Multivariant measurements of airtightness of multi-family building

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ABSTRACT

The paper presents airtightness measurements results of the multi-family building. The tests were carried out in several ways, the results obtained by different methods were compared and the likely reasons for the discrepancy of results were indicated. The object of measurements was a six storey building with 47 dwellings equipped with natural ventilation. Air inlet to the rooms through the window trickle vents controlled by relative humidity of air. Air is extracted through vertical extract ducts made of ceramic blocks.
The measurement for the whole building was carried out twice: with open and manually closed trickle vents. Additionally, the airtightness of each dwelling was measured. For several exemplary apartments, detailed measurements of airtightness were performed with and without pressure compensation in the adjacent zones.

KEYWORDS

airtightness measurement, multi-family building, multi-zone measurement

1 INTRODUCTION

The airtightness test is one of a few building envelope measurements used in practice which is quantitative, not just qualitative as e.g. infrared thermography. The airtightness test result may be a measure of the building design and construction quality and could also be used for the energy demand for heating and cooling analyses.
Although large number of single family houses were measured during last 40 years, only few results for multi-family residential buildings are available worldwide. Lack of measurement database makes it difficult to assess the energy impact of the infiltration and to formulate guidelines and requirements. In Poland almost half population live in multi-family building and even small corrections in buildings’ envelopes and ventilation systems may result in great scale IAQ improvements and energy consumption reduction.
It is extremely difficult to measure occupied multi-family buildings as a whole. As a result single dwellings measurement are conducted. With adjacent zones not pressurised equally the result is influenced with interzonal leakages. In addition the leakages of common spaces are often quite different than dwellings’, which makes the estimated result unreliable.
First sections of this paper provides a review of multi-family buildings market and the presentation of the airtightness measuring methods. Next, the case study building characteristics, test preparation and equipment are presented. It is followed by measurement methodology description and the result presentation. Conclusions are presented in the final section.

2 MULTI-FAMILY BUILDINGS

The residential stock with 75% of floor space is the largest sector of EU building stock.

Within the residential segment 64% of floor space are single family houses, 36 % are apartment buildings. In Poland multi-family houses segment is bigger with 44%, compared with 56% of single family houses (Table 1).

Table 1: Residential floor space, % (Economidou, 2011)

Region	Multi-family houses	Single family houses
EU	36	64
Poland	44	56

IAQ are dependent on ventilation operation and the density of population. Matulska-Bachura (Matulska-Bachura, 2014) gives currently floor space per capita in Poland of 26,3 m^2/person, which is quite low in comparison with western Europe countries (Table 2).

Table 2: Floor space per capita, m^2/person (Economidou, 2011)

Region	Multi-family houses	Single family houses
North & West EU	36	50
South EU	31	41
Central & East EU	20	26
Poland	average 26,3	

There are more than 13 million dwellings in Poland, 5,3 million in single family houses and 7,7 million in multi-family houses. Almost half population live in multi-family houses. Matulska-Bachura (Matulska-Bachura, 2013) stated that in cities 72% live in multi-family houses. According to Dol (Dol, 2010) Poland is the country with one of the highest share of households living in overcrowded houses in EU.

Almost all multi-family residential buildings in Poland are equipped with natural ventilation driven by chimney stack effect. Last two decades large number of multi-family buildings were retrofitted with new, airtight windows with better heat loss protection. In parallel no new ways of air supply were proposed, only since 2008 the application of trickle vents is mandatory. Since free-market economy and individual heating cost accounting implementation, the IAQ in dwellings deteriorated. It is particularly observed in multi-family buildings, with small floor space per capita.

For the existing polish multi-family stock no reliable airtightness data exists. There are some reasons of such a state. Occupied multi-family residential buildings are extremely difficult or impossible to be measured as a whole. Access to apartments is limited and require cooperation with many building occupants. Testing prior to occupancy requires balancing the construction schedule, coordination with the owner and completion of the building (all leakage influencing components). Sets of blower door units, required for measurements, are not easy to gather in one place. Until last five years there were neither investor interest nor dedicated public funding for such a tests.

