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IMPLICATION OF INFILTRATION ON BUILDING ENERGY DEMAND - A REVIEW OF VERIFICATION METHODS

Abstract:

Infiltration has a considerable impact on both, energy efficiency and occupant comfort in buildings. Due to the complexity of the analysis of this phenomenon in buildings, the verification methods are very important for its diagnostics and evaluation. In this paper, the matter of infiltration in buildings is being considered referring to both, calculation models and methods, as well as through current standards and regulations in the EU and Serbia. Different valorization methods are presented and analyzed regarding their characteristics, applicability, and complexity. Finally, preliminary infiltration measurements with a pressurization test, conducted on selected buildings of Belgrade housing stock are presented and compared with values defined by the current regulations in Serbia. Results pointed out current problems and the need for improvements regarding the treatment of infiltration in local regulations and practice.

Keywords: infiltration, building airightness, energy efficiency, verification methods, pressurization test

УТИЦАЈ ИНФИЛТРАЦИЈЕ НА ЕНЕРГЕТСКЕ ПОТРЕБЕ ЗГРАДЕ – ПРЕГЛЕД МЕТОДА ВЕРИФИКАЦИЈЕ

Сажетак:

Инфилтрација има значајан утицај у разматрању питања како енергетске ефикасности тако и комфора у објектима. Због сложености анализе овог феномена, методе верификације показале су се као веома важне приликом дијагностиковања и евалуације инфилтрације. У овом раду се питање инфилтрације разматра у односу на моделе и методе прорачуна, као и тренутне стандарде и прописе у ЕУ и Србији. Разматране су различите методе верификације кроз анализу и поређење њихових карактеристика, примењивост и сложеност. Представљена су и прелиминарна мерења инфилтрације одабраних објеката у склопу стамбеног фонда Београда тестом притиска удувавањем која су упоређена са вредностима дефинисаним важећим прописима у Србији. Резултати су указали на тренутне проблеме и потребу унапређења третмана инфилтрације у локалним прописима и пракси.

Кључне ријечи: инфилтрација, заптивеност објеката, енергетска ефикасност, методе верификације, тест притиска удувавањем

1. INTRODUCTION

Being the largest energy consumer in Europe, buildings use 40% of the total energy and are responsible for around 36% of the CO2 emission. [1] Therefore, European countries are complying with the set of international agreements to increase energy efficiency and reduce energy consumption. Achievement of these goals sets the need to minimize thermal losses through the building envelope. Today, EU strategies support the renovation of the national building stock, emphasizing the need for transformation of a building's stock into nearly zero-energy buildings (nZEB) and highlighting that the calculation of the energy needs beside energy savings must lead to optimized health, indoor air quality, and comfort levels, further defined by the Member States at the national and regional levels. Therefore, it is required that general indoor climate conditions should be taken into account when determining the minimum energy performance requirements of a building. [1]

Nowadays, it is recognized that indoor air quality plays a very important role in the health of the populations. The World Health Organization noted a rising number of illnesses and deaths related to indoor air pollutions in the last years. Consequently, matters of air quality and occupant’s health have become one of the major environmental health concerns in Europe. [2] In this context, one of the dominant questions, with a great impact on both energy efficiency and indoor air quality, is the matter of infiltration in buildings. Infiltration, together with ventilation, represents ventilation heat losses, having a significant influence when considering the total energy consumption of buildings. As such, it is one of the main factors considered when calculating heat losses in buildings. It accounts for between 25-50% of the heating load in both residential and commercial buildings. [3] Besides, 1/3 of the heating and cooling load in a building are due to infiltration. [4] Researches show that different building components contribute to a certain percentage to the distribution of infiltration through the building: walls (18-50%, av. 35%), ceiling (3-30%, av.18%), cooling/ heating systems (3-28%, av. 18%), windows and doors (6-22%, av 15% - depending mostly on window/door type), fireplace (0-30%, average 12%), vents in conditioned spaces (2-12%, av. 5%), other 1% or less. [5]

In this paper, the matter of infiltration in buildings is being considered referring to both, calculation models and methods, as well as through current standards and regulations in the EU and Serbia. Valorization methods (pressurization test, tracer gas test, and thermal infrared imaging) are presented and considered from the point of view of applicability, advantages, and disadvantages, as well as the complexity of a method. The analysis of the infiltration of representative examples of the Belgrade housing stock was investigated based on preliminary measurements with the pressurization test, and results are presented and compared with requirements of the current regulations in Serbia.

