EVALUATION OF SET POINTS FOR MOISTURE SUPPLY AND VOLATILE ORGANIC COMPOUNDS AS CONTROLLING PARAMETERS FOR DEMAND CONTROLLED VENTILATION IN MULTIFAMILY HOUSES

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SUMMARY

The main purpose has been to evaluate existing set points (thresholds) and suggest proper set points, for the regulation of the air change rate in a demand controlled mechanical ventilation (DCV) system. The DCV is controlled by measurements in the supply and exhaust air of the vapor content and volatile organic compounds (VOCs) for each dwelling in multifamily houses. Results have been achieved through a literature review and laboratory tests. The threshold for the maximum ventilation rate (0.8 ac/h) should be set at 1000 ppm (CO₂-eq.). Preferably, a minimum ventilation rate of 0.5 ac/h should be set with current thresholds (800-1000 ppm CO₂-eq.). With a lower minimum ventilation rate (e.g. 0.1 ac/h) the lower threshold should be set at 450 ppm (CO₂-eq). In order to deal with heavy moisture production the threshold for the moisture supply is suggested to be set at 3 g/m³.

INTRODUCTION

A new DCV system for multifamily houses automatically regulates the air change rate for each dwelling according to the actual moisture supply and VOC-content in the indoor air. Outside each apartment, a box is placed including sensors and dampers that regulate the air exchange for the apartment based on the measured parameters. The VOC content is measured in the exhaust air for the whole apartment, while the vapor content is measured both in the supply and exhaust air in order to calculate the moisture supply (the difference in the vapor content). The idea with such design is to ventilate only as much as necessary at all times.

In order to deal with an increased VOC-content, the system increases the ventilation rate and sets it between 0.1-0.8 ac/h depending on the load. The increase of the ventilation rate is linear in a VOC-content interval of 800-1000 ppm (CO₂ eq.). For the moisture supply the threshold is set at 2 g/m³. When the moisture threshold is exceeded the system ventilates at the maximum air change rate (0.8 ac/h) until the moisture supply has reached below the threshold. After that, the system will stepwise decrease the air change rate to the minimum rate or a rate that corresponds to dealing with the VOC-load. The system sets the highest ventilation rate that is needed to deal with either load. If the moisture supply is lower than the moisture threshold, while the VOC-content exceeds the VOC threshold, the airflow will be adjusted to deal with the VOC-load. However, if at any time the moisture supply is measured to be above the threshold, it does not matter what the VOC-load is at that moment, the ventilation rate will be maximized.
This control scheme gives rise to some questions. In order to achieve good IAQ, where should the set points (thresholds) for the VOC be set? In the case of a too low set point, the ventilation will unnecessarily increase the air change rate and thus result negatively on the energy efficiency. In the case of a too high threshold, the ventilation rate will be inadequate for achieving good IAQ. In addition, what are the maximum values on the measured parameters that we can accept in regards to loads on the building and in regards to the health of the habitants?

As the sensors register the content in the exhaust air for the whole apartment and not the individual rooms, one hypothesis is that the system will not properly deal with the actual loads in the individual rooms. A load in a certain room might be diluted when the exhaust air for the room mixes with the rest of the exhaust air. Therefore, VOC-concentration of e.g. 800 ppm (CO₂-equivalent) in the bathroom or kitchen might only register as e.g. 600 ppm (CO₂-eq.) in the total exhaust air. Consequently, a smaller load might not be detected as the variations might dampen due to the dilution. Depending on how the system is designed to deal with the measured load, the ventilation rate might become inadequate. The load in the room where the pollution originates or moisture production takes place might be damaging in regards to the habitants health and/or the durability of the building material.

A recently started research project will evaluate and analyze field installations of the proposed ventilation system from both indoor environmental, energy and economical perspectives. This paper is a part of that project. All of the presented hypotheses in this paper concern the set points and the systems functionality. Therefore, the purpose here has been to evaluate the functionality of the newly developed system, to evaluate existing set points, and to suggest proper set points, for the decrease and increase in the air change rate.

METHODS

A literature review on evaluations of the MOS-sensor and literature on VOC, moisture supply and CO₂ in correlation to ventilation rates as well as IAQ was made to cover the advantages and disadvantages of the system sensors in regard to the indoor environmental quality.

