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Energy Consumption and Indoor Air Quality of Different Ventilation Possibilities in a New Apartment Building

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Abstract – **The paper focuses on natural ventilation systems in new buildings. There is particular interest in heat energy consumption and indoor air quality with different ventilation possibilities. Indoor air quality measurements during different ventilation solutions were conducted in a new apartment building. The results of this paper show that, by applying some common ventilation solutions, the consumption of heat energy for heating the cold incoming air can reach up to 0,86 MWh/month in a 10 m^2 room in the coldest months of winter.**

Keywords – **air change rate, CO$_2$ concentration in buildings, heat energy consumption for ventilation, indoor air quality, natural ventilation.**

I. INTRODUCTION

Heat energy in apartment buildings usually is consumed for many reasons: to cover heat losses through the building envelope, to prepare hot water, and to heat air that flows into the building, thus providing fresh air. This article focuses on indoor air quality and the energy needed to heat incoming fresh air. The air has to be heated only in the winter period, which, in Latvia, is approximately 203 days [1].

It is very important to have fresh air indoors because it is one of the key components for the well-being of people situated in the building. It is also important, however, to consume as little energy as possible for heating the fresh incoming air. Therefore there are many standards, which regulate the minimal amount and quality of fresh air required indoors so that people indoors do not feel any ill effects of bad air quality and the energy consumption for heating the incoming air is minimal.

The main indoor air quality requirements are meant for air temperature, air humidity and CO$_2$ content in air. Depending on the season, thickness of clothing and human activity (metabolic rate), the indoor air temperature should be in the range of 18 – 24^{o}C [3, 4, 5, 6, 7]. Indoor air humidity depends on many factors but usually it should be kept in the range of 30 – 70 % [8, 9, 7, 10]. One very important factor of indoor air quality is its CO$_2$ content. CO$_2$ indoors is introduced by human breathing, gas stove burning and other processes. Outdoor CO$_2$ content is approximately 400 ppm, which is greater in densely populated areas. Indoor CO$_2$ content requirements usually are described in two ways:

1. Total indoor CO$_2$ content;
2. CO$_2$ content above the outdoor CO$_2$ level.

The desirable CO$_2$ level in buildings is from 350 to 1000 ppm above the outdoor level [5]. At this CO$_2$ concentration no ill effects can be felt. Only at CO$_2$ levels that exceed 10000 ppm do humans start to feel some effects that affect their health [11, 8, 12].

From the point of view of indoor air quality, it would be advisable to keep the air change rate in buildings as high as possible. In this case, CO$_2$ levels in buildings would be optimal for human health, but this would mean that, in the winter, the energy spent on heating the incoming air would be very large and expensive. In this study measurements and calculations were done to understand how different ventilation solutions in a new apartment building affect indoor air quality and the amount of heat energy needed for incoming air. By doing this, it was possible to find the optimal ventilation solution for this type of building.

II. STUDIED BUILDING

The building studied is situated in Riga. It was built in the year 2008. The building has 9 floors and is constructed of three-layer concrete panels with heat insulation in the middle layer. The building is constructed with airtight double-glazed windows in a plastic frame. The building has only natural infiltration and because the windows are airtight, there is an adjustable round air inlet beside every window. The diameter of the air inlet is 80 mm and it is equipped with a plastic cover that has an incorporated air filter (see Fig.1.).

All windows can also be opened in the so-called winter ventilation, when the handle of the window is turned upright at a 45 degree angle and a narrow slit around the window is formed where the fresh air can flow inside.

A typical room was chosen for conducting measurements in this building. This room had to conform to the following requirements:

1. During all measurements, the number of inhabitants has to always be the same;
2. The room has to be small enough to ensure uniform CO$_2$ distribution;
3. The room has to be equipped with an automatic temperature control system.

A bedroom on the 6th floor was chosen for the measurements. There was one person using this room, which ensures that the CO$_2$ gains from breathing would be the same during all the measurements. The room is only 10 m^2 and the height of the room is 2,55m, which ensured uniform CO_2 distribution in the room, which is very important for calculations. The temperature in this room is controlled by an automatic thermostatic valve on the radiator. There is one window (125x130 cm) and one balcony door (82x210 cm) in the room. Both – window and balcony door – can be opened in the winter ventilation regime.

