



Eglė JARAMINIENĖ

**INVESTIGATION OF AIR INFILTRATION
IN BUILDINGS USING UNCERTAINTY
ANALYSIS**

**Summary of Doctoral Dissertation
Technological Sciences,
Energetics and Power Engineering (06T)**

1541-M

Vilnius  **2008**
LITHUANIA
TECHNIKA

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

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Doctoral dissertation was prepared at Vilnius Gediminas Technical University in 2003–2008.

Scientific Supervisor

Prof Dr Egidijus Saulius JUODIS (Vilnius Gediminas Technical University, Technological Sciences, Energetics and Power Engineering – 06T).

The dissertation is being defended at the Council of Scientific Field of Energetics and Power Engineering at Vilnius Gediminas Technical University:

Chairman

Prof Dr Habil Vytautas MARTINAITIS (Vilnius Gediminas Technical University, Technological Sciences, Energetics and Power Engineering – 06T).

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Prof Dr Habil Rimantas KAČIANAUSKAS (Vilnius Gediminas Technical University, Technological Sciences, Energetics and Power Engineering – 06T),

Assoc Prof Dr Artur ROGOŽA (Vilnius Gediminas Technical University, Technological Sciences, Energetics and Power Engineering – 06T).

Opponents:

Assoc Prof Dr Kęstutis ČIUPRINSKAS (Vilnius Gediminas Technical University, Technological Sciences, Energetics and Power Engineering – 06T),

Prof Dr Habil Vytautas STANKEVIČIUS (Kaunas University of Technology, Technological Sciences, Civil Engineering – 02T).

The dissertation will be defended at the public meeting of the Council of Scientific Field of Energetics and Power Engineering in the Senate Hall of Vilnius Gediminas Technical University at 2 p. m. on 17 November 2008.

Address: Saulėtekio al. 11, LT-10223 Vilnius, Lithuania.

Tel.: +370 5 274 4952, +370 5 274 4956; fax +370 5 270 0112;

e-mail: doktor@adm.vgtu.lt

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VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

Eglė JARAMINIENĖ

**ORO INFILTRACIJOS PASTATUOSE TYRIMAS
TAIKANT NEAPIBRĖŽTIES ANALIZĘ**

Daktaro disertacijos santrauka
Technologijos mokslai,
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Disertacija ginama Vilniaus Gedimino technikos universiteto Energetikos ir termoinžinerijos mokslo krypties taryboje:

Pirmininkas

prof. habil. dr. Vytautas MARTINAITIS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, energetika ir termoinžinerija – 06T).

Nariai:

dr. Robertas ALZBUTAS (Lietuvos energetikos institutas, technologijos mokslai, energetika ir termoinžinerija – 06T),

prof. habil. dr. Benediktas ČESNA (Lietuvos energetikos institutas, technologijos mokslai, energetika ir termoinžinerija – 06T),

prof. habil. dr. Rimantas KAČIANAUSKAS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, energetika ir termoinžinerija – 06T),

doc. dr. Artur ROGOŽA (Vilniaus Gedimino technikos universitetas, technologijos mokslai, energetika ir termoinžinerija – 06T).

Oponentai:

doc. dr. Kęstutis ČIUPRINSKAS (Vilniaus Gedimino technikos universitetas, technologijos mokslai, energetika ir termoinžinerija – 06T),

prof. habil. dr. Vytautas STANKEVIČIUS (Kauno technologijos universitetas, technologijos mokslai, statybos inžinerija – 02T).

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Adresas: Saulėtekio al. 11, LT-10223 Vilnius, Lietuva.

Tel.: (8 5) 274 4952, (8 5) 274 4956; faksas (8 5) 270 0112;

el. paštas doktor@adm.vgtu.lt

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General characteristic of the dissertation

Research problem. Evaluation of the infiltration on the basis of the building thermal balance is limited by the uncertainty of the result. The sensitivity analysis of the method uncertainty is performed in the thesis, defining suitable building characteristics and measurement conditions.

Relevance of the problem. Energy consumption in building sector accounts for approx. 40% of all energy use in European Union, thus it offers a significant potential for improving energy efficiency. Energy demand for space heating can be reduced by insulating envelope or improving air tightness. Till now most of the attention was paid to the envelope insulation; but when the existing requirements are met, infiltration heat losses are often as high as the envelope heat losses. Therefore the importance of air infiltration assessment methods increases. Several approaches to evaluate infiltration in existing buildings are recently used: methods, based on the field measurements, and methods that do not use measurement data. Common methods, based on measurements, evaluate air infiltration rate in a building with 14%–25% uncertainty. But these field measurements are expensive, technically complex and therefore rarely performed. Methods that are not based on measured data result in large and difficult to evaluate uncertainty. In addition, air infiltration depends not only on building air tightness, but also on outdoor conditions and building exploitation, and this leads to higher uncertainty when estimating actual infiltration after measuring only once. Thus, a new air infiltration assessment method is required – it should be less expensive than existing measurement based methods and more accurate than existing methods that are not based on field measurements.

Evaluation of the infiltration on the basis of the building thermal balance without measured data of the microclimate parameters is vastly inaccurate. However contemporary buildings are more and more often equipped with modern building microclimate control systems allowing to accumulate large quantity of measurement data.

Research object is an average air change rate due to air infiltration through leaks and openings in building envelope.

Aim and tasks of the work. The work aims to formulate conditions and limitations of applying the thermal balance approach to estimate the rate of air infiltration in buildings.

