efficiency of residential buildings* (AISE), that is being carried out by two cooperating Finnish universities: Tampere University of Technology and Helsinki University of Technology during the period 2005 – 2007. The objective of this study is to find a correlation between the tightness of a building envelope and the average infiltration and energy consumption of a typical modern Finnish detached house in the cold climate of Finland, and to study the effect of other important factors, such as leakage distribution, wind and climate conditions, on infiltration, using an empirically validated simulation model.

Since the late seventies, studies have been conducted on the correlation between airtightness of a building envelope measured with a single pressurization test and annual infiltration rate. In 1982, Kronvall and Persily compared pressurization test results to infiltration rates measured with tracer-gas in detached and terraced houses in Sweden and USA (New Jersey). From their comparison, they obtained the widely used “rule of thumb” for annual infiltration rate: $n_{50}/20$ [1,2], where n_{50} is leakage air change rate per hour at 50 Pa of pressure difference. In 1988, Dubrul found that the infiltration rate can be estimated with n_{50}/K. According to the study of Dubrul, the value of the coefficient K ranges from 10 to 30, depending on, for example, the type of building, wind conditions and leakage distribution. However, the mean value 20 can be regarded as typical [3].

METHODS

Building description

This study was carried out as a sensitivity analysis simulating a single building model in various conditions. The building model describes an existing detached house comprising two floors (Figure 1). The building is situated in the metropolitan area of Helsinki; it was built in 2000. The net floor area of the building is 172 m² and the building structures are of wood-frame construction; the base floor of the house is a concrete slab on the ground. The level of thermal insulation of the house fulfils the requirements of the Finnish building code [4]; the house is equipped with a mechanical supply and exhaust ventilation system with heat recovery. The building corresponds to the typical timber-framed detached house defined by the national project "Moisture-proof healthy detached house" [5].

Figure 1 The object of the study is a detached house.

The building was studied with extensive field measurements, including, for example, a pressurization test of the building envelope and an analysis of the leakage distribution, using infrared photography. The measured leakage air change rate at 50 Pa pressure difference over the envelope (n_{50}) was 3.9 ach. The building was simulated with the measured leakage distribution and two approximated distributions shown in Table 1 [6]. In the "draughty roof" case, most of the leakage openings were at the junction of the roof and external wall, while in the "draughty base floor" case, most of the leakage openings were at the junction of the base floor.

Table 1 The vertical leakage distributions of the building. The measured distribution is based on the infrared photography of the building; the two other distributions are approximated cases.

Place of the leakage routes		Vertical leakage distribution, %		
		Measured	Draughty roof	Draughty base floor
2nd floor	Junction of roof	36	75	12.5
	Upper edge of window frame	4	0	0
	Lower edge of window frame	4	0	0
	Junction of intermediate floor	2	0	0
1st floor	Junction of intermediate floor	21	12.5	12.5
	Upper edge of window	0	0	0
	Lower edge of window frame	24	0	0
	Junction of base floor	10	12.5	75

The dynamic simulation model

This sensitivity analysis was carried out using a simulation model of the preceding detached house. The pressure conditions of this building model were compared against measurement results and the model was found to be suitable for infiltration and energy analyses [6]. The building model was done using IDA indoor Climate and Energy 3.0 (IDA-ICE) building simulation software. This software allows the modelling of a multi-zone building, HVAC-systems, internal and solar loads, outdoor climate, etc. and provides simultaneous dynamic simulation of heat transfer and air flows. It is a suitable tool for the simulation of thermal comfort, infiltration, and energy consumption in complex buildings. A modular simulation application, IDA simulation environment and IDA-ICE, has originally been developed by the Division of Building Services Engineering, KTH, and the Swedish Institute of Applied Mathematics, ITM [7,8]. IDA-ICE has been tested against measurements [9,10] and several independent inter-model comparisons have been made [11]. In the comparisons, the performance of radiant heating and cooling systems using five simulation programs (CLIM2000, DOE, ESP-r, IDA-ICE and TRNSYS) were compared; IDA-ICE showed a good agreement with the other programs.

