CHALMERS

Feed-forward Control of Indoor Climate in Office Buildings

A Measurement Study to Indicate Internal Heat and Emissions Generated by Humans

Master of Science Thesis in the Master's Programme Structural Engineering and Building Performance Design

CHRISTOFFER ISAKSSON
MARKUS JOHANSSON

Department of Energy and Environment
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CHALMERS UNIVERSITY OF TECHNOLOGY
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Master's Thesis E2011:07

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Printed by Chalmers Reproservice, Göteborg, Sweden 2011

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ABSTRACT

Energy savings is a frequently discussed issue in today's society and it is desirable to save energy with intelligent solutions that does not cost too much and still are reliable. One way to achieve this in the building sector could be by using smarter control and regulation systems for the indoor climate. The feedback system is a regular solution for control and regulation nowadays, where the investigated parameter is measured and compared with a reference value. An alternative method, called feed-forward, has been evaluated and discussed in this master thesis. The idea of the feed-forward system is to predict the forthcoming indoor climate, to prevent a change before it occurs. This is preferably done by using small measurable variations from existing sensors in the room such as thermometers, carbon dioxide sensors, relative humidity sensors and presence sensors. The aim of this thesis is to find a way to predict a forthcoming increase of the internal heat load, caused by people entering an office room. To find the most suitable parameter or a combination between them for predicting this, a number of tests measuring the mentioned parameters have been performed. The tests were performed at a very flexible test room, in an HVAC-point of view, at Building Services Engineering's test facility at Chalmers University of Technology.

Due to the limitation of the thesis, to only consider internal heat generated by humans, presence is a crucial factor that needs to be examined. Data achieved from the presences sensors does not give enough information, since they only have the ability to tell if someone enters the room and not the number of present people.

The response time (dead time) is an important feature of the sensors, which needs to be tested in order to find the parameter that first indicates that people have entered the room. The performed tests show that the carbon dioxide concentration was the fastest parameter to respond compared to the other measured parameters. This means that there is a potential in predicting a temperature raise, caused by internal heat generated by humans, by measuring the carbon dioxide concentration. The idea is to use this prediction to improve the system and thereby raise the thermal indoor climate and at the same time save energy.

Key words: Feed-forward, carbon dioxide concentration, relative humidity, temperature, presence, dead time.

Inomhusklimatsstyrning genom framkoppling i kontorsbyggnader
En mätstudie för att indikera internvärme och emissioner genererade av människor
Examensarbete inom Structural Engineering and Building Performance Design
CHRISTOFFER ISAKSSON
MARKUS JOHANSSON
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SAMMANFATTNING

Energibesparing är ett aktuellt ämne i dagens samhälle och nya sätt att spara energi på eftersträvas ständigt, helst ska de vara både kostnadseffektiva och pålitliga på samma gång. Byggsektorn står för en stor del av energiförbrukningen och ett sätt att spara energi där är genom förbättrade styr- och reglersystem för inomhusklimatet. Idag används vanligtvis återkoppling, som innebär att den undersökta parametern mäts och sedan jämförs med ett referensvärde. I denna rapport utvärderas och diskuteras möjligheterna att istället styra klimatet genom en metod som kallas framkoppling. Syftet med denna metod är att förutsäga det kommande inomhusklimatet innan det har uppstått, och på så sätt kunna förhindra oönskade förändringar. Det kan ske genom att utnyttja befintliga sensorer, såsom termometrar, koldioxidgivare, fuktgivare och närvarosensorer.

Syftet med detta examensarbete är att hitta ett sätt att kunna förutsäga en framtida ökning av internvärmelaster orsakade av människor i kontorsbyggnader. För att hitta den lämpligaste parametern för detta har ett stort antal tester genomförts, där information från flera sensorer har registrerats och utvärderats. Försöken har genomförts på Chalmers tekniska högskola, i lokaler som tillhör institutionen för installationsteknik. Genom avgränsningen att endast beakta internvärme orsakad av människor är närvaro en faktor som undersökts. De idag vanligt förekommande rörelsesensorerna ger inte tillräcklig information för detta, då de endast kan registrera om det finns människor i rummet och inte antalet.

Sensorernas dödtid är en viktig egenskap för snabb reglering, vilket är vad som eftersträvas. Den är väsentlig för att kunna välja den parameter som tidigast kan mäta förändring i rummet när någon kommer in, och därmed indikera närvaro. De genomförda testen har visat att koldioxidkoncentrationen var den parameter som reagerade snabbast och tydligast. Av de anledningarna föreslås koldioxidhalten som lämplig parameter för att förutsäga en framtida temperaturförändring, orsakad av människor. Tanken är att utnyttja denna prediktion för att såväl öka den termiska komforten som att kunna spara energi.

Nyckelord: Framkoppling, koldioxidkoncentration, relativ luftfuktighet, lufttemperatur, närvaro, dödtid.

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Preface

This study has been performed at Chalmers University of Technology, Göteborg. It is a part of the examination in the master programme Structural Engineering and Building Performance Design and comprises 30 hp. The master thesis has been carried out at the department of Energy and Environment, division of Building Services Engineering, from the middle of January to the beginning of June 2011.

The idea of the master thesis originates from Ph.D Mattias Gruber at the department of Building Services Engineering and is a part in a larger project involving his dissertation. Mattias Gruber has also been our supervisor and his knowledge in the research area has been a great asset, our different backgrounds and opinions have enriched the project in several aspects. Therefore, we dedicate him our greatest thanks due to his commitment and support. We also want to thank the research engineers Håkan Larsson and Tommy Sundström for helping us with troubleshooting and computer settings which were needed to be able to perform the tests.

Göteborg, June 2011

Christoffer Isaksson
Markus Johansson

Notations

The notations used in the report are presented below. The list is organized alphabetically according to the abbreviations. Moreover, the presented units are the most commonly used in the report, but can easily be transformed into equivalent units by using scale factors.

ACH	Air exchanges per hour [1/h]
A_D	Dubois surface area [m^2]
C_R	Room concentration of carbon dioxide [ppm]
C_{R0}	Initial concentration of carbon dioxide [ppm]
C_S	Supply concentration of carbon dioxide [ppm]
$C_{S,mean}$	Start supply concentration of carbon dioxide [ppm]
k	Constant for the properties of the duct-system
l	Length [m]
$\dot{M}$	Production rate of carbon dioxide [l/h]
M	Metabolic rate [Met, W/m^2]
m	Mass [kg]
ΔP	Differential pressure [Pa]
PMV	Predicted Mean Vote [-]
PPD	Predicted Percentage Dissatisfied [%]
Q_{o_2}	Consumption rate of oxygen [ml/s]
Q_{CO_2}	Generation rate of carbon dioxide [ml/s]
RQ	Respiratory quotient [-]
T_R	Room temperature [°C]
T_S	Supply temperature [°C]
$T_{S,mean}$	Mean supply temperature [°C]
t	Time [min]
$\dot{V}$	Supplied air flow rate [l/h]
V	Volume of the room [m^3]
v	Air velocity [m/s]
υ	Vapour content [g/m^3]

1 Introduction

Energy is an important issue in today's society and it is discussed on a daily basis. If the energy consumption is not decreased by either more efficient use or by changed behaviour of the users, global problems will occur. The building sector consumes a substantial part of the total energy use in the world; the magnitude in Sweden is about one-third of the total energy consumption (Karlsson 2005, p.1). The same number in the European Union is about 40% (Laverge, Van Den Bossche, Heijmans & Janssens 2011, p.1497). The energy consumption in the world is expected to increase even more the coming years, if the trend will not be changed (Dong, Andrews, Poh Lam, Höynck, Zhang, Chiou & Benitez 2010, p.1038). One discipline in the building sector where it is possible to decrease the energy use is in HVAC-systems since heating, cooling and ventilation affects the energy consumption for a building during the whole service life. The decrease of energy consumption should be made without decreasing the thermal comfort of the users.

1.1 Background

The main idea of this project is to find a model for control and regulation of HVAC-systems by a principle named feed-forward. The feed-forward principle is supposed to predict a forthcoming climate change by indications of upcoming changes in certain parameters, so that changes of the internal heat loads can be countered (Soleimani-Mohseni 2002, p.41). This should give a better performance of the system's regulation compared to the today commonly used feedback principle, which is illustrated in figure 1.1, and a higher thermal comfort, together with a lower energy use.

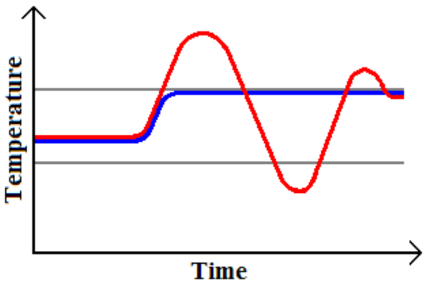

Figure 1.1. Principle of two different control and regulation systems. The red line illustrates the regulation principle of feedback control in a heating system, while the blue line shows a probable behaviour of a feed-forward strategy.

Today, feed-forward systems for buildings are mainly used considering the outdoor air temperature and not the indoor temperature that is more important for the users and their activity. The feed-forward control system is well developed and frequently used in other sectors e.g. the process industry. The feedback principle is a more common system for controlling the indoor climate, where the system makes changes due to the condition of the exhaust air, i.e. outgoing indoor air (Thomas, Soleimani-Mohseni & Fahlén 2004, p.755). It uses the measured data of a specific parameter to adjust the climate in terms of this parameter. The adjustment tries to compensate for the difference between the actual condition and the demands by comparing the resulting climate, outgoing indoor air, to the set value.

The main aim of both the feedback and the feed-forward principle in buildings is to give the users a satisfying indoor climate. The definition indoor climate includes both air quality and thermal properties; pollutants, temperature, humidity and draught. There are several ways to ensure that these parameters fulfil the demands, one way is to measure the climate by physical numbers while another way is to predict how comfortable a number of people will experience the climate. The latter approach considers the ratio of people that will be dissatisfied if a certain operative temperature is applied (PPD, Predicted Percentage Dissatisfied) and if they think that the climate is too warm or too cold (PMV, Predicted Mean Vote). The two parameters are evaluated in the diagram in figure 1.2. The PPD- value is presented in percentage, while the PMV-value is a scale from cold (-3) to hot (+3) climate (The Commtech group 2007, p.104). Normally, it is desirable to get a result in the diagram close to zero for both the x- and y-axis.

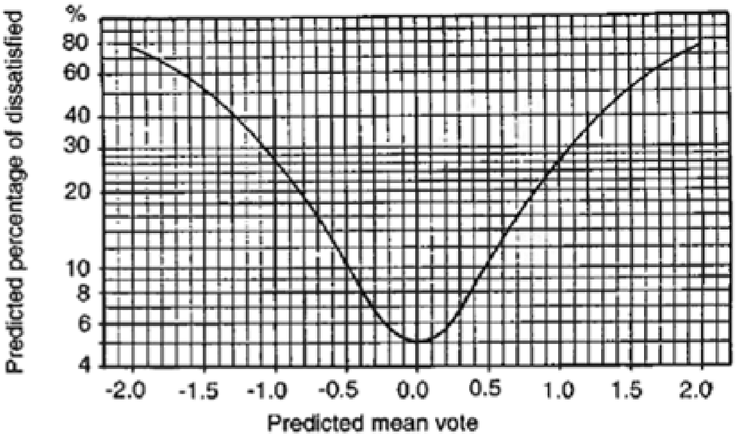

Figure 1.2. PPD and PMV indicate if the climate is comfortable or not. It is desirable to get a PMV-value close to zero, since it means that very few people will be dissatisfied. (The Commtech group 2007, p.104)

To get a measurable and controllable value of the air quality, the concentration of carbon dioxide is often used as an indicator, mainly because it is easy to measure and that it varies in the same way as other substances in the air (The Commtech Group 2007 p.142). The air temperature and the relative humidity of the air are measured by conventional equipment. All these sensor types are common in buildings today, but they are only to control the measured parameter i.e. the carbon dioxide sensor controls the air quality and the thermometer takes care of the temperature.

The span where the climate is considered to be acceptable is called the dead zone, which means that the state of the air is allowed to vary within this interval, with an upper and lower limit. It is in between those two limits the feedback and feed-forward principle tries to hold the indoor climate. A practical consequence by using a dead zone is that energy can be saved while the thermal comfort still is suitable. The dead zone in figure 1.1 is shown by the two thin black parallel lines.

1.2 Objective and scope

The purpose and the general aim of the master thesis is to attempt to find a relation between room temperature and different signal sensors such as concentration of carbon dioxide, relative humidity and presence of people. This is to be used in regulation of HVAC-systems where the ventilation is used as the heating system. The result is supposed to be used to see if there is a potential for using a regulation system called feed-forward, to raise the thermal comfort and at the same time get lower energy consumption, where unnecessary cooling and heating is avoided. The feed-forward principle is supposed to predict an upcoming indoor climate change, to provide the possibility for faster adjustment of the climate and with an improved accuracy, compared to the feedback principle. Another purpose is to find a way to identify the number of occupants in a room, so their internal load can be predicted in order to adjust the indoor climate. It is the internal heat load which needs to be predicted, therefore the temperature is commonly mentioned and temperature usually means the air temperature in this thesis (if nothing else is mentioned).

Previous research regarding prediction of internal loads has been performed by Mohsen Soleimani-Mohseni at Chalmers University of Technology. His research focused on internal heat generated by electrical equipment, while this study mainly considers presence of people.

The study is adapted for office buildings, since the test local and its ventilation system has been arranged in a way that is similar to traditional office rooms. Moreover, the investigation is limited to buildings where the ventilation is used to control the temperature, i.e. heating and cooling with air. The results may work also in buildings with hydronic temperature control, but that kind of system often has a thermal inertia which makes the benefits of a feed-forward control and regulation system less useful. Hydronic systems are, in general, heating and cooling systems based on water and are typically consisting of components such as radiators for heating and chilled beams for cooling. Airborne systems are mainly connected to the air handling unit. In order to make the results applicable to other office buildings than the specific test local, the ventilation level is varied and expressed in the unit air exchanges per hour. However, it is worth to point out that the purpose of this thesis is not to come up with a model ready to implement, but to see if there is any potential and if, how it could be used.

1.3 Method

The master thesis process begins with a literature study to get an adequate background to the subject. The work will continue with planning and setting up of laboratory tests in Building Services Engineering's test local at Chalmers University of Technology. Certain parameters will be measured in the test procedure, such as temperature, relative humidity, carbon dioxide concentration, air velocity, ventilation airflow rate and occupancy of the test room. The sensors will measure the required parameters at several locations to observe if local variations occur in the room and to confirm each other. The measurements are done for different settings such as varying number of occupants, changed ventilation level and with or without the door to the test room open. The laboratory measurements and the different settings are to be analysed and relations between predicted temperature changes and other parameters can hopefully be found. The results are evaluated and discussed to come up with conclusions and ideas for further research.

1.4 Outline of the thesis

The idea with the disposition of this report is to make it possible for the reader to read either parts of the work or all of it, depending on the reason for the reading and the basic understanding. The thesis starts with an introduction and background where very basic knowledge are presented and described, hopefully it will also clarify the purpose of the study and explain how the work has been carried out.

Chapter 2 is a continuation of the introduction and the purpose is to give the reader an adequate background of relevant parameters and limitations of those for office buildings. Furthermore, some information regarding ventilation and regulation strategies is explained in the end of the chapter.