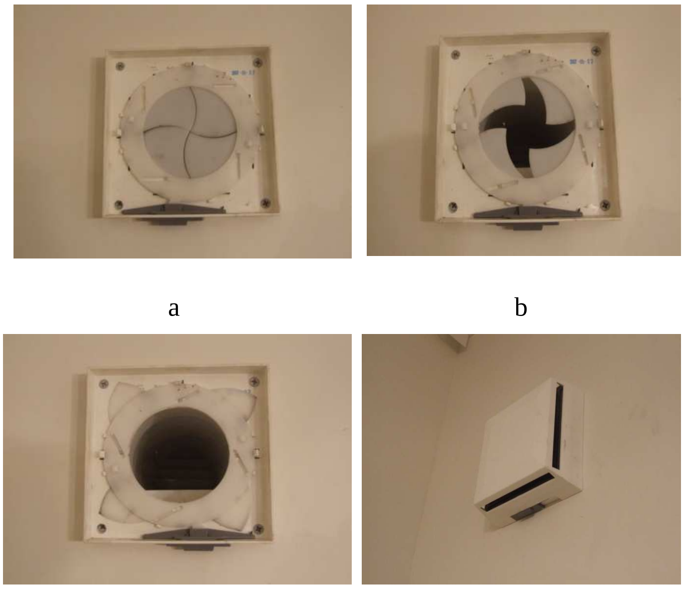
a b
c d

Fig. 1. Adjustable ventilation air inlet beside every window in closed (a), open (c) and half-open (b) state. Air inlet cover (d).

III. MEASUREMENTS AND CALCULATION METHODS

Measurements were made to understand how different ventilation solutions affect indoor air quality and heat energy consumption. During these measurements, the indoor air temperature, air humidity and CO_2 level were measured. The results of the measurements were logged at 1 minute intervals. Typical measurements lasted for one day. This was enough to obtain the indoor air quality parameters and to have enough data to calculate the air change rate in the room studied and the energy needed for heating inflowing air.

In total 6 ventilation possibilities were measured. All of these ventilation solutions can be and are used in every-day conditions. The following ventilation possibilities were subjected to measurements:

1. window, balcony door and air inlet closed (1st and 6th measurement);
2. window and balcony door closed, air inlet – opened (2nd measurement);
3. window and air inlet closed, balcony door – winter ventilation (3rd measurement);
4. window and balcony door closed, air inlet – sealed with tape (4th measurement);
5. window and balcony door closed, air inlet – half-open (5th measurement);
6. balcony door and air inlet closed, window – winter ventilation (7th measurement).

The first type of ventilation solution was measured twice because in this room this was the typical ventilation solution and it was done to see how outdoor air temperature affects air change rate and indoor air quality.

Measurements were made by beginning measurement in the evening, when the inhabitant of the apartment was in the measured room. In the morning, the room was left empty and the measurement ended the following evening, so that one measurement takes about 24 hours. Measurements were started when the inhabitant of the room came into the room. Some exceptions were made for the last two measurements, which lasted less than 24 hours (during these measurements the inhabitant of the room was awake).

During the measurements thermography was used to visualize cold incoming air and to monitor the average temperature of the radiator.

CO_2 measurements were done with Telaire 7001D, temperature and relative humidity measurements were made with HOBO U12-012 data loggers and thermography pictures were taken with a Fluke Ti30 thermal imager.

An important part of this study was to understand how the previously mentioned ventilation solutions affect the amount of energy needed for heating incoming air. This can be done by calculating the air change rate and afterwards calculating the amount of energy used for heating the air. The air change rate was calculated according to LVS EN ISO 12569:2000 “Thermal performance of buildings. Determination of air change in buildings. Tracer gas dilution method”. In this ISO standard two methods for calculating air change rate by using CO_2 measurements are described:

1. tracer gas concentration reduction method;
2. constant tracer gas concentration method.

In this particular case some adjustments of these methods had to be made because of the background concentration of CO_2.