To reach the aim of the work these tasks are set:

1. Survey the application range, limitations and uncertainty of the existing methods to evaluate air infiltration.
2. Research the potential of forming the thermal balance by using measurement data, stored in building automation and control systems (BACS).
3. Formulate the algorithm and prepare a computer model of the thermal balance approach with integrated uncertainty analysis for evaluating air infiltration and its uncertainty.
4. Create a computer model for simulating building thermal performance. With the help of the model, determine conditions and limitations of applying the thermal balance approach to estimate air infiltration rate in buildings.
5. Describe the proper outdoor conditions for using the thermal balance method in calculation of air infiltration rate.
6. Define the limits for the uncertainty of the calculation based terms in the thermal balance when this method is used for estimating infiltration.

Scientific novelty. The thermal balance approach for assessing infiltration heat losses in buildings was already addressed, but the integration of the BACS data, statistical methods and the uncertainty analysis were proposed for the first time. The algorithm of the method was formulated; conditions and limitations of applying the method were defined.

Methodology of research. The feasibility to evaluate air infiltration in buildings by using the thermal balance approach is investigated in the dissertation. The uncertainty of the method is evaluated by using sensitivity analysis, error propagation rules and Monte Carlo method. Measurement data are analysed by the methods of statistical data analysis. By the means of MS Excel, Visual Basic for Applications and add-on Poptools two computer models were created. The first model is applied for estimating air infiltration rate in buildings by using thermal balance approach. The second model is created for performing building thermal simulation in order to generate the data required for the sensitivity analysis.

Practical value. The proposed method requires relatively low expenditure and results in sufficient accuracy of evaluated actual air infiltration rate in existing buildings. This knowledge of air infiltration intensity in exploitation conditions contributes to profound assessment of economical effect of building air tightening and helps to optimize the operation of microclimate conditioning systems.

Defended propositions

1. Average air infiltration rate in building exploitation conditions can be evaluated by constructing thermal balance of the building. The use of such a method till now was limited by the scarcity of the real building performance data and the resulting uncertainty of the method. A large quantity of building performance data, measured and stored in contemporary BACS enables to construct more accurate thermal balance of the building.
2. Measurements performed in the contemporary BACS are accurate enough to estimate infiltration by using the thermal balance approach, the sufficient number of measurement data can be stored without the additional expenditures.
3. The uncertainty of the method proposed can be of comparable value as existing methods, based on measurements. The uncertainty of infiltration rate evaluation and thus the limitations of the method proposed are determined by the characteristics of the building.
4. The uncertainty of the results is sensitive to the evaluation of heat gains from the internal sources, thus the infiltration could be estimated by using the thermal balance, when the heat gains amount to an insignificant share in the certain thermal balance or could be defined accurate enough.

The scope of the scientific work. The scientific work consists of the general characteristic of the dissertation, 5 chapters, conclusions, list of literature, list of publications and addenda. The total scope of the dissertation – 131 pages, 41 pictures, 44 tables and 141 references.

1. Air infiltration in buildings and methods of infiltration assessment

Air infiltration in buildings is defined as an uncontrollable air movement through openings and leaks in a building envelope. There are some methods widely used for evaluation of infiltration in the existing buildings. Common practise is to evaluate heat losses due infiltration assuming average air change rate in dependence on the type of the particular building. The analysis has shown that infiltration heat losses evaluation achieved through assuming tabled average air change rates causes significant uncertainty. More reliable is infiltration estimation based on the airtightness, tested using pressurization methods; – uncertainty of the estimation varies from 15% to 25%. Direct infiltration rate measurements can be performed using trace gas methods. These

methods allow achieving accuracy of the 14% in the best cases. Thus the application of the existing methods is not feasible in every situation because of their technical complexity, large expenditure requirements or uncertainty of the result.

2. Uncertainty and uncertainty evaluation methods

Uncertainty is the estimated amount or percentage by which the observed or calculated value may differ from the true value. The uncertainty in the thesis is expressed in two ways: as absolute uncertainty and relative uncertainty. The uncertainty is a value of standard deviation multiplied by two and presented in absolute terms. The relative uncertainty is the uncertainty divided by the mean value of the parameter and expressed in percents.

3. Automatic control systems of buildings microclimate

Contemporary buildings, especially large public buildings, are often equipped with building automation and control system (BACS), where parameters of climate and indoor microclimate, heating, ventilation, air conditioning (HVAC) systems are measured and stored. The data of BACS is increasingly used in fault detection, consumption of energy analysis and energy use control, but BACS data use capabilities still remains largely unexploited.

4. Assessment of air infiltration rate based on the thermal balance of a building

The main point of the idea to use building thermal balance to estimate air change rate is that the difference of known components of building thermal balance often could be attributed to heat losses due uncontrolled air flow. The average air infiltration rate could be evaluated from equation:

$$n = \frac{Q_{\text{inf}}}{c \cdot \rho \cdot V \cdot \Delta\theta \cdot z \cdot 10^6}, \quad (1)$$

where Q_{inf} – monthly heat demand due to air infiltration (MWh), c – air specific heat value ((Wh/(kg·K)), ρ – air density, 1.2 (kg/m³), V – volume of the building (m³), $\Delta\theta$ – temperature difference between indoor and outdoor air (°C), z – number of hours (h).

The infiltration heat amount can be evaluated from the building thermal balance that is expressed in the following form:

$$Q_{inf} = Q_v + Q_{ig} + Q_{sg} + Q_{hs} + Q_{env} , \quad (2)$$

where Q_v – heat amount supplied by ventilation systems (MWh), Q_{ig} – heat gain from internal heat sources (MWh), Q_{sg} – solar heat gains (MWh), Q_{hs} – heat amount supplied by heating systems (MWh), Q_{env} – heat demand due to heat losses through the building envelope and thermal bridges (MWh).