The next chapter describes how the tests have been carried out, including information about the sensors and how the test procedure was adjusted and confirmed. These preparations were an important part in getting reliable results, which are described in chapter 4. This section presents the performed tests and the most essential results from the measurements. It is presented how the results should be used to indicate presence of people and regulate the indoor climate. Chapter 5 ends-up the thesis by clarifying the conclusions and comes up with ideas for further research.

The appendices follow the thesis and consist of some MATLAB-programs that have been created in order to get theoretical models and in the search for relationships between the parameters. Finally a lot of results from the measurements and comparisons are presented in diagrams.

2 Summary of Literature Studies

This chapter is used to describe characteristics of presented parameters in the thesis and is to explain the use of different kinds of control and regulation systems. It is also used to describe previous research in the field, including how control and regulation of indoor climate is used today. The idea with the section is to simplify the understanding and give the reader an adequate background of the subject.

The investigate parameters are typical factors influencing the experience of the indoor climate that are measureable. Carbon dioxide is the first parameter to be presented and vapour content and temperature follows. The parameters are frequently used for control of the indoor climate today and the measuring techniques are well developed. Carbon dioxide is well described in this chapter, but parts such as the human generation rate comply to both vapour and temperature as well.

2.1 Carbon dioxide

The carbon dioxide concentration is a crucial factor in the evaluation process of the indoor climate and it is therefore important to have basic knowledge about its behaviour in different situations. Furthermore, it is possible to predict the concentration and generation rate of the substance for situations with known input parameters.

2.1.1 Information and behavior

The atmosphere consists mainly of nitrogen and oxygen, but other gases are also present, which can be seen in table 2.1. Carbon dioxide is found at fourth place of this list, but is still very important for the air quality since it is the most common gas used to give indications about the air quality in buildings (The Commtech Group 2007, p.142)

Table 2.1. There are several substances in pure air in the atmosphere, where the carbon dioxide is the fourth most common (Ekberg 1992, p.15).

Substance	**Content**
N_2	78 %
O_2	21 %
Ar	0,9 %
CO_2	0,04 %
Ne	18 ppm
HC	5 ppm
CH_4	2 ppm
H_2	0,5 ppm
O_3	0,01 ppm

The concentration of carbon dioxide in the outdoor air is normally between 350 - 450 ppm, even if slightly higher concentration can be found in heavily polluted areas (SenseAir 2011a, p.1). The concentration of carbon dioxide in the area where the tests have been performed, i.e. at Chalmers University of Technology in the central parts of Gothenburg, is shown in figure 2.1. In the figure it is obvious that the concentration stays within the normal interval.

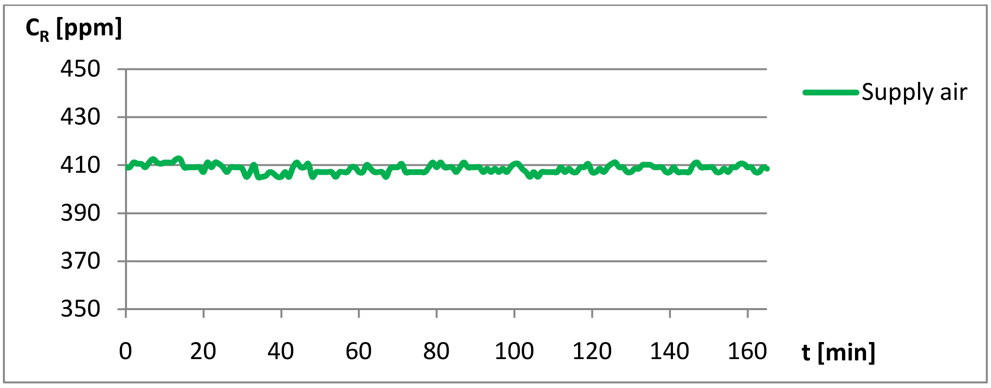

Figure 2.1. The carbon dioxide concentration in the outdoor air during the performance of test 15, the concentration is approximately 410 ppm.

As mentioned earlier, carbon dioxide is the most common gas used to indicate indoor air quality, because it is nearly harmless and gives indications of other gases that are generated as 'waste products', exhaled by humans. The concentration of carbon dioxide in the exhaled air is about 38000 ppm, but the concentration is decreased rapidly further away from the mouth and nose, since it is instantaneously spread to the ambient (SenseAir 2011a, p.1). This makes it important to avoid sensor locations too close to the persons occupying the room. Carbon dioxide is an innocuous gas in normal concentrations but if the indoor concentration gets as high as 30000 ppm it might cause unconsciousness or death (SenseAir 2011a, p.3). Since carbon dioxide is a harmless gas in low concentrations, it is often used as a tracer gas to control and regulate ventilation systems. In Sweden there is an upper recommended limit where the ventilation is considered as inadequate (Arbetsmiljöverket 2009), this is described further in chapter 2.4, *Indoor climate demands for office buildings*. There is no lower limit of acceptance but usually a too low carbon dioxide concentration indicates that the building is over-ventilated, which means that energy is wasted (SenseAir 2011a, p.2) Therefore, the concentration of carbon dioxide is also used to control the ventilation level in a ventilation strategy named DCV, demand control ventilation, which keeps the air quality 'good enough' for the users. This is explained further in chapter 2.5, *Ventilation strategies (CAV, VAV and DCV)*. Earlier studies have shown that the carbon dioxide concentration correlates to the number of occupants in a room (Dong, Andrews, Poh Lam, Höynck, Zhang, Chiou & Benitez 2010, p.1041).

2.1.2 Generation rate

The generation of carbon dioxide from a person depends on different parameters of the person; such as the activity, metabolism (diet), size and physical condition. The generation rate of carbon dioxide can be calculated by the following formulas, equation 2.1 and 2.2.

$$Q_{O_2} = \frac{M \times A_D}{21 \times (0{,}23 \times RQ + 0{,}77)} \quad (eq. 2.1) \text{ (ASHRAE 2001 p.8.7)}$$

$$Q_{CO_2} = Q_{O_2} \times RQ \quad (eq. 2.2)$$

M stands for the metabolic rate and should be inserted in the unit W/m^2, table 2.2 shows some values of this parameter. RQ is the respiratory quotient, which describes the molar ratio between exhaled carbon dioxide and inhaled oxygen, the factor equals 0,83 at low physical activity (up to 1,5 met) and varies linear up to high activity (up to 5 met) where RQ is equal to 1, this can be seen in figure 2.2.

Table 2.2. Metabolic rate for a number of different activities (ASHRAE 2001, p 8.7).

Activity	Met	W/m^2
Sleeping	0,7	40
Standing relaxed	1,2	70
Office, filing (seated)	1,2	70
Walking 4,3 km/h	2,6	150

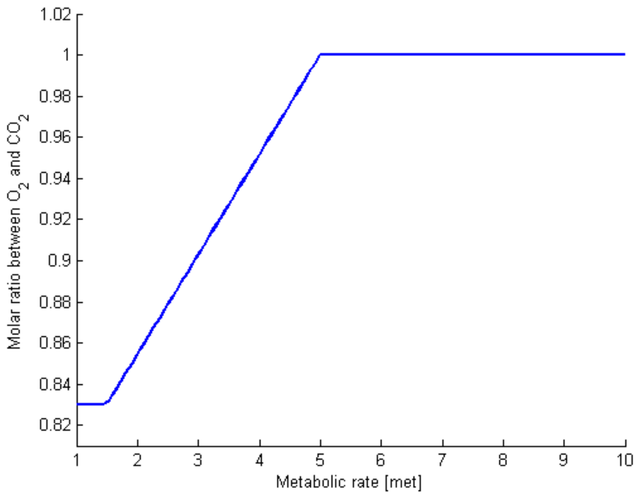

Figure 2.2. The metabolic rate [met] against the molar ratio between the inhaled O_2 and exhaled CO_2.

A_D is the Dubois surface area, which is the area of the nude human body surface and it is calculated by equation 2.3. (ASHRAE 2001, p.8.3)

$$A_D = 0{,}202 \times m^{0{,}425} \times l^{0{,}725} (eq. 2.3) \text{ (ASHRAE 2001, p.8.3)}$$

Where l is the height in metres of the person and m is the mass of the person. The average surface area (A_D) of a human is 1,8 m^2, according to ASHRAE (2001, p.8.3), but this value varies and is e.g. 1,77 m^2 in Scandinavia according to the The Commtech Group (2007, p.93). This means that a person of that size and with low physical activity (office work) generates 18,6 l/h. By using equation 2.1 and 2.2 together with the relationship between RQ, the metabolic rate and standard values of the human surface area, the following graph between the generated heat and the generated carbon dioxide can be established, see figure 2.3.

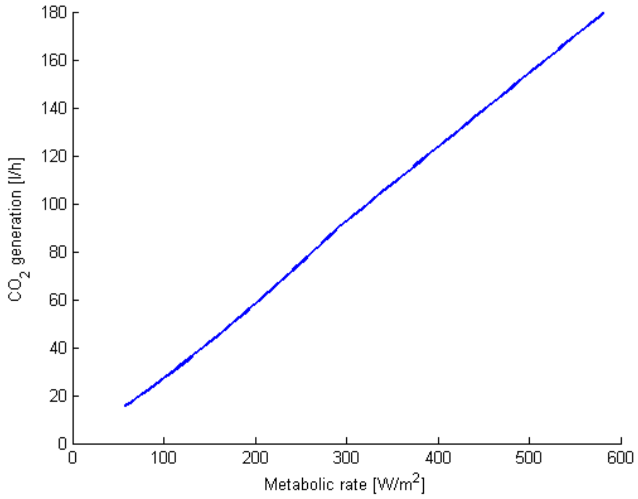

Figure 2.3. The Metabolic rate [W/m^2] plotted against the carbon dioxide generation [l/h]. Notice that the emitted heat is almost linear against the generated carbon dioxide.

Table 2.3 shows a list of the carbon dioxide generation rate for a number of situations. According to the table, the source flow of carbon dioxide for adults in an office is assumed to be 18 l/h. This is considered as close enough to the calculated value of 18,6 l/h, since there are some uncertainties depending on the persons, i.e. size and physical condition.

Table 2.3. Emitted carbon dioxide from people due to their activity [l/h]. (Ekberg 1992, p.24).

Activity	**Adults [l/h]**	**Children [l/h]**
Sleeping	10-12	7-10
Sitting	12-15	9-12
Writing on a machine	19-24	15-20
Light physical activity	33-42	25-34

Q_{O2}, calculated by equation 2.1, gives the computed value in ml/s and an illustration of the inhaled and exhaled gases towards the metabolic rate can be seen in figure 2.4. The illustrated amount of exhaled gas, Q_{CO2}, is calculated by equation 2.2.

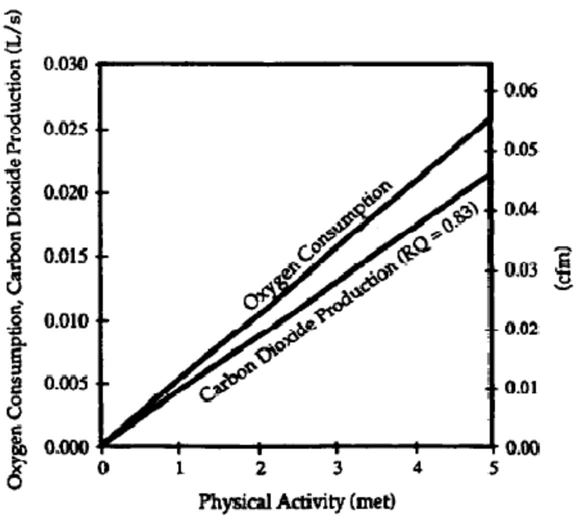

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Figure 2.4. The graph shows a comparison between the oxygen consumption and the carbon dioxide generation rate (Persily 1997, p.2). The generation rate of carbon dioxide, i.e. the production, is 83% of the consumed oxygen when the activity is low.

2.1.3 Analytical solution

It is possible to calculate an analytical solution in order to find the carbon dioxide concentration after a certain time for a specific situation. The analytical solution is valid for ideal conditions, which is hard to achieve in measurements. The input data in the analytical solution is of great importance and must correspond to the actual conditions.

The analytical solution for the concentration of carbon dioxide in the room, C_R, is given by the dilution equation shown in equation 2.4. The parameters that affect the equation are the outdoor and initial indoor carbon dioxide concentration, C_S and C_{R0}, production rate of carbon dioxide, $\dot{M}$, (e.g. number of people and their activity, see chapter 2.1.2 *Generation rate*) ventilation level, $\dot{V}$, and time, t. It might be hard to get correct numbers of these factors and this is one reason why the analytical solution and the measured test results might not always correspond to each other.

$$C_R = C_S + \frac{\dot{M}}{\dot{V}} - \left(C_S + \frac{\dot{M}}{\dot{V}} - C_{R0}\right) \times e^{\frac{\dot{V}}{V} \times t} \quad (eq. 2.4)$$ (Abel & Elmroth 2007, p.175)

2.2 Vapour content properties and behaviour

Vapour content is a parameter that is affected by both ambient conditions and indoor sources. The ambient conditions can change rather quickly according to figure 2.5 and the higher the ventilation rate is the more affected the indoor air becomes. Moreover, the relative humidity is also affected by the hygroscopic moisture buffering capacity in building materials (Laverge, Van Den Bossche, Heijmans & Janssens 2011, p.1501) and this may create a varying behavior of the vapour content depending on the investigated room or building.

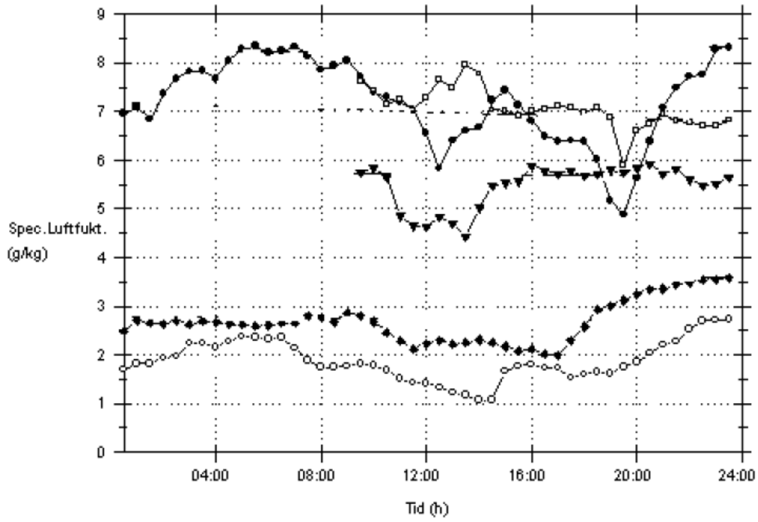


Figure 2.5. The diagram shows the variation of the specific humidity at 6 meters height during the following days: ❍ - 6/4, ◆ - 16/4, ▼ - 16/5, □ - 28/5, ● - 3/6. *The measurements are performed in the central parts of Gothenburg, next to Lilla Bommen (Forsler 1998).*

The indoor vapour content sources origin from a number of different sources, such as cooking, bathing, washing and breathing. The latter source complies more for an office building than the other sources and is around 0,1 kg/h for a human having an activity which corresponds to a carbon dioxide generation of 18 1/h (El Mankibi 2008, p.1357).

