RIGA TECHNICAL UNIVERSITY
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ANALYSIS AND PREDICTION METHODS OF INDOOR AIR QUALITY

Summary of the Doctoral Thesis

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DOCTORAL THESIS
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To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis will be publicly defended on 29 May 2015 — 2 p.m., at the Faculty of Civil Engineering, Riga Technical University, Azenes Street 16/20, Room 250.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences is my own and does not contain any unacknowledged material from any source. I confirm that this Thesis has not been submitted to any other university for the promotion to any other scientific degree.

Jurģis Zemītis …………………………….

Date: ………………………

The Doctoral Thesis has been written in English. It contains the introduction, 4 chapters, conclusions, bibliography with 90 reference sources. The Doctoral Thesis has been illustrated by 48 figures. The volume of the Thesis is 96 pages.

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INTRODUCTION

The actual commonly used standards that determine the necessary volume of ventilation air are based on fixed air exchange rates regarding different comfort levels of buildings and directly do not take into consideration that ventilation is necessary to provide certain IAQ parameters. However, it would be advisable to determine the optimal volume of ventilation air for each case individually considering the type of building and necessary IAQ parameters to obtain the minimum necessary volume of ventilation air that still provides adequate IAQ. This would ensure that the ventilation system would consume the minimum amount of energy and being with the smallest component sizes would also be more economically feasible. At the same time, this kind of dimensioning of ventilation system would still provide enough fresh air to prevent “sick building syndrome” or to maintain IAQ parameters in predetermined boundaries, which could be important for special types of buildings like museums, sport halls etc.

Research in this field has also been carried out by the following researchers: Carsten Rode, Anton TenWolde, Andris Krēsliņš, Iain S. Walker, Olli Seppänen, Kaisa Svennberg etc.

The aim of the Doctoral Thesis is to develop a methodology that allows predicting the main IAQ parameters and determining the optimal ventilation air volume.

The main **tasks** include:

1) Analysis of existing norms regulating ventilation air volume;
2) Analysis of IAQ main parameter thresholds to provide adequate air quality while reducing ventilation air volume;
3) Performing study on CO_2 and indoor moisture pollution sources as well as on the interaction between ventilation rate, moisture production and moisture buffering;
4) Development of mathematical model for IAQ main parameter prediction depending on ventilation air volume, indoor pollutants, ventilation air quality and processes occurring indoors;
5) Validating the developed method by comparing the predicted IAQ parameter results with the measured ones;
6) Based on the obtained data, providing a method to calculate the optimal volume of ventilation air for multi-story apartment buildings.

Scientific novelty: methodology for calculating the necessary volume of ventilation air according to the needs and desired IAQ parameter levels with a respect to indoor moisture absorption-desorption processes.

Practical applications:

1) Method for designers to choose the optimal volume of ventilation air, which is necessary to obtain certain IAQ parameters while minimizing the energy consumption;
2) Possibility for building managers to use the provided methods to predict indoor air parameters for buildings.

1. DESIGNING VENTILATION SYSTEMS: STATE OF ART

1.1 Contemporary Methods of Ventilation Volume Calculations

As people in general spend about 80–90 % of their lifetime indoors, it is particularly important to provide good and healthy environment. This is done through building climatic systems like ventilation, heating and air conditioning. At the same time, these systems account for a large part of total energy consumption, therefore, provide a good opportunity for savings. According to calculations, the ventilations system alone accounts for 15–25 % of energy consumption in modern, well insulated buildings. This means that by decreasing air volume it would be possible to save on energy, air handling units and ducts. At the same time, insufficient ventilation can lead to various health problems, increase risk of corrosion, growth of fungi and cause decrease in working efficiency. To prevent this, it is necessary to ensure appropriate IAQ and it is essentially important to make precise calculations for necessary volume of ventilation air.

As of now there are two local regulations in Latvia that make statements about necessary volume of ventilation air and how it should be calculated. One is Latvian Construction Norm LBN 211-08 "Daudzstāvu daudzdzīvokļu dzīvojamie nami" ("Multi-story Residential Buildings") that determines the necessary air exchange according to the type and area of occupied spaces. There is also another Latvian construction norm that mentions ventilation volumes — LBN 231-03 "Dzīvojamo un publisko ēku apkure un ventilācija" ("Heating and Ventilation of Residential and Public Buildings"). It requires a minimum of 5 l/s of fresh air per person if it is the only pollutant in the room. There is a similar situation with the standards and regulations of other countries. They determine the necessary volume of ventilation air for non-residential buildings either according to a building type and needed ventilation rate in l/s per m^2 or by l/s per person. For the purpose of comparison, the required rate of ventilation air specified by commonly used regulations for some of the most common space types is summarized in Table 1.1.

Table 1.1

Required Volumes of Ventilation Air for Non-residential Areas in Different Countries

Type of premise	Country / Standard		
	Latvia / CR 1752	**USA / ASHRAE 62.1**	**Finland / D2**
	Supply / extract air volume		
Single office	0.8; 1.4 or 2.0 l/s/m^2	0.3 l/s/m^2 + 2.5 l/s/pers.	1.5 l/s/m^2
Open space office	0.7; 1.2 or 1.7 l/s/m^2		
Conference room	2.4; 4.2 or 6.0 l/s/m^2	0.3 l/s/m^2 + 2.5 l/s/pers.	4 l/s/m^2 + 8 l/s/pers.
Classroom	2.4; 4.2 or 6.0 l/s/m^2	0.6 l/s/m^2 + 5 l/s/pers.	3 l/s/m^2 + 6 l/s/pers.

Although types of calculation that only take into account a number of persons or floor area are fast and do not require a lot of work, they do not provide information on the expected indoor air quality. Therefore, they cannot be considered precise enough, because each situation has different variables such as a living area per person, external air quality, indoor air pollutants, allowable level of pollution etc. All of these factors affect the amount of fresh air required to ensure good IAQ. The main characteristics that define IAQ are CO_2 level and relative humidity. It is, therefore, necessary to determine the threshold values of the CO_2 concentration level and relative humidity and the possible sources of these types of pollution to choose the exact ventilation rate for each given situation.