The thermal balance scheme is shown in Figure 1. Dotted line marks the limits of the analysed system.

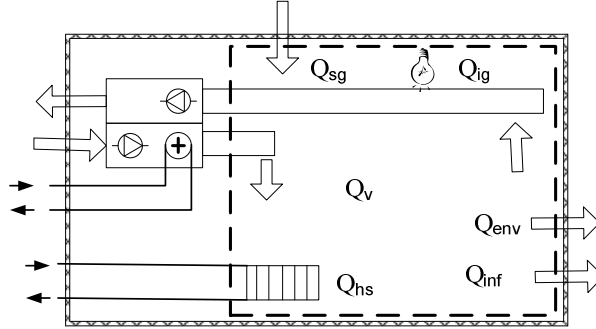


Fig 1. Scheme of the thermal balance

Contemporary buildings are often equipped with building automation and control systems (BACS) that control building operations as needed over time. It is designed to meet the communication needs of BACS for various applications such as control of heating, ventilating, air-conditioning, lighting, access and fire detection systems in addition to their associated equipment. A large quantity of building performance data is measured and stored in BACS, enabling construction of the thermal balance of the building. If the main components of the thermal balance are based on the measurement data, the actual infiltration rate under the building exploitation conditions can be estimated. The main approach is to use measured data when it is possible. In Figure 2 the scheme of BACS with parameters that require measuring is presented.

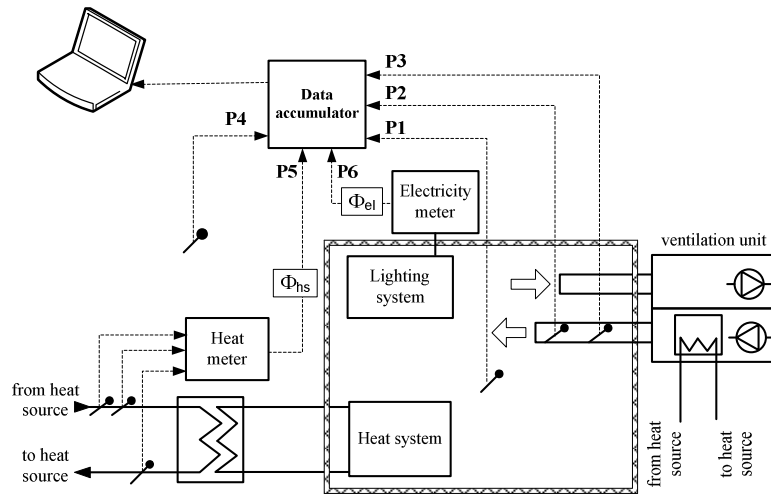


Fig 2. Scheme of BACS (P1 – indoor temperature, P2 – ventilation supply air temperature, P3 – ventilation air flow, P4 – outdoor temperature, P5 – heat consumption of the heating system, P6 – electricity consumption)

The algorithm of the thermal balance approach for evaluating air infiltration could be expressed as follows:

1. The thermal balance of the building is described by equations depending on particularity of the building and its microclimate conditioning systems.
2. Based on the equations the model of the thermal balance is prepared.
3. The required input parameters are defined. The parameters that can be measured and stored by the BACS are identified.
4. The specific heat loss value through envelope and thermal bridges in addition to its uncertainty are calculated using the computer model based on Monte Carlo approach.
5. The analysis of the measurement data is processed by using statistical methods.
6. The missing input parameters and their uncertainties are defined on the basis of expertise, literature survey or other methods.

The presented algorithm is very general, because the thermal balance of every particular building is very specific.

Based on this algorithm computer model for the particular case was created. The scheme of this computer model is presented in Figure 3.

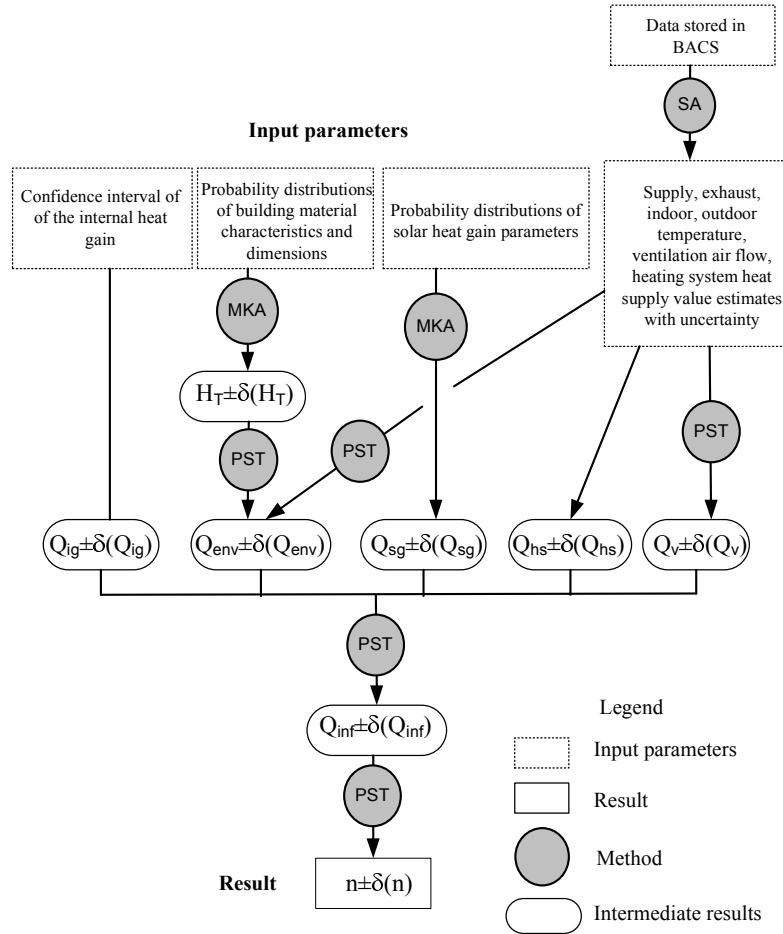


Fig 3. Scheme of the created computer model for infiltration assessment by using the building thermal balance (MKA – Monte Carlo analysis, SA – statistical analysis, PST – error propagation)

