IAQ as a function of air exchange rate

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Abstract: - This paper is devoted to the analysis of indoor air quality in buildings depending on ventilation volume. In the scope of this paper the main problems of indoor air quality in airtight buildings were identified and easily implemented calculation methods of predicting dynamically changing indoor air contaminant levels as well as relative humidity is provided.
The proposed calculation method takes into account parameters of outdoor air, internal CO_2 and moisture production, buildings volume and air exchange rate.
The paper also presents the results of monitoring of indoor air quality specifics of apartments, offices and classrooms in Latvia and compares the obtained results with the calculated ones.
The results shows that proposed method is accurate in predicting CO_2 level and could be used for evaluation of CO_2 level while the prediction of relative humidity still opposes some problems.
The paper provides example of developed methods practical application and results how different ventilation air volumes define IAQ.

Key-Words: - Ventilation, indoor air quality, CO_2 concentration, humidity, prediction

1 Introduction

According to the European Union's issued directive no. 2010/31/ES on the energy performance of buildings starting from year 2015 all new buildings in the EU will need to comply with the reduced energy consumption requirements but starting from the year 2021 they will need to be nearly zero energy. Therefore increasingly more attention to energy effectiveness of buildings needs to be paid. To obtain nearly zero energy buildings they will need to comply with today's standards of low energy houses and therefore will be similar to them from engineering point of view. As seen from the experience of these buildings the needed low level of energy consumption can only be achieved by complex solutions including - increased building envelopes thermal conductivity by applying thicker insulation, usage of low-e coated passive windows, passive solar energy use as well as higher air tightness to reduce air infiltration. The last means that there will be necessity for mechanical ventilation as no longer air will be able to penetrate through buildings envelope and by only using controlled ventilation we obtain the possibility to regain energy from the exhaust air to supply air through heat exchanger.
As the existing data of built low energy and passive houses shows the energy consumption for ventilation is making up relatively large part of total energy consumption and is in range of 15-25%. This can provide good opportunity for energy savings but if the mechanical ventilation is undersized to save money also can lead to insufficient ventilation air exchange rate and inappropriate indoor air quality and sick building syndrome. To prevent this it is necessary to incorporate into existing national building codes requirements for ventilation to ensure appropriate IAQ not specific air exchange rates.
For example, as of now the local regulations in Latvia [5] require a minimum of 5 l/s of fresh air per person if it is the only pollutant in the room or determines the necessary air exchange according to occupied space type and area [6]. Also in designing passive and low energy house air exchange rate of 0,3 h^{-1} is used as a rule of thumb [11]. However it would be more accurate to assess the necessary volume of fresh air to provide appropriate IAQ, as this is the main purpose of ventilation. The main characteristics that define IAQ are CO_2 level and relative humidity. Both of these indicators are mainly related to human beings while the air pollution can also be caused by ozone from printers/copy machines, cooking fumes and emissions from building materials and described

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using total volatile organic compound value. All these characteristics describing IAQ are affected by air exchange rate, indoor pollutants, parameters of outdoor air and room specifications. It is therefore necessary to firstly determine the threshold values of the CO_2 concentration level and relative humidity to choose the exact ventilation rate for each given situation.

The existing researches [8] on indoor air quality have shown that optimal CO_2 concentration in indoor air is up to 1000 ppm. Although data [1] on CO_2 impact on human health has shown that negative impact on breathing occurs when CO_2 concentration is above 5000 ppm. The evaluation of indoor air quality [10] has shown that allowed CO_2 concentration level is 1000 ppm with a maximum value of 1200 ppm.

According to the regulations [1] relative humidity should be maintained between 30% and 60% for indoor environments. Long periods of relative humidity below 30% can cause drying of the mucous membranes and discomfort for many people while relative humidity above 60% for extended time periods promotes indoor microbial growth. At the same time relative humidity should be below 40-45% for at least one month in a year to ensure drying out and killing of dust mites.