![Illustration of the laboratory and setup. VOC, RH and temperature were measured by sensors 1-6 and the box. Sensors A and B measured additionally the CO₂.](image)

Figure 1. Illustration of the laboratory and setup. VOC, RH and temperature were measured by sensors 1-6 and the box. Sensors A and B measured additionally the CO₂.

Furthermore, laboratory test was made in a mock up apartment with specific loads from people and activities and in order to detect potential fallbacks with the system design. The
The tests have been limited to activities that are assumed common practice in multifamily houses. Such as idle presence, cooking, showering, smoking, peeling oranges and painting.

**LITERATURE REVIEW**

**IAQ in regards to VOC and moisture supply**

In a literature review, Bernstein et al. (2008) summarized the pollutants that we may encounter in the indoor air. The review mentions the following pollutants: particulate matter, gases, microbial and chemical VOCs, smoke and outdoor ambient air. Bernstein et al. states that many experts recommend that the air pollutant levels are maintained at 50% or less than the USA National Ambient Air Quality Standards (NAAQS) for outdoor air pollutants established by the USA Environmental Protection Agency (EPA, 2014). Numerous of other studies have determined the pollutants that exist in our homes, e.g. Wolkoff & Nielsen (2001). However, none of these studies correlate VOC-content to CO₂-equivalents or to ventilation rates. Therefore, the results are not applicable in this study and set points for the system can thereby not be determined by their presented results. The lack of cross-sensitivity in the MOS-sensor means that we cannot suggest thresholds for the output based on VOC-concentrations that are acceptable in our indoor air. Further research for determining such correlations might be necessary to produce an optimal ventilation strategy in order to achieve as healthy and energy efficient ventilation as possible through DCV.

A study of the sorption of VOCs in residential rooms showed that when the adsorption rate is competitive with the air exchange rate, VOCs are adsorbed into the surrounding building materials (Singer et al., 2006). The results of this study implies that the ventilation should be set so that it adequately deals with this phenomena, in order to decrease the concentrations of VOCs in the indoor air that the habitants are subjected to. A study made by Jørgensen in 2006 concluded that due to sorption of VOCs in building materials, an office should increase the ventilation rate from 0.67 ac/h to 2 ac/h a couple of hours before the work shift starts in order to lower the resulting concentrations. The tests were performed in a test chamber with a nylon carpet (Jørgensen, 2006) which might not adequately reflect multifamily houses, although by simulating the ventilation system in an office building that has higher ventilation rates than Swedish dwellings we believe that the results are on the safe side. Qin qin et al. (2012) also concluded that higher ventilation rates prevent sorption of VOCs in building materials. At lower air change rates ≤ 0.1 ac/h sorption of VOCs are considerable, and at ≥ 0.5 ac/h some VOCs can be neglected, while at ≥ 5 ac/h sorption the effect is even weaker, and finally at ≥ 20 ac/h all sorption is negligible. These studies indicate that in order to deal with the VOC-sinks in our homes we need to have an adequate ventilation rate. We believe that this applies even more for the harmful substances that are not detected by the installed sensor.

A comprehensive study that have been conducted in Sweden, ELIB has determined the average moisture supply in multifamily buildings at 1.2 g/m³ with a ventilation rate of approximately 0.5 ac/h (Boverket, 2009). Johansson & Bagge (2010) have also determined the moisture supply to an average of 1.4 g/m³.

**Previous evaluations of the sensors**
There is no literature on the relative humidity (RH) and temperature sensor except for the data sheet from the manufacturer. According to this, the sensor can withstand 100% RH and has an inaccuracy of ±2.5% RH. For this evaluation, we will have to assume that this is correct.

The mixed gas sensor detects a variety of substances: alcohols, aldehydes, aliphatic hydrocarbons, amines, aromatic hydrocarbons, CO, CH₄, LPG, ketones and organic acids. It uses micro-machined metal oxide semiconductor (MOS) technology and has a sensing range of 0-2000 ppm (CO₂ eq.), and is functional between 5-90% RH (AppliedSensor, 2014). Herberger et al. (2010) have shown that when measuring VOCs with MOS-technology equivalent CO₂-levels of measured pollutants can be reliably predicted. However, the study was restricted to highly occupied meeting rooms. Another study made by Ulmer & Herberger (2012) has also shown reliable correlation of predicted and measured CO₂-concentrations in indoor spaces where no appreciable human activity takes place. However, this study was restricted to office rooms, meeting rooms and kitchens. In addition, a study made by Johansson & Bagge (2012) has also shown such somewhat of a correlation, although not strong. Of these studies only Johansson & Bagge’s (2012) apply for dwellings, and at the same time their measurements were not for individual dwellings separate from each other, but in the supply and exhaust air for whole apartment buildings. In other words, none of these studies properly reflect a single normally occupied apartment, which might not be a highly occupied environment and therefore the correlations may not be applicable when determining the set points for a healthy ventilation strategy in individual apartment dwellings.