The computer model consists of two stages. At first, the estimates with uncertainty for every component of the thermal balance are evaluated. Using all available information the types and parameters are attributed to the probability distributions of the not measured input parameters (internal heat gains, building dimensions, envelope thermal properties and other; over all more than 20

parameters). Specific heat losses and solar gains are evaluated employing Monte Carlo approach, where input parameters are given as probability distributions. Heat supplied with heating, ventilation and air-conditioning (HVAC) systems is estimated using statistical analysis of the measured data stored in BACS. When all the estimates of the thermal balance components are made, air infiltration rate can be evaluated. At this stage evaluation of the uncertainty is based on the rules of error propagation.

The model was verified by comparing its output with the real measurement data. In order to perform this comparison, the model was slightly modified to give a specific heat demand value instead of an infiltration rate as an output.

The created computer model was applied to investigate a real building – the shopping centre of 6,500 m² area. The actual data stored in BACS were used. The research showed a shortage of the information required to estimate the internal heat gain, and this caused the inappropriate uncertainty in the case.

The same computer model was used to carry out sensitivity analysis as described below.

6. Sensitivity analysis of infiltration evaluation uncertainty

6.1. Sensitivity analysis simulating the thermal balance

The limits of the method application are defined by the uncertainty of the model output. When the evaluation based on the thermal balance is performed, the uncertainty of the average air infiltration rate depends on the measurement accuracy and frequency, building characteristics, and outdoor conditions. The sensitivity analysis helps to examine the influence of the mentioned factors on the resulting uncertainty of the evaluation and, thus, to define the possibilities, limits and conditions of the proposed method to evaluate air infiltration.

For the purpose of the analysis the simulated data were used. There are some models for building thermal simulation and they could provide the process with the building performance data, but none of these models enable determination of the input data with their uncertainty. Thus in order to calculate the uncertainty of the measured components in the thermal balance, the computer model with MS Excel was created. The simulation of the building thermal performance parameters is based on the balance of heat flows as they are defined in the building standards. The simulation is performed on hourly basis. The pseudorandom number generation and Monte Carlo approach were used to simulate the variation and the uncertainty of the parameter values and the inaccuracy of the measurements.

Several cases of the typical buildings were chosen for performing the sensitivity analysis. The case IND corresponds to an individual detached house. The cases PC1 and PC2 correspond to shopping centres of different building volume. The shopping centres are chosen as objects for analysis because they amount to a large share in building sector, they are often equipped with BACS, and they have a specific heat balance. The cases SAND1–SAND4 correspond to industrial or storage buildings. This group of buildings can be characterized by large variations in insulation of building envelope, air tightness, and internal heat gain. The scheme of the performed sensitivity analysis is presented in Figure 4.

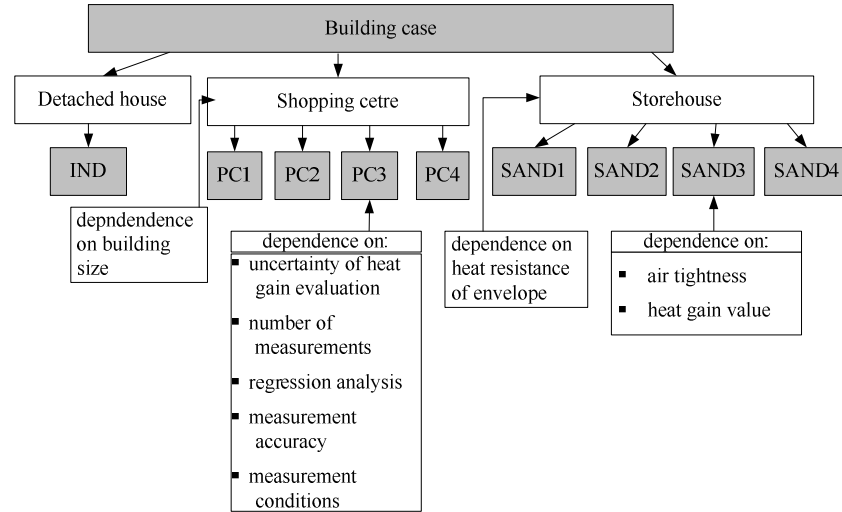


Fig 4. Scheme of the building cases in sensitivity analysis

As illustrated in Figure 4, each group of the cases requires a different type of the sensitivity analysis. By the example of the individual house (the case IND) the uncertainty of the infiltration assessment in small buildings is determined, when such buildings are not equipped with BACS and the only measured parameter is the heat consumed in their heating systems.

The cases PC1 and PC2 intend to show the relation between the uncertainty of the infiltration assessment and the size of the building. When appropriate building size is found, the sensitivity to the number of measurements and their accuracy is evaluated. The cases SAND1–SAND4 are designed to investigate the influence of insulation level on the uncertainty of

infiltration assessment. Finally, the effect of air tightness and heat gain intensity on the results is analysed.