Few airtightness results for the multi-family residential buildings exist on European and North America market (Finch, 2009, Ricketts, 2013). Bailly (Bailly, 2013) presents airtightness database developed by the Centre d'Etudes Technique de l'Equipement de Lyon (CETE de Lyon) consist of 31 000 measurements but few entire multi-family buildings are measured. Finch (Finch, 2009) gives the number of 100 000 single houses’ measurements documented and less than 500 for multi-unit buildings worldwide. Building envelopes are often far different in construction and results from different countries are inadequate to compare.

3 MULTI-FAMILY BUILDINGS AIRTIGHTNESS MEASUREMENT

As multi-family buildings are difficult to measure, a guarded zone test method (Figure 1, 2), called also guarded zone pressurization technique or balanced fan pressurization, is used to measure specific single zone air leakages in multi-zone building. To reduce the influence of

airflows between zones, both the specific zone (room, dwelling, floor, etc.) and any adjacent conditioned zones (beside, above, below) should be pressurized to the same equal test pressure (Walther, 2009, Ricketts, 2013, Hult, 2014, Finch, 2009).
Some authors (Ricketts, 2013, Finch, 2009) points out that during guarded zone test flow rate and pressure caused by one fan can affect the flow rates of the other fans. In large building and in adverse weather conditions getting multiple fans to operate in equilibrium may be challenging. Automatic fan control helps getting the equilibrium quicker.

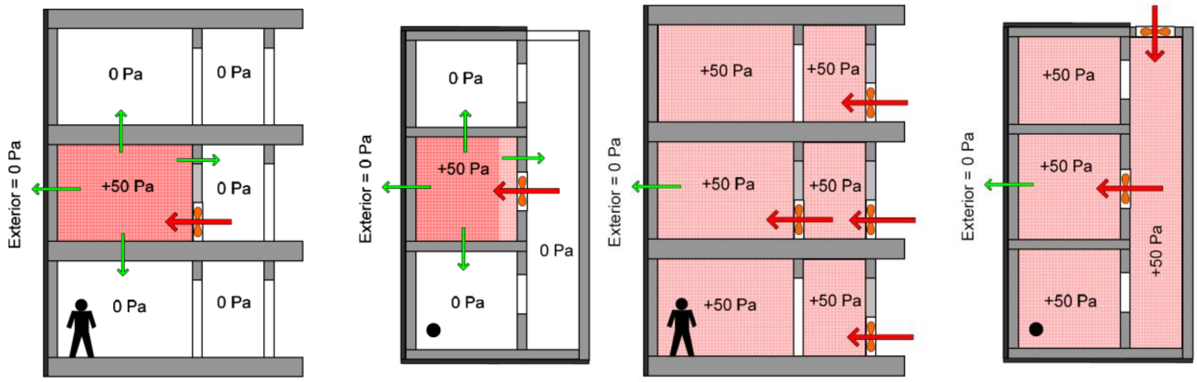

Figure 1: Single zone test with adjacent zones open to exterior (two left figures: section and plan view of test floor) and guarded zone test with adjacent zones pressurised to equal pressure (right figures) (Ricketts, 2013)

It is essential that the larger and leakier zones have the strong influence of a whole building result. For multi-family building wrong results could be obtained when determining building airtightness with use of dwellings results (or even single dwelling result) neglecting the influence of common spaces (which can be very leaky and in practice are impossible to be measured separately).

Figure 2: Simultaneously measurement of 9 apartments in multi-family residential building (NRCERT, 2011)

One may measure specific floor with adjacent floor pressurized to the equal test pressure. Anyway in buildings with large, inaccessible inter-floor leakages that cannot be sealed (such as elevator and mechanical shafts) the sum of the leakages measured for each floor does not give the real total leakage of the building (Bahnfleth, 1999). Proskiw (Proskiw, 2001) provides procedure of measuring and pressurization of single zone, with adjacent zones not pressurized, where the pressures induced in adjacent zones are measured and internal flows are calculated based on pressure differences. Method is more complicated and requires sophisticated staff and more equipment.
Measuring a zone with adjacent zones not pressurized (Figure 1, left) gives the result which include air leakages to adjacent zones (Genge, 2009, Zhivov 2009). These leakages have no influence on buildings heat losses and should be excluded from the result. Ricketts (Ricketts, 2013) find interior separators often less airtight than the exterior enclosure. Walther (Walther, 2009) describes the FLiB (Fachverband Luftdichtheit im Bauwesen e.V.) method developed for subsidies verification procedure of measuring at least 20% of dwellings in building separately. Apartments on different floors should be chosen, at least one on the top floor, one

in-between floor and one on the ground floor. The adjacent zones should be open to outdoors, to minimize the airtight influence of these zones. Weighted average from the results of the separate zones can be calculated, based on the volume (or other basis provided that it is consistent with the airtightness metric used) and is equivalent to the value that would be measured on the building as a whole. Particular zones can be up to 30% leakier than the limit value for the whole building. It is noted that the whole building measurement is more reliable, as the method is based on an assumption of zones' similar airtightness properties.