In Herberger et al.’s article (2010) it is also stated that MOS-sensors are not cross-sensitive, which is a fallback. Therefore they also state that this kind of sensor cannot be used for a scientifically correct evaluation of air composition, but that a DCV based on this technology is at least better than a DCV based on CO₂-sensors as the MOS-sensor seems to offer a better correlation with perceived air quality.

DISCUSSION

Ventilation strategy with sensor limitations

Herberger et al.’s states (2010) that a MOS-sensor cannot be used for a scientifically correct evaluation of air composition, but that a DCV based on this technology is at least better than the more common DCV based on CO₂-sensors. They state that the MOS-sensor offers a better correlation with perceived air quality due to the detection of a variety of substances. Kostianen (1994) found that the most common VOCs are alkylbenzenes, alkanes, terpenes, aliphatic aldehydes, and some chlorinated aliphatic hydrocarbons. In comparison to the specifications for the measuring device (AppliedSensor, 2014), we may deduce that the MOS-sensor used in this ventilation system should detect the majority of indoor air pollutants and therefore be an effective device to indicate the state of the IAQ.

CO₂ is sometimes used as an indicator for IAQ and this device has been shown to correlate somewhat with CO₂. Thereby setting the thresholds after recommended CO₂-concentrations levels might be the only applicable strategy, for now. This is confirmed by Herberger et al. (2010), and would mean that the maximum ventilation rate should be reached when the readings from the mixed gas sensor exceed 1000 ppm (CO₂-eq). Ensuring this CO₂-level will, according to ASHRAE, satisfy a substantial majority of visitors entering the space with respect to human bioeffluents. On the other hand, determining the minimum threshold for when the ventilation rate should start increasing is a bit more complicated. Through the literature review, we might deduce that this depends on how high the minimum air change rate is set. If the minimum air change rate is set to be ≥0.1 ac/h then the lower VOC-threshold should be as low as possible in order to ensure a healthy IAQ by dealing even with smaller
loads. If it is set to be \( \geq 0.5 \text{ ac/h} \) then the risk of an unsatisfying IAQ is lower as the ventilation rate might be adequate even for smaller loads. In the latter case, the threshold should be set higher in order to ensure that pollutants due to more significantly polluting activities are dealt with and at the same time ensuring energy efficiency. Preferably, the higher ventilation rate strategy is chosen as there are a number of pollutants that the sensor does not detect, thereby a higher ventilation rate should be applied to deal with such pollutants as well. At the same time, a higher ventilation rate might be the healthiest strategy, considering the other fallbacks that come with relying on DCV.

**RESULTS FROM THE LABORATORY TESTS**

Note that in *Figure 2* the MOS-sensor in the box reached approximately 500 ppm (CO2 eq.) when three idle adults were present in the living room. Sensor VOC1 however reached at that time approx. 800 ppm (CO2 eq). When spraying the air freshener in the shower room, sensor VOC6 increased to a peak of approx. 1800 ppm (CO2) later to be followed (± 15 min) by the box’s sensor with a peak of 800 ppm (CO2 eq.). This occurred for all tests when comparing the sensor first subjected to pollution and the sensor in the control box. The output from the CO2-sensors reached approx. 600 ppm during idle presence with an insignificant change of about +100 ppm during the spraying activity.

The same test as presented in *Figure 1* was remade but with a minimum ventilation of 0.5 ac/h. We found that the box registered a VOC-peak significantly faster (within 5 min) and the VOC-content was reduced in a faster manner to levels existing prior to the spraying.