6.2. Dependence of uncertainty on building characteristics

The analysis of the individual house (the case IND) showed that the thermal balance, when all estimates are based on design values, is not appropriate for evaluating infiltration. All the other analysed cases include the measured data, stored in BACS.

The analysis of the shopping centres (the cases PC1–PC4) demonstrated the dependence of determined uncertainty on building size (Table 1).

Table 1. Determined dependence of uncertainty on building size

Case	PC1	PC2	PC3	PC4
Building volume, m ³	100	1000	10000	20000
Estimation of the mean value of infiltration, h ⁻¹	0.24	0.16	0.17	0.17
Uncertainty, h ⁻¹	0.18	0.07	0.03	0.03
Relative uncertainty, %	73	46	20	19

The uncertainty of assessing infiltration does not exceed 20% only in the cases of large buildings – larger than 10000 m³ as analysed.

Table 2. Estimated dependence of uncertainty on building thermal insulation

Case	SAND1	SAND2	SAND3	SAND4
Specific heat loss through envelope, W/K	3882	6089	8100	15084
Estimation of the mean value of infiltration, h ⁻¹	0.16	0.16	0.16	0.16
Uncertainty, h ⁻¹	0.03	0.03	0.03	0.03
Relative uncertainty, %	18	18	19	22

As shown in Table 2, the uncertainty of the infiltration assessment is insensitive to the level of building thermal insulation. The relative uncertainty depends significantly on the air tightness of the building.

6.3. Dependence of uncertainty on the number of measurements and their accuracy

Table 3 presents how the uncertainty of the average infiltration value depends on the number of measurements.

Table 3. Dependence of the uncertainty of the average infiltration value on the number of measurements (the case PC3)

Number of measurements	56	224	672	2688
Measurement period	12 hour	3 hour	1 hour	15 minutes
Uncertainty of the measured ventilation term, %	39.8	19.9	11.3	5.6
Uncertainty of the average infiltration value, %	26.5	19.5	18.2	17.5

As seen in Table 4, the output uncertainty depends highly on the number of measurements in cases when this number is small, that is below 100. In the analysed case more than 200 measurements were required in order not to exceed the uncertainty of 20%. This number of measurements corresponds to measuring frequency of every three hours in a period of one month.

The accuracy of the temperature measurement was varied from 1.0 °C to 0.02 °C, the accuracy of the air flow measurement was changed from 5% to 20% of the value. As it was found, the uncertainty of the result is almost insensible to the accuracy of these measurements, if it is caused by random error only, but not system error.

6.4. Dependence of uncertainty on the outdoor conditions

The analysis was performed assuming the values of wind speed and outdoor temperature that are typical of the heating season in Lithuania. The research revealed that the method is insensitive to the fluctuations of wind speed or outdoor temperature during the analysed period. The average wind speed has no significant impact too. Differences in average outdoor temperature during the analysed period could cause different results, but such an analysis was not performed in the thesis due to its large scope. Thus the results of the research are applicable when the average outdoor temperature is bellow 0.2 °C.

7. General conclusions

1. The literature survey and the analysis performed in the work demonstrate a need for new methods to estimate infiltration. The existing theoretical approach results in great uncertainty and the methods, based on measurements, are expensive and technically complex, especially in buildings of large volume. The uncertainty of the existing methods, which are based on measurements, reaches from 14 to 25 percent.

2. Based on the survey of the possibilities of building microclimate control systems, that are more and more common in contemporary buildings, it can be concluded that data stored in such systems are sufficient to construct thermal balance. If the thermal balance of a building is based on measurement data, the actual average infiltration rate under building exploitation conditions could be estimated.

3. The algorithm and the computer model for assessing average air infiltration by using the thermal balance of buildings were proposed for the first time. The uncertainty analysis was integrated in the model.

4. The uncertainty analysis was performed for several typical buildings using the developed computer model with integrated stochastic approach for thermal balance simulation. The performed analysis showed that measurements made by automation systems in contemporary buildings are accurate enough (air temperature – 0,2 K, air volume – 5% of the measured value, heat flow – 3% of the measured value). The sufficient frequency of measurements is every three hours in the period of one month (approx. 200 measurements). The period for analysis is recommended to be at least one month, as this ensures the elimination of daily and weekly variations of heat gains which cause a large uncertainty.

5. On the basis of the performed sensitivity analysis it can be stated that the infiltration could be evaluated from the thermal balance by using data, stored in automation and control systems of buildings, when the volume of these buildings is larger than 100 thousand m³ and the air tightness is less than 1.2 h⁻¹ (at a pressure difference of 50 Pa). The determined uncertainty of assessing infiltration is lower in buildings with better envelope thermal insulation, but this factor has insignificant impact on evaluated uncertainty of the assessment when the building meets the above mentioned criteria of area and air tightness.

6. The analysis was performed assuming the typical values of wind speed and outdoor temperature during the heating season in Lithuania. The research revealed that the method is insensitive to the fluctuations of wind speed during the analysed period, the influence does not exceed 1% of the uncertainty value.

The results of the analysis are applicable when the average outdoor temperature is below 0.2 °C.

7. As the uncertainty of the results is sensitive to the evaluation of heat gains from the internal sources, the infiltration could be estimated by using the thermal balance, when the heat gains amount to an insignificant share in the certain thermal balance or could be defined accurate enough. In order to assess the rate of infiltration air change with the uncertainty of 20%, when the mean value is equal to 0.15 h^{-1} , the absolute uncertainty of the heat gains must not exceed $147 \text{ Wh/m}^3/\text{month}$ at the average monthly temperature difference between outdoor and indoor air of 20 °C; and correspondingly $220 \text{ Wh/m}^3/\text{month}$ at the temperature difference of 30 °C.