The first calculation method (tracer gas concentration reduction method) is used when initially there is high CO_2 concentration in the room and there are no CO_2 sources in a room (this happens after a person leaves the room). In this case the rate of CO_2 concentration reduction is monitored. By knowing the rate of CO_2 concentration reduction it is possible to calculate the air change in the room:

$$n_{av} = \frac{\ln C(t_1) - \ln C(t_2)}{t_2 - t_1}\ , \tag{1}$$

where
n_{av} – air change rate, h^{-1};
$C(t_1)$ – CO_2 level in the beginning (with subtracted background CO_2 level), ppm;
$C(t_2)$ – CO_2 level in the end (with subtracted background CO_2 level), ppm;
t_2-t_1 – time between CO_2 level measurements, h.

In both calculation methods, the CO_2 level has to be adjusted because of the background CO_2 concentration. During this study, measurements were carried out and the background or the outdoor CO_2 level was determined.

The second method (constant tracer gas concentration method) is used when the CO_2 level in room stabilizes and this happens some time after a person has been in the room. By knowing the CO_2 level and the amount of CO_2 that flows into the room it is possible to calculate the air change rate.

$$n_{av} = \frac{V_{tra}}{C_{t\arg} \cdot V}, \tag{2}$$

where
V_{tra} – amount of CO_2 inflow, m^3/h;
C_{targ} – CO_2 concentration (level) in room;
V – volume of the room, m^3.

When the air change rate of the room is known, it is possible to calculate energy needed for heating incoming air:

$$Q = \frac{c_p \cdot \rho}{3600} \cdot (T_1 - T_2) \cdot n_{av} \cdot V, \tag{3}$$

where
Q – needed heating power for heating incoming air, W;
c_p – specific heat of air, 1008 J/(kgK);
ρ – density of air, 1,23 kg/m^3 (at 12°C – weighed indoor and outdoor temperature);
T_1 – average indoor temperature, °C;
T_2 – average outdoor temperature, °C.

In this case, the tracer gas concentration reduction method is more precise than the constant tracer gas concentration method because, for the second method, the exact amount of CO_2 inflow in the room must be known, which is difficult in this case as the amount of CO_2 exhaled by humans varies in quite a wide range. In this study the first method (tracer gas concentration reduction method) was used whenever possible but in some cases only the second method (constant tracer gas concentration method) could be used. Therefore, the results of the first method were used to determine the amount of CO_2 exhaled by the inhabitant of the room studied. The amount of exhaled CO_2 was chosen in such way that the results using both calculation methods give the same air change rates.

IV. RESULTS

Due to the fact that the air change rate of buildings is affected by the outdoor conditions (in winter, the main criteria is outdoor temperature), all the results are valid in the range of outdoor temperatures, which were measured during the measurement phase of this study (see Fig.2.).

The vertical lines in Fig.2. separate the 7 measurements that were made. The total time of these measurements was 6 full days.

Outdoor temperatures during the measurements were in the range from -2 °C to -12 °C. These kinds of temperatures occur in the coldest part of the winter in Latvia.

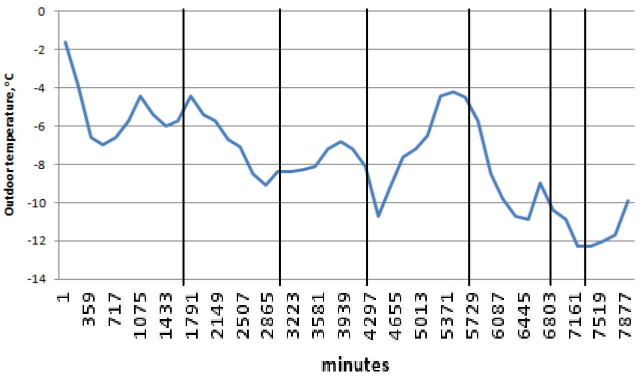

Fig.2. Outdoor temperatures during measurements.

A. *Temperature measurement results*

In Fig.3. the indoor temperatures during the measurements can be seen.

