Indoor climate and energy consumption in residential buildings in Estonian climatic conditions

TEET-ANDRUS KOIV[1], HENDRIK VOLL[1], ALO MIKOLA[1], KALLE KUUSK[1], MIKK MAIVEL[1]

[1]Department of Environmental Engineering,

Tallinn University of Technology

Ehitajate tee 5, 19086 Tallinn

ESTONIA

teet.koiv@ttu.ee; hendrik.voll@ttu.ee

Abstract:- Investigation shows that in apartment buildings with passive stack ventilation the indoor air quality (IAQ) changes greatly. In the investigated apartment building the relative humidity level in bedrooms of different apartments varied greatly, from 20 to 72% in the autumn period. In the winter period the RH maximum reduces to 55%**.** High relative humidity is accompanied by problems of mould and a very low relative humidity level causes an unpleasant feeling when people get up in the morning. Greatly varying was also the morning CO2 level in bedrooms of different apartments, from 1000 ppm to 4200 ppm, the latter being quite critical. Higher levels of CO2 concentrations were first of all in bedrooms with renovated windows and with doors closed. By simulation the smallest is the energy consumption in the case of supply-exhaust ventilation. The results of the simulation of indoor climate are close to the results of the data recorded. The indoor climate of residential buildings is greatly affected by the arrangement of air change which in its turn is influenced by the external climate of the country.

*Keywords:-*IAQ, Energy conservation, Carbon dioxide, RH, Air change determination

1 Introduction

The need to increase the energy efficiency of buildings, while providing satisfactory indoor environmental quality, has become a key factor in the building sector. Energy conservation and IAQ are two sides of the same coin. To successfully manage IAQ and energy, both must have the same priority throughout the life of a home.
Problems of energy conservation and indoor climate in residential buildings and the importance of both of them have been dealt with by many authors, such as Ken-ichi Kimura [1], Walker [2], Koiv [3], [4], Tali [5].

The report [6] treats of the joint effect of the IAQ and the characteristic aspects accompanying them.
To analyze energy consumption in residential buildings extensive use is made of simulation programs. The above–mentioned authors have made the following investigations [7], [8], [9]. To determine the air change in naturally ventilated rooms with people in them several authors Koiv [3], Stravova [10] have used a change in the CO2 concentration in the air of the room. The IAQ investigations were carried out in old type panel apartment buildings in two stages: in the autumn period with an external temperature of -3…+9°C and in the winter period with an external temperature -8…
-20°C. The investigations referred to serious IAQ problems, first of all in bedrooms were people spend quite a lot of time in the night. CO2 levels have been recorded and compered in different cases. Simulations of the CO2 and RH levels have been made with the software IDA ICE and the results compared with the data recorded.

2 Method

2.1 The carbon dioxide concentration and air change

Suppose that initial carbon dioxide concentration in the air of the room before the beginning of the human activity is C_o. As the human activity starts, the carbon dioxide level begins to rise with an intensivity of m. Air change in the room is relatively small. The distribution of temperature in rooms is uniform (conditions are isothermal), supply and exhaust airflows are equal. Carbon dioxide concentration in inflow air is C_v and in outflow air C.

Proceeding from these conditions we can write the balance equation

$$m\cdot d\tau + L\cdot C_v\cdot d\tau - L\cdot C\cdot d\tau - V\cdot dC = 0 \qquad (1)$$

From equation (1)

$$dC = -d\left(\frac{m}{L} + C_v - C)\right) \qquad (2)$$

By integration of equation (1)

$$\frac{L}{V}\cdot\tau = -\ln\frac{\frac{m}{L}+C_v-C}{\frac{m}{L}+C_v-C_o} \qquad (3)$$

where
m - carbon dioxide generation in room ,
L - air change in room,
V - volume of room or design volume,
C_v - carbon dioxide concentration in external air (in supply air),
C - carbon dioxide concentration in room air (in exhaust air),
C_o- carbon dioxide concentration in the air of the room at the beginning of the human activity,
τ - time.

From equation (3) we can deduce the basic equation for carbon dioxide concentration C at time moment τ

$$C = C_v + \frac{m}{L} - \left(C_v + \frac{m}{L} - C_o\right)\cdot\left(e^{-\frac{L}{V}\cdot\tau}\right) \qquad (4)$$

By carbon dioxide concentration (in external air, in room air at the beginning of the human activity and in room air at time moment of τ), carbon dioxide generation rate in room and parameters of room, by formula (3 or 4) it is possible to determine air change in a room.

3 Results

3.1 Air change and indoor climate determination

Parameters of indoor climate in bedrooms of renovated apartment buildings are another essential topic of investigation. A lot of attention is sometimes paid to energy saving in renovating the apartment buildings, but the importance of indoor climate is not considered sufficiently. Investigations have shown that from the point of view of indoor climate one of the rooms that cause IAQ problems is the bedroom, in which by the waking-up time the CO2 concentration reaches its maximum value. It often happens that in residential buildings renovated are the envelope elements and the heating system, but the ventilation has been left as it was.