1.2 CO_2 Concentration as an Indoor Air Quality Indicator

The most commonly used indicator that is applied to validate and measure the indoor air quality is CO_2 concentration. One of the benefits of validating IAQ according to CO_2 is a relatively easy way of measuring as the concentration is high, around 350–3000 ppm. Another strong benefit of using CO_2 concentration as an indicator is due to the fact that in most cases it is only affected by the persons that are in the given room. The concentration increases rapidly in case of presence of living beings, either humans or pets, trough the respiratory process and by generating sweat. However, the CO_2 concentration by itself is usually not responsible for the complaints by occupants, but a high level of CO_2 may indicate that other contaminants in the building may also be present at higher levels and could be responsible for occupants' complaints.

The actual construction and sanitary norms in Latvia do not regulate the allowed CO_2 levels for indoors; therefore, it is necessary to follow standards and norms for harmless IAQ parameters from other countries. The most common and widely spread general knowledge states that the CO_2 concentration should not exceed 1000 ppm. Other existing studies state that the CO_2 concentration already above 800 ppm can cause symptoms as headaches, tiredness, lack of concentration and irritation of eyes and nasopharynx.

It should be noted that the indoor CO_2 concentration is directly dependent on the outdoor concentration. Depending on the location, the concentration of outdoor CO_2 can vary from 350 ppm in countryside or unpolluted city to 700–800 ppm in an average city center. This is the reason why some standards do not determine the absolute CO_2 concentration but only state the allowed increase between outdoor and indoor concentrations.

1.3 Relative Humidity as an Indoor Air Quality Indicator

Differently from the CO_2 concentration for indoor air that only has the upper limit, the relative humidity should be inside a certain range with limited lower and upper value to provide a good environment. This is because excessive humidity levels increase the occurrence of mold, which contributes to the building structure deterioration, as well as could stimulate or cause human diseases. In turn, too low humidity can also cause increased risk of health problems and promote eye drying.

The only standard that regulates the relative humidity in Latvia is the Regulations No. 359 of the Cabinet of Ministers "Darba aizsardzības prasības darba vietās" ("Occupational Health and Safety Requirements in the Workplace"). It states that the indoor relative humidity should be between 30 % to 70 % for the whole year. In practice, the lowest allowed level of relative humidity is taken as 30 %, which is harmless to humans and cause no health problems. If the relative humidity is lower than 30 %, it can cause eye/upper airway irritation, dry skin symptoms and general discomfort. The maximum allowable level of relative humidity in the room is determined by the threshold, after which the growth of fungus and mold drastically increases. It is believed that the fungal growth risk exists if the surface moisture for several days in a row is more than 80 %, while the corrosion risk exists if the surface moisture for several days in a row is more than 60 %.

1.4 Analysis of Indoor Moisture Sources

To predict the indoor relative humidity, the outside air relative humidity range has to be established as it directly influences the level indoors. It must be noted that the moisture content of the outside air is very variable and ranges from 0.002 kg/kg to about 0.015 kg/kg during the whole year. It strongly depends on the location of the building, and in case of Latvia it is relatively large due to proximity of the Baltic Sea.

Some of the possible indoor moisture sources include people, plants, floor and dish washing, clothes drying, moisture release from building materials, cooking, showering and moisture diffusion through building envelope. Existing studies provide information about the amount of moisture release by these processes.

Moisture released by people is estimated to be in the range of 30 g/h to 70 g/h according to existing studies. About 2 g/h of water vapor is released by the cat and 7 g/h by a medium size dog. Another source of moisture indoors is showering and bathing. A five-minute shower contributes between 0.11 kg and 0.23 kg of water vapor. The amount of moisture released from dish washing varies between 0.2 kg and 0.3 kg for a family of four. During one occurrence of clothes washing and drying indoors, the total amount of released moisture is estimated to be 2.0 kg up to 4.7 kg. The studies report that a floor cleaning releases 0.005 kg/m^2 to 0.15 kg/m^2 of water vapor. According to the measurements of water vapor release from plants, an average plant releases from 39 g/day to 101 g/day or 5–20 g/h depending on the plant size.

In addition to the discussed humidity loads, it should be noted that there are also causes of humidity that do not originate from household activities and cannot be controlled. One example would be release of moisture from construction materials after construction has been completed or from wet foundations. According to studies, they could be estimated to reach even 10 kg/day. They are dependent on the quality of building envelope and the prevailing wind direction and strength in the given territory, but the literature indicates that they can range from 0 kg/day to 105 kg/day.

1.5 Moisture Buffering by Indoor Materials

Many of the previously described activities, such as showering, cooking or floor mopping, release bursts of water vapor in relatively short periods of time. However, it has been demonstrated by many studies that moisture is temporarily stored on surfaces and inside hygroscopic materials and is released only after humidity has lowered and stabilized. Therefore, the amount of steadily released humidity, not the momentary rate of release, is the most important for long-term indoor humidity calculations. However, it is a complicated task to predict the possible moisture buffering by indoor materials as they are usually chosen only after the design stage and their buffer capacity varies depending on the moisture capacity, water vapor permeability, density and the period of humidity variation. Therefore, it would be necessary to make estimations of moisture buffering potential of the most commonly applied types of material and after knowing this data to provide an averaged standard value of moisture buffering potential depending on the building type, room type and potential interior design.

Existing studies show the importance of moisture absorption-desorption properties of materials in the stability of indoor air parameters and demonstrate the potential for energy consumption reduction up to 30 %. This significant reduction in energy consumption can be achieved by the use of hygroscopic materials in combination with precisely controlled HVAC systems. Therefore, the air exchange rate can be reduced by 30–40 %, thus reducing energy consumption up 10 % to 17 % in the wintertime.

2. DEVELOPED PREDICTION METHOD OF IAQ PARAMATERS

To develop the prediction method of IAQ parameters for an indoor environment, the mass balance principle should be applied. In general, it states that the mass that enters a system must, by conservation of mass, either leave the system or accumulate within the system. To theoretically predict the dynamically changing indoor air quality parameter levels based on air ventilation rate, pollution rate and outdoor air parameters, a theoretical model was developed. The calculation methods to obtain the equitation describing the CO_2 concentration in indoor air at any given time moment can be expressed by the following equations:

$$\frac{dM_{CO2}}{dt} = CO_2 outdoors + CO_2 produced - CO_2 exhausted \ . \tag{2.1}$$

Knowing that mass can be expressed as multiplication of concentration and volume, we can replace the left side of equitation (2.1) $\frac{dM_{CO2}}{dt}$ with $\frac{Vdc_{in}}{dt}$ and in the right side we express the produced CO_2 as multiplication of number of persons and CO_2 produced by one person. Thus, we obtain the following equation:

$$\frac{Vdc_{in}}{dt} = nVc_{out} + n_{pers}q - nVc_{in} \, , \tag{2.2}$$

where: V — the room volume, m^3;

n — the air exchange rate;

c_{out} — the outdoor concentration of CO_2, kg/m^3;

$n_{pers.}$ — a number of persons in room;

q — CO_2 produced by one person, kg/h;

c_{in} — the indoor concentration of CO_2, kg CO_2/m^3.