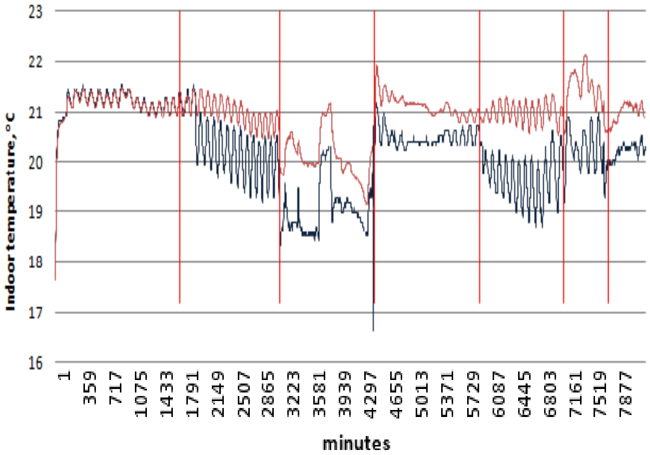

Fig.3. Indoor temperatures during measurements.

In the indoor air temperature measurement chart, two temperature lines can be seen. The upper line is from the temperature logger situated at a height of 0,5 meters and the lower temperature line is from the temperature logger, which was placed on the floor (for the first measurement both temperature loggers were placed at a 0,5 meters height). It can be seen that the temperatures at the floor level are lower than at the height of 0,5 meters. Table I shows the average temperatures in the room and the temperature difference between the two temperatures.

As can be seen from Fig.3. and Table I, the largest temperature differences were more than 1 °C. This kind of temperature difference can lead to discomfort in the room because the temperature distribution is not uniform in the room.

TABLE I
MEASURED TEMPERATURES AND TEMPERATURE DIFFERENCE

Measurement Nr.	**Average air temperature at height of 0,5 meters, ºC**	**Average air temperature on floor level, ºC**	**Temperature difference, ºC**
1.	21,17	Not measured	n/a
2.	21,01	20,15	0,86
3.	20,10	19,05	1,05
4.	21,11	20,49	0,62
5.	20,98	19,70	1,28
6.	21,42*	20,22	1,20
7.	20,97*	20,21	0,76

* higher temperature due to higher internal heat gains during measurement

It can also be seen from Fig. 3. that temperatures are following a sinusoidal line. This kind of temperature behavior can be explained by the correct functioning of the automatic thermostatic valves that have been installed on the radiators in the building. Non-sinusoidal temperature lines can be seen in the 3rd measurement (balcony door in winter ventilation). This is due to the fact that the amount of air inflowing in the room is so large that the installed radiator does not have enough power to heat the incoming air. This was also proven by thermography, which was conducted to measure temperature on the surface of the radiator. With the typical ventilation solution (1st measurement), the average temperature on the radiator surface was 32°C, but in the 3rd measurement, the average temperature on the radiator surface was 55°C, which corresponds to the temperature of the heat carrier in the heating system of the building.

In the fourth measurement air temperature lines for some while are constant. This is because in the maximally reduced air inflow scenario, the thermostatic valves close the radiator in the room and practically no heat energy is sent through the radiator. The average surface temperature on the radiator during this measurement was 22°C.

All indoor air temperature measurements showed that it is possible to ensure satisfactory temperature levels for all ventilation solutions.

B. *Relative air humidity measurement results*

Relative air humidity was also measured. Results of these measurements are shown in Fig. 4.

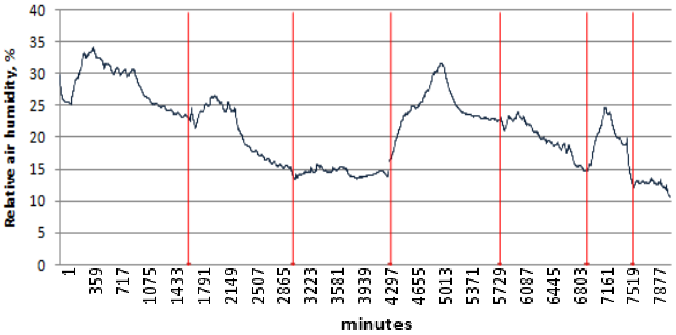

Fig.4. Relative air humidity during measurements.

Indoor air humidity is strongly dependant on outdoor air humidity and outdoor temperature (the colder and dryer the outdoor air, the lower the indoor air humidity). As can be seen, the lowest indoor air humidity is 15% (during the 3rd and 7th measurements). This is due to the increased air change rate during these measurements. The highest air humidity is only 34%, which is the lowest satisfactory air humidity level. This means that during the coldest part of winter in Latvia, the indoor air should be humidified. The person living in the apartment, where the measurements were carried out, complained about a sore throat, which is one of the symptoms of dry air.