Due to difficulties in measuring the whole residential buildings the ATTMA standard (ATTMA, 2010) gives also the possibility of testing at least 20% zones, in this case of building's exterior walls area, but concludes that the leakages limit should be 10% smaller than that for the whole building.

As concluded above, the leakages of common spaces play very important role in these assumptions. With very leaky zone not selected for the test (usually common spaces) described methods could lead to wrong results. Lift and technical shafts, halls and stairwells ventilated naturally are often responsible for cause significant leaks. Walther (Walther, 2009) noticed that there is lack of feed-back from the use of mentioned method and it seems that these methods have been derived according to expert intuition but without solid argumentation.

There is the possibility to use single blower door for zone pressurization in multi-zone building but the purpose of the test is different. Armstrong (Armstrong, 1996) describes method of sequence blower door tests with different building component sealed in consecutive measurements. Each change in airflow is attributed to the corresponding set of components that were sealed. Gorzenski (Gorzenski, 2014b) used this method to determine the average leakage through the wall in aquapark.

Performing and interpreting results from air leakage tests are more complicated and more time consuming in multi-zone buildings than in single-zone ones (Hult, 2014, Ricketts, 2013, Finch, 2009). There are no existing standards for multi-zone building airtightness testing, although some standards (ISO 9972, 1996, EN 13829, 2000) allow to measure air leakages to outdoor for single zone in multi-zone building with equal pressure induced in adjacent zones.

Hult (Hult, 2014) examined uncertainty for multi-zone air measurements. Uncertainty in leakage to outside due to pressure fluctuation and calibration error in guarded test result is relatively small. If the interzonal leakage area is small relative to the leakage area to the outside then the uncertainty in the leakage measurement is 4%. If the interzonal leakage area is increased, the uncertainty in the measured leakage is 14%. But leakages in interconnected zones that are not pressurized during the test may have much more substantial impact on the order of 30÷100% of the leakage directly to the outdoors (Hult, 2014). Gorzenski (Gorzenski, 2014a) presented large aquapark (volume of 200.000 m^3) multi-zone airtightness test results doubled in case of no adjacent zones pressurized, compared with the guarded zone test results. Still some authors (Ferdyn-Grygierek, 2012) give examples of measurements made for single dwellings and rooms with adjacent zones not equally pressurized and even suggesting the resulted airflow could be used for calculating the specific window leakages.

4 CASE STUDY BUILDING

An unoccupied multi-family residential building located in Poznan, Poland was chosen for the research (Figure 3). It was under construction, but all envelope components which have the influence on airtightness were completed (roof, windows with windowsills, doors, finished envelope plastered from outside and inside, once painted, floors prepared to be covered, electrical and HVAC plumbing mounted). Tests were performed during autumn and wintertime in late 2013.