Subsequently, we divide both sides by V and take the parameter n before brackets:

$$\frac{dc_{in}}{dt} = -n(c_{in} - c_{out}) + \frac{n_{pers.}q}{V}. \qquad (2.3)$$

Then we substitute $(c_{in} - c_{out})$ with y, which yields $\frac{dy}{dt} = \frac{dc_{in}}{dt} - \frac{dc_{out}}{dt}$, but since c_{out} is constant than $\frac{dc_{out}}{dt} = 0$ and $\frac{dy}{dt} = \frac{dc_{in}}{dt}$. This is placed in the left side of (2.3), which leads to:

$$\frac{dy}{dt} = -ny + \frac{n_{pers}q}{V}. \qquad (2.4)$$

Rearranging the last equitation and integrating it by time from $t=0$ to $t=t$ we obtain:

$$\int_{y(0)}^{y(t)} \frac{dy}{\left(\frac{n_{pers} \cdot q}{V}\right) - n \cdot y} = \int_0^t dt. \qquad (2.5)$$

This results in:

$$\ln\left(\frac{n_{pers.}q}{V} - ny(t)\right) - \ln\left(\frac{n_{pers.}q}{V} - ny(0)\right) = -nt. \qquad (2.6)$$

By replacing y with the initial equitation and knowing that at the starting time $t = 0$ the CO_2 concentration in the room will be C_0, we can obtain the following equitation:

$$ln\left(\frac{n_{pers.}q}{V} - n(c_{in} - c_{out})\right) - ln\left(\frac{n_{pers.}q}{V} - n(c_0 - c_{out})\right) = -nt. \qquad (2.7)$$

By applying the residual characteristics of logarithmic equations, exponenting both sides of expression and transferring the equitation members and expressing the necessary c_{in} we can obtain the following final equitation for dynamically changing CO_2 concentration in indoor air:

$$c_{in}(t) = c_{out} + (c_0 - c_{out})e^{-nt} + (1 - e^{-nt}) + \frac{n_{pers}q}{nV}. \qquad (2.8)$$

In theory, it should be possible to determine indoor humidity in a similar way.

3. EXPERIMENTAL MEASURMENTS AND DATA ANALYSIS

3.1 Validation of CO_2 Prediction Method

To validate the calculation method and precision of the provided model, both field and climatic chamber measurements were performed. The validation process involved measuring the real CO_2 concentration and comparing the results with the predicted ones. The field measurements were done in two types of buildings with different functionality and occupancy profiles — one office building and one residential building. For each of these objects the test was repeated two times for higher credibility.

The multi-story residential building is a typical Soviet time residential building constructed in the 1970s. The ventilation system is considered to be natural with the supply air coming through windows and construction imperfections, while exhaust air leaves trough channels in the bathroom and toilet. The room is occupied by one person, who stays in it from about 6:30 p.m. to 10 a.m. The outside CO_2 concentration level is 570 ppm in the given location and time.

The office building is of wooden type renovated in the 1960s. The office does not have mechanical ventilation and, like the residential building, has natural ventilation with supply through leaky wood windows and exhaust trough the bathroom. The occupancy of office changes through the day from 9 a.m. to 7 p.m. with a maximum number of persons being 6, while on average it is 4. The measured outside CO_2 concentration is 580 ppm.

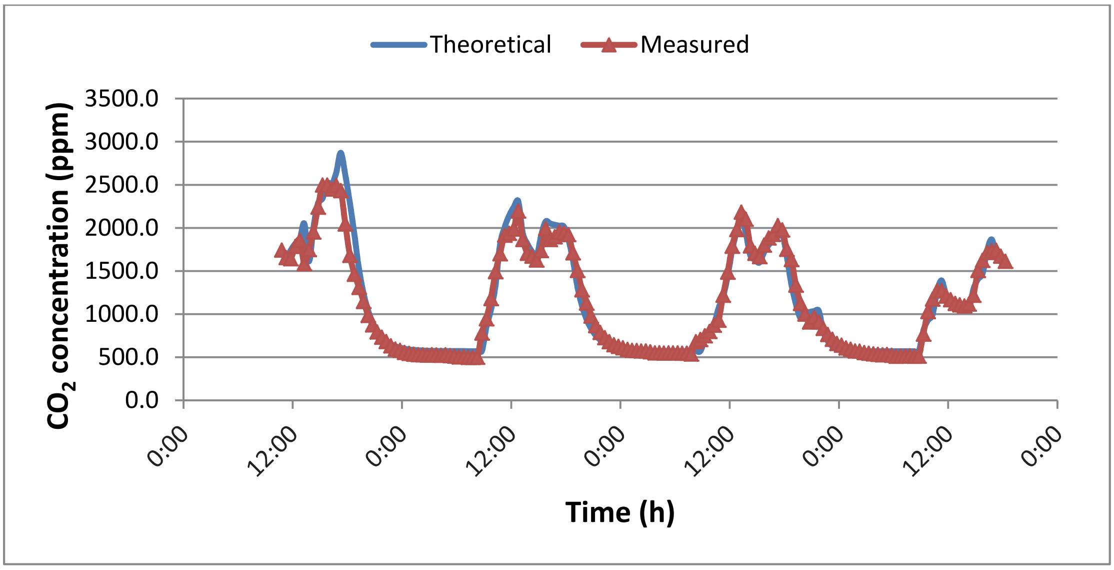


Fig. 3-1: The predicted and measured CO_2 concentration in the office room.

The obtained results have proved that the proposed method provides good results for CO_2 concentration prediction (see Fig. 3-1) and the average precision is 93 %.