One parameter that might be possible to use for indication of presence of people in a room is the relative humidity. This parameter has no unit but depends on the air temperature and the vapour content. The indoor climate is often considered as uncomfortable if the air is too humid or dry, but the acceptable span for humans is rather wide compared to the acceptable span for certain machinery. Moreover, the span within the relative humidity where humans are satisfied is rather wide compared to the measurement accuracy of the sensors used in measurements.

2.3 Temperature and thermal comfort

The temperature variations of the outdoor air during a day might influence the indoor climate, depending on the magnitude of the changes and how advanced the ventilation system is. There is a significant temperature difference between the outdoor and indoor air during some periods of the year, i.e. in Sweden primarily during the winter. To take care of the temperature difference and create a comfortable indoor climate with a high air quality, both the ventilation, heating and cooling system have to be well designed. In some situations, these two aspects are regulated by the same system; when the indoor temperature is controlled by the ventilation system. It is well known that the outdoor air temperature varies during the year, but the indoor air temperature should be rather constant to fulfil the demands for a specific activity. The outdoor air temperature does not vary only during a year, but might vary rather much during a day and those variations are to be disposed by the heating and cooling systems. An example of the supply air temperature and its variation can be seen in figure 2.6, where the outdoor air temperature increased from – 0,5 °C to 0,5 °C during the test.

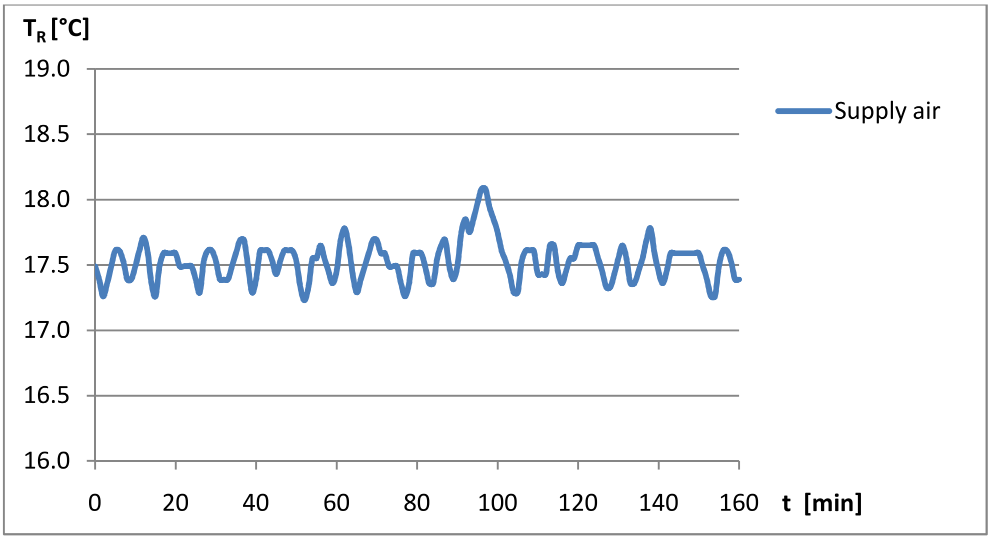


Figure 2.6. The supply air temperature during test 15.

There exist standards and recommendations for a number of aspects to define a healthy indoor climate; this is described in chapter 2.4*, Indoor climate demands for office buildings.*

2.4 Indoor climate demands for office buildings

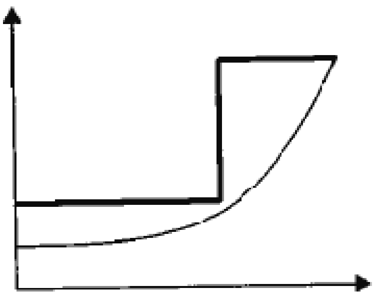
The concentration of carbon dioxide is, as mentioned earlier, often used as an indicator of the air quality, while the temperature and air velocity are used to evaluate the thermal comfort. In Sweden there are guidelines, published by VVS-tekniska föreningen (Ekberg 2006), regarding these parameters to get a suitable indoor climate. The guideline, R1, includes a number of classifications depending on the required comfort level and the activity.

Operative temperature is one of the classified parameters in R1 and the recommendations for an office building is that the temperature should be between 20-24 °C during winter and 23-26 °C in the summer (Ekberg 2006, p.33). Those limits are set for an office and divided into two classes, where class TQ1 is harder to achieve than TQ2.

Carbon dioxide concentration is another parameter that is considered in the guidelines for an office in R1, there are three classes for the indoor carbon dioxide concentration; the upper limits for each class are 700 ppm, 900 ppm and 1200 ppm (Ekberg 2006, s. 56). The lower the chosen class is, the better the indoor air quality becomes. If the concentration reaches 1200 ppm, it is recommended to implement changes (Ekberg 1992, p.25). A common upper limit that indicates acceptable air quality is 1000 ppm and the concentration should not exceed this value for a longer period of time (SP 2009, appendix 1 p.9). To be able to keep the concentration below the limits, the R1 recommend airflow rates of at least 0,35 l/(s,m^2) or 7 l/(s, person) in an office building (Ekberg, 2006, p.54). The test local where the measurements are performed is 32,6 m^2 which means that the recommended minimum air flow rate in our case is 11,4 l/s, when only one person is present, since the area flow is greater than the needed hygiene flow of 7 l/s per person. If the number of people in the room would be increased, the hygiene flow would be designing. There are also limitations regarding the air velocities in order to avoid draught. This category consists of two classes, TQ1 says that the velocity should be lower than 0,10 m/s if the air temperature is 20 °C and lower than 0,15 m/s if the air temperature is 26 °C., while the corresponding values for TQ2 is 0,15 m/s and 0,25 m/s (Ekberg, 2006, p.35).

2.5 Ventilation strategies (CAV, VAV and DCV)

There are mainly three different strategies to control and regulate ventilation systems, the preferable principle depends on the kind of building and how the building is supposed to be used. A principle called CAV (Constant Air Volume) might be considered as the least technical advanced control method and uses a constant ventilation level, with either one or two steps. Another common strategy is VAV (Variable Air Volume) where it is possible to change the airflow rate continuously. The principle of the CAV and VAV systems are illustrated in figure 2.7 and 2.8. The choice of ventilation strategy depends on the activity and how flexible the ventilation system needs to be, the CAV system might be preferable in buildings where the activity is rather constant while the VAV system often is used when the needed airflow varies a lot (Karlsson 2008 p.11). The two strategies have different demands of components in the system; the CAV should only be able to change the temperature of the supplied air while the VAV also should have the possibility to vary the airflow rate (Karlsson 2008).



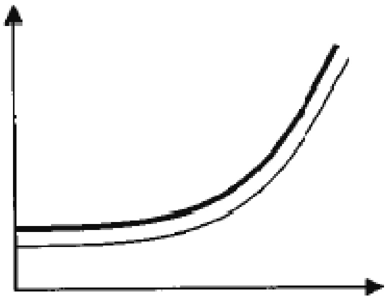


Figure 2.7 (left). The principle of a CAV system (Karlsson 2005, p.66). The airflow rate is changed in two steps to keep the air quality good enough. Hence, the thick line corresponds to the actual airflow, while the thin line describes the demand. The y-axis shows the airflow rate and the x-axis shows the duration (time).

Figure 2.8 (right). The principle of a VAV and DCV system (Karlsson 2005, p.67).

A third principle called DCV might be considered as an extension of the VAV system. It is built upon the principle that the supplied air to the building should be based on the actual demands at the moment. The DCV and VAV system might work identical if the latter one follows the needed airflow exactly. In a DCV system, the airflows at different times may vary considerably and a consequence of this is that the components in the system should be able to work with both high and low airflow rates (Karlsson 2005, p.72). To work properly, the DCV system needs to have at least one parameter that controls a measurable change in order to fulfill purpose of the system. The purpose might be that a building should have as low ventilation level as possible, but still maintain the thermal comfort and air quality; this could be controlled by some kind of presence sensor (Karlsson 2005, p.53). Today it is common to use presence sensors to control and regulate the ventilation level (Karlsson 2005, p.56), but it may be preferable to try to estimate a change that have not occurred yet; i.e. to use a feed-forward system instead of, the today commonly used, feedback system.

2.6 Working principle of a control and regulation system

The system used for managing an HVAC-system is normally called a control and regulation system. The name control and regulation have two different meanings, control refers to a control that is unaffected by the controlled parameter, this means control without any feedback information. Regulation is affected by the controlled parameter and this is called feedback, which performs changes in a closed loop until the desired value is reached[1]. Control is not that advanced, in a technical point of view, compared to the latter mentioned regulation. Regulation is built up as the following figure shows, figure 2.9.

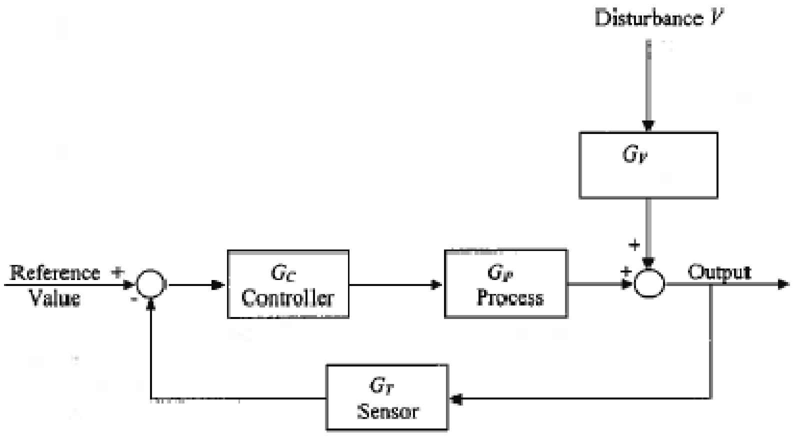


Figure 2.9. Block diagram of a feedback regulation system (Soleimani-Mohseni 2005, p.42).

The difference between the control and the regulation is, according to figure 2.9, the G_T sensor that measures the output and compares it to the reference value, it does not exist in a pure control system. The difference between the value measured at the output and the reference value is used as input signal, called error signal. A regulation that considers more input data is the feed-forward regulation system, figure 2.10 shows a block diagram of the function. The idea of the feed-forward system is to avoid a disturbance, which needs to be corrected before it affects the output value, hence the room climate (Soleimani-Mohseni 2005, p.42). Simplified; this means that a change of internal loads or ambient are to be predicted without affecting the indoor climate.

[1] Anders Trüschel PhD, Senior lecturer, Chalmers University of Technology 2011-01-31

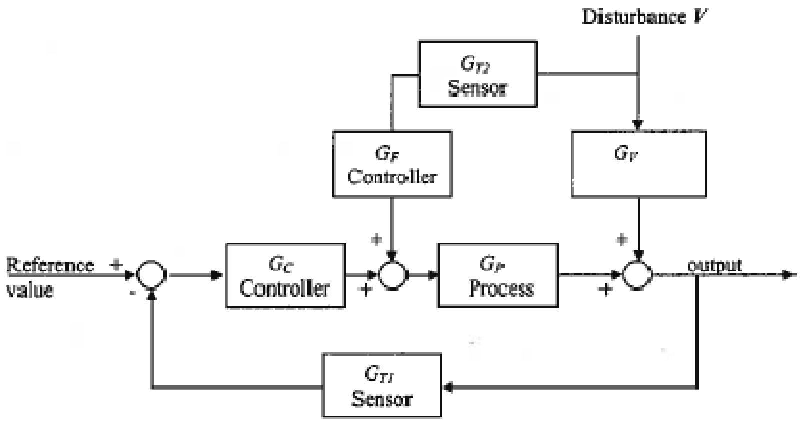


Figure 2.10. Block diagram of a feed-forward regulation system (Soleimani-Mohseni 2005, p.43).

The regulation are performed by regulators and they work in either floating (on-off) or modulating action, where the latter consists of a mixture of proportional action (P), integral action (I) and derivative action (D)[2]. The floating action can only operate between two positions, closed or open, while the modulating control can adapt to an infinite number of values (ASHRAE 2001, p.15.3). P-, I- and D-action can be put together in various combinations, depending on the required demands. P-action has a proportional response for an error signal; see figure 2.11, the equation for P-action can be seen in equation 2.5[2].

$u(\tau) = K \times e(\tau) = K \times a \ (eq. 2.5)$[2]

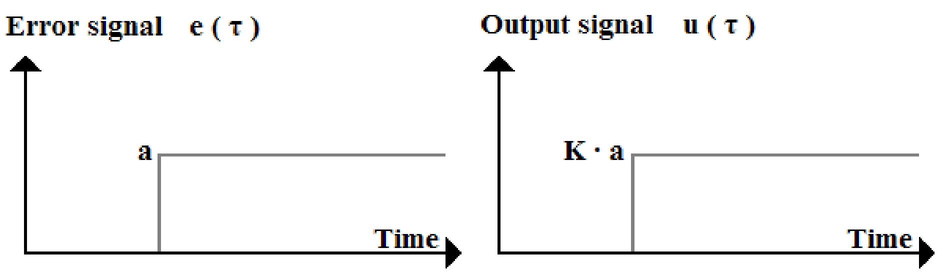


Figure 2.11. Error and output signal for proportional action[2].

I-action is to be used together with P-action and, if required, D-action. The output from the regulator will change more the longer the error signal exists; this can be seen in the diagram on the right hand side in figure 2.12. How the output signal varies with time can be seen in equation 2.6[2].

$u(\tau) = K \times \frac{1}{T} \int_i^T e(\tau) dt = K \times a \frac{\tau}{\tau_i} \ (eq. 2.6)$[2]

[2] Anders Trüschel PhD, Senior lecturer, Chalmers University of Technology 2011-01-31

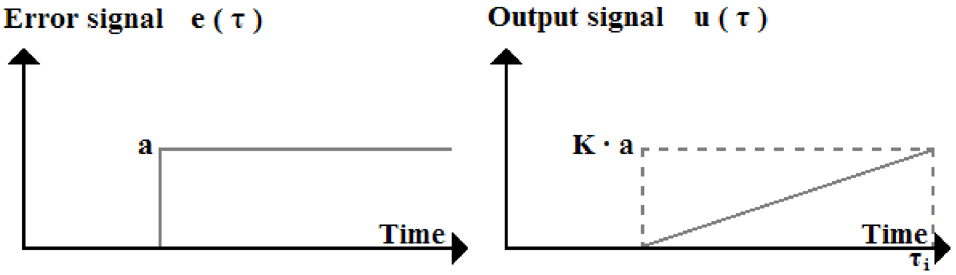


Figure 2.12. Error and output signal for integral action[3].

Figure 2.13 shows the function of D-action, which works by creating a large change when an error signal is noticed, to rapidly adjust the error and go back to stability. D-action is used together with P-action but it could also be used together with both P-action and I-action. Equation 2.7[3] shows the variation of the output signal with time.

