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Indoor climate and ventilation performance on top floors of typical old-type apartment buildings

Teet-Andrus Kõiv

Department of Environmental Engineering, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia; teet.koiv@.ttu.ee

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Abstract. The article gives a survey of the basic parameters of indoor climate in buildings. The main purpose of heating and ventilation systems is to guarantee a healthy and comfortable environment for the occupants. Dependence of the performance of the ventilation system on envelope elements and heating system in top-floor apartments of typical old-type apartment buildings is analysed. The results of monitoring indoor air temperature, relative humidity and CO_2 concentration are presented. Different solutions for improving air change in top-floor apartments of old-type buildings are considered.

Key words: indoor climate, air change, mould, ventilation.

1. INTRODUCTION

Indoor climate includes physical parameters of air (temperature, humidity, air velocity, noise), microbiological factors (mould, fungi and spores), chemical factors (organic compounds, dust, carbon dioxide, etc.) and psycho-social aspects.

Factors that influence indoor climate of residential buildings are [1]:

– usage and maintenance of the building,
– human activity and its results,
– pollutants emission from building and finishing materials,
– furniture,
– used equipments,
– cleaning and maintenance means,
– parameters and quality of external air (pollen, spores, bacteria, etc.).

According to the Estonian standard of Indoor climate [2], in winter conditions optimal indoor temperature in residential buildings is 22 °C, relative humidity from 25 to 45% and concentration of carbon dioxide until 1500 ppm. The latter guarantees the minimum air change of 5 l/s per person. Recommended design values of the indoor operative temperature for buildings of different comfort categories (winter season) are [3]:

A (excellent)	21 °C
B (good)	20 °C
C (satisfactory)	19 °C

The indoor humidity also affects the comfort of people. High relative humidity brings about the growth and spread of microbes. With high relative humidity the secretion of pollutants of building materials increases [4], low relative humidity increases static electricity. In apartments with very low air change, high relative humidity is a problem. An increase in air change essentially decreases relative humidity in apartments.

Mould spores are everywhere around us. They need only humidity, food and heat for evolution. Very good conditions for their development arise if the relative humidity is close to 70% and the indoor temperature is a little higher than normal [5,6]. Mould formation is possible with lower relative humidity if the temperature of the indoor surface of the external wall is low. The major causes of mould growth are condensation of moisture on surfaces due to excessive humidity, lack of ventilation or low temperature [7]. If in winter conditions the relative humidity of the air is close to 60%, the formation of mould on cold surfaces is usual.

In the top-floor apartments of multi-storey apartment buildings with natural ventilation the air change is typically very low. The situation worsens drastically after the windows are changed. In partly renovated apartment buildings problems with low air change often arise. In buildings put up before the last 15 to 20 years, or which have been retrofitted and which do not feature a mechanical ventilation system, air change rates between 0.01 and 0.5 h^{-1} were measured in apartments with windows closed. In the bedrooms of such buildings with doors and windows closed, the CO_2 concentrations of up to 4300 ppm were measured, whereby the limit 1500 ppm [8] was exceeded.

It should be remarked that the carbon dioxide, produced by people, can be used as a natural tracer gas for ventilation measurements [9]. A new approach, based on the analysis of metabolic CO_2 concentrations, obtained during continuous monitoring in homes, has been introduced as “the CO_2 method” [10].

The main purpose of heating, ventilation and air-conditioning systems is to provide a healthy and comfortable environment for the occupants of the spaces. Indoor air quality has also an economic impact. After the energy crisis, there were savings in spite of increased ventilation rates and the increased energy use this entailed [11]. Occupant behaviour may have a considerable influence on the yearly energy efficiency of ventilation systems. The energy efficiency depends, among others, on the flow-rate settings chosen by the occupants and on the way they use natural ventilation openings [12].

Unlike in Estonia, Finish residential buildings have a relatively good air change rate. The measurements show that the value of the recommended air change rate 0.5 l/s can be attained in 90% of the houses. The recommendation for minimum air change rate in the Finnish building code is 6 l/s per person. In 60% of the measured two-person bedrooms of the houses, the recommended air change rate was achieved [13].