Apart from the field measurements, the same type of measurements were repeated in the controlled situation of climatic chamber to more precisely validate the method. During the test, a single person was located in the climatic chamber for a period of four hours. At first, the CO_2 concentration rate was not precisely predicted. The CO_2 production rate by person was assumed to be 0.02 m^3/h; however, after trial and error type of experimenting it was noted that if the CO_2 production rate was lowered to 0.012 m^3/h, the predicted results were very close to the measured ones (see Fig. 3-2). Therefore it can be assumed that for a given person the actual CO_2 production rate is lower.

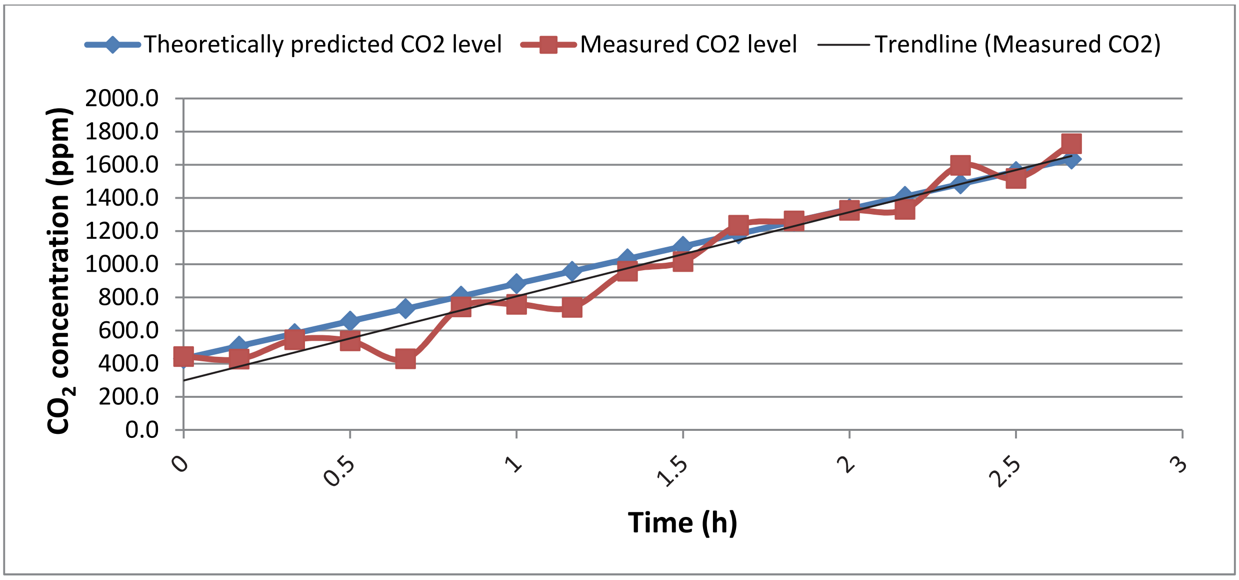


Fig. 3-2: The predicted and measured CO_2 concentration inside the climatic chamber with adjusted CO_2 production rate.

3.2 Measurements of Material Moisture Buffering Capabilities

For the analysis of moisture absorption by furniture, eleven different furniture samples were chosen. These samples were made of plywood material with either two larger or all sides laminated. They represent one of the most common materials widely used in households or schools as table material.

During the experiment the analyzed samples were placed in the airtight climatic chamber with the non-existent air exchange rate and controlled moisture and heat gains. The moisture content of indoor air was measured using the humidity meters and for materials by regular weighting of samples. The weighing data of measured samples was noted with several day intervals. For the evaluation of moisture buffering capacity of heavy timber structures, the air temperature was kept in the range of $+23.0 \pm 2\,^{o}C$ and relative humidity — 60 ± 5 %.

During the experiment, the overall capacity and rate of moisture absorption by materials were analyzed. The materials were left in the climatic chamber for as long as the mass kept noticeably increasing. To make assumptions on how the relative humidity influences materials and vice versa, both the relative mass change should be calculated and mass change according to surface area should be presented.

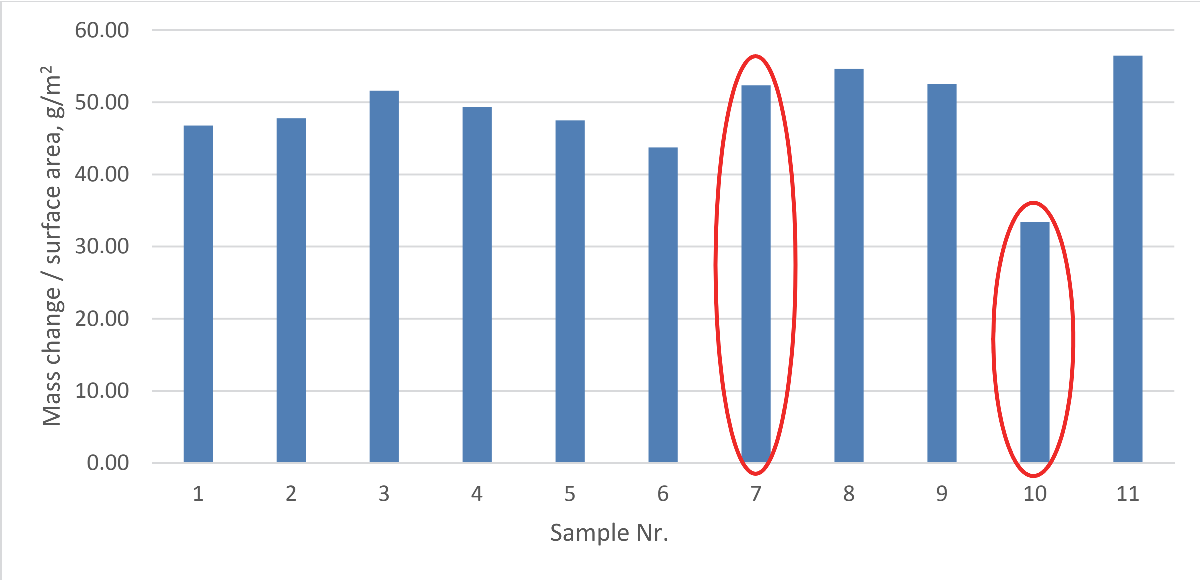


Fig. 3-3: Ratio of mass change and surface area of sample materials.