From Fig. 4. it can also be seen that during each measurement, the relative air humidity varies. This is because, in the beginning of conducting the measurements, the room had one person in it, but in the middle of the measurement, the person left the room and no more humid air was injected in the room (human breathing humidifies air).

C. *CO_2 measurement results*

The main part of this study was aimed at CO_2 levels in the room, because using the results of CO_2 measurements it is possible to calculate the air change rate in the room and the energy needed to heat inflowing air. CO_2 measurement results can be seen in Fig.5.

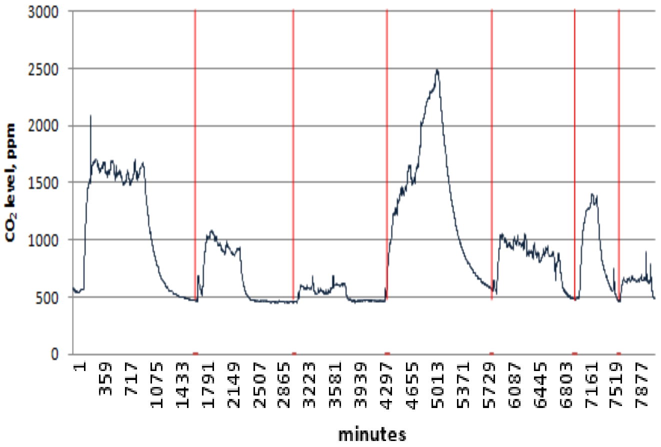

Fig.5. CO_2 levels in the studied room during different ventilation solutions.

From Fig.5. one can see that the CO_2 levels are in the optimal range during all measurements except in the 4th measurement with the maximally-reduced ventilation. It is important to remember that there was only one person in the room during these measurements. In these measurements it can clearly be seen when the person is at home (increasing and stabilized CO_2 levels) and when there is no one in the room (decreasing CO_2 levels).

As mentioned previously, the air change rate was calculated by using two calculation methods. The more exact method, which uses decreasing CO_2 level measurements, was used to determine the air change rate for the 1st, 2nd, 4th, 5th and 6th measurements. For the 3rd and 7th measurements, the less exact method had to be used because there is no phase of measurement, where the CO_2 level in the room would decrease according to the way it is needed for the more exact method (this is because of the rapid air change that occurred during 3rd and 7th measurements). By using the 1st, 2nd and 5th measurements, the amount of CO_2 exhaled while sleeping and by using 6th measurement amount of CO_2 exhaled while awake by the inhabitant of the room studied was calculated. The amount of exhaled CO_2 while sleeping was used to determine the air change in the 3rd measurement, and the amount of exhaled CO_2 while awake was used to determine the air change rate in the 7th measurement (the person in the room was sleeping during the 1st, 2nd, 3rd and 5th measurements and was awake during 6th and 7th measurements). Calculations showed that the CO_2 exhaled while asleep is 13,75 l/h (0,01375 m^3/h) and while awake – 16,9 l/h (0,0169 m^3/h). In a literature review it was found that, during normal activity, humans exhale approximately 400 liters of CO_2 in a 24 hour-period or 16,67 l/h.

By using equations (2) and (3) air change rates for all ventilation solutions were determined.

A sample calculation for the 1st measurement, which uses the first method, is given below:

$$n_{av} = \frac{\ln(1192-460)-\ln(598-460)}{16:47-12:40} = 0{,}41\ h^{-1}$$

As the results from the equation demonstrate, the CO_2 level at 12:40 was 1192 ppm and at 16:47 it had fallen to 598 ppm. The outdoor CO_2 level measurements showed the CO_2 level to be 460 ppm.

A calculation sample for the 3rd measurement, which used the second method, is given as follows:

$$n_{av} = \frac{0{,}01375}{(0{,}000574-0{,}000460)\cdot 25{,}5} = 4{,}73\ h^{-1}$$

As demonstrated in the calculation, the average stabilized CO_2 level in the room during the 3rd measurement was 574 ppm, CO_2 inflow was 0,01375 m^3/h because the person in the room was sleeping.

The results of the air change rate calculations are summarized in Table II.