The thermal environment and air quality in buildings affect occupants' health, comfort and performance. Today the heating, ventilating and air-conditioning (HVAC) of buildings is designed to provide a uniform living environment. In apartment buildings, different ventilation solutions are possible: natural ventilation, supply-exhaust ventilation on the basis of central or apartment air handling unit (AHU) with heat recovery, supply-exhaust ventilation on the basis of room AHU-s with heat recovery equipment in each living- and bedroom and exhaust ventilators in the bathroom and kitchen, central mechanical exhaust ventilation and apartment mechanical exhaust ventilation with ventilators in bathrooms and kitchen and with external fresh air valves in bedrooms and livingrooms [14]. Additional losses may be associated with the energy needed to operate mechanical ventilation systems [15].

In Finland, 12 apartment buildings were investigated as a part of the European project HOPE. The final goal of the project HOPE was to provide means to enhance the construction of energy-efficient buildings that at the same time are healthy. This will help to decrease the use of energy in buildings and consequently results in the reduction of CO_2 emissions from primary energy used for ventilation, heating and humidity control [16]. U-values of envelope elements in old typical apartment buildings are very high. The heating system in such buildings is usually a single-pipe system and the ventilation is natural.

The aim of this paper is to show possibilities for improving the indoor climate and living conditions on top floors of typical old-type apartment buildings. The given results are based on the research, carried out in a typical 9-storey apartment building. An analysis of three systems was carried out:

- supply-exhaust ventilation on the basis of apartment AHU with heat recovery,
- supply-exhaust ventilation on the basis of room units with heat recovery equipment in each living- and bedroom and exhaust ventilators in the bathroom and kitchen,
- mechanical exhaust ventilation, ventilators in the bathroom and kitchen (on each duct) and with external fresh air valves in bedrooms and living rooms.

It is evident that with mechanical ventilation and with an increase in the air change, the expenditure on electricity goes up, but at the same time the use of heat recovery units and better controlled small units of apartment ventilation decreases the rise of the expenditure.

2. ENVELOPE ELEMENTS, VENTILATION SYSTEMS AND ENERGY CONSUMPTION

For typical apartment buildings, constructed more than 17 years ago, typical U-values are very high, for external walls 1.0 and for roof-ceilings 0.8 W/(m^2 °C). Bad quality and faults in the constructions are reflected in the thermographic recordings of top-floor apartments. Prefabricated panels typically have thermal bridges in areas, where the thermal insulation is missing. The U-value of these areas of the panels is approximately three times higher than for areas with thermal insulation.

Bad quality of the constructions and thermal bridges are characterized by the thermograph picture of an external wall of a top-floor apartment (Fig. 1) [17,18].

Up to the 1990s, natural ventilation was used in apartment buildings in Estonia. The air driving force is the bigger the higher up the air duct reaches and the higher is the density difference between the outdoor and indoor air. It is interesting to remark that on middle and lower floors of old buildings with badly sealed windows natural ventilation is satisfactory.

Air change with natural ventilation is influenced by external air temperature and wind velocity. The result is that with low external temperature the ventilation is satisfactory or too intensive, but in warm weather it is very bad.

In apartment buildings with roof-ceilings on top-floor apartments, air change with natural ventilation is many times less than required. Typical solutions for natural ventilation in multi-storey apartment buildings are shown in Fig. 2.

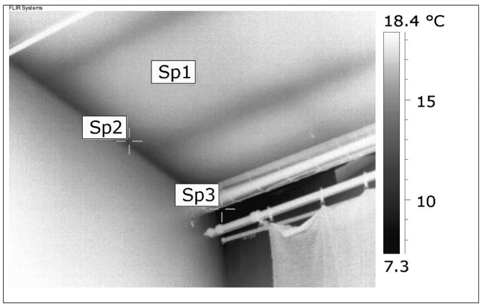

Fig. 1. Thermographic picture of a top-floor apartment: external temperature – 9 °C, indoor temperature 18 °C, temperatures at the surface of the sealing *T* (Sp1) = 16.4 °C, *T* (Sp2) = 11.7 °C, *T* (Sp3) = 6.1 °C.