$u(\tau) = K \times T_D \times \frac{de}{d\tau}$ $(eq. 2.7)$[3]

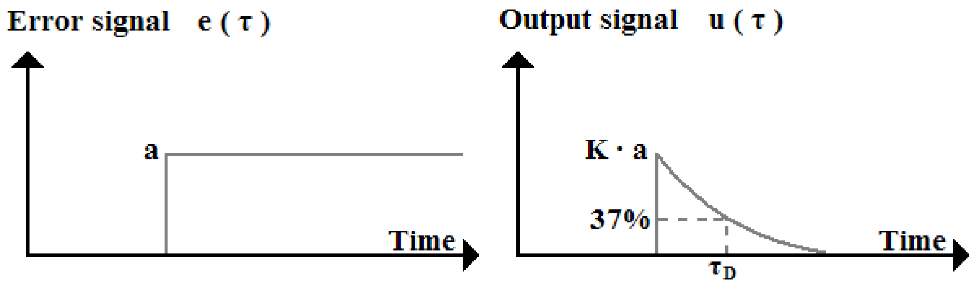


Figure 2.13. Error and output signal for derivative action[3].

A combination of P- and I-action in a regulation system works to adjust an error as illustrated figure 2.14. Notice how the changes is decreased as the variation gets closer to the set point.

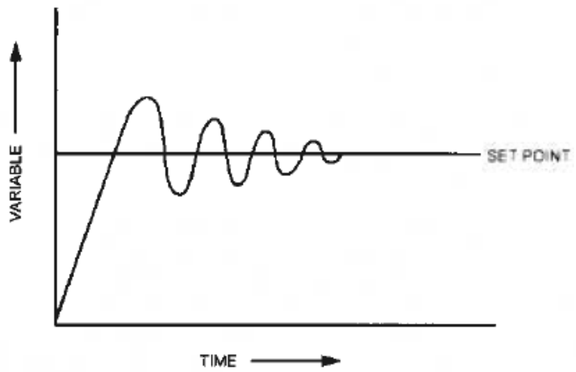


Figure 2.14. PI-action adjusting a parameter towards the set point (ASHRAE 2001, p.15.3).

The control and regulation depends a lot of how those regulators are combined and how they are set to work. A good tuned regulator can give both better thermal indoor climate and save energy compared to a badly tuned regulator.

[3] Anders Trüschel PhD, Senior lecturer, Chalmers University of Technology 2011-01-31

3 Test procedure

Several tests have been performed to find out how different parameters change when people enters and are present in a room. The tests have been performed in a test local which is rather advanced in an HVAC point of view, with several kinds of sensors, a number of air devices and a regulation system with high flexibility. The sensors are used both to control and adjust the indoor climate, but also in order to store measured data for evaluation and follow-up. The measured parameters are temperature, concentration of carbon dioxide, relative humidity, presence of people, airflow rates and differential pressure. The control system is, in the tests, mainly used to control the supply and exhaust air, which is supplied by intelligent air devices from Lindinvent and extracted by air devices from Swegon. The air temperature is controlled by the ventilation system, which is equipped with heating and cooling coils in the air handling unit.

The purpose of the study is to predict presence of people in an office; the test room has therefore been configured to simulate this situation. This has been done by only using one supply and one exhaust air device, with reasonable temperatures and common airflow rates. Common for all tests, where there are people present in the test local, is that the entry occurs five minutes after the test has started.

3.1 Location and layout of the test local

The measurements have been performed in a test room that is located in the test facility for the division of Building Services Engineering at Chalmers University of Technology. The facility is located close to the campus in the central parts of Gothenburg, without any considerable sources of carbon dioxide generated by heavy traffic or combustion processes in the neighbourhood. The test room measures 5,6 meters in width and 6,2 meters in length according to figure 3.1.

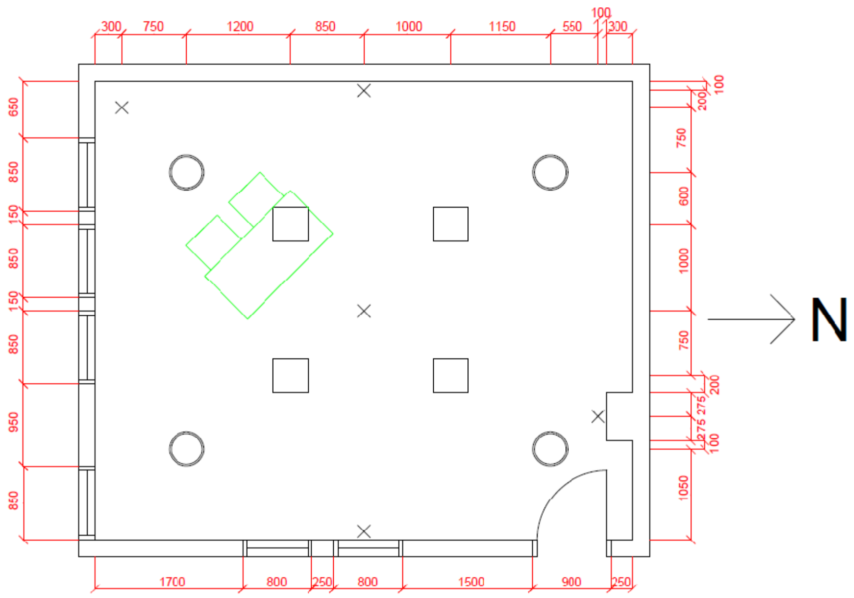


Figure 3.1. The layout of the test room with 'x' marking the portable sensor positions, circles marking the supply air devices, squares marking the exhaust air devices and the test persons' location is marked in green.

The south wall with windows and the west wall are facing the outdoor ambient and the north wall is facing the test facility. The east wall, which has two windows and a door, is facing the control room. The height of the test room is 2,4 meters and the total volume is 78,8 m^3.

The intelligent supply air devices from Lindinvent, are able to maintain the air cast length even if the airflow is changed[4]. The supply devices are equipped with a number of sensors that are able to measure parameters such as room temperature, differential pressure, airflow and presence. The exhaust air devices manufactured by Swegon is not as advanced as the supply devices. However, there are still possibilities to get information about the exhaust air since there are a number of sensors located in the duct system. The air devices and their locations can be seen in figure 3.2, where position number one to four correspond to the air devices. The other numbers is used to describe positions where portable sensors are located in different tests.

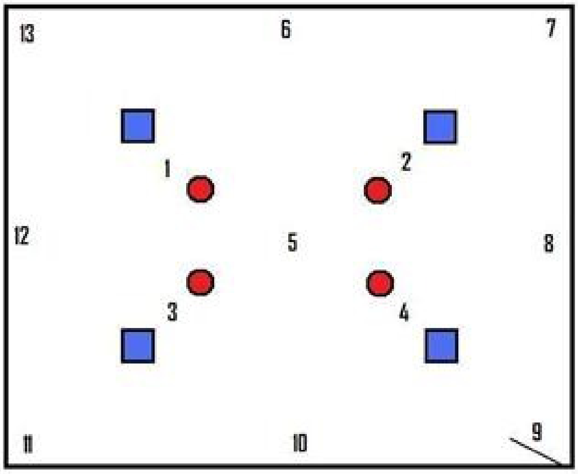


Figure 3.2. Layout of the test room with supply and exhaust devices (number one to four) and different measurement positions (number five to thirteen). The blue squares illustrate supply air devices, while the red circles correspond to exhaust air devices. The door, located close to position 9, is situated at the eastern wall connecting the test room to the control room.

The air handling system, which supplies and extracts air from the room, is rather advanced and very adaptable. It consists of one large air handling unit, which conditions the air and transports it into a pressure chamber. The pressure chamber is connected to the four supply air devices by four separate supply air ducts. Each small separated duct has its own small fan, which together with the large fan in the air handling unit pressurizes the system. The same principle exists on the exhaust side, but since the air is extracted the pressure chamber is located after the small exhaust fans and before the large air handling unit. The supply side of the large air handling unit consists of a filter, a cooler, a heater and a fan while the exhaust side only consist of a fan. The system has the ability to recirculate extracted air from the room, which saves energy and unnecessary conditioning. Another special feature with the system is

[4] Thomas Lindborg Sales Manager Lindinvent, 2011-02-16

the ability to recirculate air on the supply side of the air handling unit. This recirculation improves the possibility to supply the room with the desired temperature and air quality.

The air handling unit is located quite close to the test room, while the outdoor air inlet is located at the other side of the test facility. This means that the air is transported by a 20 meter long air duct going through the test facility. A figure illustrating how the air handling unit is located compared to the outdoor air duct can be seen in figure 3.3; the importance of this is described in chapter 3.4, *Corrections and modifications of the test procedure*. The air duct has two filters close to the outdoor air inlet, the remaining components is located in the air handling unit.

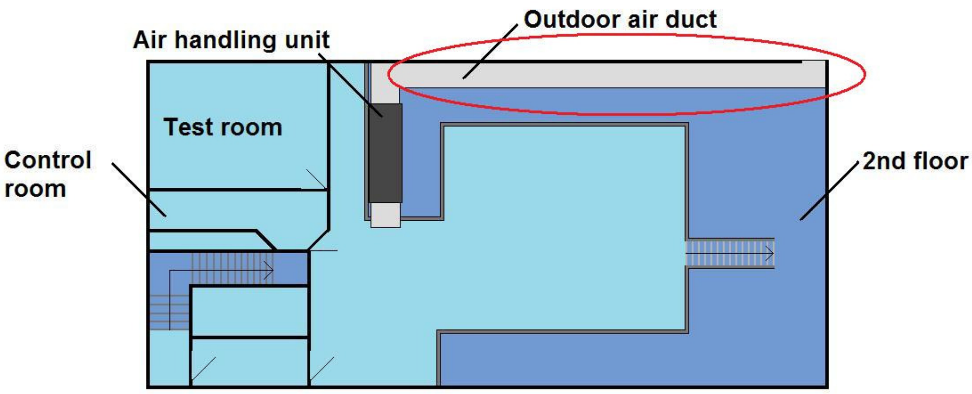


Figure 3.3. Layout of the test facility, including the duct that transports the outdoor air.

3.2 Sensors

Several kinds of sensors are used in order to get information about the climate in the test local. The used sensors are: carbon dioxide sensors, thermometers, hygrometers, presence sensors and an anemometer, which measures air movement. An Airflow sensor is also used, but mainly to control the climate in the room so the supply of heat and outdoor air become stable without too much fluctuation. This is important for the comparison of test results in the evaluation process, in order to make correct conclusions.

To be able to perform the tests it is crucial to use appropriate sensors and have information about their accuracy and function. Both portable sensors and sensors with fixed position have been used to perform the measurements, where the fixed sensors mostly are built-in into the air supply and exhaust system. The logging interval is set to one minute for both the portable and fixed sensors. The portable sensors are positioned in locations suitable for the tests, according to figure 3.2, where position 5 to 13 are sample positions. The used sensors have different features and advantages; some of the portable sensors have built-in loggers and memory, which gives a possibility to collect values and store them at certain intervals. The portable sensors are placed at a height of 1,1 m; this is a height which has been used in other similar tests, since it corresponds to a seated person (Maripuu 2009, p.14). Further information about technical data of the portable sensors can be found in table 3.1. It is worth to notice the accuracy for each sensor, because this might affect the absolute value considerably. Tests measuring the absolute value can be affected by this, but it does not comply with tests measuring the relative change.

Table 3.1. Features for different sensors used in the tests. EASYlog24RFT is mainly used to measure vapour content and temperature in the air, while the primary function of SenseAir and pSENSE-RH is to measure carbon dioxide concentration.

Portable sensors	EASYlog24RFT	SenseAir	pSense-RH
Temperature	X	X	X
Measurement range	-25 – +60 °C	0 – +50 °C	-10 – +60 °C
Accuracy	±0,1 °C	±0,5 °C	±0,6 °C
Relative humidity	X	-	X
Measurement range	0 – 100%	-	0 – 95%
Accuracy	-25 – +60 °C	-	±3%
Carbon dioxide	-	X	X
Measurement range	-	0 – 6000ppm	0 – 3000ppm
Extended range	-	6000 – 10000ppm	3000 – 9999ppm
Accuracy	-	±20ppm	±30ppm
Memory	X	X	-
Battery	X	Not working	X

All the fixed sensors have the ability to collect data, since they are connected to the computer that controls and regulates all systems regarding heating, cooling and ventilation for the test local. The fixed sensors are mainly located in the duct system and in the supply air units, figure 3.4 shows their positions. The sensors at position number 1 measure the outdoor air condition, including carbon dioxide, temperature and relative humidity. The sensor in the next position, number 2 in the figure, measure the carbon dioxide concentration in the supply air duct which should show the same result as sensor 1 if there is no leakage or infiltration into the air duct. The sensors in position 3 are located in the pressure chamber and show information regarding the supplied air. The thermometer in the next position, number 4, measures a combined value of the condition in the supply air and the room. The last position, number 5, presents data of the exhaust air condition. To get adequate results, it is important that the sensor is located in a suitable position and correctly installed. It should measure a representative value with as few disturbances and uncertainties as possible (The Commtech group 2007, p.593).

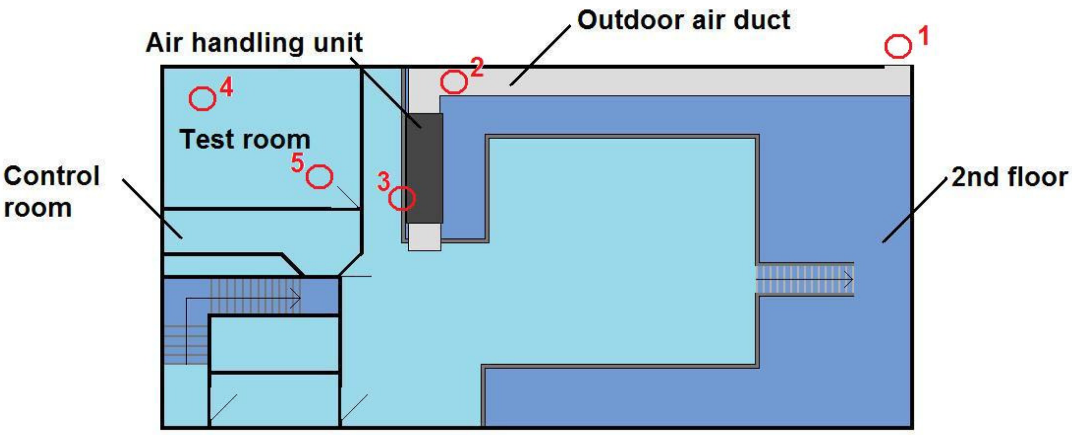


Figure 3.4. The red circles, marked 1-5, show the location of the fixed sensors.

The fixed sensors, which have been used in the tests, are manufactured by t.a.c and are named SCD100, SHD100 and STD400. SCD100 measures the concentration of carbon dioxide and have technical properties according to table 3.2. SHD100 and STD400 measure the relative humidity and the air temperature, their technical information are also presented in table 3.2.

Table 3.2. Technical data of the fixed sensors, all manufactured by t.a.c.

Fixed sensors	SCD100	SHD100	STD400
Temperature	-	-	X
Measurement range	-	-	-50 – +50 °C
Accuracy	-	-	±0,4%
Relative humidity	-	X	-
Measurement range	-	0 – 95%	-
Accuracy	-	±2%	-
Carbon dioxide	X	-	-
Measurement range	0 – 2000ppm	-	-
Extended range	-	-	-
Accuracy of measurement range	±1%	-	-
Accuracy of measurement value	±5%	-	-
Memory	Computer	Computer	Computer

3.2.1 Carbon dioxide sensors

The sensors used for measuring the concentration of carbon dioxide are both of portable and fixed types. The main purpose of the carbon dioxide sensors is to use the change in concentration to indicate if someone enters the room and the number of people that enters. This could be used to predict a forthcoming temperature rise.