List of published works on the topic of the dissertation

In the reviewed scientific periodical publications

1. Jaraminienė, E.; Juodis, E. 2008. Uncertainty analysis of infiltration assessment based on thermal balance of the building, *Energetika*, 54(2): 20–25 (in Lithuanian). ISSN 0235-7208 (INSPEC).
2. Jaraminienė, E.; Juodis, E. 2006. Heat demand uncertainty evaluation of typical multi-flat panel building, *Journal of Civil Engineering and Management*, 12(1): 69–75. ISSN 1392-3730 (INSPEC).

In the other editions

3. Jaraminienė, E.; Juodis, E. 2008. The discrepancy between design heat demand and actual heat consumption due to air infiltration, in *Proceedings of the 7-th International Conference “Environmental Engineering”, held in Vilnius on 22–23 May, 2008*. Vilnius: Technika, 804–811. ISBN 9986-05-771-X (Thompson ISI Proceedings).
4. Sribikytė E., Juodis E. 2004. Uncertainty of heat demand in apartment buildings, in *Proceedings of the 6-th International Conference “Energy for Buildings”, held in Vilnius on 7–8 October, 2004*. Vilnius: Technika, 367–374. ISBN 9986-05-771-X (Thompson ISI Proceedings).
5. Jaraminienė, E.; Juodis, E. 2008. Uncertainty analysis of infiltration evaluation from building thermal balance, in *Proceedings of the Conference of Young Scientists on Energy Issues 2008, held in Kaunas on 29 May, 2008*. Kaunas, CD: IV-26–IV-35. ISSN 1822-7554.
6. Jaraminienė, E.; Juodis, E. 2007. Feasibility of air infiltration evaluation on the base of building thermal Balance, in *Proceedings of the International*

Congress “E-nova 2007: Intelligent Energy Systems”, held in Pinkafeld on 9–11 November, 2007. Oberwart: Schmidbauer GmbH, 53–57. ISBN 978-3-9500919-7-7.

7. Jaraminienė, E. 2007. Analysis of the thermal balance based on building automation and control system data, in *Proceedings of the National Conference “Innovative Building”, held in Kaunas on 26–27 October, 2007*. Kaunas: Technologija, 178–82 (in Lithuanian). ISBN 978-9955-25-381-5.
8. Sribikytė E., Juodis E. 2004. Uncertainty of heat loss through envelope calculation, in *Proceedings of the National Conference “Building service systems”, held in Vilnius on 23 January*. Vilnius: Technika, 5–8 (in Lithuanian). ISBN 9986-05-605-5.

About the author

Eglė Jaraminienė was born in Vilnius, on June 23, 1974.

First degree in Power Engineering, Faculty of Environmental Engineering, Vilnius Gediminas Technical University, 2001. Master of Science in Energy Planning, Faculty of Environmental Engineering, Vilnius Gediminas Technical University, 2003. In 2003–2008 – PhD student of Vilnius Gediminas Technical University in the field of Technological Science in a branch of Energetics and Power Engineering. At present – assistant in Heating and Ventilation Department of Vilnius Gediminas Technical University.

ORO INFILTRACIJOS PASTATUOSE TYRIMAS TAIKANT NEAPIBRĖŽTIES ANALIZĘ

Mokslo problemos aktualumas. Daugelyje šalių pastatuose suvartojama bent 40 proc. visos suvartojamos energijos, todėl čia egzistuoja didelis energijos vartojimo efektyvumo didinimo potencialas. Energijos poreikį pastatų mikroklimato palaikymui galima sumažinti gerinant atitvarų šilumines savybes ir didinant pastatų sandarumą. Iki šiol daugiausia dėmesio buvo skiriama atitvarų šiltinimui, tačiau griežtėjant reikalavimams dėl pastatų išorinių atitvarų šiltinimo, santykinai didėja šilumos nuostoliai dėl nekontroliuojamos oro kaitos. Esant dabartiniams pastatų atitvarų šiltinimo ir sandarumo reikalavimams, šilumos nuostoliai dėl infiltracijos sudaro iki 50 proc. visų pastato šilumos nuostolių. Todėl pastatų sandarumo ir infiltracijos vertinimo metodai tampa vis aktualesni. Šiuo metu, priklausomai nuo pastato gyvavimo ciklo etapo ir tyrimo tikslo, taikoma keli pastatų sandarumo ir infiltracijos vertinimo metodai: projektuojant pastatus infiltracija prognozuojama pagal analogiškų pastatų statistinius duomenis arba modeliuojama kompiuterinėmis programomis, esamų pastatų sandarumas tiriamas atliekant natūrinius matavimus. Tačiau statistinių duomenų naudojimas ir modeliavimas lemia didelę gaunamų rezultatų neapibrėžtį, o natūriniai sandarumo matavimai dėl savo techninio sudėtingumo ir didelės kainos atliekami gana retai. Visa tai lemia poreikį tokių oro infiltracijos pastatuose vertinimo metodų, kurie būtų tikslesni už skaičiavimą ar modeliavimą, neparemtą faktiniais matavimais, ir pigesni už matavimais paremtus.

Infiltracijos vertinimas pagal pastato šilumos kiekių balansą neturint mikroklimato parametrų matavimo duomenų yra labai netikslus. Tačiau šiuolaikiniuose pastatuose vis plačiau taikomos pastatų automatizuoto valdymo sistemos, vis didesnis šiose sistemose atliekamų matavimų tikslumas, pigesnė duomenų registravimo ir saugojimo įranga, vis didesnės duomenų analizės galimybės sudaro prielaidas sukaupti tikslesniam vertinimui reikalingą matavimo duomenų kiekį.