As seen from Fig. 3-3, the mass of analyzed samples changed by about 40 g/m^2 to 50 g/m^2. The results of the analyzed material samples show that they are very similar for all the cases except the one. It was expected that samples with all sides laminated (marked with red) would absorb less moisture as the laminate served as a barrier limiting the vapor influence. However, the results are inconclusive as one of these samples showed higher resistance to the moisture in the environment while the other absorbed the same amount of water vapor as non-laminated samples.

3.3 Field Measurements of Moisture Release by Clothes Drying

During the Doctoral Thesis for the purpose of evaluating some of possible moisture generation sources, the measurements of moisture production by clothes drying, plants and people were performed. For measurements of moisture generation and release in indoor air by clothes drying after washing in an automatic washing machine, 5 pieces of typical clothes were selected — jeans, cotton underwear, sweater, T-shirt and suit shirt. The clothes were washed inside a typical automatic washing machine with mechanical clothes drying at 1200, 800 and 500 revelations per minute. After the washing process the clothes were weighted. The drying took place inside a flat at a temperature of +22 ^{o}C and relative humidity of about 55 %.

Comparing the results of the three drying processes at 1200, 800 and 500 revelations, it can be seen that on average the relative difference in clothes weight directly after the washing process in comparison with that before washing is strongly dependent on the drying process and changes from 42 % to 66 % to 89 %, respectively. Also there is a difference in relative weight depending on fabric of clothes and can vary from 50 % up to 90 %. The largest increase in weight is for T-shirt and smallest for simple shirt. It can lead to a conclusion that the clothes that are smaller and light and are made of cotton type of material account for the largest increase in mass percentagewise.

All the extra moisture that clothes contain after the washing process is released to indoor air during natural drying process of clothing. These results about clothes natural drying after mechanical drying at analyzed revelations are shown in Fig. 3-4.

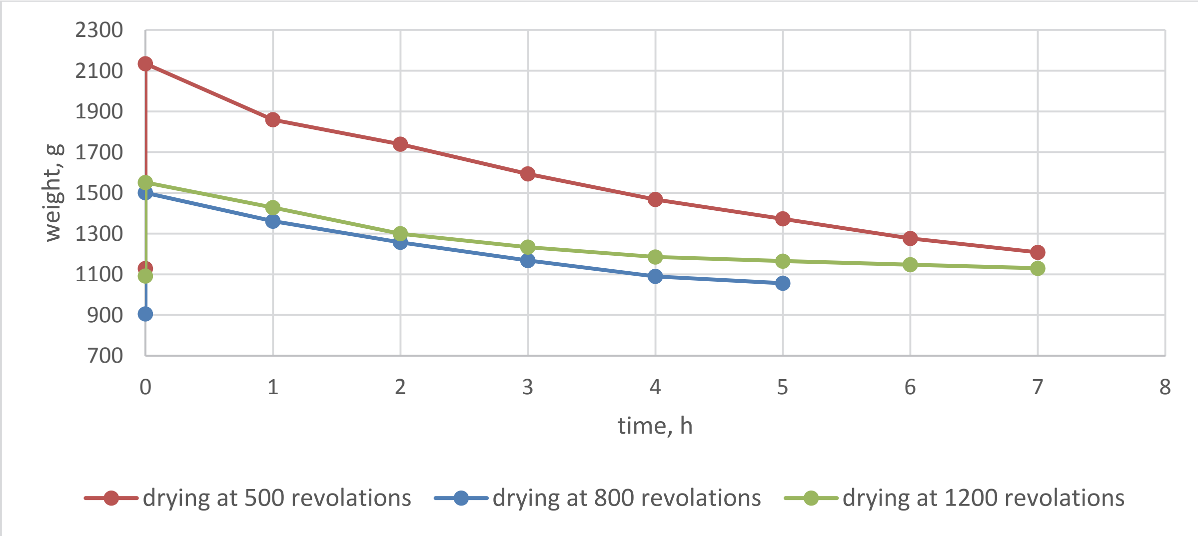


Fig. 3-4: Change in weight of clothes after washing in the automatic washing machine and indoor drying process.

To estimate the overall moisture production of clothes washing, it is necessary to determine the total number of clothes that a person washes each week. Knowing that an average washing machine is intended for washing capacity of 7 kg and by applying results that on average the weight increases by about 66 % per washing process it can be calculated that the total increase would be 9240 g or about 1320 g/day if two fully stacked washing machines are done per week.

3.4 Climatic Chamber Measurements of Moisture Release from Plants

To measure the moisture generation from plants, two experiments were performed. During the first one a sample consisting of three plants was put in the climatic chamber, while for the second one six plants were located in the chamber. All the plants were average sized. During the tests the relative humidity as well as temperature was measured.

To determine the actual moisture generated by the plants located in the climatic chamber, the total humidity and its change were calculated. According to the results of the first experiment, at the starting moment of measuring the absolute humidity in the chamber was 175 g of total water vapor. However, at the end of measuring period the humidity had risen to 245.3 g. This means that on average the moisture has increased just by 4.7 g/day or if assuming that all three plants produce the moisture at about the same rate as they are comparable in size then one plant would account for 1.57 g/day. The obtained results from the second measurement series with six plants show that during the 5-day period the total humidity increased by 84.2 g from 205.7 g to 289.9 g. This means that on average the increase is 16.84 g/day or 0.7 g/h. If assuming that all plants are equal, each of them would generate around 2.8 g/day or 0.12 g/h.