Earlier studies have shown that carbon dioxide sensors have sufficiently fast response to control the indoor climate due to air quality (Maripuu 2009, p.7). Both the portable and fixed sensors measure the concentration of carbon dioxide by a technology named Non-dispersive infrared (NDIR), which use the principle of light absorption. Even faster response can be achieved, which is desired, by using electrochemical sensors instead of NDIR-sensors (Maripuu 2009, p 86). The NDIR technology works by the principle that a certain gas absorbs infrared light at a certain wavelength and this is used to calculate the gas concentration (Maripuu 2009, p.56).

The used portable sensors are manufactured by SenseAir and named SenseAir and pSENSE-RH. The sensor SenseAir has a built-in memory that can store collected data throughout the test, pSENSE-RH lacks this possibility and has to be read manually. The accuracy and more technical data about those two sensors can be found in table 3.1 (SenseAir 2011b & SenseAir 2011c). The two portable sensors are to be placed at two different positions in each test. This is done to see if there are local variations in the concentration of carbon dioxide in the room. This could be used later, to find out where the best sensor location is for a feed-forward control system.

Two fixed carbon dioxide sensors manufactured by t.a.c, SCD100, are used in the tests. The first sensor is located in the supply air pressure chamber and the other one is located in the exhaust air duct which connects the exhaust pressure chamber to the active exhaust device situated in the test room. The sensor located in the supply air pressure chamber gives approximately the same carbon dioxide concentration as the outdoor air and is used as a reference, which give information about variations in the outdoor air. This is important since steady-state is assumed in the analytical solution and a varying outdoor climate might affect the indoor climate. The sensor located in the exhaust air duct is used to measure the actual concentration of carbon dioxide leaving the room and it might be a possible sensor for controlling a feed-forward system.

3.2.2 Thermometers

Both portable and fixed thermometers are used in the tests. The thermometers used are mainly supposed to find out if, and after how long time, a temperature raise can be noticed when a person enters the room. This indication is to be compared with other parameters in order to evaluate which one is the fastest indicator.

Three portable thermometers and two portable carbon dioxide sensors with built-in thermometers are used to give information about the temperature changes. The two built-in thermometers, SenseAir and pSENSE-RH, have quite low accuracy compared to the three "real" thermometers and are therefore just used to give an indication of the temperature while performing the tests. The three thermometers are of the type EASYlog24RFT and measure both temperature and relative humidity. Information regarding their accuracy and some other technical data can be found in table 3.1. The EASYlog24RFT sensors have a built-in memory that allows them to store temperature readings during the test, which can be received after completing each test.

The fixed thermometers, STD400, are located in the air handling system, within the ducts and air devices. In total five thermometers are measuring the air temperature on its way to the room, their location is shown in figure 3.4. The sensor in the air supply device from Lindinvent, number four, gives a combined value of the room temperature and the supplied temperature since the device mixes the room air with fresh supply air. This thermometer is not of the STD400 type, since it is installed in the Lindinvent air device. The sensor located in the exhaust duct, number five in figure 16, shows the temperature of the air leaving the room, i.e. the room temperature. There are also thermometers measuring the supplied heating and cooling, but they are just checked manually in order to make sure that they do not vary too much during the tests.

3.2.3 Hygrometers

The hygrometers are mainly used to give information to be compared to the thermometers, carbon dioxide sensors and presence sensors. The comparison is done to show which one of the measured parameters gives the fastest response of people entering the room. The relative humidity depends on temperature and vapor content. This means that the relative humidity can decrease even if the amount of vapour in the room is increased. The measured relative humidity is therefore converted into vapour content by using the temperature measured at the same position.

The equipment for measuring the relative humidity is the same as for the portable thermometers; three EASYlog24RFT that collect both temperatures and relative humidity's and with the ability to log the measured data in a built-in memory. pSENSE-RH also measures relative humidity but since it cannot store the data in a memory, it is only used as a carbon dioxide sensor. More technical information about the EASYlog24RFT and pSENSE-RH sensors can be found in table 3.1.

A fixed relative humidity sensor, SHD100 from t.a.c, located inside the outdoor air duct is used to give information about the air humidity supplied to the room. This sensor is located just before the air handling unit, at position 3 in figure 3.4.

3.2.4 Anemometer

An anemometer measures the air movement at a certain position. The purpose of this sensor is to find out if there is any change in air movement when people enters or are already present in the room, in this way the sensor could act as a presence sensor. A limitation with the used type of anemometer is the lack of information about the direction of the air movements, since only the air velocity is measured.

The portable sensor used in the tests is of the type SwemaAir 300. The device consists of a long metal stick, approximately 0,85 meter tall, with the sensor mounted on the top. The air velocity is measured with a certain interval and a mean value is calculated for a period of three minutes. The mean value is used to avoid unreasonable deviations that not are representative for the situation.

3.2.5 Airflow sensor

To be able to get convincible results, it is of great importance that the airflow rates are measured correctly. The supply airflow rate is controlled by a computer in which it is possible to set values and make adjustments. The principle of a feedback-system is used, where the sensor with fixed position is connected to the computer that regulates the flow depending on the measured information. The fixed sensor is located in the supply air device and measures the supply airflow rate. The portable sensor is both used to confirm the supply airflow rate given by the fixed sensor and to measure the exhaust airflow rate.

The equipment that is used to confirm the supply airflow and to measure the exhaust airflow is called an orifice plate. The orifice plate function is built upon the theory of pressure differences and the assumption of turbulent flow. The orifice plate is connected to a measuring device, named SwemaAir 300, and this tool measures the differential pressure and together with a 'k-value' the airflow can be calculated according to equation 3.1 (Swegon 2010). The k-value for the test case equals 16,4 due to the duct properties.

$$\dot{V} = \sqrt{\Delta P} \times k \ (eq. 3.1)$$

The fixed sensor is built-in into the air supply device, manufactured by Lindinvent. It both gives information about the differential pressure over the supply device and the airflow through the device.

3.2.6 Presence sensor

Presence sensors are today used in many control and regulation systems for buildings, but they are not able to register the number of occupants. An advantage with the presence sensor is that the time to response is very short when someone enters the room, while there is a risk that the sensor believes that the room is empty if the activity in the room is calm.

There is one presence sensor installed in each supply air device in the test room, but there is only one sensor activated in the test since the other are covered while the tests are performed. This means that there is a risk that the sensor does not detect presence far away, i.e. in any of the corners in the room. However, this will not be any problem in a local where the use of the devices is adapted to the specific room.

3.3 Preparations of the test procedure

Before testing can be performed some settings must be prepared and some controls needs to be done. To avoid mistakes a checklist with things to do before testing is used:

- Programming the sensors to start logging values, at a certain time, and decides the logging interval in addition to set the stop time.
- Control the climate so steady state is reached before testing, both regarding carbon dioxide concentration and temperature. The room can be aired in order to fasten the time it takes to reach the steady state level. It is important to get convincible results; otherwise there will be a need to redo the test.
- Measure the airflow rate by an orifice plate to confirm the supply airflow measured by the supply air device and to find out and adjust the exhaust airflow.
- Put the sensors in the right positions and check that the air leakage, from the closed supply devices, is negligible.
- Perform documentation of the test procedure and the settings, before and after the test, in order to be able to evaluate the results correctly and have the possibility to repeat it.

3.4 Corrections and modifications of the test procedure

In total, 49 tests have been performed to get information of resulting changes for different conditions and settings. In the initial tests some unexpected problems of the settings and unforeseen behaviour of the test local occurred. The results from the first measurements, test one to 14, were not considered as successful, since the results deviated significantly from the analytical solution. Therefore a period of troubleshooting of the control system and the test room was initiated. The idea was to get measured results that were similar to the analytical solution in order to confirm that the test method was reliable. An important assumption in the analytical model is total mixing of air in the room; to achieve this situation a number of portable table fans were used. Moreover, it is also assumed that the supply and exhaust airflow is of the same magnitude, i.e. balanced airflow rate.

The first problem that was found considered the sensor measuring the outdoor air concentration of carbon dioxide; the sensor indicated very high concentrations and it was rapidly increased during the day and declined to normal values during the night. A relationship between the carbon dioxide concentrations, the number of people in the test facility and the occupancy hours were found. The position of the sensor was identified to be located in the end of the long duct inside the test facility and not outdoors. The error was caused by improper installation of the sensor, since the carbon dioxide sensor was mounted so it did not reach into the duct and therefore the indoor air concentration in the test facility was measured, instead of the desired outdoor concentration. This was adjusted by giving the sensor a more suitable position where it could reach down to the supplied outdoor air. After performing the adjustment, the measurements still did not show satisfying results; the concentration was too high compared to measurements from a portable carbon dioxide sensor. Because of the unreliable results, a sensor located in the supply air pressure chamber was used instead. This sensor gives stable values that are slightly higher than the outdoor air concentration, but its location gives the real supply air concentration of carbon dioxide and that is what is desired.

Another problem that occurred regarded the room temperature. The temperature is controlled by a floor heating system, which also could be used as floor cooling, and heating and cooling coils in the air handling unit. In the initial tests, the temperature fluctuated too much to give reliable test results. The problem was solved in the control and regulation computer by changing the heating control system so a less varying temperature interval could be set. This created a more stable supply and indoor temperature, which gave the possibility to proceed the testing.

Other issues that caused problems with the tests depended on the ventilation. The most severe one considered the airflow, since only the supply airflow could be measured and not the exhaust airflow. This caused unbalanced ventilation in the room, and the measured values did not follow the expected behaviour of the room. To solve this issue holes were drilled in the air ducts to give the possibility to measure the differential pressure by an orifice plate, which together with calculations gives the airflow rate. This was done for both the supply and exhaust air ducts; the airflow rates could now be compared to confirm that balanced ventilation is achieved. The supply and exhaust of air, to and from the test room, is distributed via one supply device and extracted through one exhaust device, even if there are four of each type. This means that the other devices are inactive; the supply devices can be closed by the control computer but the exhaust devices lacks this possibility since there are no dampers installed, on either the supply or exhaust side. Because of this, the exhaust devices were sealed and to ensure that no leakage would occur through the closed supply devices, the same thing was done on them.

A problem that includes both the ventilation and the carbon dioxide concentration considers the pressure and airflow inside the air handling system. This problem has the same origin as the problem with the outdoor air carbon dioxide sensor and the main issue is the outdoor air duct and the air handling unit. Because when the airflow was too low in the outdoor air duct, too much air from the test facility leaked in into the duct and air handling unit. This gave too high supply concentrations of carbon dioxide and since the air originated from the test facility, it varied a lot throughout the day.

3.5 Performed tests

The purpose with the performed tests has been to investigate if any of the measured parameters fulfil the desired properties:

- Quick response
- Reliable indications
- A clear change
- Small noise
- Slow natural variation

To investigate those properties, tests have been performed with varying sensor positions to find out if the response is quicker in certain locations. This is also investigated with a smoke gas test which is described further in chapter 3.7 *Analysis of the airflow pattern (smoke gas test).* Moreover, it is important to get a clear change to be sure about the correctness of the indications and by that avoid mistakes in the control and regulation strategy. The noise should be considered to not influence the results and has been investigated for both low and high concentrations, the latter means at steady state levels and this is treated in chapter 3.8 *Noise test.* The desired properties have been evaluated for factors that might vary in a normal office room, such as the number of present persons, which have been varied between one, two, three and four persons. The same applies for the airflow rate which has been varied between one, two and three air exchanges per hour. A couple of tests have been performed with 0,6 air exchanges per hour, but it is hard to keep a stable airflow at those low rates so those tests have been neglected. Tests have also been performed when having the office door open, since this is normally done at an office building. Those tests have been performed with both varying airflow rate, one, two and three air exchanges per hour and varying differential temperature, one, three and five degrees. Tests where the numbers of test persons have been varied during a test have also been simulated and those tests were performed with two persons present in the room and a third person entering after some time. The time it takes until the third person enters have been chosen to indicate interesting patterns in the measurements. A test to verify the test local has also been performed and in this test full mixing of the air was applied since the air volume in the room should be homogenous, which is assumed in the analytical solution described in chapter 2.1.3 *Analytical solution*. All measurement results can be found in appendix 1.

3.6 Confirmation of the test procedure

In order to verify the test procedure and confirm the room conditions, a test with full mixing of the test room air was performed. The measured concentration of carbon dioxide, at different positions, is illustrated in figure 3.5 together with three different analytical solutions, where the generation rate of carbon dioxide has been varied.

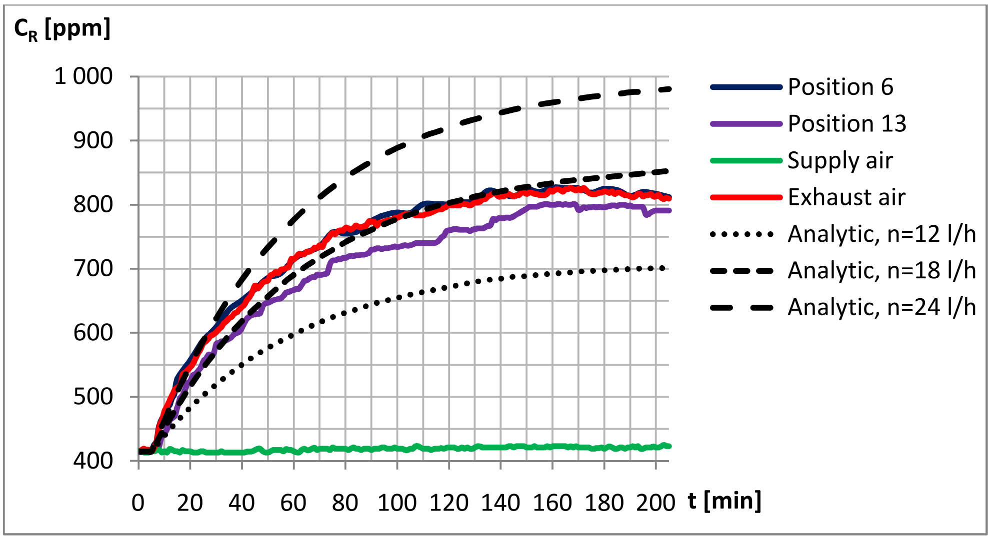


Figure 3.5. Test 28: One 1/h and full mixing of the air. The measured values are normalized to the supply air concentration.

To get full mixing of the air in the room, two 'table fans' placed at position 7 and 11 circulated the air to avoid peak concentrations at certain positions. The test was performed with two persons sitting down with low activity level, except for some shorter moments where the test persons moved around to create forced induced movement of the air. These movements were applied when the measured test values started to deviate from the analytical solution.

There are three different analytical solutions regarding the carbon dioxide concentration in the room, marked with dashed lines, presented in figure 3.5. The difference is the generation rate (marked 'n' in the figure), i.e. how much carbon dioxide that is emitted from the people in the room. The analytical solution with a source flow of 18 1/h corresponds best to the measured results, which is reasonable compared to the recommended values in table 2.3. Moreover, the analytical solutions assumes ideal conditions, i.e. no infiltration or air leakage, presence of two people that enters the room after five minutes and an airflow of one 1/h with a supplied start concentration of carbon dioxide of 408 ppm, which has behaved rather constant during the test performance.