RESULTS

The effect various factors on infiltration and heat energy consumption of Finnish detached house were simulated. Most of the simulations were carried out with the hourly weather data of Helsinki (1979), which is commonly used as test-reference data for energy calculations in Finland [12]. The temperature dependence of infiltration was studied in two separate cases using the weather data of 1979 from Jyväskylä and Sodankylä. The Finnish climate is cold and the annual average outdoor temperatures of 1979 was 4.3°C in Helsinki, 2.8°C in Jyväskylä and -0.8°C in Sodankylä. The measured annual average wind velocity of these places was between 3 and 4m/s, so the wind conditions were very similar.

Studied cases

The studied factors of the sensitivity analysis and the description of the simulated cases are listed in Table 2. All the cases, except the simulations of different Finnish climate conditions, were simulated with three levels of airtightness. Almost completely airtight detached houses were described with a building leakage rate of n_{50} = 0.15 ach, while the airtightness of typical timber-framed detached houses was simulated using n_{50} = 3.9 ach [5]; the leakage air change rate n_{50} = 10 ach describes leaky detached houses. The effect of wind pressure on infiltration was studied with three levels of wind shielding: an exposed area, a sheltered suburban area and a theoretical case without wind at all. Exposed wind conditions are quite rare in Finland because the country is mostly forested and suburban areas are typically closely built. The sheltered wind conditions describe the typical wind conditions of Finnish suburban areas; the effect of stack-induced infiltration alone is studied in the theoretical case of no wind effect. The effect of the distribution of leakage openings were simulated using the measured and the two estimated distributions shown in Table 1. The effect of the balance of the mechanical ventilation system was studied with equal supply and return air flow rates or with supply air flow rates 15% greater or less than the return air flow rates. The air change rate of the building was 0.56 ach in all the simulation cases fulfilling the minimum requirement (0.5 ach) of the Finnish building code [13].

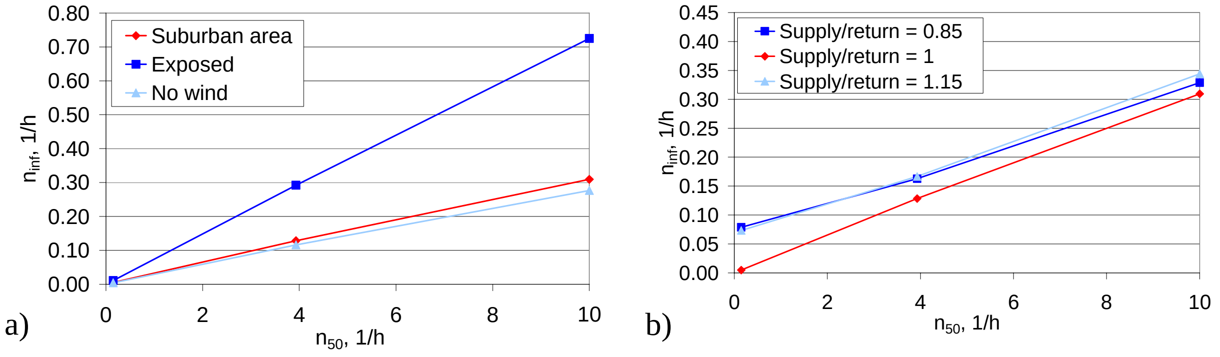
Table 2 The description of the simulated cases.

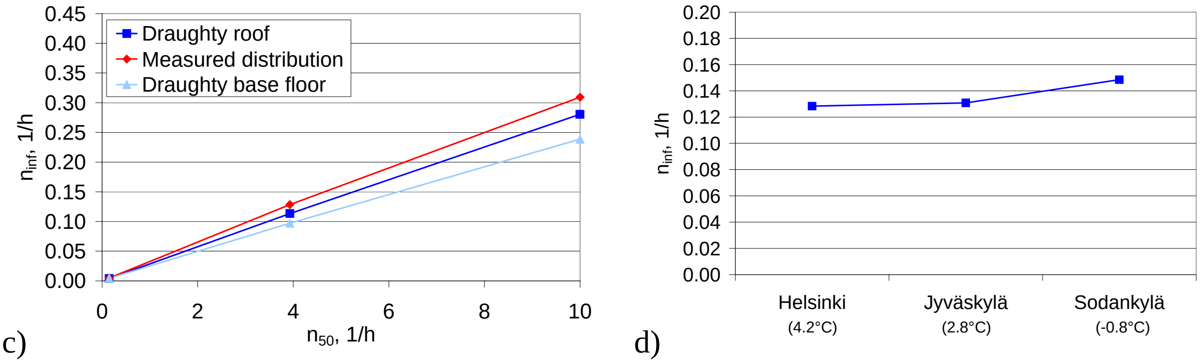
Focus of the simulation	Studied factors				
	Wind conditions	Leakage distribution	Supply/ return	Climate	Airtightness n_{50}, ach
Wind conditions	Exposed	Measured	1	Helsinki	0.15-3.9-10
	Suburban	—||—	—||—	—||—	0.15-3.9-10
	No wind	—||—	—||—	—||—	0.15-3.9-10
Leakage distribution	Suburban	Draughty roof	—||—	—||—	0.15-3.9-10
	—||—	Measured	—||—	—||—	0.15-3.9-10
	—||—	Draughty base floor	—||—	—||—	0.15-3.9-10
Ventilation performance	—||—	Measured	0.85	—||—	0.15-3.9-10
	—||—	—||—	1	—||—	0.15-3.9-10
	—||—	—||—	1.15	—||—	0.15-3.9-10
Finnish Climate conditions	—||—	—||—	1	Helsinki	3.9
	—||—	—||—	—||—	Jyväskylä	3.9
	—||—	—||—	—||—	Sodankylä	3.9