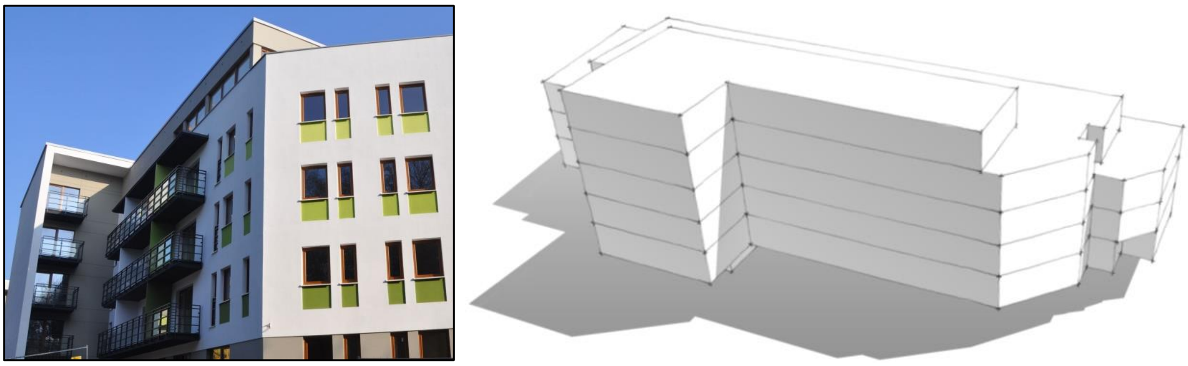

Figure 3: Case study multi-family residential building and its 3D model

4.1 Building characteristics

The object is a multi-family six storey (underground garage and five aboveground floors) residential building built in 2013. Outer walls are made with 24 cm thick silicate bricks and insulated with 15 cm thick expanded polystyrene. Walls are finished with gypsum plaster layer from inside and with silicate thin-layer plaster on polystyrene from outside. The inner walls are made with 8÷24 cm thick silicate brick or concrete. Floors are made with beam-and-block concrete, roof is wooden truss system covered with heat-weldable roofing membrane. Floors are covered with concrete topping.

Building is equipped with natural ventilation system with trickle vents mounted into triple pane window frames and with ceramic blocks extract ducts with diameter of 150 mm dedicated for each apartment (Figure 4).

Figure 4: Trickle vents (left) and ceramic blocks used for extract ducts (right)

The floor area is 33,400 ft² (3,100 m²) and the interior volume is 277,200 ft³ (7,850 m³). Total enclosure area including exterior walls, roof and below grade surfaces is 39,300 ft² (3,650 m²).

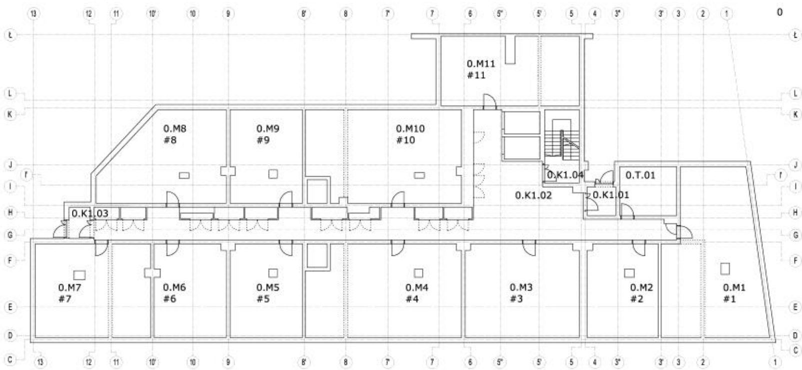

Figure 5: Ground floor layout

There are 47 dwellings with floor area of 25.6÷81.7 m² (average 53.6 m²). Floors consist of a central hallway with apartments on each side (Figure 5). There are one staircase, two elevator shafts and several technical shafts, all running vertically the full height of the building. There are 131 trickle vents mounted into window frames. With high outdoor (~90%) and indoor (~75%) air relative humidity it was assumed and observed that during test trickle vents were fully open (Figure 6).

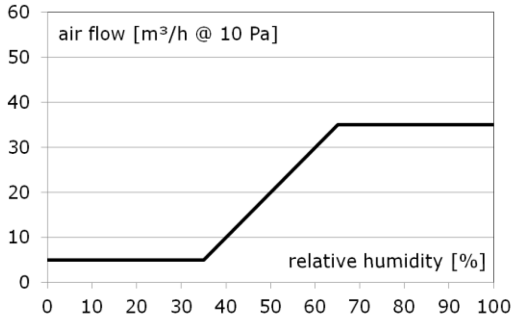

Figure 6: Trickle vents air flow as a function of relative humidity characteristics by manufacturer

4.2 Preparation for testing

All building zones (dwellings and common spaces) except unconditioned garage space on underground floor were included in the whole building test area. On underground floor only staircase and lift shafts are included into conditioned zone and air tightly separated from the garage. Garage is connected to the roof level with some ducts (garage, smoke and trash room ventilation). Ducts are made with steel and equipped with fire dampers, which were closed during the test.

Measurements were conducted with accordance to EN 13829. For the whole building test all ventilation extract ducts were shut with use of 146 inflatable inner rubber bladder (Figure 7).