2. INFILTRATION CALCULATION MODELS AND METHODS

2.1. Infiltration in buildings

Adequate airtightness of a building ensures adequate indoor environmental quality in buildings, lowers the usage of the energy. Both too high and too low infiltration rates may have a negative impact on building energy demand and occupant comfort. Poor airtightness of a building envelope results in impaired internal comfort conditions (thermal, air, and sound comfort), may influence hydrothermal building performances, fire permeability, and can lead to potential building material and structural damages. Air infiltration has a huge impact on the moisture flow across the building envelope possibly causing moisture accumulation and condensation in buildings, that can influence building material properties. [5] In the long term, additional condensation in a building can affect building structural performance and performance of building materials, with the appearance of mould and ice particles inside the materials and construction, changing the properties of materials and interrupting building construction integrity. Poor airtightness can also lead to unexpected heat loss in buildings causing the need for additional usage of heating, ventilation, and air-conditioning systems (HVAC). Although high airtightness prevents energy loss in a building, it may have a negative effect on indoor air quality. The tendency to reduce excessive air changes per hour during the heating period, results in a lack of a minimum amount of fresh air, due to accumulation of internal pollutants that cannot be discharged into the atmosphere by exfiltration, but only by natural and mechanical ventilation.

2.2. Infiltration calculation models and methods

Infiltration calculation models are essential in the building thermal design process - used in calculating the resulting air change rates, energy requirements and costs, and estimating indoor air quality. The output can be used both as a part of the design process (to modify the building characteristics and optimize the design) and during the time of exploitation of a building to check the performance of a building and its components. Air infiltration rate is a very uncertain quality to be measured because of a variety of calculation models and methods available. Also, because of a high variety of available building components and construction techniques, it is hard to define and evaluate the infiltration rate and its characteristics. [6]

Infiltration can be calculated in different methods chosen by the building type and possibility of application. Generally, methods are divided as theoretical (based on previous experience and practice) and empirical (requiring different measurement tools and models). Based on the results of some previous researches, [5,6,7] different models of infiltration calculation are presented and compared in this chapter. They are divided into five categories: air change methods, reduction of pressurization data test, regression techniques, theoretical network methods, and simplified theoretical methods. [5] Empirical models are air change methods, reduction of pressurization test data, and regression techniques, and the remaining two methods are classified as numerical methods with different complexity. Air change methods are considered the least complex and most applicable. Theoretical models can be used as predictive even during the design process and can help during the design decision process, while empirical models require concrete cases and situations on which the verification methods can be applied. The analysis of infiltration calculation models - theoretical and empirical is presented in Table 1.

2.2.1. Theoretical models

All theoretical models are defined on the mass balance - preposition that infiltrating air displaces the equivalent volume of internal air, mantling the balance between masses. [6] The simplest form of theoretical models is a single zone model, that assumes all different zones in a building as a single enclosed space, while more complex multizone models break down building into series of interconnected zones. Single-zone models calculate infiltration considering flow paths and characteristics, building height, internal/external temperature gradient, area

wind speed, local shielding conditions, terrain roughness factors, and mechanical ventilation system properties. [6] Multizone models also require knowledge of flow path details and characteristics, building location, geometry, etc., but multizone calculations in the calculation add the equations representing the airflow/leakage across internal zones and partitions. [6] Simulations are very valuable as control methods during the design process but they cannot be completely accurate. Since there is a large amount of input needed and a lot of values usually based on generic coefficients, these results are generally not precise, and not adapted completely to local conditions and building characteristics. For the results to be accurate, the verification methods should be provided with precise values and input. Multizone models allow simulation of infiltration that can be helpful during the heating/cooling design process and are allowed to predict indoor air conditions and the hygrothermal performance of a building. Usually, these models are based on homogenous indoor air and unformed temperature, neglecting airflow and because of that these assumptions can lead to an error. [8] Because of that, the CFD (computational fluid dynamics) methods are developed capable of reducing the number of assumptions needed for a multizone approach while still providing detailed airflow values, temperatures, and pollutant distribution conditions. Some of these simulations require complex mathematical apparatuses or long-time span, and as such are not adequate for small scale models and general implementation. [5]

2.2.2. Empirical models

Empirical models are a very important tool both for research and understanding of this phenomenon and practical application in different cases, as well as for creating a numerical database of infiltration rate. [5] Empirical models are described as three methods - air change methods, reduction of pressurization test data, and regression techniques. [6] Regression techniques and air change methods are predictive measuring techniques based on adopting values from a database and calculating the infiltration rate based on previous experience and expert estimations, while pressurization test data requires in-situ measurements defining infiltration rate for a special case and current conditions. Air change rates are the simplest tools that require basic building design details but do not provide detailed infiltration predictions. Regressions methods consider infiltration measurement data with parallel records of location climate conditions and may be applied only on existing buildings that were measured by the tracer gas method but also give unreliable results. Tools that can define and measure the infiltration rate *in situ* - are verification methods. The reduction of pressurization test data is the most commonly used verification tool used as a method to measure the airtightness rate. This verification method applies only to existing buildings pressure tested, but it is incapable to define leakage trace and crack location. Therefore, for a complete diagnostic and observation of a problem, an additional tool is needed to define exact problem areas and leakage intensity.