![Figure 2. Results from the first test.](image)

*Figure 2. Results from the first test. T = 0 min, presence of three idle adults in the living room. T = 50 min, spraying air freshener in the bathroom. T=65 min, the smell of the air freshener is noticed in the living room. T=80 min, bathroom door is opened.*
CONCLUSIONS

Based on the laboratory tests

From the tests conducted in the mock-up apartment we may deduce the following:

1) Due to the system design and the placement of the control box the air is in fact greatly diluted and lower loads are registered with the controlling box’s MOS-sensor. This results in an insufficient ventilation rate in order to deal with the actual load at the source. Thereby also resulting in the spread of the pollutant to the rest of the apartment (as all other sensor outputs consequently followed). However, this did not occur for all tests as some pollutions that originated close to the extract supply resulted in a faster registration with the sensor in the box than the one placed right next to the source of pollution. See Figure 3, and compare VOC4 with VOC-Box.

2) The sensors and consequently the system do react to a variety of both occupant and non-occupant pollutants and increase the ventilation rate according to design. However, the sensors do not detect idle presence. Most likely for two reasons: a) the activity does not constitute a sufficient increase as a pollution, and b) the produced concentration is diluted before it reaches the controlling sensor and therefore not registered as a significant pollution.

3) A higher ventilation rate is preferred in order to deal with the pollutants in the indoor air as quickly as possible, preventing prolonged exposures. This conclusion is based on a remake of the test presented in Figure 2 but with a minimum ventilation rate of 0.5 ac/h.
4) For some tests two CO₂-sensors were logging simultaneously with the VOC-sensors. A thorough analysis of the correlation between these outputs has not been made, but the produced graphs suggest that such a correlation exists, although not entirely. This was expected as the VOC-sensors detect pollutions that the CO₂-sensors do not.

5) Stronger outputs for the VOC-sensors were noted for some activities over others. E.g. peeling oranges gave a higher output than frying eggs or spraying air freshener.

6) In some rooms the output was stronger than in others when no activity occurred in the apartment; compare outputs VOC2 and VOC3 in Figure 2. Most likely due to the emission of VOCs from the furniture as VOC2 was closer to the bed than VOC3.

7) When the threshold for the moisture supply is exceeded, the ventilation rate is maximized.

8) Tests indicate that the VOC-sensor reacts to moisture. However, we have not confirmed if this is the case as it is possible that VOC-emissions form the surface materials in the apartment are increased to a higher relative humidity (Xu & Zhang, 2011).

**Recommendation of set points and ventilation strategy**

The mixed gas sensor registers a variety of substances. However, the sensor does not register all substances that may exist in our indoor environment, to mention some: ozone and sulfur dioxide. Thus, even if the level of these pollutants are high, the system will not increase the ventilation rate in order with them. Therefore, we do not recommend to rely solely on the output from the sensor in order to regulate the ventilation rate. A safer way is to determine a minimum ventilation rate in combination with a minimum threshold for the sensor output.

The literature review has shown that there is a lack of research within this area. Both when it comes correlations between VOCs and CO₂ as well VOCs and ventilation rates. The recommended thresholds should thereby be based on indirect relations between IAQ and CO₂-concentrations in our indoor air, which is also the strategy suggested by Herberger et al. (2010). In addition, the ventilation strategy needs to consider fallbacks of the system design which is mainly: the effects due to the dilution of the pollution by the time it has reached the controlling sensor, the lack of cross-sensitivity and that not all pollutants that exist in our indoor air are detected by the sensor.

The threshold for the maximum ventilation rate (0.8 ac/h) should be set at 1000 ppm (CO₂-eq.), in coherence with current recommendations of achieving good IAQ based on CO₂-levels. Preferably, a minimum ventilation rate of 0.5 ac/h should be set with current thresholds (800-1000 ppm CO₂-eq.) in order to deal with the fallbacks of the system design and the MOS-sensor. If a lower minimum ventilation rate is instead chosen (e.g. 0.1 ac/h) the lower threshold should be lowered to 450 ppm (CO₂-eq), which was the outdoor lowest outdoor value registered by the system during a 3-month period.

The system provides satisfactory ventilation in regards to moisture supply above 4 g/m³, even though the registered moisture supply is a diluted value in comparison to the loads in the individual rooms. The threshold for the moisture supply is suggested to be set at 3 g/m³ in order to ensure that the system deals with heavy moisture producing activities but does not ventilate unnecessarily. Normal values on the moisture supply are 1.4 g/m³ and as the system regulates the ventilation rate mainly according to the MOS-sensor output with the moisture supply as a supplement, a high value should be set so that the supplement does not interfere with the main control, but at the same time deals with damaging moisture production.
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