The object of the investigation was a 72-apartment typical 9-storey apartment building, built with prefabricated concrete elements in which 45% of windows had been changed. The end walls had been insulated up to U-value 0.3 W/(m^2K). The building has natural passive stack ventilation with vertical channels. The heating system had been renovated and provided with the heat consumption measuring system on the level of heatig coils. For dataloggering RH, indoor air temperature and CO2 data Hobo loggers U012-013 were used and for measuring the CO2 levels Carbon Dioxide Monitor Telaire 7001 were used. The IAQ investigations were carried in 16% of the apartments. Air change in bedrooms of different apartments was calculated by the measured CO2 concentration data in them by equation (3).

3.2 IAQ investigation in the autumn period

The results of the calculation on air flow rates in the autumn period (column 2) investigated bedrooms are presented in Table 1. For the check up of the results the air flow rates in apartments were measured with SwemaFlow.

In addition to air change data in Table 1 the maximum CO2 levels are presented.
Table 1 shows that in the bedrooms of different flats the difference in air change is very great, varying from 0.3 to 6.4 L/s per person. It should be pointed out that in apartments with unrenovated windows the air change is considerably better than in bedrooms with new windows.

Results of recording CO2 concentrations, RH and indoor temperature in the bedrooms of the apartments with unrenovated windows are presented in Figs. 1, 2 and 3.

Table 1. Results of determining air change and the maximum CO2 concentration in bedrooms of the 9-storey apartment building at night-time in the autumn period

Apartment	Air change, L/s per person	Maximum level of CO_2 concent-ration, ppm
1	1.2	3698
8*	0.6	1967
21	2.1	2724
25	1.9	1963
31*	1.2	2557
36	1.7	2325
54	0.4	2364
58	0.3	3999
69	1.0	3278
71	2.0	2761
72*	6.4	1104

*Windows unrenovated

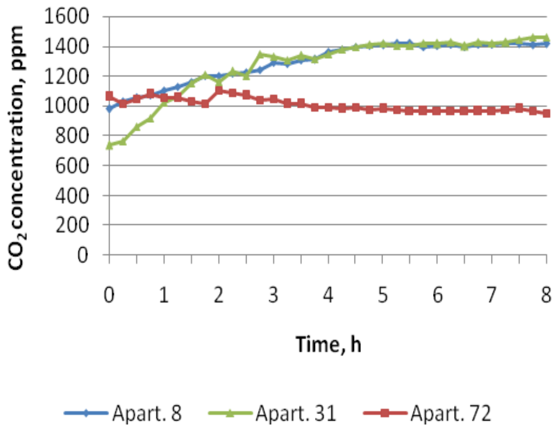

Fig.1 Nightly change of the CO2 concentration in bedrooms with old windows

From Fig.1 we can see that in bedrooms with old windows the CO2 level is below 1500 ppm and in one of them about 1000 ppm. Consequently the air change is on a good (apart 72) or more or less acceptable level. In those bedrooms the CO2 level does not exceed the maximum level 1500 ppm allowed by the Indoor Climate standard [11].

Figs. 2 and 3 presents changes in RH and indoor air temperature in bedrooms with old windows.

In apartments 8 and 72 the RH exceeded by about 5% the allowed maximum level 45% for the cold period, which is not dangerous from the point of view of a rise in mould.

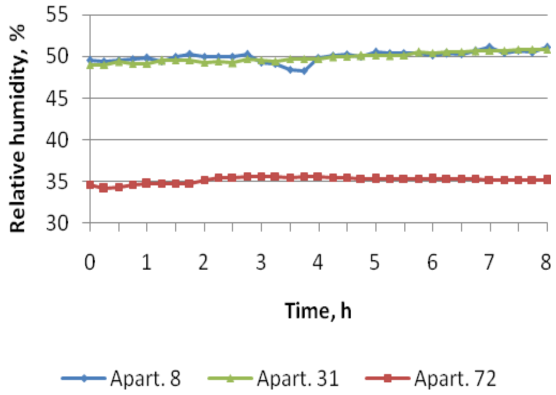

Fig.2 Changes in the relative humidity in bedrooms with old windows.

Figs. 4, 5 and 6 present the results of recording the CO2, RH and indoor air temperature in bedrooms of apartments with renovated windows. In Fig. 4 we can see that in all the bedrooms investigated the morning CO2 level exceeded the permitted level 1500 ppm [11], maximally amounting to 4200 ppm.

Fig.5 shows that in bedrooms with renovated windows the relative humidity level exceeds the maximum value, 45% the standard [11] allows for the cold period and amounts to a highly critical level 72%.