Table 1. *Infiltration calculation models analysis*

models	application	type		disadvantages	output
THEORETICAL	- can be used on building models for simulations -valuable as control methods during the design process;	single-zone models (different zones in a building as a single enclosed space) multizone models (break down building into series of interconnected zones)		- require substantial data input -might be too complex - unreliable;	- values based on prediction and generic coefficients
EMPIRICAL	-applicable for existing buildings; - calculating the average infiltration in a building; -a very important tool for research and understanding of infiltration phenomenon; -valuable for evaluating creating a numerical database of infiltration rate;	PREDICTIVE MEASURING	air change methods (predictive measuring technique based on previous experience)	- do not provide detailed infiltration predictions; - do not reflect buildings specific properties and local conditions	the numerical value (based on construction airtightness) q_{inf} =V*(ACH)*C q_{inf} (W/^{O}C h) infiltration heat loss V (m^3) space volume ACH (h^{-1}) air change rate per hour C (J/m^3 ^{O}C) air heat capacity
			regression techniques (predictive measuring technique based on previous experience)	- does not consider information about impact of wind, temperature, and local topography and conditions	numerical value (infiltration data measurements combined with some climatic data) Qinf =a'+b'DT +C'v2 Qinf infiltration rate per hour, DT internal/external temperature difference (C), v (m/s) wind speed, a', b' and c' regression coefficients
		VERIFICATION METHOD	reduction of pressurization test data (requires in-situ measurements defining infiltration rate for a special case and current conditions)	- do not reflect building-specific properties and local conditions	the numerical value (the average infiltration in a building) n=n_{50}/N n_{50}=V_{50}/V n50 (h-1) air change rate at 50Pa, V50 (h-1) air leakage test, V (m3) building volume, N correlation factor

INFILTRATION ACCORDING TO STANDARDS AND REGULATIONS

2.3. Infiltration according to eu standards

The present European building regulatory framework is developed to continuously improve energy efficiency and performance of building stock, reduce CO_2 emission, and ensure good Indoor Air Quality. In previous years sets of regulations related to these problems have been developed and implemented in European countries. European Union continuously sets goals of improving energy efficiency and reducing energy consumption. Goals have been updated and set higher with a set of measurements:

- to reduce primary energy consumption in the EU by 20% by 2020;
- 40% cuts in greenhouse gas emissions (from 1990 levels), 32% share for renewable energy, 32.5% improvement in energy efficiency by 2030;
- to be climate-neutral by 2050 – an economy with net-zero greenhouse gas emissions.

The main legislative instrument affecting energy use and efficiency in both new and existing building stock in the EU is The Directive on Energy Performance in Buildings (EPBD) originally approved in 2002, followed by the recast in 2010 (2010/31/EU) and amending directive in 2018 (2018/844/EU). Consequently, the European Committee for Standardization (CEN) developed a set of standards regarding the energy performance of buildings (EPB standards).

Table 2. *Airtightness requirements in Europe (based on BPIE study[9])*

Country	unit	Air permeability	Pressurization tests
BRUSSELS	h-1	0.6	unknown
DENMARK	l/(sm2)	< = 1.5 when tested @50Pa <1 for low energy building class 0.5 for nZEB buildings	Not mandatory, calculated as the average measurement using overpressure and under pressure
FRANCE	m3/(h*m2)	< = 0.6 individual buildings < = 1 multifamily building	Mandatory for all new dwellings, @4Pa
GERMANY	h-1	< =3 buildings with natural ventilation < =1.5 buildings with mechanical ventilation < = 0.6 passive house standard	airtightness value results from the blower door test @50Pa
ITALY	** only some regions have standards Bolzano - mandatory blower door tests in energy certification of new dwellings (according to EN13829) Trento – requested in energy certification of high-class buildings (for the A+ class)		
POLAND	m3/(m·h)	-9 for low or moderately high buildings (up to 55 m) -3 for high-rise buildings (more than 55 m)	Recommended after the construction phase @100Pa
SWEDEN	l/(s·m2)	< 0.6 (specifically, for single-family homes (<50m2))	unknown
UK	m3/(h·m2)	10 m3/(h·m2) 5 m3/(h·m2) (notional dwelling)	unknown