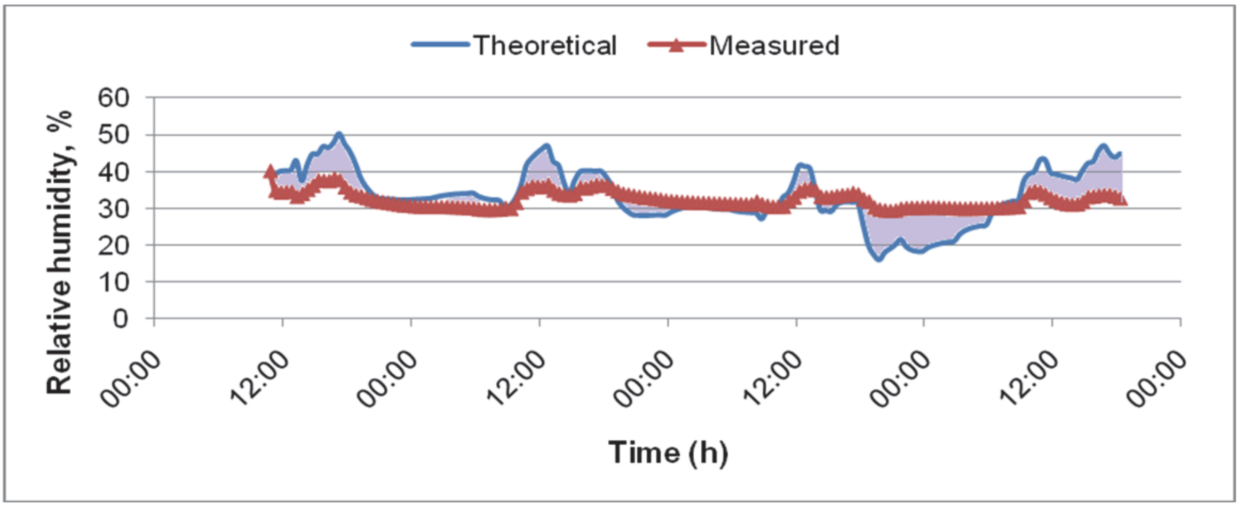
3.5 Climatic Chamber Measurements of Moisture Release from People

To verify the existing information about moisture generation from people, a climatic chamber measurement was performed. During the test a single person was located at the chamber for four hours. The results showed that for the first half an hour the moisture content was stable and did not change. This could be explained by the fact that the room contained some objects like table, chair and the clothes on the person. After this period, the objects reached the saturation state and the produced moisture directly influenced the air. If it is taken into account, the actual produced moisture should be calculated starting from the one-hour mark. The calculated moisture release is estimated to be 20.94 g/h. Comparing it to the existing data suggesting that a person emits from 30 g/h to 120 g/h (on average about 50 g/h), it can be concluded that according to our test the results are 1.5 up to 5 times lower.

3.6 Validation of Relative Humidity Prediction Method

For validation of relative humidity prediction method, the same buildings as for CO_2 measurements were used. At first, the same principles as for CO_2 prediction were used according to (2.8). The results of measured and predicted relative humidity are shown in Fig. 3-5.

The results have showed that this type of theoretical method is not accurate for predicting relative humidity. The fluctuation rate of change in relative humidity was not predicted too precisely. The actual measured relative humidity level is more stable and does not change as widely as predicted. This could be explained by several reasons. First of all, it is difficult to assess the exact internal moisture load as the sources in the building are diverse. However, the most significant cause of error could be the reason that the objects in the room also affected the moisture content of air, which was taken into account.



— Difference between the theoretically predicted and measured relative humidity

Fig. 3-5: The theoretically predicted and measured relative humidity in the office with 3 persons and 30 m^2 area during time period of 29/03/2011 to 01/04/2011.

To assess it, the previously presented moisture prediction equitation should be changed by implementing the moisture buffering effect. This is done by adding coefficient that limits the smooth and sudden moisture sources. Therefore, the equitation should be changed to the following one:

$$G_{in}(t) = G_{out} + (G_0 - G_{out})e^{-n \cdot t} + (1 - e^{-nt}) + \frac{(G_{smooth}a) + (G_{rapid}b)}{nV}, \tag{3.16}$$

where: V — the room volume, m^3;

n — the air exchange rate;

G_{out} — the moisture content of outdoor air, kgH_2O/m^3;

G_{in} — the moisture content of indoor air, kgH_2O/m^3;

G_0 — the initial moisture content of indoor air, kgH_2O/m^3;

G_{smooth} — the smoothly produced moisture content, kgH_2O/m^3;

G_{rapid} — the rapidly produced moisture content, kgH_2O/m^3;

a — the coefficient of indoor material influence on the smooth moisture content production;

b — the coefficient of indoor material influence on the rapid moisture content production.

The exact limiting coefficients in each case will vary depending on the room type, possible moisture sources, and interior materials. During further calculations the moisture introduced by ventilation, produced by people, plants and pets is considered to be smooth and moisture produced through floor mopping, showering, clothes drying and dish washing is considered to be a rapid type. The applied coefficients are determined by trial and error as well as by taking into account measurements about the moisture buffering potential of indoor materials. They are different for bedroom cases and offices as the indoor environment is not the same. In case of the office room, the coefficient for smooth moisture sources was taken 0.87 and for rapid sources — 0.50, while in case of the bedroom they were 0.84 and 0.74, respectively.

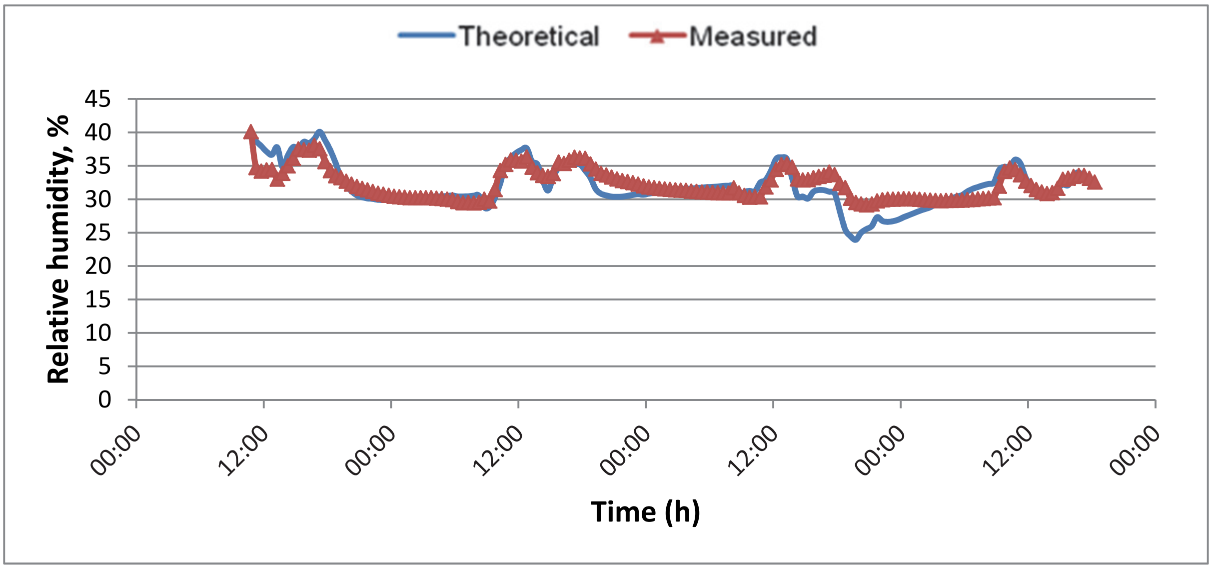


Fig. 3-6: The predicted and measured relative humidity in the office, including moisture buffering

As Fig. 3-6 shows, the proposed method by adding coefficients limiting the moisture production influence gives improved prediction accuracy. The predicted rates of relative humidity fluctuations are represented with closer relation to actual measured data than previously. However, they still tend to overvalue the moisture production affect. To further improve the prediction accuracy, more data needs to be gathered and standardized coefficient values depending on room type should be given to apply during the building design stage. This would allow for relatively quick and accurate way of predicting indoor relative humidity.