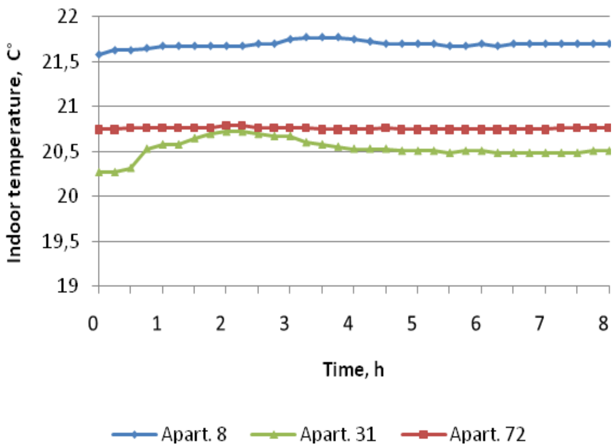

Fig.3 Indoor temperature in bedrooms with old windows

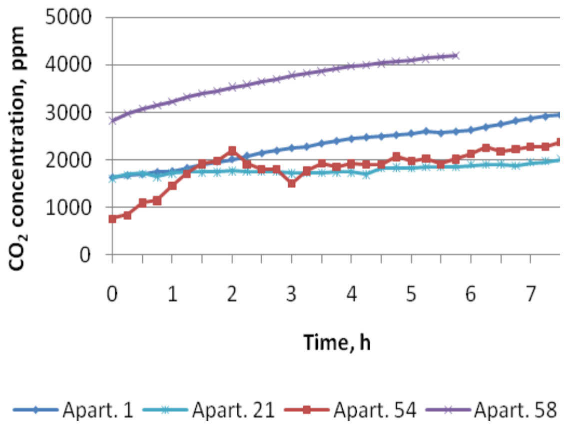

Fig.4 Nightly change of the CO2 concentration in bedrooms with new windows

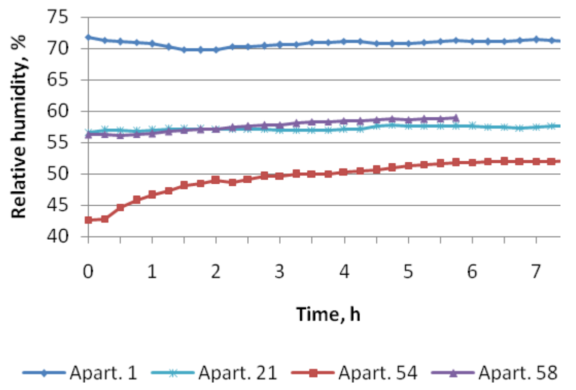

Fig.5 Nightly relative humidity level in bedrooms with renovated windows

In the conditions of such a high RH the rise of mould is practically inevitable.

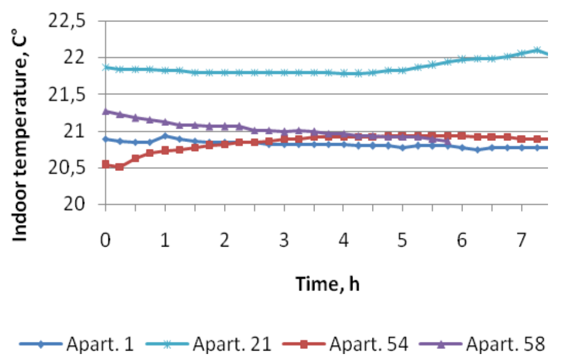

Fig.6 Indoor temperature in bedrooms with renovated windows

Figs. 3 and 6 show that the indoor temperature in the bedrooms investigated varied from 20 to 22°C, which is acceptable.

Fig.7 shows the cumulative distribution of the CO2 concentration in the bedrooms of apartments investigatrd in the autumn period.

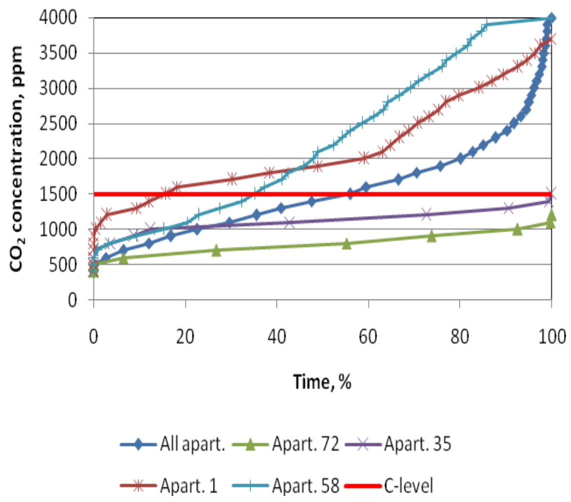

Fig.7 The cumulative distribution of the CO2 concentration in the bedrooms in the autumn period

Of the apartments investigated only 2 apartments (35 and 72) corresponded to the maximum permitted CO2 level – 1500 ppm (level C). Only apartment 72 corresponded to the permitted level 1250 ppm (level B). There was no apartments corresponding to level A (1000 ppm). In the autumn period the CO2 concentration remained below 1500 ppm 56%, below 1250 ppm 38% and below 1000 ppm 23% of the time of the measuring period.

The formation of the indoor climate in bedrooms at night-time is greatly affected by the position of the bedroom door, whether it is open or closed. Fig. 8 shows the comparison of the changes in the CO2 concentration in 1-person bedrooms in the case of open or closed doors.

Fig.8 shows that in apartments (69 and 72) in bedrooms with an open door the CO2 level does not practically change during the night remaining below 1000 and 1500 ppm respectively, because of the interfusion of the CO2 with the air of the neighbouring rooms. But in bedrooms with closed doors the CO2 concentration rises considerably reaching 2200 ppm in apartment 39 and 3000 ppm in apartment 1.