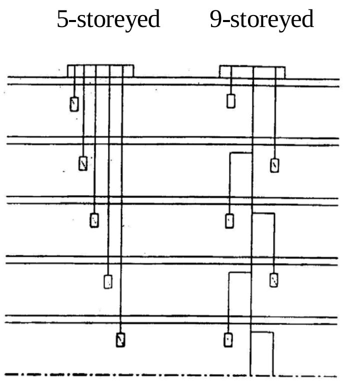

Fig. 2. Natural ventilation solutions in different apartment buildings.

Other examined solutions of apartment ventilation are: a) supply-exhaust ventilation on the basis of apartment AHU with heat recovery, b) supply-exhaust ventilation on the basis of room units with heat recovery equipment in each living- and bedroom and exhaust ventilators with variable loads in the bathroom and kitchen, and c) mechanical exhaust ventilation – ventilators in bathrooms and kitchen (on each duct) and with external fresh air valves in bedrooms and living rooms.

Specific heat loss H of air heating is calculated as

$$H = 0.28 L c \rho, \text{ W/°C}, \quad (1)$$

where L is air change (m^3/h), c is specific heat of air (kJ/(kg °C)) and ρ is density of air (kg/m^3).

It is possible to calculate energy requirements of air heating Q by degree-days with sufficient accuracy [19] in case the AHU is continuously functioning:

$$Q = 24 \times 10^{-6} HS(1 - \Psi), \text{ MWh}, \quad (2)$$

where S is the number of degree-days and Ψ is the coefficient of heat recovery. For AHU without heat recovery unit, $\Psi = 0$. Coefficient Ψ is determined on the basis of temperature efficiency of the heat recovery unit, supply temperature of air and external climate conditions. For example, in conditions of Tallinn, if the temperature efficiency of the heat recovery unit is 60% and the supply temperature of air is 20 °C, Ψ is close to 0.7. In calculations the price of thermal energy is 1 EEK kWh and the price of electricity is 1.5 EEK kWh. Electricity consumption was determined by the consumption power of the equipment and duration of work.

For collecting data about indoor temperature, additional heating and the renovation of windows in the investigated building, a questionnaire survey was carried out. Answers were received from 26 apartments; the average response rate was 30%, for top-floor apartments 50%. The survey included three questions about indoor temperature in the cold period 2006/2007, the operation of the heating system and the renovation of windows in apartments:

– on what level was the indoor temperature in your apartment in the cold period?
– was additional electric heating used in the apartment?
– have the windows in your apartment been renovated (changed)?

We received 20 answers from apartments on the lower 8 floors and 6 answers from top-floor apartments.

The indoor temperature was below 18 °C in 3 apartments of the lower 8 floors (15%), but in 5 top-floor apartments (83%). On the top floor, the indoor temperature was normal only in one apartment, where all envelope elements had been renovated.

Additional electrical heating was used in 7 apartments (35%) on the lower 8 floors, but in 83% of apartments on the top-floor. The windows were renovated in 50% of apartments on the lower 8 floors and in 67% of top-floor apartments.

In top-floor apartments the renovation of windows only did not guarantee the normal temperature.

The questionnaire showed that 83% of apartments on the top floor have problems with indoor climate in the cold period. In the single-pipe heating system the thermal balance (heat output and heat losses) is guaranteed only if the heating area, the temperature curve and the flow rate are correct. If thermal losses change, it is necessary to use a new temperature graph and a newly designed flow rate or renovate the connection scheme of heating coils.

3. INDOOR CLIMATE AND WAYS FOR ITS IMPROVEMENT

3.1. Indoor climate monitoring

The main reasons for the formation of mould on cold surfaces are:

- bad quality of envelope elements, very high U-value in connection points,
- high relative humidity in apartments, caused by too low air change in apartments, especially in apartments with renovated windows,
- low indoor temperature in top-floor apartments, the reason being arbitrary adjustment of the heating system (water temperature and flow rate do not correspond to heat losses).