In figure 3.5, it can be seen that the sensors react uniformly in the beginning of the test. The differences between the sensors are very small; this might depend on the short sampling interval of one minute. The figure also shows that the exhaust air sensor and the sensor in position 6 have very similar behavior, which confirms sufficient mixing of the air. Furthermore, it is reasonable that the concentration at position 13 is somewhat lower than the other concentration levels since the sensor is located right behind the air supply device. The supplied air is directed towards the corner, which means that the contaminated air in the room is mixed with the newly supply air that has not been affected by the carbon dioxide concentration in the room yet. The carbon dioxide concentration of the supply air is rather constant, which is good since this is assumed in the analytical solution.

The sensors at position 6 and in the exhaust air are, as mentioned above, very similar to one of the analytical solutions for the first 150 minutes. The measured concentration of carbon dioxide indicates that the steady state level has been reached, which means that the room concentration stays at a level of 820 ppm when the airflow is one 1/h. The carbon dioxide concentration in the analytical solution with a source flow of 18 l/h only has a slight increase after this moment and reaches steady state after approximately five hours. The difference is probably due to infiltration and leakage between the room and the ambient.

Similar confirmation has not been performed for the temperature or the relative humidity, since there is a lack of information about the test room's construction such as wall materials and their thickness etc. Therefore, it was considered better to not create a model for either temperature or relative humidity, because so many assumptions needed to be done to get a proper model.

The used sensor positions were determined by a smoke gas test, which is described further in the following chapter 3.7, *Analysis of the airflow pattern (smoke gas test).*

3.7 Analysis of the airflow pattern (smoke gas test)

A smoke gas test has been performed to identify the airflow pattern in the room. The test was supposed to give information about where to place the portable sensors. The sensors are to be placed at positions where the airflow both is high or low, a high airflow in this case means denser smoke and early distribution (high start concentrations). A smoke producer was placed at the position where the test persons normally are located, which means quite close to the active supply device. The device lifted the smoke up and sent it away backwards towards the room corner; see the following figures 3.6, 3.7 and 3.8.

Figure 3.6 (left). A smoke test was performed to illustrate the airflow pattern. The picture shows the smoke gas tests settings just before activating the smoke generator.

Figure 3.7 (middle). The same setting some seconds after the smoke generator has been started. Observe the small green object placed in between the supply devices lamellas and how the smoke is drawn against the supply device.

Figure 3.8 (right). The smoke gas test after some more time, a vortex of smoke can be seen next to the supply device. The device sucks the smoke up and mixes it with the supplied outdoor air.

The air flow pattern, ocular observed from the smoke test, are illustrated in figure 3.9 and 3.10 (plan and section drawing). It could be seen that the supply air device sent the smoke backwards because the device is equipped with a plug, to avoid injection flow, i.e. that the supply air goes towards the middle of the room and is extracted directly. When the smoke hit the southwest corner it started to follow the walls, slightly more along the south wall than along the west wall, next to the ceiling and fell down along the wall to the floor. At the same time, the smoke at the south wall continued to follow the south wall next to the ceiling to the next corner; there it started to form a vortex from where the smoke started to spread in all directions. The smoke following the west wall went next to the ceiling until approximately half the wall length and then it started to turn into the middle of the room and reached the exhaust device. The smoke following the floor slightly began to rise when it get close to the exhaust device.

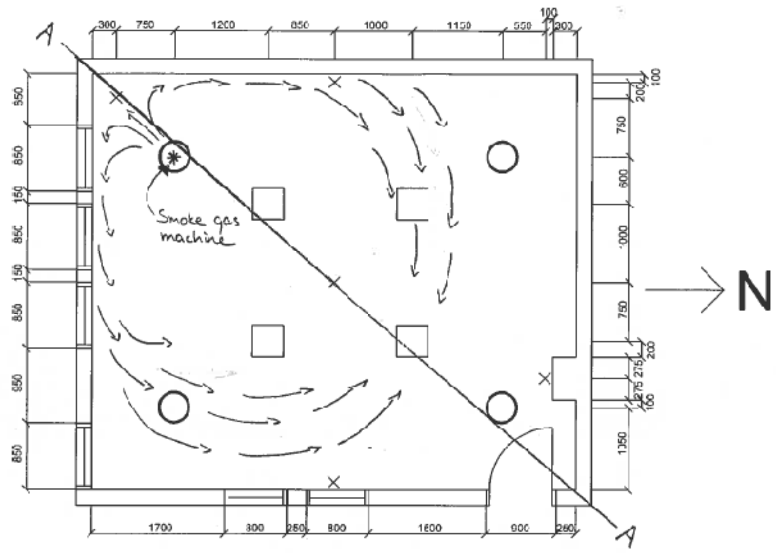


Figure 3.9. A principal sketch of the air flow pattern, plan. The paths of the high smoke concentration are illustrated by arrows.

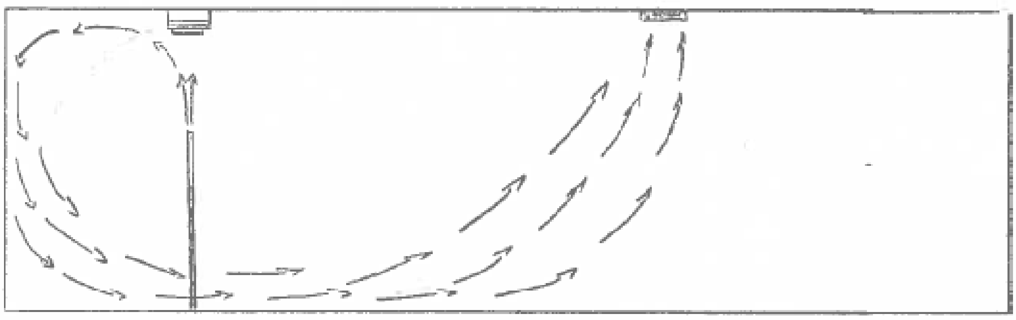


Figure 3.10. A principal sketch of the air flow pattern, section. The smoke slowly rises from the floor with time.

3.8 Noise test

To be able to find out how much noise the used sensors have, an 'empty test' was performed. The carbon dioxide concentration varies much more compared to the other parameters (temperature and relative humidity) and therefore it was considered to be investigated. The noise test has to be performed with very stable ambient conditions, since no persons or other sources emitting carbon dioxide or generating internal heat were allowed in the room. Therefore, the only factor affecting the sensor is the room itself and the ventilation system which is affected by the ambient. Test 29 was considered to be an appropriate noise test where the ambient conditions stayed constant enough. The following figure, figure 3.11, illustrates the measured variations in the noise test and those small variations are considered as measurement noise.

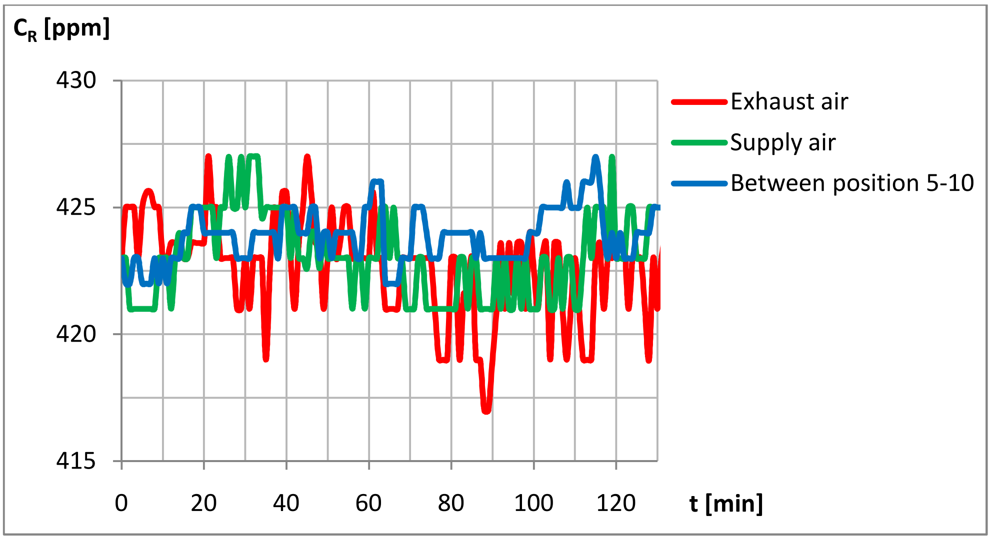


Figure 3.11. Test 29: One 1/h, noise test.

The measured noise applies to low carbon dioxide concentrations and this might not apply to high levels. Because of this, a test with high concentrations has also been performed. The procedure for this test was to do a 'regular' test, reach steady state and stay there for a while. The measured changes occurring after reaching the steady state level may also be considered to be measurement noise and can be seen in figure 3.12. It could also be seen that the variations are of another magnitude compared to the low level noise.

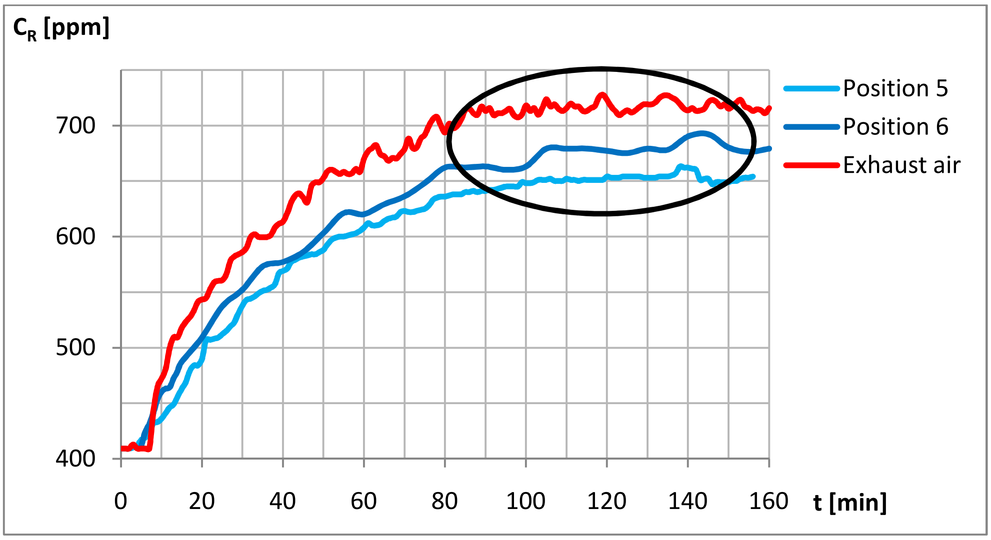


Figure 3.12. Variations of the carbon dioxide concentration at the steady state level, to be seen inside the black circle, for test 15, with an air exchange rate of one 1/h. Those variations can be considered as measurement noise at high concentrations.

4 Results and discussion

The results presented in diagrams in the following chapters are, if nothing else is mentioned in the text, normalized to the supply air to simplify comparisons between the different tests. The standard test procedure includes one to four test persons entering the test room five minutes after starting the loggers. Moreover, the analytical solution assumes a source flow, i.e. generation rate of carbon dioxide, of 18 l/(h, person). The airflow rate is presented as air exchanges per hour, which easily can be transformed into l/(s, person). Table 4.1 shows the used airflow rates in four different units. The lowest airflow rate corresponds rather well to the basic ventilation criteria of 0,35 l/(s, m^2), presented in chapter 2.4, *Indoor climate* d*emands for office buildings*, and 7 l/(s, person) if there are two persons present in the room. Finally, the test number is mentioned if the reader would like to get more information about a specific test, which can be found in appendix 1.

Table 4.1. The unit of the airflow rate can easy be converted into other units.

ACH	**L/s**	**L/(s,m^2)**	**L/h**
0,6	13,1	0,38	47280
1	21,9	0,63	78800
2	43,8	1,26	157600
3	65,7	1,89	236400

4.1 Test results

49 tests have been performed to give satisfying results for different conditions and all tests that are used in this thesis can be found in Appendix 1. The presented parameters are air temperature, carbon dioxide concentration and vapour content in different locations. The vapour content has been transformed from the measured relative humidity into the specific unit g/m^3, by using temperatures measured in the same location.

The settings that have been changed between the different tests are the number of people in the test room and the air exchange rate. The evaluated airflows are chosen to simulate commonly used airflow rates in office buildings and vary between 0,6 to 3 1/h. It is hard keep the airflow rate stable at low ventilation levels, therefore 0,6 1/h only has been used in very few tests. The sensor locations that have been tested are chosen due to the results from the performed smoke test, described in chapter 3.7, *Analysis of the airflow pattern (smoke gas test).* The aim of the smoke gas test was to find positions with both fast and slow response time of the changes.

This chapter describes and evaluates differences between the different test results. It also presents and discusses the supply conditions, because stable conditions are needed to get reliable results, since an inevitable variation of the supply parameters always occurs.

It is worth to point out that the axis in the figures have the same units, but with different scales which is important to remember when comparing the values in different diagrams. It is also worth to notice that the test persons enter the room after five minutes in each test, if nothing else is presented.

4.1.1 Position of the sensors

To be able to use information from carbon dioxide sensors for a feed-forward system, rapid and significant response from the sensors is of great importance. A number of different sensor positions have been compared and evaluated to find the most suitable location. The smoke test, described in chapter 3.7, *Analysis of the airflow pattern (smoke gas test)*, was performed in order to identify the airflow pattern in the room and determine positions where the sensors should have fast respective slow response. According to the smoke test, position 6, 12 and 13 should have the fastest response, but slightly lower final concentrations compared to the other positions. The remaining positions should have slower initial increase of carbon dioxide concentration but a higher steady state level. As mentioned in chapter 2.1.1 *Information and behavior*, it can be a risk to put the sensors too close to people due to the risk of an unrepresentatively high carbon dioxide concentration (Persily 1997). In the measured results, sensors in all positions of the room, expect the exhaust air sensors, behaved similar for at least the first twenty-five minutes.

When comparing the different sensor positions, test with two persons present in the test room and an airflow rate of one 1/h, which varies between the tests have been used. A clear trend in the measurements, which is visible in figure 4.1, is that the sensor in the exhaust duct was a good indicator that people entered the room. Since the interest is to find the sensor position with the fastest response to people entering the room, the exhaust air sensor would, according to the performed tests, be the most suitable.

The sensor in the exhaust air does not correspond to the result achieved from the smoke test, which indicated that it takes a while for the air to move into the exhaust device. However, according to the measured results, the sensor in the exhaust air is probably the best location to use, if rapid changes in carbon dioxide concentration are wanted.