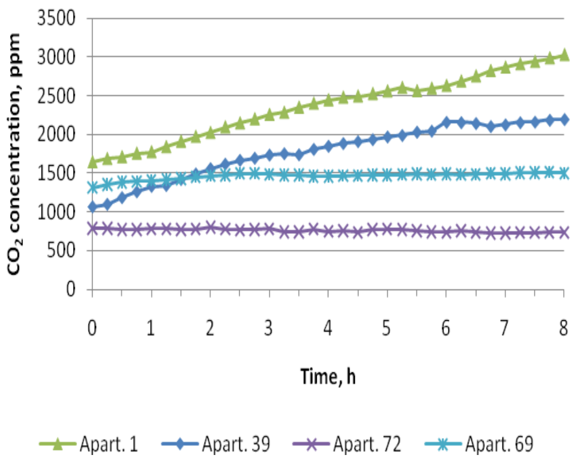

Fig.8 Comparison of the changes in the CO2 concentration in 1-person bedrooms in the case of open or closed doors: in apartments 1 and 39 the doors are closed, in apartments 72 and 69 - open

3.2 IAQ investigations in the winter period

In the winter period investigation were carried out at low external air temperatures from -8 to -20°C. Due to that the passive stack ventilation functioned more effectively. However old windows were tightened and ventilation grills were partly cosed.

Table 2 presents the air change determined on the bases of the measured CO2 values and the maximum CO2 concentration in different apartments.

Table 2. Air change values per person and the maximum CO2 concentration values in bedrooms

Apart-ment	Air change rate, l/s per person	Maximum concentration of CO_2, ppm
1	1.3	2642
8*	1.1	1244
17*	0.8	2946
23	3.6	3242
25	1.5	1845
33	1.5	3216
39	2.2	2460
54	0.4	3293
58	0.5	2825
71	2.7	2224
72*	7.0	1337

Fig.9 presents the comparison of the air change in the winter and the autumn periods. The figure shows that in the winter conditions the air change is better which is natural in the conditions of the passive stack ventilation. An exeption is apartment 25 where the situation is the reverse owing to the fact that the windows are tightened and the ventilation grills are partly closed in the conditions of low external temperatures.

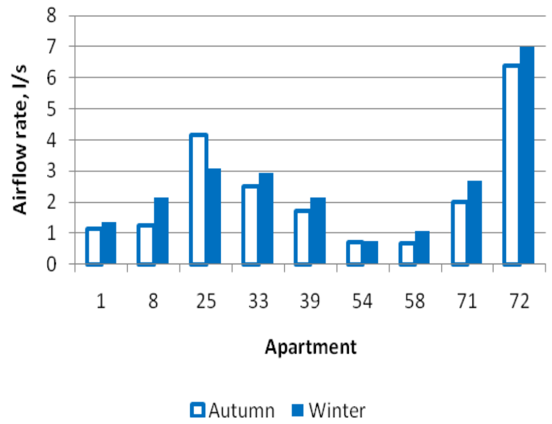

Fig. 9 Comparison of the air change in the winter and the autumn periods in different apartments

Results of recording CO2 concentrations in the bedrooms of the apartments with unrenovated windows in the winter period are presented in Figs. 10, and 11.

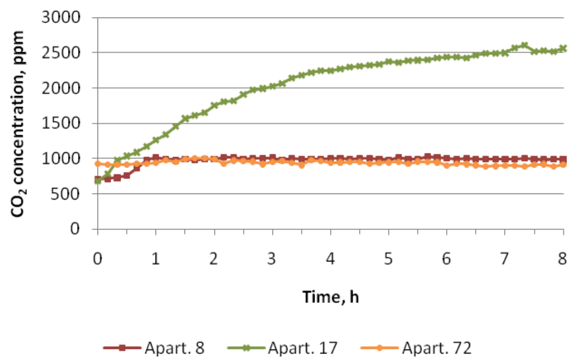

Fig.10 Nightly change of the CO2 concentration in bedrooms with old windows

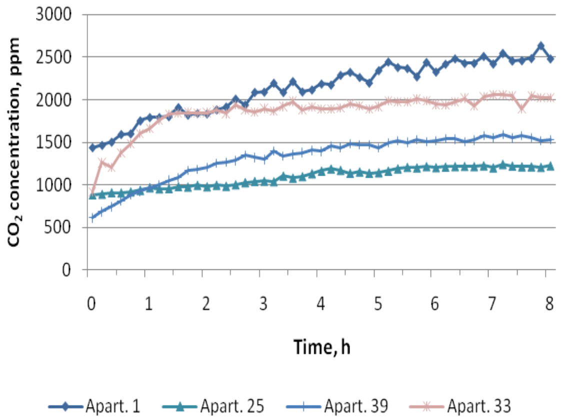

Fig.11 Nightly change of the CO2 concentration in bedrooms with new windows

From Figs 10 and 11 we can see that in the winter period in bedrooms both with old and new windows the IAQ is considerably better than in the autumn period. But in some bedrooms the CO2 concentration at night exceeds 1500 ppm and reaches up to 2500 ppm.