For indoor climate monitoring, data loggers Hobo (Onset Computer Corporation) and a measuring unit of Telair International GmbH were used, the latter being used for determining the CO_2 concentration.

For long-period relative humidity and temperature measurements the logging interval was 15 min and for short-period CO_2 concentration measurements it was 2 min. The monitoring period was 5 months with short intervals in the cold period.

As an example, the results of relative humidity logging in 2 apartments (2-room apartments with 2 people) in the winter of 2006/2007 are presented in Figs. 3 and 4.

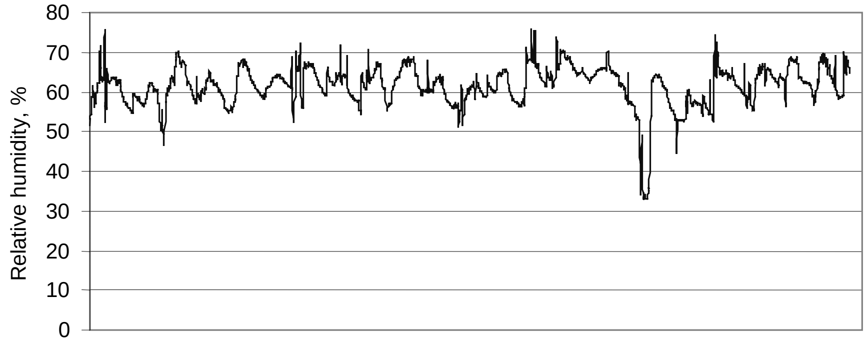

Fig. 3. Variation of the relative humidity in the bedroom of the apartment No. 107, from December 1 to 23, 2006.

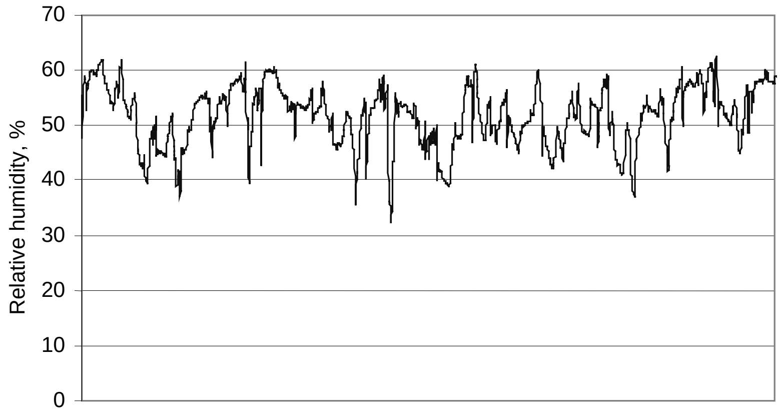

Fig. 4. Variation of the relative humidity in the apartment No. 179, from October 31 to November 20, 2006.

We can see that the relative humidity in the apartments rose up to 75%. For a long period the relative humidity was from 50 to 70%, which is too high for the winter period. With such a high relative humidity, on indoor surfaces of unrenovated envelope elements mould formation is inevitable.

In apartments with a low air change there is typically a very high CO_2 concentration in bedrooms. Figure 5 presents the dynamics of CO_2 concentration at night for a bedroom of 36 m^3 with 2 people. We can see that the rise in the concentration of CO_2 during 4 hours exceeds 1000 ppm. The final level at 7 o'clock is 2381 ppm, which is about 1.5 times higher than the standard value for the lowest class of comfort. The reason for that is a very low air change in the bedroom, 2.5 l/s per person.