Buildings Performance Institute Europe (BPIE) did research overviewing the regulatory framework for IAQ, thermal comfort, and daylight in EU countries. It demonstrated that matters of infiltration and ventilation are important factors considering both energy efficiency and indoor air quality. In many energy performance regulations across European countries, it is noted a great difference in the treatment of the matters of infiltration and airtightness in buildings. (Table 2) For some EU members, airtightness can only be defined with measurements (blower-door testing) while some countries allow the use of a quality management approach. [9] The value of airtightness is expressed in different units among countries, varying from litres per second per floor area ($l/s/m^2$) to volume per hour (m^3/h), and the referent value is given in either minimum airtightness requirements or maximum envelope leakage. [9] The default value for building airtightness is different from country to country, respecting differences in building construction types.

In some countries, the Pressurization test (blower-door testing) has become an obligatory part of a building air permeability diagnostics process. In the BPIE research, it is noted that calculation methods vary among countries and measured airtightness data are not fully comparable. [9]

2.4. Infiltration according to standards in serbia

Infiltration in Serbia has been treated through ventilation losses, in addition to transmission losses and heat gains, representing an important aspect of the total energy needs of the building. According to current regulations in the Republic of Serbia, [10] the annual required energy for heating and specific annual energy requirements for the heating of buildings, besides transmission, solar and internal gains include ventilation losses.

The annual energy required to compensate for the heat loss is calculated by the equation:

$$Q_{H,ht}=(H_t+H_v)\cdot 24\cdot HDD\cdot 10-3\ [kWh/a] \qquad (1)$$

H_t (W / K) coefficient of transmission heat loss,

H_v (W / K) coefficient of ventilatory heat loss

HDD degree of the day of heating for a particular location.

Coefficient of ventilation loss is defined as:

$$H_v=\rho_a\cdot c_p\cdot \sum_i V_i\cdot n_i\ [W/K] \qquad (2)$$

V (m^3) space volume,

n (h-1) air changes per hour,

ρ_a * c_p = 1200 (J/m^2K).

Following the Building Energy Efficiency Regulation, the infiltration rate is defined by the number of air changes per hour - n [h-1], based on building display, facades exposed to the wind and infiltration rate of the building envelope. The infiltration rate of the envelope is determined according to the standard SRPS EN ISO 13789 Thermal performance of a building – Transmission and ventilation heat transfer coefficients – Calculation methods, [11] that specifies a method and provides conventions for the calculation of the steady-state transmission and ventilation heat transfer coefficients of buildings. The infiltration rate @50Pa is defined relative to the actual measured values of the number of air changes per hour n [h-1] at a pressure difference of 50 Pa.

Table 3. *Air changes per hour regarding building display and infiltration rate of a facility (SRPS EN ISO 13789) - Residential multifamily buildings with natural ventilation [12]*

		ACH (air changes per hour) n (h-1)			ACH (air changes per hour) n (h-1)		
Building display to the wind		More than one facade			Only one facade		
Infiltration rate		high/leaky	median	low/airtight	high/leaky	median	low/airtight
disposition	open	1,2	0,7	0,5	1,0	0,6	0,5
	medium hidden	0,9	0,6	0,5	0,7	0,5	0,5
	very hidden	0,6	0,5	0,5	0,5	0,5	0,5

Table 4. *Air changes per hour regarding building display and infiltration rate of a facility (SRPS EN ISO 13789) - Residential single-family buildings with natural ventilation [12]*

				ACH (air changes per hour) n (h-1)
Infiltration rate		high/leaky	median	low/airtight
disposition	Open	1,5	0,8	0,5
	Medium hidden	1,1	0,6	0,5
	hidden	0,76	0,5	0,5

In the Republic of Serbia, it is not obligatory to verify the airtightness of the building envelope. The assessment of the infiltration rate is based on the expert assessment of the responsible energy efficiency engineer, and its expertise. The practice demonstrated that the assessment usually comes down to the quality of construction work and craftsmen's precision during the installation of building components. After determining the infiltration rate, the number of facades exposed to the wind and the disposition of the building, tabulated value of the number of air changes per hour - n [h-1] are adopted, separately for single-family and multi-family buildings. The minimal number of air changes per hour in buildings is defined by the Rulebook on the energy efficiency of buildings, and it should be minimally 0,5 (h-1). [10]