Infiltration

The effect of wind on the average infiltration air change rate is about 10% in the sheltered suburban area (see Figure 2a) of Helsinki. Wind-induced infiltration is more significant than stack-induced infiltration only in the exposed wind conditions, where wind effect is about 60% of the average infiltration air change rate. The effect of the balance of the ventilation system on pressure conditions of the building and infiltration is emphasized in the airtight building (see Figure 2b). If the airtightness of the building is poor, the balance of the ventilation system is not important.

The difference in infiltration between the different leakage distributions is shown in Figure 2c. The average infiltration air change rate is about 10-25% higher in the building with the measured leakage distribution than in the building with the estimated distributions. The effect of the Finnish climate conditions on infiltration is shown for the detached house with a typical level of building leakage rate of n_{50} = 3.9 ach (see Figure 2d). Those cases were simulated with the wind conditions of the suburban area. The average infiltration air change rate slightly increases with decreasing annual average outdoor temperature, but the difference is insignificant (2%) between Helsinki and Jyväskylä. The difference in infiltration between the climate conditions of Helsinki and Sodankylä is 16% according to the simulation results.





c) d)

Figure 2 The effect of several factors on the annual infiltration air change rate. Figures show the effect of wind conditions of the building site (a), the balance of the ventilation system (b), the leakage distribution (c), and the Finnish climate conditions (d). (The annual average temperatures are shown in the brackets.)

The results show that the correlation between airtightness and average infiltration air change rate is almost linear when the ventilation supply and return air flow rates are in balance. Then, the annual average infiltration rate n_{inf} can be approximated by dividing the building leakage rate n_{50} by a constant parameter x

$$n_{inf} = \frac{n_{50}}{x}. \qquad (1)$$

If the average annual infiltration air change rate is used in the heat energy calculation, the dependence of infiltration air flows on the temperature-driven pressure difference between indoor and outdoor air should be taken into account in the cold climate. During the heating season in Finland, the infiltration air flow increases with the increasing temperature difference between indoor and outdoor air (see Figure 3).

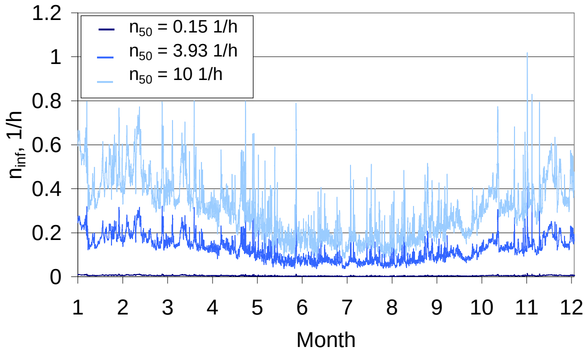


Figure 3 Infiltration air change of the detached house with three different building leakage rates in Helsinki.