Figure 7: Extract ducts closed with use of inflatable inner rubber bladder

Figure 8: Chimneys top with gaps between chimney walls and ventilation duct

Windows and doors to outside were closed, inner doors left open. Sewer traps were filled with water or sealed. Trickle vents were set to close and open position in successive tests.
During preparation huge gaps between chimney walls and garage ventilation duct (Figure 8) were observed at roof level. Roof hatch window was found to be leaky one.

4.3 Equipment

A total of 3 Minneapolis Blower Door (BD) were used for the tests. During whole building test set was mounted in the balcony door on the third floor (Figure 9).

Figure 9: Minneapolis Blower Door set used for the tests

5 CASE STUDY MEASUREMENTS AND RESULTS

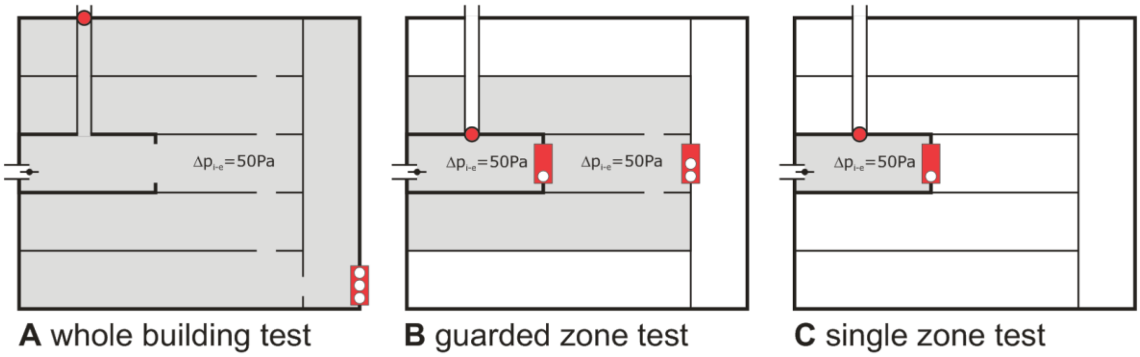

Figure 10: Measurements configurations (pressurized zone marked with grey colour)

Several measurements (Figure 10) were conducted:

- A - whole building airtightness test with use of 3 BD units, extract ducts were sealed from the top on roof level, variants:
  - both pressurisation and under-pressurisation,
  - both closed and open all trickle vents,
- B - guarded zone test of selected 5 different dwellings located on third floor, extract ducts sealed at the dwelling level, trickle vents closed, under-pressurisation only, use of 1 BD for zone pressurising and 2 BD for three floors (above, current and below) pressurising,
- C - single zone test for all 47 apartments in building, no adjacent zones pressurization, extract ducts sealed at the dwelling level, trickle vents closed, under-pressurisation only, 1 BD used.

Whole building airtightness tests (A) were conducted in multi-point sequence according to EN 13829 in two variants: first one with all trickle vents open and second one with all of them closed. n_{50} values were found to be 1,20 h^{-1} for vents closed and 1,55 h^{-1} for open. The difference in V_{50} airflow was only 2800 m³/h, which for 131 trickle vents gives the difference in airflow of 21,4 m³/h between closed and open vent at the pressure difference of 50 Pa. Based on Figure 6 the difference should be 30 m³/h at the pressure difference of 10 Pa and 88 m³/h at the pressure difference of 50 Pa, assuming flow exponent of ⅔. Obtained airflow is more than 4 times smaller than it should be, based on manufacturer data. Further research with trickle vents in pressure/temperature/humidity chamber would be essential.

Table 3: Whole building airtightness test results (A)

Trickle vents	Pressure	V_{50} [m³/h]	n_{50} [h^{-1}]	q_{50} [m³/(h·m²)]
closed	under-pressure	9310	1.19	2.55
	overpressure	9493	1.21	2.60
	average	9402	**1.20**	**2.58**
open	under-pressure	12492	1.59	3.42
	overpressure	11874	1.51	3.25
	average	12183	**1.55**	**3.34**

Building was found to be air tight, even with trickle vents open. One should keep in mind that extract ducts were sealed from the top on roof level during the test.

Results of guarded zone (B) and single zone tests (C) for selected 5 different apartments located on third floor are presented in Table 4. Extract ducts were sealed at the dwelling level, trickle vents were closed. In guarded zone test (B) equal pressure in adjacent zones (three floors: above, current and below) was generated with 2 Blower Doors.