In Fig. 6 we can see the results of indoor temperature monitoring for an apartment with improved mechanical ventilation and an apartment with natural

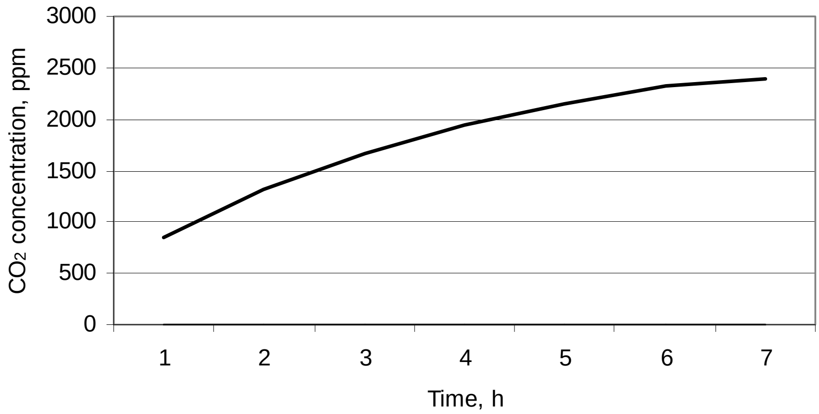

Fig. 5. Dynamics of CO_2 concentration at night in a bedroom with 2 people.