4. EXAMPLES OF PRACTICAL APPLICATION OF IAQ PREDICTION METHOD

4.1 Analysis of Ventilation Systems for Standard Type Houses of Latvia

One application of the proposed IAQ prediction method could be the calculation of exact necessary ventilation air volume for existing typical buildings and estimating the potential economical savings. In Latvia, a major part of existing building stock consists of the Soviet time buildings. The total area of these buildings is about 20.79 million of m^2 while the overall area of residential buildings was about 54.6 million of m^2 in 2009. Knowing that during the nearest period the existing buildings need to be renovated, this can be a good opportunity to improve the ventilation systems. During renovation special attention should be paid to ventilation systems as the original buildings were planned to have a natural ventilation system that has air supply through building construction imperfections but after renovation they are closed causing a lack of ventilation.

To apply the developed method for calculating the necessary volume of ventilation air, a spreadsheet type document was prepared. In the document, the location of the buildings, as well as average outside temperature and data about buildings were inputted. For calculating the necessary ventilation volumes, the following regulations and methods were taken into account — according to LBN 211-08 "Daudzstāvu daudzdzīvokļu dzīvojamie nami", according to LBN 231-03 "Dzīvojamo un publisko ēku apkure un ventilācija", assuming the air exchange rate of 1 time per hour and calculating the ventilation volume that the CO_2 never exceeds 1000 ppm. To calculate the necessary volume of ventilation air according to a number of persons and to limit the CO_2 concentration, it was assumed that there were about 20 m^2 per person living in the building.

Fig. 4-1 shows the results of necessary heating energy calculated for ventilation air if the air volume is determined according to the previously described norms and principles. The results show that by regulating the ventilation air volume according to the CO_2 level, the air volume and, therefore, heating energy can be reduced by around 40 % to 41.24 kWh/m^2/year on average for all standard series buildings. This could contribute to notable financial savings. If it were assumed that the ventilation volume could be changed in all of the existing buildings and decreased to the optimal level, the savings could be calculated. For this purpose, we assume that all the energy is provided by a central heating system and compensated through the radiators or in the AHU after heaters. Knowing that at a given date the energy costs 0.06 EUR/kWh then the total annual savings will be 32.69 million EUR.

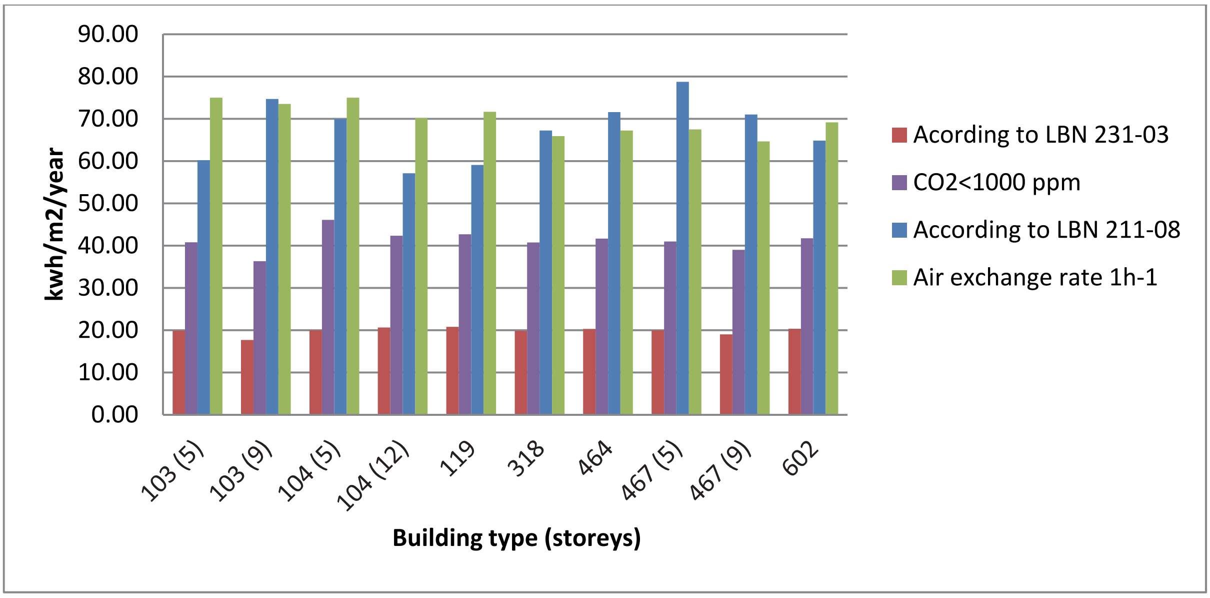


Fig. 4-1: Comparison of calculated energy consumption necessary for air heating of ventilation air to the total area (kWh/m^2/year).

4.2 CO_2 Concentration Analysis and Prediction of Buildings at the Design Stage

The proposed method can also be applied to predict the CO_2 concentration for new buildings at the design stage and to determine the optimal volume of ventilation air. It can be especially useful for buildings that have large volumes, which could serve as a buffer space, therefore lowering the necessary volume of ventilation air to provide good IAQ. For example, cinemas or theaters could need lower ventilation volumes than proposed in standards. Also these buildings have rooms that are only periodically occupied; therefore, if the ventilation volume is constant and is chosen appropriately the room will be completely vented before the next group of people occupies it.

For our further example it was chosen to calculate the ventilation air volumes of single family residential building according to the existing regulations, and the developed method was used to foresee the changes in the CO_2 concentration during the period of one week. The theoretically chosen building was planned to be a single-story family building with a total area of 180 m^2 and building volume of 450 m^3. The planned number of occupants was 5 persons.