Table 4: Guarded (B) and single (C) zone test results

Dwelling	Floor area [m²]	Volume [m³]	B/C V_{50} [m³/h]	B/C n_{50} [h^{-1}]	C/B diff. [%]
2.M8	75.4	190.8	130/146	0.68/0.77	12
2.M9	65.8	166.4	100/138	0.60/0.83	38
2.M7	36.2	91.6	60/72	0.65/0.79	20
2.M3	57.2	144.6	90/160	0.62/1.11	78
2.M2	60.5	152.9	100/127	0.65/0.83	27
average				**0.64/0.86 h^{-1}**	**35 %**

Weighted (per volume) average air leakages are about 35% higher (C/B factor) in a case of single zone (n_{50}=0.86 h^{-1}) compared to guarded zone method (n_{50}=0.64 h^{-1}). It is due to taken interzonal airflows into account.

Single zone tests (C) were conducted in multi-point sequence according to EN 13829 for all 47 dwellings in building. Single point measurement (50 Pa) and under-pressurisation was used. Adjacent zones were not pressurized. Extract ducts were sealed at the dwellings level, trickle vents were closed. Total floor area of all dwellings is 2520 m² and the inner volume is 6345 m³. Common spaces (staircases, lift shafts, corridors) floor area is 595 m² and the interior volume is 1505 m³.

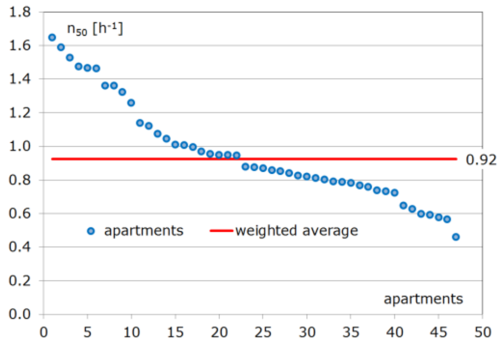

Figure 11: n_{50} values for apartments - single zone test (C)

Results of 47 single zone tests (C) for all dwellings are presented on Figure 11. The weighted (per volume) n_{50} average is 0,92 h^{-1}.

Table 5: Results of single zone tests for 47 dwellings (C) and other estimated (*) values

#	Area	Volume [m³]	Description	V_{50} [m³/h]	n_{50} [h^{-1}]
1	47 dwellings	6345	measured, single zone (C) - FLiB	5893	0,92
2	47 dwellings	6345	#1 reduced by C/B 35% factor	4365*	0,68*
3	whole building	7850	measured, whole building (A)	9310	1,20
4	common spaces	1505	subtraction #3 - #2	4945*	3,28*
5	whole building	7850	ATTMA (#1 +10%)	8016*	1,02*

If one assumes obtained result (#1) is 35% higher (C/B factor), due to internal leakages included in result (Table 4), the corrected V_{50} value for all dwellings is 4365 m³/h (n_{50}=0,68 h^{-1}). Estimated (weighted per volume average) n_{50} value for the whole building, with 100% dwellings tested (more reliable result than required 20%), would be:

- 0,92 h^{-1} - FLiB method (#1),
- 1,02 h^{-1} - ATTMA method (#5).

The most accurate result, for the whole building (A, #3), was n_{50}=1,20 h^{-1}. Both methods would result in underestimation of n_{50} value: 15% for ATTMA and 23% for FLiB method. The common spaces n_{50} value was found to be 3,28 h^{-1}. The main leakages are gaps in ventilation and technical shafts.

6 CONCLUSIONS

Results of airtightness tests of multi-family residential buildings and its 47 dwellings were presented. The whole building (one zone) testing (A) was found to be the only one method resulting in real value for the building. Dwellings were found to be airtight with average of n_{50}=0,64 h^{-1} for 5 dwellings and guarded zone test and n_{50}=0,92 h^{-1} for all dwellings and single zone test (35% higher). Influence of relatively small (19% of internal volume), but very leaky (n_{50}=3,28 h^{-1}) common spaces results in n_{50}=1,20 h^{-1} for the whole building.
Using methods for estimating the whole building airtightness based on single zone test for dwellings results in underestimation of n_{50} value. It was due to very leaky common spaces in comparison with dwellings.
Trickle vents were found to be 4 times more tight than it should be basing on manufacturers data: at 50 Pa pressure difference airflow was found to be 21,4 m³/h per vent instead of 88 m³/h.
Single zone test, with adjacent zones not pressurized, gives the result which contains outdoor and indoor leakages. Determination of zones' outdoor leakages is possible with guarded test method. Anyway it is practically impossible to measure the leakages of common spaces separately, that is why only whole building (one zone) airtightness test only gives the reliable result. On the other hand, measurement of multi-family buildings as a whole is practically possible only if building is unoccupied.