Fig.12 shows the cumulative distribution of the CO2 concentration in all the bedrooms of apartments investigated during the autumn period.

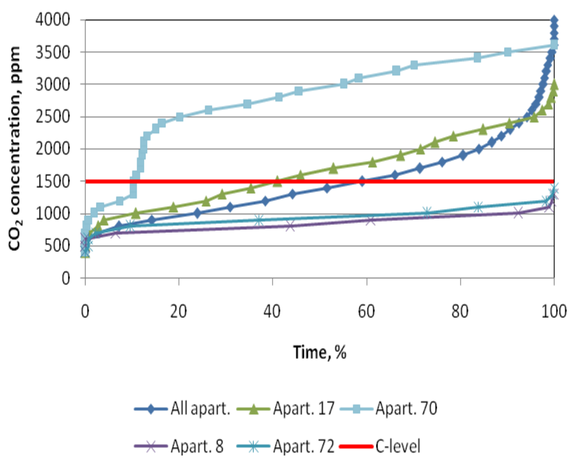

Fig.12 Cumulative distribution of the CO2 concentration in the bedrooms of apartments investigatrd in the winter period

In the winter period of the apartments investigated only 2 apartments (35 and 72) corresponded to the maximum permitted CO2 level – 1500 ppm (level C). Only apartment 72 corresponded to the permitted level 1250 ppm (level B). There was no apartments corresponding to level A (1000 ppm). In the winter period the CO2 concentration remained below 1500 ppm 59%, below 1250 ppm 41% and below 1000 ppm 24% of the time of the measuring period.

Figs. 13 and 14 present changes in RH in bedrooms with old and new windows in the winter period.

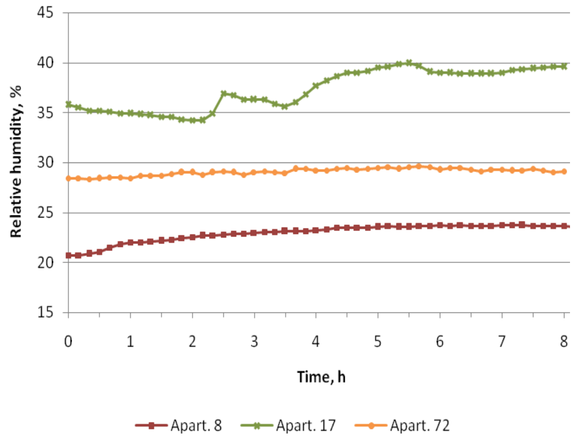

Fig.13 Nightly relative humidity level in bedrooms with old windows

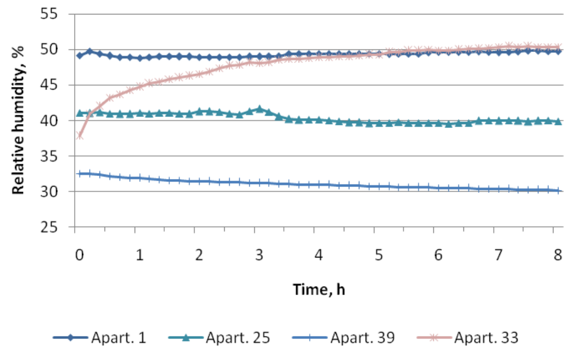

Fig.14 Nightly relative humidity level in bedrooms with renovated windows

Owing to a decrease in the moisture content of the external air and an increase in air change (due to the stack effect) the RH in the majority of the apartments remains within the limits of 25-45% foreseen by the standard [11], amounting to 50% in 2 apartments and remaining below 25% in one apartment, but does not fall below the critical 20%.

Figs. 15 and 16 shows the comparison of the changes in the CO2 concentration and RH in 1-person bedrooms in the case of open or closed doors.

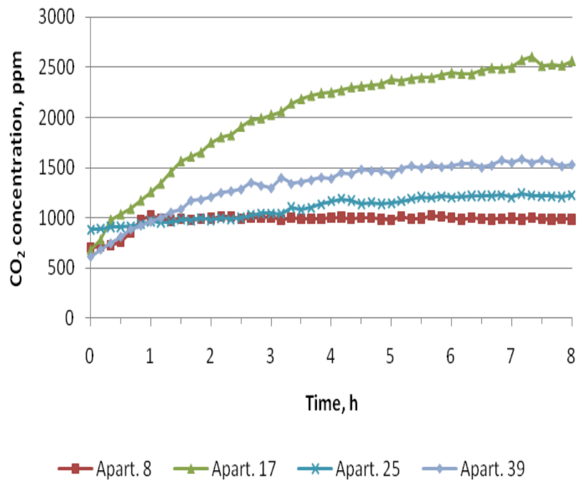

Fig. 15 Comparison of the changes in the CO2 concentration in 2-person bedrooms in the case of open or closed doors: in apartments 39 and 17 doors closed, in 8 and 25 – open

In Fig. 15 we can see that in bedrooms with closed doors the nightly CO2 concentration considerably rises in the conditions of passive stack ventilation.