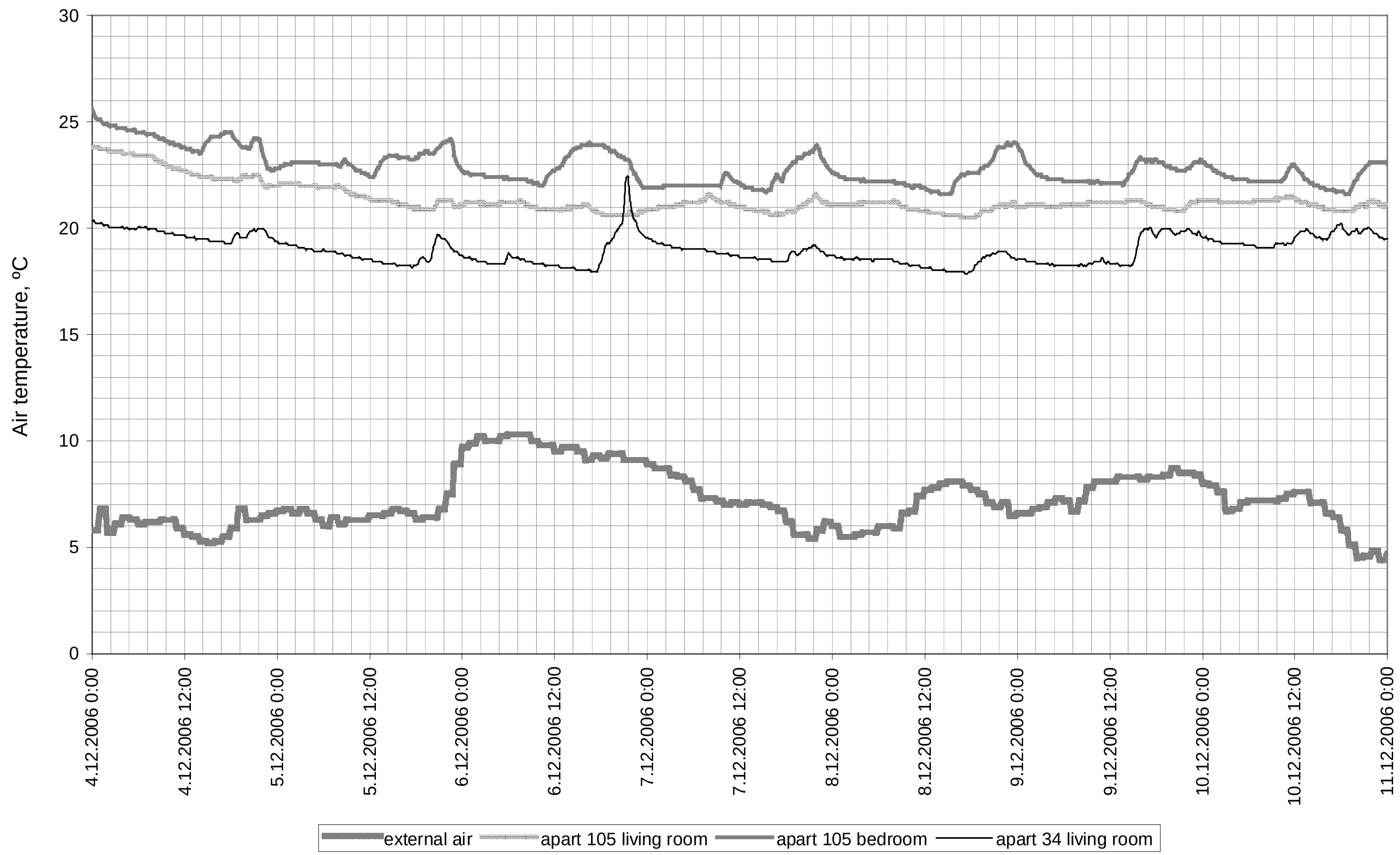

Fig. 6. The results of indoor temperature monitoring of an apartment with improved mechanical ventilation (apartment 105) and with natural ventilation (apartment 34); Sütiste 41, 9th floor, in December 2006.

ventilation. We see that in the apartment 105 with AHU the indoor temperature is 2–3 °C higher than in the apartment, where the ventilation was not renovated.

3.2. Ways for improving the indoor climate

To make indoor climate healthy and comfortable on top floors of typical old apartment buildings with roof-ceilings the following should be done.

– It is necessary to insulate the walls and roofs, which have considerable thermal bridges and low U-values.
– The recommended average air change rate in apartments is 0.5 h^{-1} and the air change in bedrooms during the night about 5 l/s per person.
– It is necessary to adjust the single-pipe water heating system to the right flow temperature curve and flow rate.

To improve the air change in top-floor apartments of buildings with roof-ceilings it is necessary to use either central or more flexible individual mechanical ventilation.

For applying mechanical apartment ventilation there are different possibilities. In this investigation three of them were investigated, which guaranteed the minimum of 0.5 h^{-1} air change rate in apartments:

a) supply-exhaust ventilation on the basis of apartment AHU with heat recovery (Fig. 7),
b) supply-exhaust ventilation on the basis of room units with heat recovery equipment in each living- and bedroom and exhaust ventilators with variable loads in the bathroom and kitchen (Fig. 8),
c) mechanical exhaust ventilation, ventilators in bathrooms and kitchen (on each duct) with external fresh air valves in bedrooms and livingrooms.

Fig. 7. Supply-exhaust ventilation on the basis of apartment AHU (in the kitchen) with heat recovery.