3. METHODS FOR VERIFICATION OF INFILTRATION

Evaluation of infiltration can be very complex because of many characteristics regarding building itself and buildings surroundings that should be included in its evaluation. Because of that, verification methods are a very valuable tool for measuring buildings airtightness. Few verification methods can measure a building's airtightness or demonstrate critical points of a building. The most common airtightness verification method is the method of pressurization test, performed with blower door device that can provide a numerical indicator of buildings infiltration rate. Besides the pressurization test, often used is the tracer gas method, that can evaluate and demonstrate air leakage points of a building, and thermal infrared imaging that can show air leakage points and point out problematic spots on a building envelope. The application of these verification methods can be of importance in various situations: for the needs of energy rehabilitation, checking the quality of the building construction and components, checking the technical condition of the building before the exploitation period, for the certification of buildings, before buying real estate.

The infiltration rate is most commonly verified as a part of the evaluation regarding the energy performance of a building of indoor air quality analysis. All verification methods are defined by standards, but as shown in research by BPIE, [9] the standards may vary from one country to another, making the evaluation process hard to compare. Also, during the research of different case studies that evaluate IAQ or EE performance of a building, it is noted that there is no defined methodology for evaluating infiltration in buildings. Measurements are done in different seasons and period over the year, in different weather conditions. Also, infiltration rates calculations are done with a variety of measurement results that vary from one-day measurements to all-year-round measurements that are compared and evaluated. In this chapter, different verification methods will be presented.

3.1. Pressurization test - static method of measuring - blower door

This method is based on the mechanical achievement of compression/decompression in the building and on the measurement of airflow through the building envelope at a certain difference of internal and external static pressure. In practice, the compression/decompression test is a term used to measure the airtightness rate of an individual building component, or whole building envelope. The desired pressure difference from the outside and the inside is achieved by extracting air, creating a pressure difference most commonly of 50 Pa, and then measuring the airflow through the fan unit required to maintain the pressure difference. The obtained values of pressure difference and airflow represent the results of the test. This test determines the amount of air that infiltrates / exfiltrates the object at a given value of pressure difference. A standard regarding the matter of performing and evaluating pressurization test in Serbia is SRPS EN ISO 13829:2008, Thermal performance of buildings - Determination of air permeability of buildings - Fan pressurization method, (ISO 9972:1996, modified). [12] In the Republic of Serbia, the reference parameter in the calculation of the energy performance of objects is the number of changes in the air per hour n, that is, the variation of the value n50.

Applying compression/decompression tests results in high values of pressure differences, most commonly at 50Pa. Based on a large number of tests, a correlation of results was found, for both residential and non-residential buildings. The number can be converted to air change rates per hour by the equation that divides the measured value with building volume and correlation factors. In different researches, this factor varies from 10-30, and it should be defined regarding local conditions. [13] As described in research by Jankovic et al., [14] the standards that are in use in the region, including Serbia, are based on ISO standard and only roughly defines the infiltration rate. Consequently, partial disagreements between the real and the measured results are possible. The authors point out that for more precise estimation, more factors should be considered taking into account climatic conditions, building height, possible sheltered facades, and physical damage to the façade envelope. [14] The separate evaluation of each parameter would give a more precise evaluation of the infiltration rate. Standard used in Serbia, SRPS EN ISO 13789 [12], estimates the annual infiltration rate as n_{50}/N where N=20, referring to this number for a steady-state calculation method:

$$n_{50}=V_{50}/\mathrm{V} \quad (3)$$

$$n=n_{50}/\mathrm{N} \quad (4)$$

where,

n_{50} (h^{-1}) air change rate at 50Pa,

V_{50} (h^{-1}) air leakage test - measured value,

V (m^3) building volume,

N correlation factor

Results calculated by this equation classify buildings by infiltration rate that varies between low/airtight, median, and high/leaky, and the values for single and multi-family buildings are given in Table 5.

Table 5. *Categorization of infiltration rate of the envelope according to the measured values of the number of changes of air per hour at a pressure difference of 50 Pa - n50 [h-1] SRPS EN ISO 13789 [12]*

ACH (air changes per hour) n50 [h-1]		Infiltration rate
Single-family houses	Multi-family houses	
<4	<2	low/airtight
4-10	2-5	median
>10	>5	high/leaky

3.2. Tracer gas method

This technique consists of introducing a certain quantity of a known gas in the space where the air exchange rate is supposed to be measured. Once the tracer concentration evolution with time is known, it is possible to evaluate the airflow rates through the envelope of the space, with appropriate mathematical analysis. [15] There are three basic tracer gas methods: decay, constant concentration, and constant injection. [16] The decay technique is the most common one. [17] This method is simple and suited for making short term measurements or spot checks at sites, giving the calculation of the infiltration rate to the effective volume. It simplifies the calculating method assuming that the infiltration rate remains constant, and it requires the minimum amount of equipment. This method requires that a trace detector is connected to a single channel chart recorder, or the measurement may be taken by hand. Then the volume of tracer gas to bring the concentration of traces to the full scale of the analyzer is released. This system can stabilize and record data until the concentration drops below its starting value (approx. ½ - 2 hrs.).