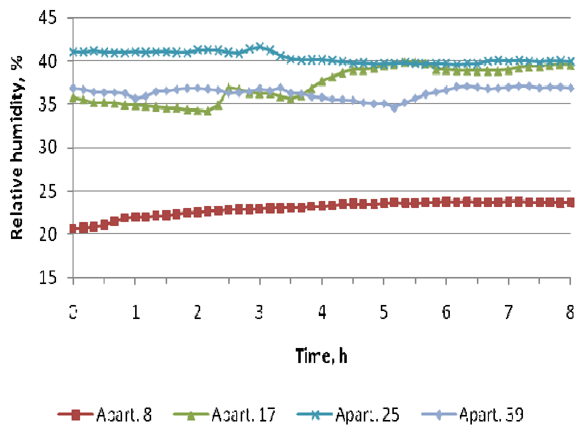

Fig.16 Comparison of the differences in the level of RH in 2-person bedrooms in the case of open or closed doors: in apartments 39 and 17 the doors are closed, in apartments 8 and 25 – open

In Fig. 16 we can see that changes in the RH level are small in bedrooms with both closed and open doors.

Fig.17 and 18 present changes in indoor tempe-rature in bedrooms with both old and new windows.

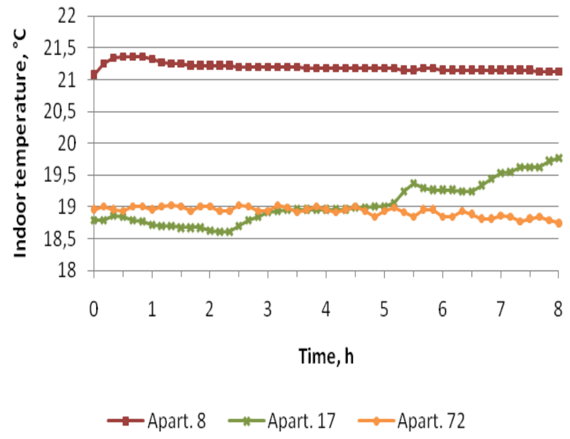

Fig.17 Indoor temperature in bedrooms with old windows

In the winter conditions the indoor temperatures are lower than those of the autumn period.
In several apartments the temperature was below 19°C and fell even to 16°C.
The low 16-17°C temperatures in the winter conditions are caused by the wish of people with low income to economise on the heating expenses. Unfortunately that saving was amplified by the distribution of the heating expenses applied: the permanent cost 30% and the varying cost 70% (i.e the cost for the heat consumed) in the conditions of measuring the heating expenses by the heating coils.

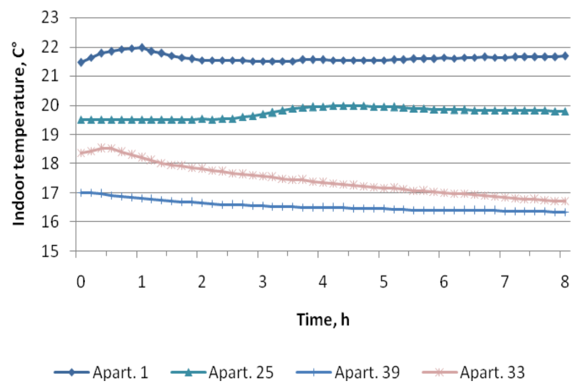

Fig.18 Indoor temperature in bedrooms with new windows

It should be pointed out that an investigation of energy consumption, carried out by TUT in 2009 by dynamic simulation showed that in old panel apartment buildings even switching off the heating in a apartment decreases the heating expenses of the whole apartment building relatively little: depending on the location of the apartment

15-30% [13]. This is due to an extensive heat trancfer between the unheated apartment and the neighbouring apartments. At the same time the temperature in the apartment decreased maximally by 3-4°C.

Thus the distribution of the heating expenses applied is wrong and should be at least the reverse: i.e. the permanent expenses 70-75% and the varying expenses 30-25% or even less, because no heating expenses for the common rooms are taken into account in the case of heat measuring in heating coils.

Such a wrong distribution of heating expenses causes social tension between the inhabitants and contributes to the low quality of the indoor climate in apartments, because a number of apartments decrease the air change to deminish the heating expenses.

3.3 Simulations of energy consumption and indoor climate

Analysis of energy consumption and the CO2 concentation simulations was made by the simulation program IDA ICE on the basis of recorded data.
Energy consumption in an apartment building with different ventilation systems is presented in Table 3. It can be seen that in the case of passive stack ventilation the energy consumption for air change is about 2 time smaller than by using mechanical exhaust ventilation.

Table 3. Energy consumption in an apartment building with different ventilation systems

	Energy consumption for heating and air change MWh/a
Natural ventilation, air change n=0.2	651
Mechanical exhaust ventilation, air change n=0,5	774
Supply-exhaust ventilation with heat recovery unit, air change n=0.5	622

The smallest is the energy consumption in the case of supply-exhaust ventilation with heat recovery unit.