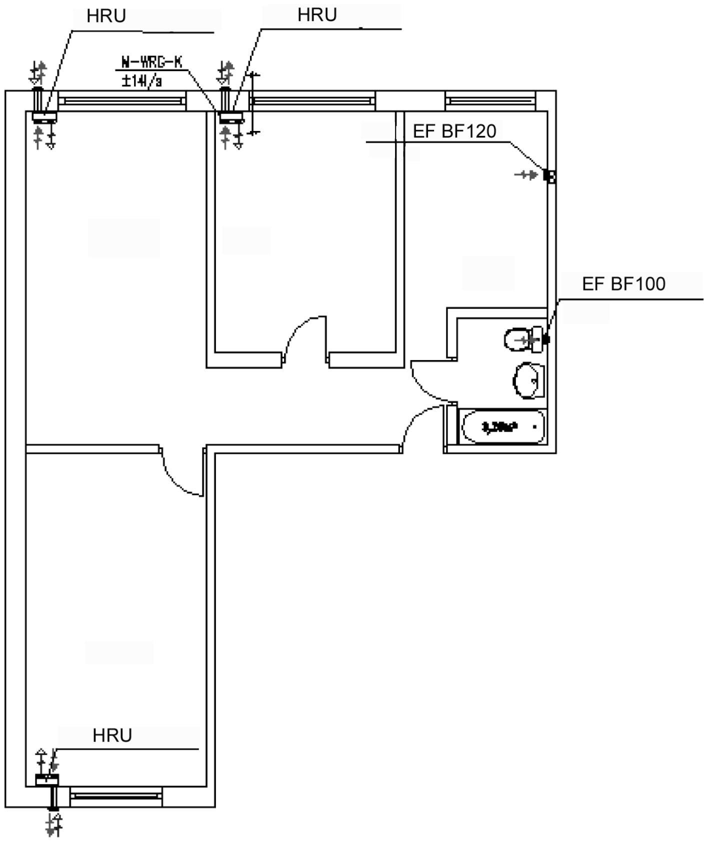

Fig. 8. Supply-exhaust ventilation on the basis of room units with heat recovery units (HRU) in each living- and bedroom and exhaust fans (EF) with variable loads in the bathroom and kitchen.

A comparison of these ventilation systems is presented in Table 1. The initial relative cost is the sum of the cost of equipment, materials and installation. In addition the total relative cost includes the operative cost of electricity and thermal energy.

Table 1. Comparison of different apartment ventilation systems to improve air change

Type of the system	Initial relative cost	Total relative cost in 15 years (initial and operative)	Indoor air quality
a) Apartment supply-exhaust ventilation by apartment AHU	5	1.15	Excellent
b) Supply-exhaust ventilation by room AHU and exhaust ventilators in the bathroom and kitchen	4	1	Good
c) Exhaust ventilators in the bathroom and kitchen, and fresh air valves in living- and bedrooms	1	1	Satisfactory

System (a) guarantees the best air quality, but its realization is difficult as the height of typical apartments is not sufficient for duct installation and usually an additional suspension ceiling is necessary.

The best feature of the system (b) is the absence of air ducts in the apartment, but a mini-AHU is necessary in each bed- and livingroom. As this kind of mini-AHU has no air heating unit, it is usually necessary to use some additional heating elements in rooms (for example, an electrical air convector). For small apartments the initial cost is lower when compared with system (a).

System (c) is very simple, initial cost is low, but with high energy prices the life cycle cost may turn out to be the highest since the heat recovery possibility is missing.

4. CONCLUSIONS

The indoor climate in top-floor apartments in non-renovated typical buildings is, as a rule, problematic. As the air change is low, relative humidity changes from 50 to 70% and the CO_2 concentration in bedrooms reaches 2400 ppm. In the investigated building, 83% of top-floor apartments have problems with indoor climate. As a rule, the U-values of envelope elements are high and have essential thermal bridges. This results in mould formation in apartments. This situation is worsened by large-scale renovation of windows without improving the ventilation.

Possible reasons for mould formation on cold surfaces in top-floor apartments of typical buildings are:

- bad quality of envelope elements and very high U-value in connection points of panels;
- high relative humidity in apartments, caused by very low air change, especially in apartments with renovated windows;
- low indoor temperature in top-floor apartments.

To normalize the indoor climate in top-floor apartments of typical apartment buildings it is necessary:

- to use mechanical ventilation in apartments;
- to insulate thermally external envelope elements;
- to improve adjusting or to renovate single-pipe heating systems.

The best ventilation solutions are apartment supply-exhaust ventilation by apartment AHU or supply-exhaust ventilation with room AHU and exhaust ventilators in the bathroom and kitchen.

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Ventilatsiooni efektiivsus ja sisekliima vanade tüüpkortermajade ülemise korruse korterites

Teet-Andrus Kõiv

On antud ülevaade sisekliima olukorrast hoonetes. On vaadeldud kütte- ja ventilatsioonisüsteemide toimimist ning piirdetarindite seisukorda tüüpkortermajade ülemise korruse korterites. On esitatud õhutemperatuuri, suhtelise niiskuse ja CO_2 kontsentratsiooni monitooringu tulemused. On analüüsitud korterite õhuvahetuse parandamise võimalusi mehaanilise ventilatsiooni abil.