TABLE II

AIR CHANGE RATES FOR ALL STUDIED VENTILATION SOLUTIONS

Measurement Nr.	**Calculation method**	**Air change rate, h^{-1}**
1.	First method	0,41
2.	First method	1,23
3.	Second method	4,73
4.	First method	0,24
5.	First method	1,19
6.	First method	0,79
7.	Second method	3,49

First method - tracer gas concentration reduction method

Second method - constant tracer gas concentration method

As the figures in Table II illustrate, the air change rate in the studied room varies from 0,24 h^{-1} to 4,73 h^{-1}. As Fig. 5. shows, in this case it is enough with an air change rate that is 0,4 h^{-1} to achieve good air quality. If either window or balcony doors are opened in the winter ventilation mode, the air change rate escalates and the CO_2 levels decrease near outdoor CO_2 levels.

By knowing the air change rate for all ventilation solutions and by using the equation (3) it is possible to calculate the power needed to heat the inflowing air. In this calculation, the outdoor air temperatures were applied according to the average outdoor temperatures from Fig. 2. A sample calculation for the 1st measurement follows:

$$Q = \frac{1008\cdot 1{,}23}{3600}\cdot(21-(-5))\cdot 0{,}41\cdot 25{,}5 = 94\ W$$

The results of all calculations are shown in Table III.

TABLE III

POWER AND COSTS NEEDED FOR HEATING INFLOWING AIR

Measurement Nr.	**Power needed for heating inflowing air, W**	**Costs for heating the inflowing air in measured room (area of room - 10 m^2), Ls/month**
1.	94	3,00
2.	302	9,58
3.	1192	37,97
4.	57	1,81
5.	303	9,62
6.	222	7,06
7.	981	31,16

The calculations show that it is enough to use only 94 W of power for air heating to ensure satisfactory indoor air quality, , but if either window or balcony doors are in the winter ventilation mode – then 10 times more energy is needed.

If the balcony door would stay in the winter ventilation mode for one month and the outdoor conditions would be the same as during the measurements made in this study (basically if the outdoor conditions would be the same as in the three coldest months of winter), then the amount of energy needed to heat inflowing air would be:

$$1192[W]\cdot(30\cdot 24)[hours/month]\cdot 10^{-6} = 0{,}86 MWh/month$$

Since the building is situated in Riga and the heat energy is delivered from AS “Rigas siltums”, then the amount of energy calculated in terms of money (using the heat tariff from June 2010) would be:

$$0{,}86[MWh/month]\cdot 44{,}14[Ls/MWh] = 37{,}97 Ls/month$$

Costs for heat energy for all ventilation modes are shown in Table III. This means that one window or balcony door that is in the winter ventilation mode can cost up to 38 Ls/month. The problem is that in Latvia this type of ventilation solution is very popular. In older buildings this could be a minor problem because the air extraction stacks are old and clogged. But in new buildings air extraction stacks are clean and make it possible for the air to circulate through the building. If a proper ventilation solution would be appplied (1st ventilation solution) in the room studied, the costs for heating inflowing air would be 2,99 Ls/month. Furthermore, as Fig. 3. shows, in this case the indoor air temperature would also be higher than in the case when 37,97 Ls/month are spent to heat the inflowing air.

V. CONCLUSIONS

This study showed that in the building studied the indoor air quality can vary in quite a wide range. During the coldest part of the heating season it is advisable to humidify indoor air because the relative humidity can go down as much as 15%, which can cause problems and illness to human breathing organs.

Indoor air temperatures in the building studied for all ventilation solutions were satisfactory (lower temperatures were measured when the window and balcony doors were in the winter ventilation mode).

Satisfactory indoor CO_2 levels were measured for all but one ventilation solution. As expected, if ventilation is drastically reduced, CO_2 levels exceed the recommended levels. But even in that case, there is a very small possibility of any ill effects being caused as a result of increased CO_2 levels in the room.

If the windows or balcony doors are opened in the winter ventilation mode, the costs for heating the inflowing air can reach up to 38 Ls/month.

The results should be similar for new apartment buildings that are built in Latvia in the last 5 to 7 years.

The results of this study suggest that there is a need for mechanical ventilation systems in newly-built apartment buildings because improper choice of a ventilation solution in a naturally-ventilated building can lead to increased heat consumption and higher heating payments in these buildings.