2 Methods

2.1 Theoretical method to determine dynamically changing contaminant concentration in indoor air

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 which is based on mass and energy balance. The calculation methods to obtain the equitation describing CO_2 concentration in indoor air at any given time moment can be expressed by equations 1 - 3:

$$\frac{dM_{CO2}}{dt} = CO_2 outdoors + CO_2 produced - CO_2 exhausted \quad (1)$$

Expressing the necessary values by room and air parameters we can obtain following equation:

$$\frac{V * dc_{in}}{dt} = n * V * c_{out} + n_{pers.} * q - n * V * c_{in} \quad (2)$$

Dividing both sides by V, assuming that $(c_{in} - c_{out}) = y$ yields:

$$\int_{y(0)}^{y(t)} \frac{dy}{((n_{pers.} * q)/V) - n * y} = \int_0^t dt \quad (3)$$

By knowing that at the starting time $t=0$ the CO_2 concentration in room will be C_0 and integrating we obtain the following final equitation for dynamically changing CO_2 concentration in indoor air:

$$c_{in}(t) = c_{out} + (c_0 - c_{out}) * e^{-n*t} + (1 - e^{-n*t}) * + \frac{n_{pers.} * q}{n * V} \quad (4)$$

Where V – room volume, m^3; n – air exchange rate, c_{out} – outdoor air CO_2 concentration, kg/m^3, $n_{pers.}$ – number of persons in room; q – CO_2 production by one person, kg/h, c_{in} – indoor air CO_2 concentration, kg CO_2/m^3.

Similar equitation's for CO_2 concentration prediction has been provided in existing researches [4, 12]. Analogous it could be possible to determine the relative humidity in indoor air by calculating the absolute humidity.

2.2 Measurements of CO_2 and RH in buildings

For the purpose of practical evaluation of IAQ and to verify the precision of the developed theoretical model, measurements in two apartments, two offices and a classroom where done and results were analyzed. The ventilation systems in apartments and offices where hybrid type with natural air supply through windows and construction gaps and with mechanical exhaust from kitchens and bathrooms, while in classroom it was mechanical during classes and additional ventilation by opening of windows during breaks.

During measurements windows remained closed in apartments and offices to obtain constant air exchange rate and the number of people in rooms was registered for each half an hour. For classroom number of students was registered for each class as well as timing of window opening. The measurements in apartments were done in periods from 12.02.2011 till 15.02.2011 and from 04.04.2011 until 07.04.2011, the office buildings where measured from 16.02.2011 till 18.02.2011 and from 29.03.2011 until 01.03.2011 while the classroom from 19.11.2011 till 21.11.2011.

For indoor air quality measurements the data loggers with the following parameters were used: temperature: -20^{0}C to 70^{0}C (±0.35^{0}C); relative humidity: 10% to 90% (±2.5%); CO_2 level: 0 to 2500 ppm (±50 ppm or 5% of reading).

3 Results

The example of results for theoretically predicted and measured levels of CO_2 in office building is shown in Figures 1 while Figures 2 shows the relative humidity.

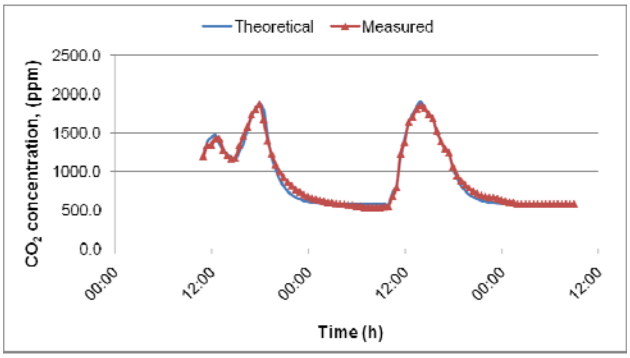

Figure 1: Theoretically predicted and measured CO_2 concentration at Office with 3 persons and 30 m^2 area

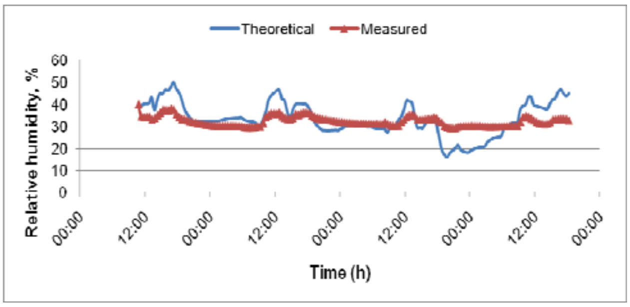

Figure 2: Theoretically predicted and measured relative humidity at Office with 3 persons and 30 m^2 area

The calculated precision of developed method for CO_2 concentration prediction can be seen in Table 1 while Table 2 shows the size of errors for relative humidity prediction and the prediction accuracy in percents.