Figs. 19, 20 and 21 present the results of the simulation of the CO2 concentration and the comparison of them with the results measured in different apartments.

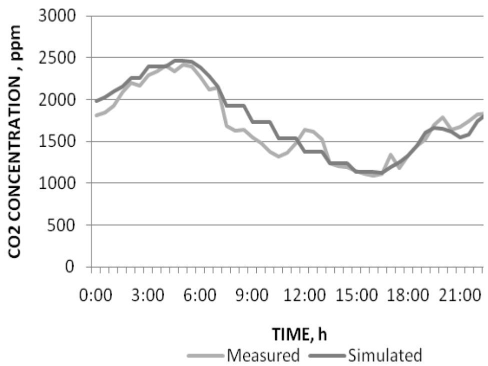

Fig.19 Comparison of the changes in the CO2 concentration in 1-person bedroom in the case of simulation and measurements in the winter period (apartment 1)

It must be pointed out that the results of the simulation are very close to the results of the measurements in partments 1 and 17. In apartment 21 the nightly maximum CO2 concentration by simulation is higher than the results measured.

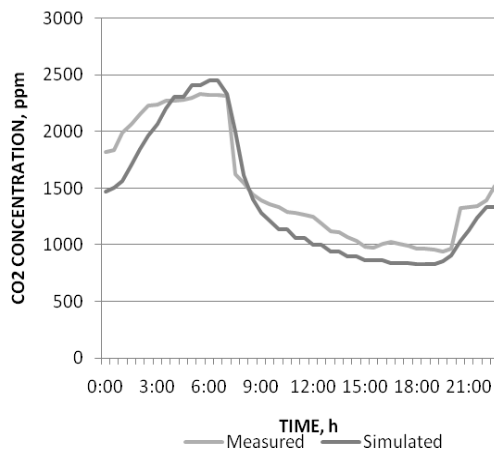

Fig.20 Comparison of the changes in the CO2 concentration in a 2-person bedroom in the case of simulation with the results measured in the winter period (apartment 17)

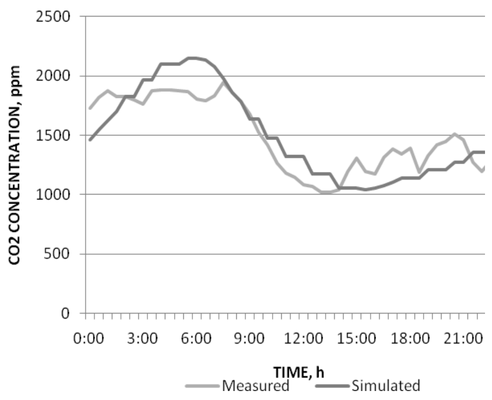

Fig.21 Comparison of the changes in the CO2 concentration in 2-person bedroom in the case of simulation with the results measured in the winter period (apartment 21)

Figs. 22, 23 and 24 present the results of the simulation of the RH level in bedrooms and the comparison of them with the results measured in different apartments.

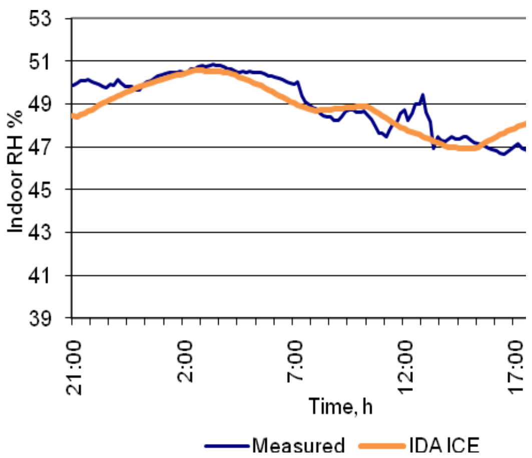

Fig.22 Comparison of the changes in the RH level in a 2-person bedroom in the case of simulation with the results measured in the winter period (apartment 1, the door is open)

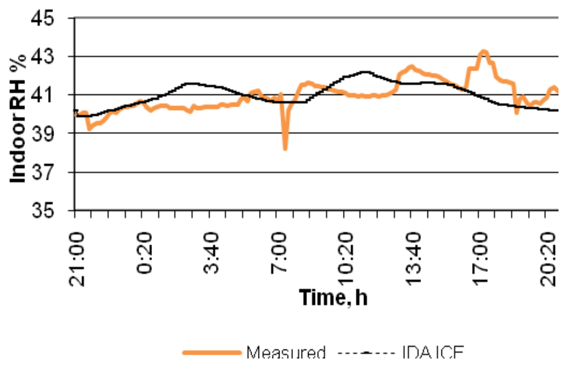

Fig.23 Comparison of the changes in the RH level in a 2-person bedroom in the case of simulation with the results measured in the winter period (apartment 25, the door is open)