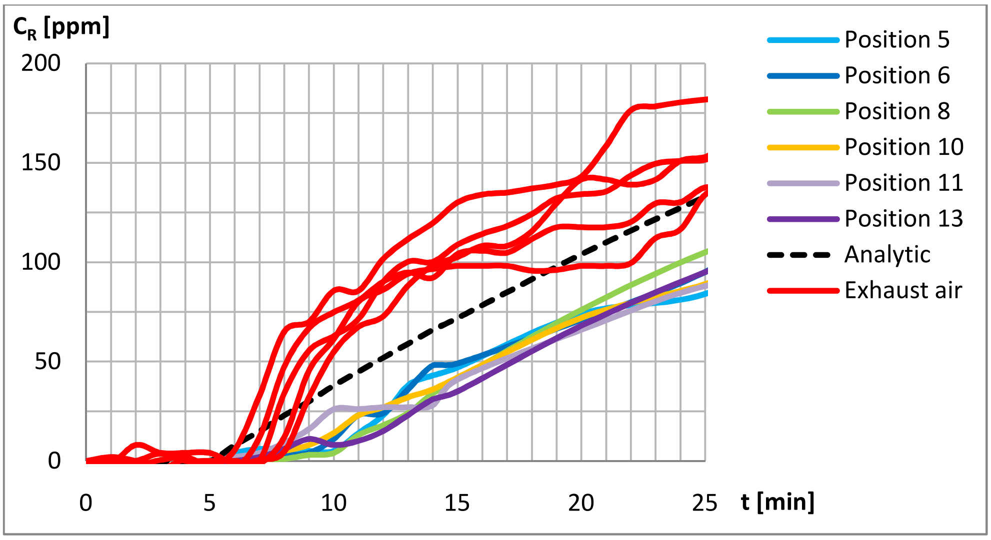


Figure 4.1. The air exchange is one 1/h and the diagram illustrates the increase of carbon dioxide concentration when there are two persons present in the room, entering after five minutes. It is obvious that all the portable sensors in the room have a uniform response of carbon dioxide concentration, the carbon dioxide concentration measured by the sensor in the exhaust air is very similar in the different tests. The figure presents data from test 15, 16, 17, 18 and 27. It can also be seen that the sensor in the exhaust air duct reacts faster and more significant than the sensors located in the room.

An earlier study has been performed where the same thing, the location of the sensor, was investigated. In that case only small differences were found between the sensor located close to the wall and the sensor located in the exhaust air duct, the results from those measurements are illustrated in figure 4.2.

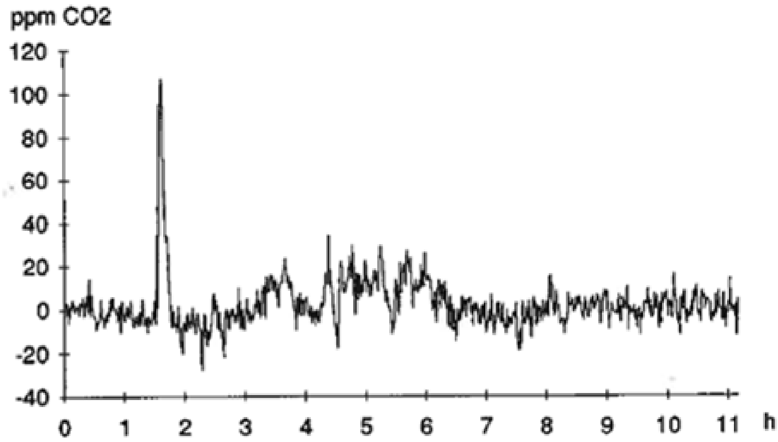


Figure 4.2. There is no big change registered by carbon dioxide concentration sensors close to the wall and in the exhaust air duct, according to tests performed by Ruud, Fahlén and Andersson (1993, p.16). The y-axis shows the difference between the sensors and the x-axis presents time from the start of the test. The concentration in the room increased from approximately 350 ppm to 800 ppm during the test. (Ruud, Fahlén & Andersson 1993, p.16).

4.1.2 Air velocity variations

An anemometer has been used to see if presence of people can be indicated by changed air velocity. This has been investigated for a number of different airflows and the air velocity in those tests can be seen below, in figure 4.3.

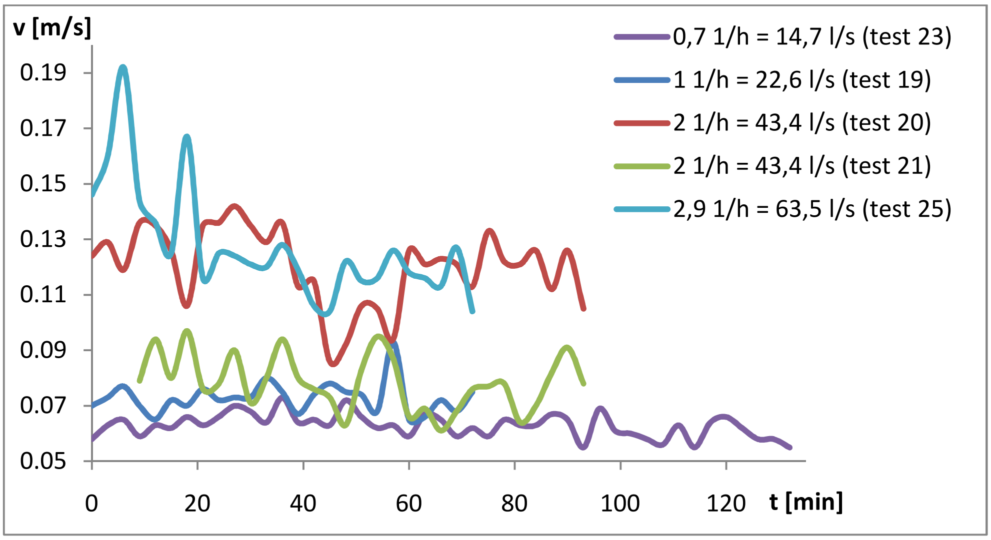


Figure 4.3. The air velocity in the room varies for different airflow rates.

As it can be seen in the figure, the measured air velocities do not indicate any changes after the test persons' entry. The only conclusion that might be drawn is that increased airflow means increased air velocity. This does not comply with the measured air velocities in test 20 and 21, since they have the same airflow but quite large differences in the air velocity. The idea was that the air velocity should change from one level to another after the test persons' entry, which means after five minutes of testing. Because of these results, the anemometer has been regarded to not be useful in order to decide presence of people. A remark to a strange graph in the figure; test 21 the anemometer was started when the test persons entered the room, this is why the graph starts later than the rest of the graphs, but this did not influenced the result.

4.1.3 Vapour content variations

As mentioned before; temperature, carbon dioxide concentration and relative humidity are measured and compared to each other to find out which of the parameters are most suitable to indicate presence in a room. The vapour content is calculated with the measured relative humidity and the temperature at the same position. The amount of vapour in the air might depend on other sources than the presence of people; hence the control system can be given signals which are not according to the reality. It does not have to be any problem for ordinary office work, but the feed-forward system needs to be able to work for activities that may occur in an office building. One of the tests was performed while eating pizza in the room and the resulting vapour content behaved very strange compared to other tests, see figure 4.4. Another disadvantage with using vapour as an indicator is the natural variation that could occur during a day, which have been shown in figure 2.5. This applies to the outdoor air temperature as well, but the supply temperature is continously controlled and adjusted which the vapour usually is not. How the outdoor vapour content change can also be seen in figure 4.4.

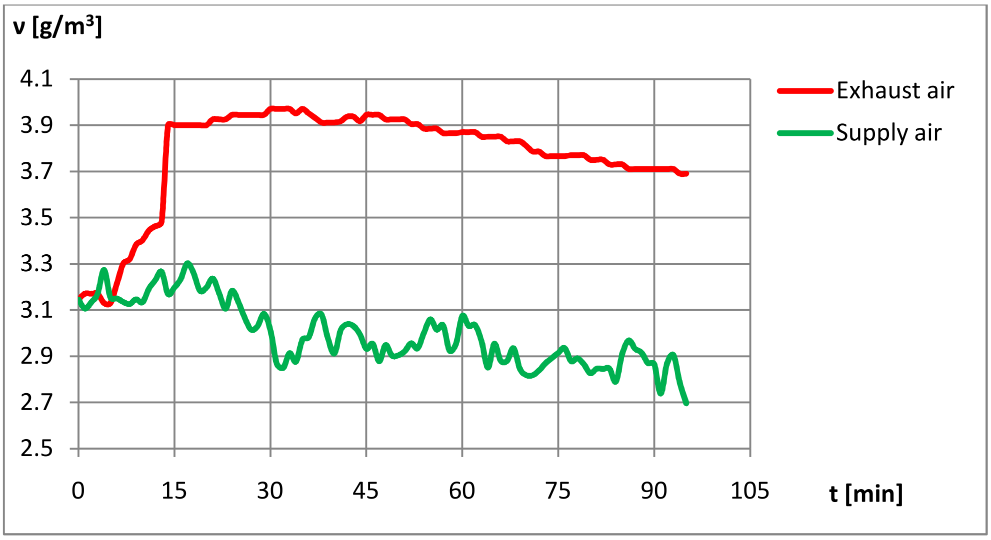


Figure 4.4. The vapour content variation in test 30, which was performed with four test persons and an airflow rate of two 1/h. The high initial increase might depend on the activity, eating pizza. It is also worth to notice that the measured vapour content drops both in the exhaust air and in the supply air with time.

4.1.4 Temperature variations

The theory is that the temperature increase, ΔT_R, should become smaller as the air exchange rate is increased, since a high ventilation flow rate works as air cooling when the outdoor temperature is lower than the indoor temperature. However, ΔT_R is mostly affected by the internal loads, which in this case mainly comes from the test persons. This can be seen in table 4.2 to 4.4 with some exceptions, but overall the trend follows the theory. The test length varies and the reason for this is that steady state condition for the carbon dioxide concentration occurs later the lower the airflow rate is. The supply start temperature varies between the tests, which can be seen in the tables, this depends on both the supplied heating effect and the outdoor temperature. How the outdoor temperature affects the results is quite obvious e.g. in test 35 and 40, seen in table 4.3, where the outdoor temperature is considerably higher than in the other tests.

Table 4.2. There are variations of the temperature for tests with two test persons and varying airflow.

ACH [1/h]	Test	Duration [min]	ΔT_R [°C]	ΔT_S [°C]	$T_{S,mean}$ [°C]
0,7	23	135	1,8	+/- 0,3	17,2
1	15	165	2,0	+/ - 0,2	17,5
2	21	95	1,0	+/- 0,3	18,3
3	25	75	1,4	+/- 0,25	19,8

Table 4.3. The temperature varies in tests with three test persons and changed airflow.

ACH [1/h]	**Test**	**Duration [min]**	**ΔT_R [°C]**	**ΔT_S [°C]**	**$T_{S,mean}$ [°C]**
1	48	130	1,7	+/- 0,50	16,6
2	40	115	1,0	+/- 0,50	21,8
3	35	105	1,2	+/- 0,50	22,9

Table 4.4. There are temperature variations for tests with four test persons and varying airflow.

ACH [1/h]	**Test**	**Duration [min]**	**ΔT_R [°C]**	**ΔT_S [°C]**	**$T_{S,mean}$ [°C]**
1	47	130	2,6	+/- 0,45	17,7
2	30	95	1,7	+/- 0,45	19,7
3	31	85	1,4	+/- 0,45	20,4

In theory and in practice, according to the performed smoke test described in chapter 3.7, *Analysis of the airflow pattern (smoke gas test)*, different locations of the sensors should indicate differences in response time and total change of temperature and carbon dioxide concentration. The measured temperatures do not apply to this; there are still differences in temperature at the different positions in various tests, but not according to the smoke test.

The supply air temperature varies around a set value in the tests, but it does not affect the room temperature and there is no relation between variations of the supply air temperature and the room temperature sensors. The initial supply air temperature, $T_{S,start}$, varies in between the tests; this depends on the airflow rates, since an increased airflow transports more heat from the heating coil in the air handling unit to the room. How the supply air temperature varies can be seen in the following diagram, figure 4.5, and it could also be seen that the variations does not affect the room temperature.

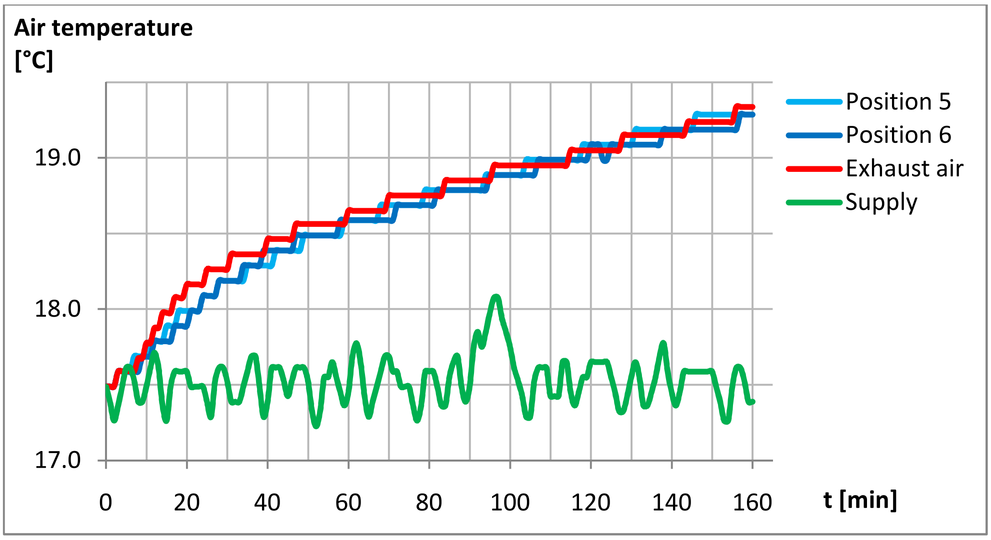


Figure 4.5. The temperature in the room increased during test 15, while the corresponding supply air temperature is varying without affecting the air temperature in the room.

4.1.5 Carbon dioxide concentration variations

The concentration of carbon dioxide has been measured in all performed tests and the start conditions and the total change in carbon dioxide concentration during a test is gathered, for some representative tests, in the following tables, table 4.5 to 4.7. The hypothesis is that the more persons and the lower the air exchange rate is, the larger the total change in carbon dioxide concentration will be, ΔC_R.

Table 4.5. Variations and changes in start concentrations of carbon dioxide for varying airflow for tests with two test persons.

ACH [1/h]	**Test**	**Duration [min]**	**ΔC_R [ppm]**	**ΔC_S [ppm]**	**$C_{S, mean}$ [ppm]**
0,7	23	135	493	+/- 5	417
1	15	165	307	+/- 4	409
2	21	95	195	+/- 4	415
3	25	75	135	+/- 8	420

Table 4.6. Variations and changes in start concentrations of carbon dioxide for varying airflow for tests with three test persons.

ACH [1/h]	Test	Duration [min]	ΔC_R [ppm]	ΔC_S [ppm]	$C_{S, mean}$ [ppm]
1	48	130	436	+/- 7	421
2	40	115	299	+/- 4	425
3	35	105	211	+/- 11	435

Table 4.7. Variations and changes in start concentrations of carbon dioxide for varying airflow for tests with four test persons.

ACH [1/h]	Test	Duration [min]	ΔC_R [ppm]	ΔC_S [ppm]	$C_{S, mean}$ [ppm]
1	47	130	785	+/- 5	411
2	30	95	450	+/- 8	428
3	31	85	277	+/- 4	429

4.2 Presence and number of occupants in the room

This chapter evaluates the differences in carbon dioxide concentration between different numbers of test persons for the same airflow rate. The comparison have been done for tests with an occupancy level of one, two, three or four test persons, tests have also been made with two persons from start and a third person entering at different times. The main idea of these comparisons is to find the gradient of the carbon dioxide concentration and put this into a relation for HVAC-control in feed-forward systems. The comparison is performed for carbon dioxide, since it is the parameter that has complied best with the desired properties.