To evaluate actual air exchange, gas tracing dilution methods have been developed and standardized. A current standard regarding this matter is SRPS EN ISO 12569:2017 Thermal performance of buildings and materials - Determination of specific airflow rate in buildings - Tracer gas dilution method (ISO 12569:2017) [18]

3.3. Thermal infrared imaging

The use of thermal infrared (IR) imaging is a valuable tool for inspecting and performing nondestructive testing of building elements. Thermography is commonly considered as a qualitative method that is used primarily to indicate variations in thermal resistance on a wall or roof. [19]

The result of a thermal infrared imaging investigation is a recorded visual display (digital picture) - thermograph, usually presented with a regular photograph of an object and a follow-up report. [20]

This method allows easy diagnostics of irregular thermal patterns - thermal anomalies, demonstrated by the temperature difference on an observed surface. These inspections of the building envelope can be used to detect air leakage, targeting specific problem area which helps with easier diagnostics of problem areas. With this method, it is possible to identify air leakage, but it is not possible to see the air or measure the air temperature. [19] Standard defining procedure and conditions for thermal infrared imaging are SRPS EN ISO 6781-3:2016 Performance of buildings - Detection of heat, air and moisture irregularities in buildings by infrared methods - Part 3: Qualifications of equipment operators, data analysts and report writers (ISO 6781-3:2015). [21]

Table 6. *Comparison of infiltration verification methods*

THERMAL INFRARED IMAGING	TRACER GAS METHOD	PRESSURIZATION TEST - STATIC METHOD OF MEASURING - BLOWER DOOR	
existing buildings	existing buildings	existing buildings	APPLICATION
process of measuring is fast and efficient	process of measuring is fast and efficient	installation of device and equipment is required, process of measuring is fast and efficient	COMPLEXITY
yes	yes	yes	TRAINING
camera, computer and additional softer (for data analysis)	the gas tracker can use sophisticated devices but can also be done with simple tools, by hand	blower door device, computer and additional softer (for data analysis)	EQUIPMENT
measuring process is fast	measuring process varies from a method used; localized action; slow; needs to be repeated for results to be more precise	measuring process is fast installation of device and equipment are required	DURATION
temperature scale must be specified	-	baseline pressure test needed	DEVICE INPUT
winter, night or cloud day, the temperature difference between outside and inside, no wind	there are no special conditions needed	winter, the temperature difference between outside and inside, no wind	CONDITIONS
location and a general indication of intensity (demonstrated by temperature difference)	location and a general indication of intensity (indicated by gas movement)	numerical value	OUTPUT
results are visible on the device, but for more complex analysis software is needed	results are visible; reading can be done on the device itself, but for more complex data analysis software is needed	reading can be done on the device itself, but for more complex data analysis software is needed	DATA
does not give numerical values, can be used just as an indicator; does not take in count impact of local climate and topography characteristics; cannot be used on reflective facades (curtain walls)	does not give numerical values, can be used just as an indicator	does not take in count impact of local climate and topography characteristics; for locating the leakage area additional verification methods are required	DISADVANTAGES AND LIMITATIONS

3.4. Infiltration verification methods comparison

Verification methods for measuring infiltration that has been described - pressurization test/blower door, tracer gas method and thermal infrared imaging are tools that can be used for in situ measuring of infiltration rate. The analysis of different verification methods is described in Table 6. It is noted that all methods require expertise and professional training, and are more easily performed with computer software that provides data analysis. For the tracer gas method process of measuring takes a longer time, while the pressurization test requires more preparation and equipment installation. None of the measuring techniques does take into count the impact of local topography and climate. During the blower door method and tracer gas test, results can be detected on the measuring device itself, but for more complex calculations the data analysis software is needed. Traces gas test can be done without computer device, by hand, providing general knowledge of infiltration rate, but for more complex and more accurate measurements, measuring devices should be used.