To calculate the ventilation volumes, we used the same standards like in the previous example for multi-story apartment buildings. The only difference was choosing an air exchange rate of 0.3 times per hour instead of 1 time as this volume was mentioned in different sources as suitable for low energy residential buildings. The results for the assumed occupancy profile can be seen in Fig. 4-2.

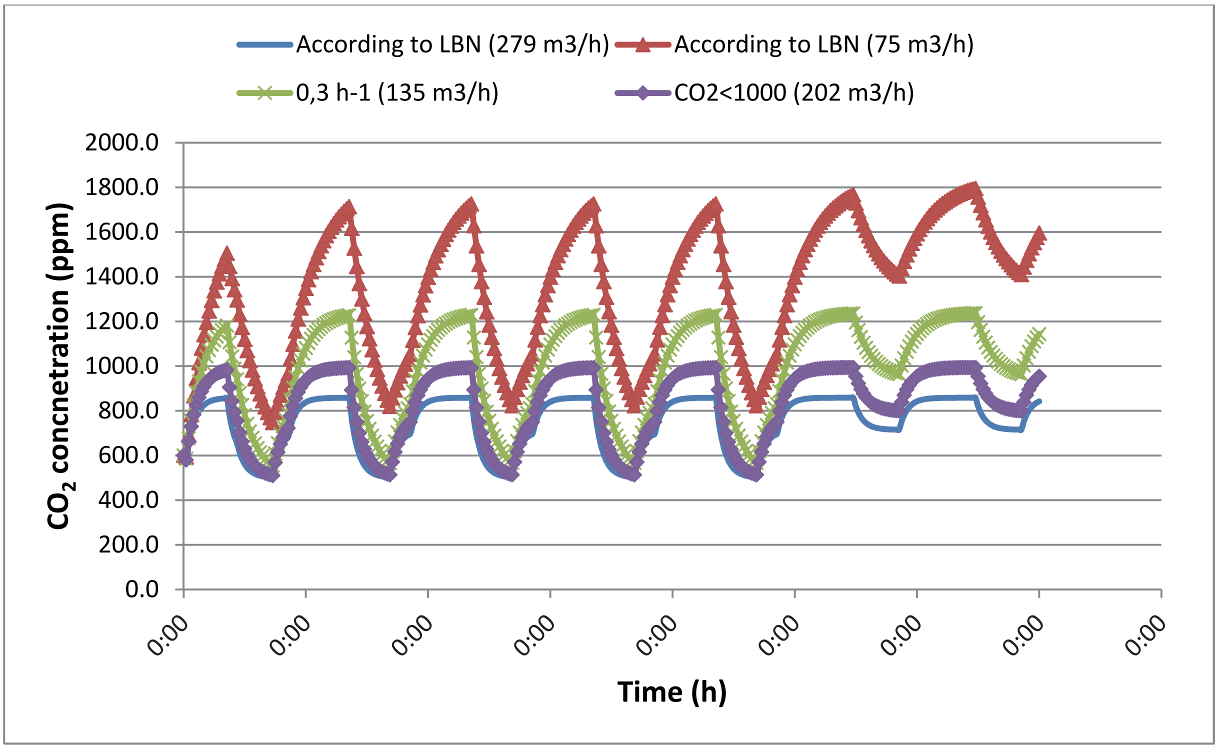


Fig. 4-2: CO_2 level (ppm) in the building during a week at different volumes of ventilation air.

As seen from the figure, in case when ventilation air is chosen according to the Latvian construction standards, the concentration of CO_2 does not exceed 860 ppm, which is below the norms and, thus, the amount of air exchange could be reduced. On the basis of calculations, it can be determined that the ventilation air quantity of 202 m^3/h is needed to ensure such a state that the CO_2 concentration in the building at any given moment shall not exceed 1000 ppm. This means that ventilation air can be reduced by75 m^3/h or 27 %, there by saving energy for movement of air and heating up comparing to the norms and standards.

CONCLUSIONS

1) Current regulations, both in Latvia and in other countries, do not require ensuring specific IAQ when choosing ventilation air volume. They regulate the ventilation rate either according to the type of premise and its floor area or the number of occupants and state the necessary exhaust air for specific rooms. Therefore, they do not take into account the volume of room and the necessity to choose the air volume to provide an indoor environment for each case individually and possibility to reduce energy consumption.
2) The IAQ could be determined by the CO_2 concentration and relative humidity. The optimal level of CO_2 concentration indoors according to the existing studies is in the range of 800 ppm to 1200 ppm or 400 ppm to 1000 ppm above the outdoor air level. To provide good IAQ and avoid negative effect on human health, the suggested range of

long-term relative humidity for indoor air according to the existing studies should be in the range of 30 % to 60 %.

3) Measurements of moisture buffering potential of common furniture materials have been performed showing their influence on indoor moisture balance by absorbing part of introduced moisture.
4) Measurements of indoor moisture rates produced by clothes drying, plants and peoples have been performed. The results for indoor clothes drying have indicated that this process accounts for an average of 1320 g/day, the moisture generation by plants is estimated to be in the range of 0.07 g/h to 0.12 g/h and a human generates about 21 g/h.
5) The validation of the proposed method for predicting the indoor CO_2 concentration has showed that there is a close relation between the predicted and measured values. For the examined cases, the CO_2 concentration has been predicted with average precision of 93 % and mean square error of 83 ppm.
6) The simplified method for relative humidity prediction, not taking into account the moisture buffering, have not accurately predicted the actual rate of indoor relative humidity variations. By introducing additional moisture buffering coefficients that represent indoor material influence on smooth and rapid moisture production, the results improved and closely represented the measured values.
7) The developed method for determining optimal volume of ventilation air to ensure CO_2 concentration under 1000 ppm for existing standard type multi-story apartment buildings has been provided. The results are compared to the existing ventilation volumes and show that these buildings are over-ventilated and by reducing the ventilation air volume for all of them a total of 32.7 million EUR/year could be saved at actual heating prices due to consuming less heating energy for ventilation air.

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3. Zemītis, J., Borodiņecs, A. Zema enerģijas patēriņa ēku ventilācija. Saarbrűcken, Germany: GlobeEdit, 2014. 65 lpp. ISBN 9783639688900.

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