The fluctuation of the infiltration air change between the heating season and summer season can be taken into account by, for example, calculating the annual infiltration air change weighted by the temperature difference of the indoor and outdoor air

$$n^{e}_{inf} = \sum_{i=1}^{8760} \frac{(T_{in} - T^{i}_{out})_i \cdot n^{i}_{inf}}{(T_{in} - T^{i}_{out})_i}, \qquad (2)$$

where n_{inf}^{e} is the average annual infiltration air change rate suitable for heat energy calculation and n_{inf}^{i} is a normal hourly infiltration air change and T_{in} is a set point temperature of heating, T_{out}^{i} is hourly outdoor air temperature. If the weighted infiltration air change rate is calculated using the form of Equation (1), the temperature correction could be performed using a correction factor k as follows

$$n_{inf}^{e} = \frac{n_{50}}{k \cdot x}. \qquad (3)$$

The resultant parameters of the most important simulation cases for the simple calculation methods of Equations (1) and (3) are shown in Table 3. A suitable value of parameter x for the detached house is about 31 in suburban areas in Helsinki. Then, the average infiltration air change can be approximated by dividing the building leakage rate n_{50} by 31. In that case, the correction factor k for the heat energy calculation is about 0.8 and the weighted infiltration air change rate is 20% higher than the mean value of the infiltration air change rate. Substituting the preceding values of parameter x and the correction coefficient k into Equation (3), the simple calculation method for the weighted infiltration air change rate reduces into the form $n_{50}/25$. The determined values of parameters x and k are accurate enough for the climate conditions of Jyväskylä also. In the exposed wind conditions, the average infiltration air change is about two times bigger than in the shielded suburban area and the mean value of parameter x is about 14. If the supply and return air flow rates of the mechanical supply and exhaust ventilation system are unbalanced, the average infiltration rate cannot be approximated using the simple linear calculation method of Equations (1) and (3), especially when the envelope is extremely airtight, because the infiltration air flow rate depends on the difference between supply and return air flow rates.

Table 3 Parameters of the most important simulation cases for the simple calculation methods shown by Equations (1) and (3).

Building leakage rate n_{50}, ach	$x = n_{50}/n_{inf}$	Correction factor for heat energy calculation k
Suburban area, measured leakage distribution, supply/return air flow rate = 1		
0.15	31	0.8
3.9	31	0.8
10	32	0.8
Exposed area, measured leakage distribution, supply/return air flow rate = 1		
0.15	14	0.9
3.9	13	0.9
10	14	0.9
Suburban area, measured leakage distribution, supply/return air flow rate = 0.85		
0.15	2	1
3.9	24	0.9
10	30	0.9

Energy consumption

The effect of wind conditions and the balance of the ventilation system on heat energy consumption are shown in Figure 4. The resultant energy consumption covers the heat energy consumption of the building zones and the ventilation system. The correlation between the tightness of the building envelope and the heat energy consumption is almost linear in simulated wind conditions (see Figure 4a). Because of that, the preceding correlation reduces into a simple rule of thumb: The increase of one unit of the building leakage rate n_{50} gives rise to an increase of about 6% in the heat energy consumption of the zones and the ventilation system. At the same time, the increase in total heat energy consumption is about 4% consisting heat demand of domestic hot water and household electricity. The preceding simple rule is valid for the studied detached house in a sheltered suburban area in the climate conditions of Helsinki. The effect of the balance of the ventilation system on the heat energy consumption of the building is slightly greater in the airtight building (see Figure 4b).

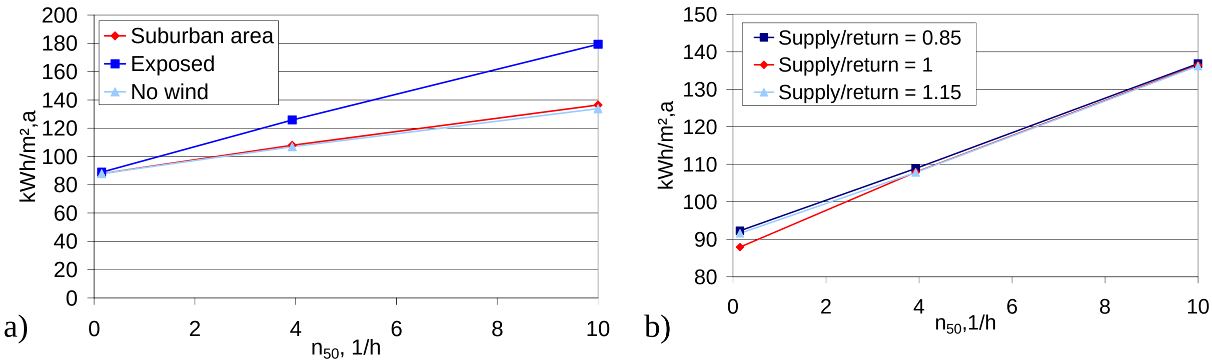


Figure 4 The effect of wind conditions (a) and the balance of the ventilation system (b) on heat energy consumption of the zones and the ventilation system.