Tiriamoji problema. Oro infiltracijos intensyvumo nustatymo galimybės pagal pastato šilumos kiekių balansą yra ribojamos gaunamo rezultato neapibrėžties. Šiame darbe tiriamas neapibrėžties jautrumas matavimo sąlygoms ir pastato charakteristikoms, tokių būdu nustatant metodo taikymui tinkamas jų vertes.

Tyrimų objektas – vidutinė oro kaita per pasirinktąjį laikotarpį dėl oro infiltracijos per pastato atitvarų nesandarumus ir angas.

Darbo tikslas – suformuluoti oro infiltracijos įvertinimo pagal pastato šilumos kiekių balansą algoritmą, nustatyti šio vertinimo galimybes, apribojimus ir sąlygas.

Darbo uždaviniai

1. Apžvelgti dabar naudojamų metodų taikymo sritis, apribojimus ir šiais metodais gaunamų rezultatų neapibrėžtį.
2. Įvertinti galimybes šilumos kiekių balanso sudarymui panaudoti matavimų duomenis, kaupiamus pastatų automatizuoto valdymo sistemose, nustatyti infiltracijai vertinti pagal šilumos kiekių balansą reikalingų matavimų tikslumą ir dažnį.
3. Sudaryti oro infiltracijos nustatymo pagal pastato šilumos kiekių balansą algoritmą ir kompiuterinį modelį bei įvertinti realaus pastato infiltraciją pagal faktinius matavimų duomenis.
4. Parengti pastato šilumos kiekių balanso imitacinį kompiuterinį modelį ir naudojantis šiuo modeliu nustatyti pastatų savybes, ribojančias infiltracijos vertinimą pagal šilumos kiekių balansą.
5. Nustatyti infiltracijai vertinti pagal šilumos kiekių balansą tinkamas aplinkos sąlygas.
6. Nustatyti infiltracijai vertinti pagal šilumos kiekių balansą reikalingų skaičiavimais vertinamų šilumos kiekių balanso dedamųjų vertinimo neapibrėžties apribojimus.

Mokslinis naujumas. Šiame darbe pirmą kartą neapibrėžties analizės pagrindu nustatytos oro kaitos dėl infiltracijos vertinimo pagal pastato šilumos kiekių balansą galimybės, sąlygos ir ribos.

Tyrimų metodika. Darbe tiriamos oro kaitos dėl infiltracijos nustatymo pagal pastato šilumos kiekių balansą galimybės. Neapibrėžties tyrimui darbe naudoti jautrumo analizės ir Monte Karlo metodai. Statistinių duomenų, kaupiamų PAVS, apdorojimui naudojami statistinės duomenų analizės metodai.

MS Excel, Visual Basic for Applications ir įskiepio Poptools priemonėmis atliekamas kompiuterinis pastato šiluminių reiškinių modeliavimas, integruojant neapibrėžties analizę.

Praktinė vertė. Šiame darbe analizuojamas metodas, kuris leidžia mažomis sąnaudomis, bet pakankamu tikslumu įvertinti faktinę oro kaitą dėl infiltracijos esamuose pastatuose. Oro kaitos dėl infiltracijos įvertinimas eksploatacijoje

metu leidžia nustatyti pastato sandarinimo ekonominį efektą, optimizuoti pastato mikroklimato kondicionavimo sistemų valdymą.

Ginamieji teiginiai

1. Vidutinę oro kaitą dėl infiltracijos pastato eksploatacijos sąlygomis galima įvertinti sudarant pastato šilumos kiekių balansą. Tokio infiltracijos nustatymo metodą iki šiol riboja faktinių duomenų stoka ir dėl to susidaranti didelė tokio vertinimo neapibrėžtis. Vis dažniau šiuolaikiniuose pastatuose įrengiant pastato automatizuoto valdymo sistemas, atsirado galimybė sukaupti didelį kiekį duomenų, leidžiančių sudaryti tikslesnį šilumos kiekių balansą.

2. Šiuolaikinių pastato automatizuoto valdymo sistemų atliekamų matavimų tikslumas yra pakankamas infiltracijos vertinimui, sistemose be papildomų investicijų gali būti sukaupiamas pakankamas matavimų skaičius.

3. Siūlomo metodo neapibrėžtis gali būti panašaus dydžio kaip ir esamų, matavimais pagrįstų metodų, neapibrėžtis. Infiltracijos nustatymo pagal šilumos kiekių balansą neapibrėžtį, o tuo pačiu ir šio metodo taikymo apribojimus ir sąlygas lemia pastato charakteristikos.

4. Infiltracijos vertinimo pagal šilumos kiekių balansą rezultatų neapibrėžtis ypač jautri šilumos pritekio vertinimui, todėl metodas gali būti taikomas, kai šilumos pritekis sudaro nežymią šilumos kiekių balanso dalį arba gali būti pakankamai tiksliai įvertinamas.

Darbo apimtis. Disertaciją sudaro įvadas, 5 skyriai, pagrindinės išvados, naudotos literatūros sąrašas. Darbo apimtis – 131 puslapis, kuriuose pateikta 41 paveikslas, 44 lentelės ir 141 literatūros šaltinis.

Bendrosios išvados

1. Informacijos šaltinių apžvalga ir darbe atliktas įprastiniais metodais gaunamų rezultatų neapibrėžties tyrimas rodo naujų metodų poreikį infiltracijai esamuose pastatuose nustatyti. Esamų matavimais pagrįstų infiltracijos vertinimo metodų neapibrėžtis siekia nuo 14 iki 25 proc., tačiau pastato sandarumo ir infiltracijos matavimai yra brangūs ir techniškai sudėtingi, ypač kai jei atliekami dideliuose pastatuose. Matavimais nepagrįstų metodų neapibrėžtis sunkiai įvertinama ir didesnė nei 50 proc.