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Gatis Žogla, Andra Blumberga. Jaunas daudzdzīvokļu ēkas vēdināšanas risinājumi un to ietekme uz ēkas siltumenerģijas patēriņu un telpas gaisa kvalitāti

Siltumenerģija ēkās tiek zaudēta divos veidos – siltuma vadīšanas ceļā caur norobežojošajām konstrukcijām un gaisa apmaiņas (infiltrācijas) dēļ. Latvijā celto jauno ēku norobežojošās konstrukcijas ir siltinātas, bet aukstā gaisa infiltrācija parasti netiek ierobežota vai samazināta līdz normatīvos noteiktajam līmenim. Šī iemesla dēļ jaunās daudzdzīvokļu ēkas var zaudēt daudz siltumenerģijas tieši gaisa apmaiņas un infiltrācijas dēļ.

Šis pētījums tika veikts jaunā daudzdzīvokļu ēkā. Apskatīti dažādi vēdināšanas risinājumi (visi no kuriem var tikt un tiek reāli izmantoti) un veikti mērījumi. Izvēlētajā ēkas telpā tika veikti gaisa kvalitātes (gaisa temperatūra, relatīvais mitrums, CO_2 koncentrācija) mērījumi, kas deva iespēju noteikt papildus siltumenerģijas zudumus pārvēdinātu telpu dēļ.

Pētījuma rezultāti parādīja, ka pārvēdinātu telpu dēļ aukstākajos ziemas mēnešos no 10 m^2 lielas telpas var rasties siltumenerģijas zudumi 0,86 MWh/mēnesī jeb 38 Ls/mēnesī apjomā. Šī pētījuma rezultāti arī paskaidro, kāpēc ēku iedzīvotāji bieži vien sūdzas par neapmierinoši zemu telpu gaisa temperatūru, kaut gan tai pašā laikā radiatori telpās ir karsti un maksājumi par siltumenerģiju ļoti augsti.

Pētījuma laikā tika atklāts, ka būtiska problēma ir telpu relatīvais gaisa mitrums ziemas aukstākajos mēnešos. Mērījumi parādīja, ka telpu gaisa relatīvais mitrums var nokrist līdz pat 15%. Lai izvairītos no elpceļu slimībām, ziemas aukstākajos mēnešos nepieciešams veikt telpu gaisa mitrināšanu.

Šī pētījuma rezultāti ir piemērojami lielākajai daļai jauno dabiski ventilēto daudzdzīvokļu ēku Latvijā.

Гатис Жогла, Андра Блумберга. Решения системы вентиляции для нового многоквартирного здания и её влияние на энергопотребление и качество воздуха в помещениях

Потери теплоэнергии в зданиях происходят двумя способами – путём теплопроводимости через ограничивающие конструкции и из-за обмена воздуха (инфильтрация). В Латвии ограничивающие конструкции новых зданий утепляют, а инфильтрацию холодного воздуха обычно не ограничивают, и она превышает уровень, допущенный нормативными актами. По этой причине новые многоквартирные дома теряют много теплоэнергии именно в результате обмена воздуха и инфильтрации.

Это исследование было проведено в новом многоквартирном здании. Рассматривались разные решения вентиляции (все, которые могут быть и используются в практике) и проводились измерения. В выбранном здании проводились измерения для оценки качества воздуха (температура воздуха, относительная влажность, концентрация CO_2), что позволило оценить дополнительные потери тепла в результате проветривания помещений.

Результаты исследования показали, что из-за проветривания в холодные зимние месяцы в помещениях, площадь которых больше 10 m^2, теплопотери могут достигнуть 0,86 MWh/месяц или 38 Ls/месяц. Результаты этого исследования также объясняют, почему жители зданий часто жалуются на неудовлетворительно низкую температуру воздуха в помещениях в то время, когда радиаторы в помещениях горячие, и счета за теплоэнергию очень высокие.

Во время исследования было выявлено, что значительную проблему создаёт относительная влажность воздуха в холодные зимние месяцы. Измерения показали, что относительная влажность воздуха может снизиться до 15%. Для того, чтобы избавиться от болезней дыхательных путей, в холодные зимние месяцы необходимо увлажнять воздух в помещениях. Результаты этого исследования относятся к большинству новых зданий в Латвии с искусственной вентиляцией.