DISCUSSION

According to the simulation results, wind has a minor effect on the average infiltration in typical suburban areas of Helsinki and the stack-induced infiltration is dominant in the Finnish cold climate. A correlation between the airtightness of the building envelope and the annual infiltration air change rate is almost linear. In this case, the annual infiltration air change rate can be approximated with the simple equation $n_{50}/31$. The average infiltration air change rate for the heat energy calculations can be calculated by weighting the average infiltration air change rate with the heat demand of a building. The correction for the heat energy calculation can be performed by multiplying the denominator of the preceding equation by the correction factor, which is 0.8 in a typical suburban area. Then the weighted annual average infiltration air change rate can be approximated with the simple equation $n_{50}/25$. These simple approximations are valid in the climate conditions of Helsinki and Jyväskylä, respectively located in Southern and Central Finland. The resultant increase in heat energy consumption regarding zones and the air handling unit is 6% on average, when the value of the building leakage rate n_{50} increases by one unit. Respectively, the increase in total heat energy consumption is about 4%.

ACKNOWLEDGEMENT

This study was supported with a grant from the Finnish Academy (grant 210683). Financial support from the National Technology Agency of Finland TEKES and from the participating companies is gratefully acknowledged. The authors would like to thank the steering group of the AISE-project for their valuable comments.

REFERENCES

1. Kronvall, J. 1978. Testing of houses for air leakage using a pressure method. ASHRAE Transactions, Vol 84, No. 1. pp. 72-79

2. Persily, A, Linteris, G. 1983. A comparison of measured and predicted infiltration rates. ASHRAE transactions, Vol. 89, Part 2B, pp. 183-200.
3. Dubrul, C. 1988. Inhabitants behaviour with respect to ventilation. Technical note 23. Air infiltration and ventilation centre AIVC. 63p.
4. C3 Finnish code of building regulations. 2003. Ministry of the Environment. Thermal insulation in a building, Regulations. Helsinki. 7p.
5. Vinha, J, Korpi, M, Kalamees, T, et al. 2005. Puurunkoisten pientalojen kosteus- ja lämpötilaolosuhteet, ilmanvaihto ja ilmatiiviys (Indoor temperature and humidity conditions, ventilation and airtightness of Finnish timber-framed detached houses). Research report 131. Structural Engineering laboratory, Tampere University of Technology. 102p. (in Finnish).
6. Jokisalo, J, Kalamees, T, Kurnitski, J, et al. 2007. Infiltration simulation in a detached house – empirical model validation. Proceedings of 9th REHVA World Congress - Clima 2007
7. Shalin, P. 1996. Modelling and simulation methods for modular continuous system in buildings", Doctoral Dissertation. KTH, Stockholm.
8. Björsell, N, Bring, A, Eriksson, L, et al. 1999. Article in proceedings of the IBPSA Building Simulation '99 conference. "IDA indoor climate and energy". Kyoto, Japan.
9. Moinard, S, Guyon, G. (Ed.). 1999. Empirical validation of EDF ETNA and GENEC test-cell models. Subtask A.3, A Report of IEA Task 22. Building Energy Analysis Tools. 68p.
10. Travesi, J, et al. 2001. Empirical validation of Iowa energy resource station building energy analysis simulation models, IEA Task 22, Subtask A.
11. Achermann, M, Zweifel, G. 2003. RADTEST – Radiant heating and cooling test cases. Subtask C. A report of IEA Task 22. Building Energy Analysis Tools. 83p.
12. Tammelin, B, Erkiö, E. Energialaskennan säätiedot – suomalainen testivuosi (Weather data for energy calculation – The Finnish test-year), Finnish Meteorological Institute, Weather department – Technical climatology, Report 7, Helsinki, 1987, 108p. (in Finnish)
13. D2 Finnish code of building regulations. 2003. Ministry of the Environment. Indoor climate and ventilation of buildings, Regulations and guidelines. Helsinki. 41p.