It is noted that every method has its advantages and disadvantages. Pressurization tests measurement is a method that quickly and efficiently determines the infiltration rate of a building envelope. The main disadvantage of this method is that although it measures the infiltration rate it cannot locate or quantify a specific part of the envelope where airflow occurs. Because of that, it needs additional verification methods for quantification to be more accurate. Tracer gas method and thermal infrared imaging are methods that can define and locate the problematic area but are not capable of giving precise infiltration rate value. Because of that pressurization correlations are, potentially, the superior method for predict infiltration loads and long-term indoor air quality concerns.[4] For a more complete analysis of the infiltration rate and location of a problematic area, the best solution would be to combine pressurization tests with either tracer gas methods or thermal infrared imaging.

4. PRESSURIZATION TEST MEASUREMENTS – CASE STUDY

In order to investigate the real effects of infiltration and to compare them with theoretical assumptions declared in the current regulations, some preliminary measurements of airtightness have been undertaken on the selection of buildings from the Belgrade building stock. The general idea is to investigate the characteristics of the existing housing stock regarding the airtightness and infiltration with respect to the previously defined building typology [22,23]. It has been noticed that in many cases, energy improvement of existing buildings often included partial interventions on the façade that were made individually by the tenants, which refers to the first place window replacement. The original, usually wooden window is usually replaced by a PVC window as a measure of improving the sealing of the building envelope, while in exceptional cases it was replaced by a higher performance - wood-aluminium window. Having this in mind, in the first step of the investigation, three types of windows were selected for the test:

- Wooden windows (since different types of wooden windows have been found as the original window solution on most of the buildings),
- PVC windows (as cheaper and common energy renovation solution) and
- Wood aluminium windows (as more expensive but more energy-efficient renovation solutions).

4.1. Methodology

The windows have been measured in 5 different buildings.

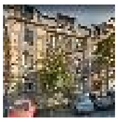
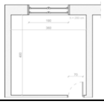
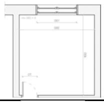
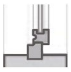
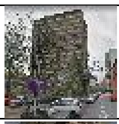
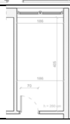
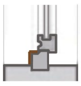
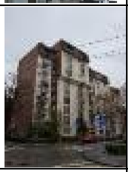
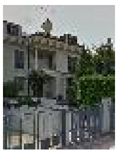
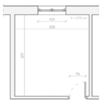
The original, wooden window was measured on a building from the construction period 1919-1945, the PVC window was measured on two different buildings dating from 1961-70, and wood aluminium window has been measured on two buildings, one from the period 1981-90 and one from the following period, 1991-2012.

First, the infiltration rate has been assumed (IR (a)) based on current regulations in Serbia [11] and then based on measured values (n50) the infiltration rate of the windows have been defined (IR(m)) based on the current standard - the correlation factor N has been adopted N=20 based on the current standard in the Republic of Serbia. The results are demonstrated in Table 5. Measurements have been done in six individual rooms, with Blower Door Minneapolis DG700 device, during December 2019 and January 2020. Buildings did not have any additional openings (such as shutters, ventilation, and air conditioning openings) and all windows and doors have been closed providing the preconditions for pressure tests. All measurements have been done according to standard SRPS EN 13879 [12] in optimal conditions (optimal wind, adequate temperature difference, and normal atmospheric pressure). The value of the measured infiltration rate that has been taken into further calculation is a middle value that the device detected during the measuring process @50Pa. So far, this research has been done on a small sample of buildings, therefore, for more precise conclusions the more detailed research should be performed.

4.2. Case study

Based on the National typology of residential buildings in Serbia it is noted that the majority of the buildings have originally installed wooden windows. The rooms with the wooden window have been measured on a building built in period 1919-1945. This building has a wooden window (double frame, double sash (wide box) with single glazing windows) and facade walls without insulation. On both chosen rooms windows were original, maintained by owners only by painting. Chosen rooms are on the ground floor, the building facade is west oriented, sheltered building position. During the diagnostics and measurement, the window in the room one was found to be in slightly worse condition than the window in room two, with few visible damages on the window, and some paint missing. Because of windows' quality and age, they were assumed to have a high infiltration rate.