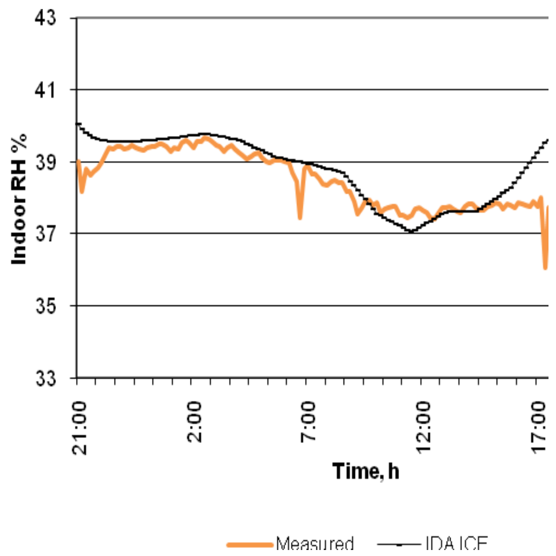

Fig.24 Comparison of the changes in the RH level in a 1-person bedroom in the case of simulation with the results measured in the winter period (apartment 71, old windows)

From Fig. 22, 23 and 24 we can see that if we know the nunber of the people, the profile of their presence and the data on air change, it is relatively easy to determine the RH levels of the rooms by simulation.

4 Conclusions

The investigation shows that in apartment buildings with passive stack ventilation the IAQ changes greatly. In the autumn period the level of indoor temperature 20…22°C can be considered quite

normal, but the relative humidity level in bedrooms of different apartments varied greatly from 35 to 72%. It must be remarked that high relative humidity is accompanied by problems of mould. Greatly varying was also the morning CO2 level in bedrooms of different apartments, from 1000 ppm to 4200 ppm, which is quite critical. Higher levels of CO2 concentrations were first of all in bedrooms with renovated windows.
In winter conditions due to higher intensivity of the passive stack ventilation the CO2 concentration in bedrooms is somewhat lower, yet at night-time it reaches 2500 ppm and during all the period of measuring 3200 ppm.
In the winter period no exessive RH level was observed, but in some apartments the RH level was below 25% which is too low.

Low temperatures (in some apartments even 16°C) in the winter conditions are caused by the wish of people with low income to economise on heating expenses. This is contributed to by the incorrect sharing of the varying heating expenses in the case of measuring heat by heating coils. In the apartments of people with low income causes a considerable deterioration of the IAQ because people close the openings of the inflow of external air.
Such a wrong distribution of heating expenses causes social tension between the inhabitants owing to great differences in heating expenses.

By simulation the smallest is the energy consumption in the case of supply-exhaust ventilation with heat recovery. It should be pointed out that the results of the simulation of indoor climate (CO2 concentration and RH level) are relatively close to the results of the measurements.
It should be pointed out that indoor climate of residential buildings with passive stack ventilation is greatly affected by the arrangement of air change which is influenced by the external climate of the country.

References:

[1] Ken-ichi Kimura. Relationship between energy conservation in buildings and indoor air quality. *Indoor air quality*, 2003.
[2] A.Walker. *Natural Ventilation*. National Renewable Energy Laboratory, March, 2008. http://www.wbdg.org/resources/naturalventilation.php.
[3] T.-A.Koiv. Indoor climate and ventilation in Tallinn school buildings. *Proc. Estonian Acad. Sci. Eng.*, 2007, 13, 1, 17-25.
[4] T.-A.Koiv, H.Voll, M.Rebane. Indoor climate in education and residential buildings. *The International Conference in Sustainable Development in Building and Environment.* Chongqing 28–30 October, China, 2009, 2.
[5] T.-A.Kõiv. (2008). Indoor climate and ventilation performance on top floors of typical old-type apartment buildings. *Estonian Journal of Engineering*, 14, 17 – 28.
[6] M.Tali. *Indoor climate and energy consumption in panel apartment buildings*. Masters theses, TUT, 2009, Estonia.
[7] *Energy Conservation and Indoor Air Quality: Benefits of Achieving Both in Homes*, January 2009. http://www.aerias.org/uploads/IAQ%20Energy%20Homes%20FINAL.pdf
[8] M. Maivel, K. Kuusk. Energy consumption and indoor climate analysis in detached houses. *2nd WSEAS International Conference on Urban Rehabilitation and Sustainability*, Morgan State University, Baltimore MD, USA, November 7-9, 2009, WSEAS, 2009,
[9] T. A. Kõiv, A. Hani, T. Kalamees. *Määruse "Energiatõhususe miinimumnõuded" täiendav analüüs*, TUT, 2010, 118p.
[10] Stavova, P., Melikov, A.K., Sundell, J. A new approach for ventilation measurement in homes based on CO_2 produced by people. *17th Air Conditioning and Ventilation Conference* 2006, May 17-19, 2006, Prague, pp291-296.
[11] EVS 839. 2003. Indoor climate. Estonian Centre for Standardisation.
[1 [12] EN-15251. 2007. *Indoor environmental input parameters for design and assessment of energy performance of buildings- addressing indoor air quality, thermal environment, lighting and acoustics*. CEN.
[13] E.Seinre. *Energy consumption analysis of an apartment building with BSIM simulation software.* Masters theses, TUT, Tallinn, 2009.
[14] K. Kuusk. *Energy consumption and indoor climate simulation of apartment buildings*. Masters theses, TUT, 2009, Estonia.