7 REFERENCES

Armstrong, P., Dirks, J., Klevgard, L., et al., (1996). *Infiltration and ventilation in Russian multi-family buildings*, Proceedings of the 1996 Summer Study on Energy Efficiency in Buildings, Washington

ATTMA, (20062010). *ATTMA Technical Standard 1. Measuring Air Permeability of Building Envelopes*, Air Testing and Measurement Association, The British Air Tightness Testing and Measurement Association 2006

Bahnfleth, WP., Yuill, GK., Lee, BW., (1999). *Protocol for field testing of tall buildings to determine envelope air leakage rate*, ASHRAE Transactions, Seattle

Bailly, A., Jiang, Y., Guyot, G., Desfougères, F., (2013). *Preliminary analysis of French buildings airtightness database*. Proceedings of the 34th AIVC Conference, Athens

Dol, K., Haffner, M. (2010). *Housing statistics in the European Union 2010*, Delft University of Technology, Delft

Economidou, M., et al (2011). *Europe's buildings under the microscope. A country-by-country review of the energy performance of buildings*. Buildings Performance Institute Europe (BPIE), Brussel

EN 13829:2000 Thermal performance of buildings - determination of air permeability of buildings - fan pressurization method, European Committee for Standardization,

Ferdyn-Grygierek, J., Baranowski, A. (2012). *Szczelność i wymiana powietrza budynkach mieszkalnych i użyteczności publicznej*, conference proceedings Kompleksowa diagnostyka cieplna in situ budynków, Politechnika Śląska, Gliwice

Finch, G., Straube, J., Genge, (2009). *Air leakage within multi-unit residential buildings: testing and implications for building performance*, 12th Canadian Conference on Building Science and Technology proceedings, Montreal

Genge, C. (2009). *Controlling Air Leakage In Tall Buildings*, ASHRAE Journal 51(4): 50-60

Górzeński, R., Szymański, M., Górka, A., (2014). *Large buildings airtightness measurements using ventilation systems*, Proceedings 35th AIVC Conference, Poznań

Górzeński, R., Szymański, M., Górka, A., Mróz, T. (2014). *Airtightness of Buildings in Poland*, International Journal of Ventilation 12(4): 391-400

Hult, E., Sherman, MH. (2014). *Estimates of uncertainty in multi-zone air leakage measurements*, International Journal of Ventilation, 12(4): 359-368

ISO Standard 9972 Thermal performance of buildings - determination of air permeability of buildings - fan pressurization method, International Organization for Standardization, 1996

Matulska-Bachura, A., et al. (2013). *Zamieszkane budynki. Narodowy spis powszechny ludności i mieszkań 2011*, Główny Urząd Statystyczny, Warszawa

Matulska-Bachura, A., et al. (2014). *Gospodarka mieszkaniowa w 2013r.*, Główny Urząd Statystyczny, Warszawa

NRCERT, (2011). *Multifamily Blower Door Process*, New River Center for Energy Research and Training, proceedings DOE National Weatherization Training Conference, New Orleans 2011

Proskiw, G, Parekh, A. (2001). *A Proposed Test Procedure for Separating Exterior Envelope Air Leakage from interior Partition Air Leakage*. Performance of Exterior Envelopes of Whole Buildings Conference proceedings, Atlanta

Ricketts, L., Finch, G., Bombino, R., (2013). *Air Leakage Control in Multi-Unit Residential Buildings*, RDH Building Engineering Ltd., Vancouver 2013

Walther, W., Rosenthal, B., (2009). Airtightness Testing of Large and Multi-family Buildings in an Energy Performance Regulation Context, ASIEPI

Zhivov, A., Pietilainen, J., Reinikainen, E., Schmidt, F., Woody, A., (2009). *IEA ECBCS ANNEX 46 Energy Process Assessment Protocol*, Energy Branch US Army Corps of Engineers