Table 7. *Results of performed blower door tests*

Window type			Building		room				position and exposure of the room			IR (a)	n50	IR (m)
									orientation	floor	exposure			
wooden	 Wooden, double framed with a single glass	original	1919-1945		room 1		Area	14.40m2	west	ground	sheltered	high	5.70	high
							Volume	40.32m3						
							Window area	2.85m2						
					room 2		Area	14.40m2	west	ground	sheltered		4.8	median (to high)
							Volume	40.32m3						
							Window area	2.85m2						
PVC	 PVC, double low-E glass unit, inert gas filling	replaced	1961-70		room 1		Area	7.53m2	west	6th	open	low	1.85	low (to median)
							Volume	19.6m3						
							Window area	2.25m2						
		replaced			room 2		Area	19,60m2	north	3rd	sheltered		2.21	median
							Volume	49m3						
							Window area	3,08m2						
wood-aluminium	 Wood aluminium, double glazed low-E glass unit, inert gas filling	replaced	1981-1990		room 1		Area	14,39m2	west	4th	open	low	1.95	low (to median)
							Volume	36,69m3						
							Window area	2,93m2						
		original	1991-2012		room 2		Area	12.2m2	north	1st	sheltered		0.53	low
							Volume	33.4m3						
							Window area	2.59m2						

The rooms with PVC windows have been measured in two different structures built between 1961 and 70. In these buildings, in the last 10 years period, some of the occupants replaced the original windows and installed PVC windows as a measure of energy renovation. The buildings originally had wooden windows and facade walls without insulation. Measurement has been conducted on two rooms, having PVC windows (double low-E glass unit, inert gas filling) that replaced original ones, with no noticeable anomalies regarding window quality and quality of the installation. These windows have been assumed to have a low infiltration rate. Room 1 is on the 6th floor, the building facade is west oriented with open building position, and room 2 is on the 3rd floor, north-oriented facade on building with the sheltered position.

The room with aluminum-wood window was considered on two buildings - one from the construction period 1981-1990 where it was installed after energy rehabilitation, and another on the building built after 1991-2012, where it was originally installed. Both buildings have an insulated external wall. Chosen rooms both have wood aluminum windows (double glazed low-E glass unit, inert gas filling) with no noticeable anomalies regarding window quality and quality of installation, and are assumed to have low infiltration rate. Room 1 is on the 4th floor, the building facade is west oriented with open building position, room 2 is on the 1st floor, facade north-oriented, and sheltered position.

4.3. Results and discussion

The results of the measurement showed disagreements between the predicted and measured results. (Table 7) All of the measured values satisfy minimal requirements defined in the current regulations, some measured values vary slightly from predicted results, indicating potential problems, but for a more accurate investigation, further research should be performed. In the case of a wooden window, due to the age and quality of the window, it was expected for a window to have a high infiltration rate. Measured values did show high infiltration rate, but demonstrated that the quality of the window could significantly affect its performance – the value for room two was high, but almost at the border with the median value of the infiltration rate. PVC windows, as a measure of energy improvement, are considered a solution with a low infiltration rate. The measurement showed that the window in room 1 falls into the predicted category, at the border with the median infiltration rate, while the window in room 2 has worse performance than the predicted ones. Such results may have to do with the quality of the window mounting, but to determine this additional diagnostic is required. Wood aluminium windows, as a more energy-efficient solution, are assumed to perform a low infiltration rate. This assumption has been confirmed by performed measurements. A difference in the infiltration measured has been demonstrated – in room one where the window was installed afterwards as a measure of energy renovation the infiltration rate measured was closer to the median. This result may indicate the poor quality of installation of the opening during the renovation process, but this prediction should be confirmed by other diagnostic methods.

This research pointed out the loosely defined regulations in Serbia, not able to precisely define the infiltration rate and leaving room for mistakes. To prove this further, it is necessary to perform measurements on a much larger sample of objects in combination with additional diagnostic methods

5. CONCLUSION

Although the infiltration is recognized as one of the most important aspects when considering both energy consumption and indoor air quality in buildings, it is noted that there is no uniform methodology for testing infiltration. Case studies presented in the literature, show large variations in the duration of the measuring time, different periods of the year in which the measurement is performed, data processed, etc. However, regulations in Serbia that consider infiltration issues are not sufficiently precise in defining the calculation methods and quite roughly define values leaving a lot of space for assumptions. It is noted that in the Republic of Serbia, it is not obligatory to measure the airtightness of the building envelope - the infiltration rate of the building is based on an expert assessment. Preliminary measurements of airtightness of Belgrade housing stock with pressurization tests demonstrated a certain difference between assumed and measured values of infiltration rate in buildings, indicating potential problems regarding the evaluation of infiltration in practice. It is concluded that for more precise analysis, pressurization tests should be combined with another verification method that diagnostics the location of leaky points on the building. Consideration should also be given to introducing mandatory measurement of infiltration in buildings in Serbian regulations since this parameter is of great importance for energy consumption and both indoor air and environmental quality.

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