Table 1: Accuracy and mean error for CO_2 concentration prediction

Measurements	Mean error of predicted CO_2 conc. (ppm)	CO_2 prediction accuracy (%)
Apartment 1	111±16,6	93,4±1,2
Apartment 2	118±18,7	89,9±1,6
Office 1	38±7,2	95,5±0,8
Office 2	84±15,0	92,6±1,0
Classroom	64±16,2	93,4±1,4

Table 2: Accuracy and mean error for relative humidity prediction

Measurements	Mean error of predicted RH (%)	RH prediction accuracy (%)
Apartment 1	5,2±0,7	88,2±1,6
Apartment 2	4,4±0,6	89,5±1,3
Office 1	4,0±0,4	86,6±1,4
Office 2	5,0±0,6	84,4±1,7
Classroom	4,6±0,5	87,6±1,6

4 Discussion

4.1 Analysis of obtained results

As seen from the obtained results given theoretical method of predicting CO_2 level as function of indoor pollutants, outdoor air parameters, air exchange rate and room specifications gives accurate results with the average precision of 93.0%. The main cause of error could originate from not knowing the actual volume of air in the room due to furniture, equipment and people who take up the free space. Also the air exchange rate was calculated and compared with existing data [2] for similar types of buildings not measured. For the residential building calculated air exchange rate was 0.5 ach while for the office 0.7 ach. The classroom had a constant air exchange of approximately 2.5 ach with increase to 5.0 ach during time when windows where opened.

The results show that developed method gives better results in office and classroom cases due to fact that there are fewer variables because number of people as well as their activity level is more constant compared to apartment where people walk back and forth more intensively. Nevertheless the figures showed that given method precisely predicts the rate of change in CO_2 concentration and gives precise prediction values which presumably would be even higher if measurement would be performed in laboratory conditions.

The results show that this type of theoretical method is not as accurate for predicting relative humidity. The average prediction accuracy is 87.3% and as seen from figure 2 the fluctuation rate of change in relative humidity is 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 following reasons.

First of all it is difficult to assess the exact internal moisture load as the sources in building are more diverse (people, showers, cooking, plants, construction ect.) than compared to the lone source of CO_2 which is people. Also the data stated in the

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literature on moisture generation vary in the sources and disparity can be as high as ten times [7].
The second source of error occurs due to changing moisture content in outside air. The obtained data only provides values for outside relative humidity and temperature with tree hour intervals.
The most significant cause of error could be the reason that the objects in the room also affect the moisture content of air, which in the developed method has not been taken into account. As the existing studies [3, 13] shows, the majority of the moisture, which is released into the room across short time periods at first is absorbed on the surfaces and absorbent materials, and only then released into the air. Thus stabilizing the moisture content in the air and the calculation method must take into account the average amount of moisture released during the day or even week rather than the momentary rate of release. The exact amount of absorbed moisture is difficult to determine and it varies in each individual case depending on the objects in the room and their materials. For example, in offices that has a lot of plain paper and wooden tables the percentage of absorbed moisture will be much higher compared to empty apartment. This means that the method of calculating the relative humidity should be supplemented by a variable, which would describe the moisture absorption capability of the room.

4.2 Example of developed methods practical application

Further provided example for practical application of developed method is given for low-energy one story high residential building with total living area of 180 m^2 and ceiling height of 2.5 m. The building is assumed to be occupied by family of 2 parents and 3 children and the number of persons at home for every hour of weak are taken from existing research data [9]. In most cases it might be difficult to predict the exact occupancy profile of a building and the actual profile would differ, therefore fixed design value should be used. Nevertheless the occupancy rate for dwelling houses is well investigated and gives accurate results. For calculations it is assumed that one person emits 20 L of CO_2 per hour and the outside CO_2 concentration is 500 ppm and estimated production of moisture is 10 kg per day for 5 person household [7].
According to the local regulations [5, 6] the necessary volume of ventilation air is 75 m^3/h, if calculated by number of people, or 279 m^3/h according to area size and usage type. In practise many handbooks suggest using air exchange rate of 0.3 h^{-1} as appropriate which in given case means 135 m^3/h of fresh air. By using the equitation (4) it is possible to calculate that the necessary air volume to provide CO_2 less than 1000 ppm at all times would be 202 m^3/h. The predicted dynamically changing CO_2 concentrations during whole weak at these air volumes are given in the Figure 3.