2. Apžvelgus literatūros šaltinius apie pastato mikroklimato automatizuoto valdymo (PAV) sistemas, vis dažniau įrengiamas šiuolaikiniuose pastatuose, nustatyta, kad šiose sistemose nuolat kaupiamų matavimo duomenų pakanka pastato šilumos kiekių balanso sudarymui. Šilumos kiekių balansą sudarant pagal matavimų duomenis, galima nustatyti vidutinį faktinį infiltracijos intensyvumą pastato eksploatacijos sąlygomis.

3. Darbe pirmą kartą sudarytas oro infiltracijos intensyvumo nustatymo pagal pastato šilumos kiekių balansą algoritmas. Pagal šį algoritmą sukurtas kompiuterinis modelis su integruota neapibrėžties analize, leidžiantis įvertinti vidutinį infiltracijos intensyvumą ir šio vertinimo neapibrėžtį.
4. Darbe parengus kompiuterinį pastato šilumos kiekių balanso modelį, imituojantį stochastinį pastate vykstančių šiluminių reiškinių ir jų parametrų matavimų pobūdį, atlikta jautrumo ir neapibrėžties analizė keletui tipinių pastatų. Remiantis atlikto tyrimo rezultatais galima teigti, kad šiuolaikinių pastato automatizuoto valdymo sistemų atliekamų matavimų tikslumas (oro temperatūros – 0,2 K, oro debito – 5 proc. nuo matuojamos vertės, šilumos kiekio – 3 proc. nuo matuojamos vertės) yra pakankamas infiltracijos vertinimui. Pakankamas matavimų skaičius gaunamas vieną mėnesį registruojant matavimų duomenis kas tris valandas (gaunama apie 200 matavimų). Ne trumpesnis kaip mėnesio trukmės vertinimo laikotarpis pasirinktinai dėl šilumos pritekio paros ir savaitės svyravimo įtakos rezultato neapibrėžčiai sumažinimo.
5. Atliktos analizės rezultatai parodė, kad pasirinkus 20 proc. infiltracijos neapibrėžties vertinimo ribą, infiltracija pagal šilumos kiekių balansą gali būti nustatoma pastatuose, kurių šildomas plotas ne mažesnis nei 10 tūkst. m², o sandarumas ne didesnis negu 1,2 h⁻¹ prie 50 Pa. Infiltracijos vertinimo neapibrėžtis mažesnė pastatams, kurių atitvaros geriau izoliuotos, tačiau vertinimo neapibrėžties priklausomybė nuo atitvarų šiluminės varžos yra silpna, kai vertinamas pastatas atitinka aukščiau pateiktus pastato dydžio ir sandarumo kriterijus.
6. Analizė atlikta esant būdingoms Lietuvos klimatui šildymo sezono aplinkos oro temperatūroms ir vėjo greičiams. Atliktas tyrimas parodė, kad infiltracijos vertinimo pagal pastato šilumos kiekių balansą neapibrėžtis nėra jautri vėjo greičio svyravimams vertinamuoju laikotarpiu, vėjo greičio svyravimo poveikis sudarė ne daugiau nei 1 proc. vertinimo neapibrėžties. Analizės rezultatai taikytini, kai vertinamuoju laikotarpiu vidutinė lauko oro temperatūra yra lygi arba žemesnė nei 0,2 °C.
7. Infiltracijos intensyvumo vertinimo pagal pastato šilumos kiekių balansą neapibrėžtis jautri šilumos pritekio vertinimui, todėl metodas gali būti taikomas, kai šilumos pritekis sudaro nežymią šilumos kiekių balanso dalį arba gali būti pakankamai tiksliai įvertinamas. Siekiant gauti 20 proc. infiltracijos neapibrėžtį esant 0,15 h⁻¹ vidutinei infiltracijai, šilumos pritekio absoliutinė neapibrėžtis turi būti mažesnė nei 147 Wh/m³/mėn., kai vidutinis mėnesio temperatūrų skirtumas tarp pastato vidaus ir aplinkos oro lygus 20 °C, ir mažesnė nei 220 Wh/m³/mėn., kai temperatūrų skirtumas lygus 30 °C.

Trumpos žinios apie autorių

Eglė Jaraminienė gimė 1974 m. birželio 23 d. Vilniuje.

2001 m. įgijo termoinžinerijos bakalauro laipsnį Vilniaus Gedimino technikos universiteto Aplinkos inžinerijos fakultete. 2003 m. įgijo energetikos mokslo magistro laipsnį Vilniaus Gedimino technikos universiteto Aplinkos inžinerijos fakultete. 2003–2008 m. – Vilniaus Gedimino technikos universiteto doktorantė. Šiuo metu dirba asistente Vilniaus Gedimino technikos universiteto Šildymo ir vėdinimo ir katedroje.

Eglė Jaraminienė

**INVESTIGATION OF AIR INFILTRATION
IN BUILDINGS USING UNCERTAINTY ANALYSIS**

**Summary of Doctoral Dissertation
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TAIKANT NEAPIBRĖŽTIES ANALIZĘ**

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Vilniaus Gedimino technikos universiteto
leidykla „Technika“, Saulėtekio al. 11,
LT-10223 Vilnius, <http://leidykla.vgtu.lt>
Spausdino UAB „Baltijos kopija“,
Kareivių g. 13B, 09109 Vilnius
<http://www.kopija.lt>