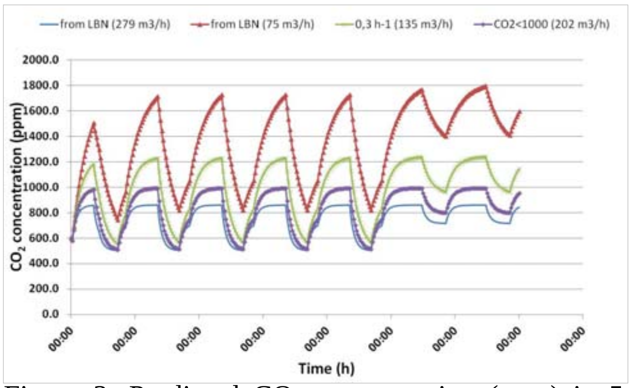

Figure 3: Predicted CO_2 concentration (ppm) in 5 person occupied 180 m^2 building during one week at different design air volumes

As seen from Figure 3 the CO_2 concentration is dependent on ventilation air volume and can reach up to 1800 ppm at lowest volume of air allowed to regulations. Although this level of concentration is not dangerous is not advisable because it can cause headaches and sleepiness. The suggested air exchange rate of 0.3 provides acceptable indoor air quality with CO_2 peaking up to 1200 ppm. Figure 3 also shows that air volume of 279 m^3/h as calculated by regulations is too high and can be reduced for 27% to 202 m^3/h therefore saving energy needed for air heating and transportation.
Nevertheless it would is inaccurate to assume that the whole building is one ventilated zone, because the rooms are divide by closable doors and there is low air circulation between them and the ventilation air volume needs to be calculated for each one separately. Therefore assuming a bedroom with area of 20 m^2 and following occupancy profile for a working day:

- From 9:00 till 17:00 – 0 people
- From 17:00 till 18:00 – 1 people
- From 18:00 till 8:00 – 2 people
- From 8:00 till 9:00 – 1 people

Analogous as for the whole building air exchange volumes according to local regulations as well as to assure that the CO_2 level is below 1000 ppm are calculated and predicted CO_2 concentration is shown on at the Figure 4.

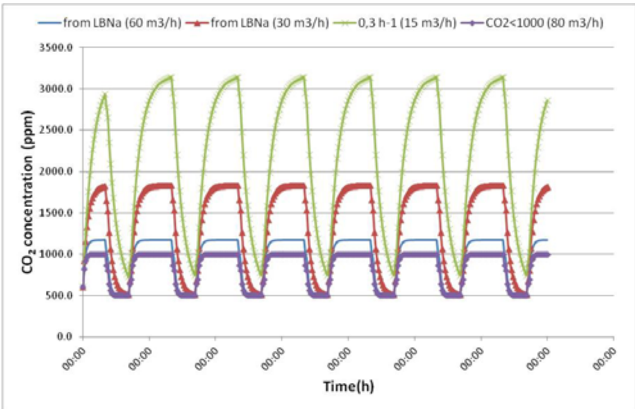

Figure 4: Predicted CO_2 concentration (ppm) in 2 person occupied 20 m^2 bedroom during one week at different design air volumes

As the Figure 4 shows all cases when ventilation air is chose according to regulations IAQ is inappropriate and the CO_2 concentration can reach up to 3000 ppm during nigh time. This is much different than in case when the whole building was looked as one zone. This is due to the fact that peoples who are the main pollutants stay in bedrooms for most of the time and therefore not only the total air exchange rate but also division of supply air is important.

5 Conclusion

The proposed method gives accurate results for predicting indoor air quality parameters. The average precision for CO_2 concentration prediction is 93.0% while for relative humidity 87.3%. Precision for predicting relative humidity can be improved if absorption and desorption processes are taken into account and average moisture gains for prolonged periods are used. Further case studies to express the absorption factor for each given situation as single non-dimensional value must be done.

The application of given method can be used to determine the optimum air exchange rate in new low-energy buildings to provide the necessary indoor air quality by using the minimal volume of fresh air to reduce total energy consumption.

The method can be used for automation of ventilation system without installation of control devices if a precise occupancy profile is predesigned, for example in classrooms or theatres.

The method can be also applied in situations if rooms have large volume. By calculations it can be possible to determine the optimal starting and turning off moments of ventilation systems as the CO_2 concentration gradually reaches the allowed value.

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