4.2.1 Comparison between different number of occupants

The generation rate of carbon dioxide affects the sensors response time and the amount of carbon dioxide in a room. Figure 4.6 shows the measured carbon dioxide concentration, measured in the exhaust air, in test 21, 30, 40 and 45. The difference between the tests is the number of test persons, while the airflow has been kept constant at a level of two 1/h. The other settings are kept the same between the tests. The number of test persons that have been tested are one, two, three and four persons.

Interesting observations to be seen in the figure is the change of inclination between the tests and the obvious increase of steady state level. This change of inclination makes it possible not to just indicate presence in the room but also to determine how many persons that have entered.

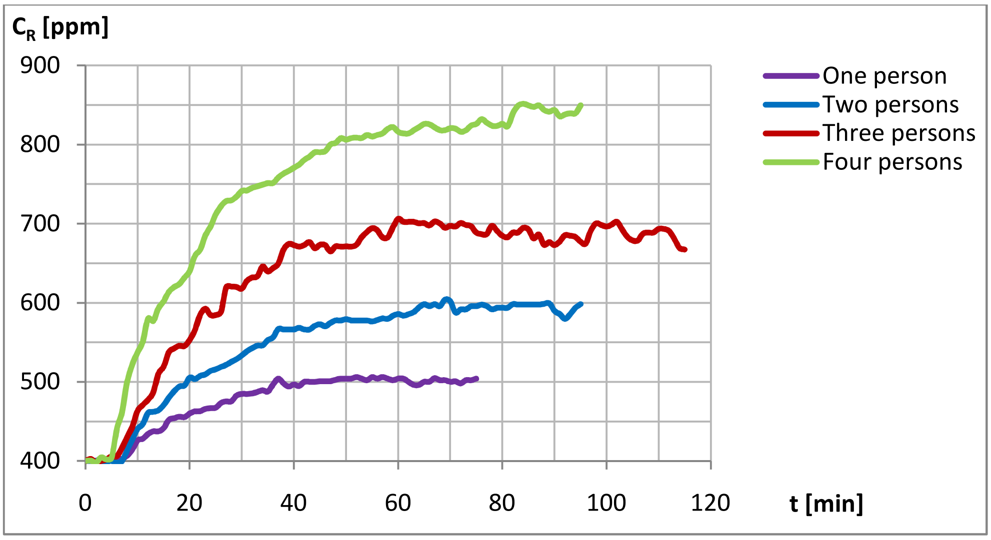


Figure 4.6. The concentration of carbon dioxide for tests with varying number of test persons is measured when the constant airflow two 1/h. The measurements are performed in test 21, 30, 40 and 45.

Another interesting observation in figure 4.6 is that the more persons that enter the room, the earlier indication can be noticed, after the entrance at five minutes. This is easier seen in figure 4.7, which is a zoomed figure 4.6.

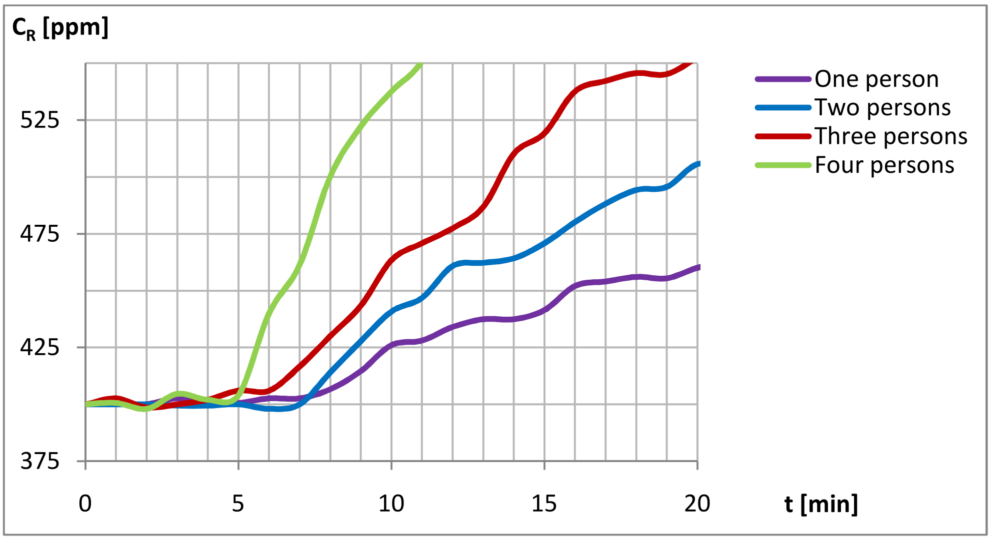


Figure 4.7. The graphs in this diagram are exactly the same as in the previous figure, but zoomed in to show the time to response for different number of occupants.

The graph shown in figure 4.8 illustrates the carbon dioxide concentration measured for different number of test persons and an airflow of one 1/h, which has not been changed between the tests. The major observations that can be done between the tests are the initial inclination and the increased steady state level. Moreover, it is worth to notice, even if the values are normalized to the supply air concentration, that the concentration of the carbon dioxide exceeds the recommended limits, mentioned in chapter 2.4, *Indoor climate demands for office buildings*, to keep a good air quality when the airflow rate is low and with a lot of people present in the room.

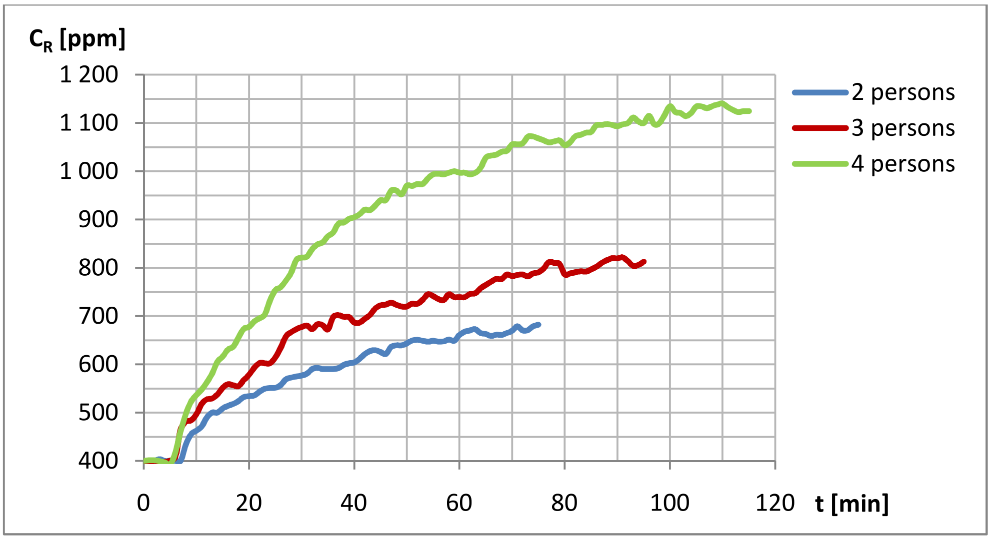


Figure 4.8. The diagram illustrates the measured concentration of carbon dioxide for tests with two, three and four occupants in the room with a constant airflow of one 1/h. The situations with two, three and four persons correspond to test 15, 48 and 47 respectively.

As mentioned earlier, all values are normalized to the supply air concentration, but it is still obvious that the increase in carbon dioxide concentration is less when the airflow rate is high. The case with three 1/h, presented in figure 4.9, can be compared with the previous figure when the airflow is one 1/h.

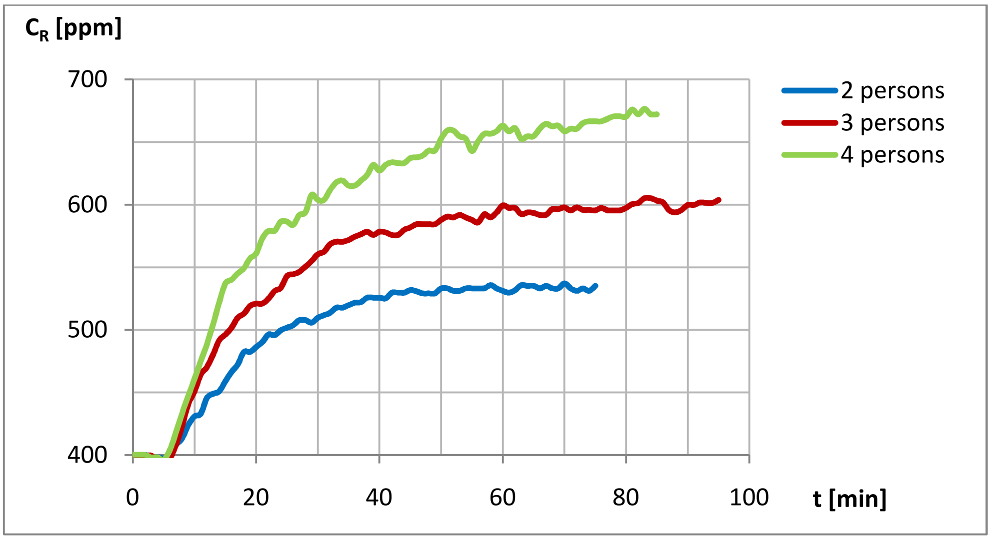


Figure 4.9. The diagram shows the same tendency as the previous figure. The conditions are the same, except for the airflow rate which is three 1/h in this diagram.

4.2.2 Two persons, and a third person entering after a while

Some of the tests have been performed with two persons occupying the room during the whole test while one more person has entered the test room after a certain predetermined time. The third test person has entered the room after 11, 30 and 60 minutes of testing, which means at the times 16, 35 and 65 in the diagram, see figure 4.10. Test 43 had a third person entering after 16 minutes, test 37 after 35 minutes and test 42 after 65 minutes. Each entrance of the third test person is done in separate tests. The theory, for the performed tests, is that if the third test person enters the room after 11 minutes the inclination of the curve will change from a typical two person test to a three person test, but with a slightly delayed inclination.

For the test where the third person enters after 30 minutes the curve just continues to climb, even if the two persons have reached their steady state level. This occurs since the carbon dioxide concentration continues to rise until the steady state level for three persons is reached.

The test when the third test person enters after 60 minutes has already reached steady state for the two persons during the first 60 minutes of testing. This gives that the carbon dioxide concentration curve starts to climb to the three persons' steady state level. The three different cases compared to the 'ordinary' two and three person tests can be seen in the following figure, figure 4.10.

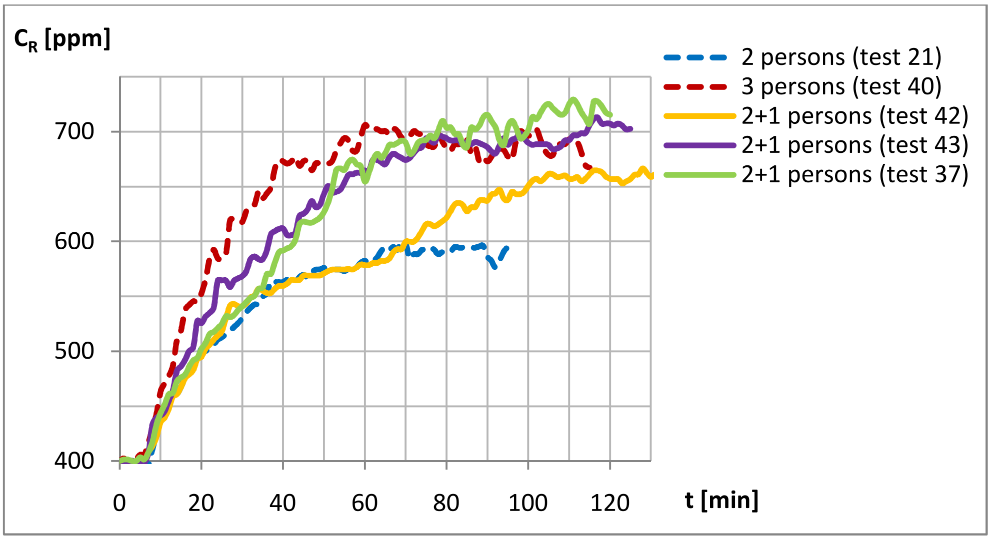


Figure 4.10. Two person tests with a third person entering after certain times, compared to a two and three person tests. Test 43 corresponds to the situation when the third person enters the room 16 minutes after the test has started, while test 37 and 42 corresponds to 35 and 65 minutes respectively.

4.3 Influence of having the door open

In an office building it is common that some of the doors to the separate offices are open. Therefore, some tests have been performed with the door, between the test room and the facility, open. The open door tests have been done by either changing the supply airflow or the differential temperature, between the test room and the facility. The airflows that have been tested are one, two and three 1/h. The differential temperature has been varied for an airflow of two 1/h and the temperature differences have been one, three and five degrees. The measurement results can be found in Appendix 1 and a comparison between the open door tests and closed door tests can be seen in figure 4.11 and 4.12. In figure 4.11, the airflow rate has been varied between the tests and it can be seen that the tests with open door have a slightly higher final carbon dioxide concentration. However, overall the difference between the tests performed with open and closed door is rather small and it is hard to find any obvious behaviour to distinguish between the two situations.

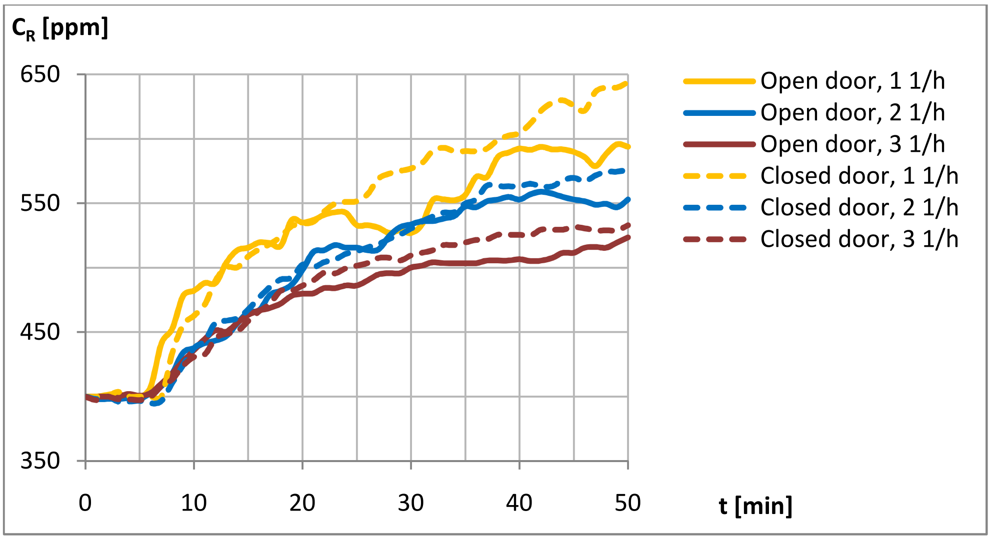


Figure 4.11. Tests with open door and varying airflow rate, compared to tests with closed door and the same airflow rates. The results are achieved from test 15, 21, 25, 36, 44 and 46.

Figure 4.12 shows the test result from tests with a constant airflow rate, two 1/h, and three levels of differential temperature between the test room and the test facility. Unfortunately, it is hard to find any conclusions from these results, especially since it was expected that the temperature difference really should make sense since it will contribute to changed air streams. The unexpected results may depend on uneven vertical distribution of the carbon dioxide concentration. Moreover, it is hard to judge the differential temperature, since it gradually will converge towards the same temperature.

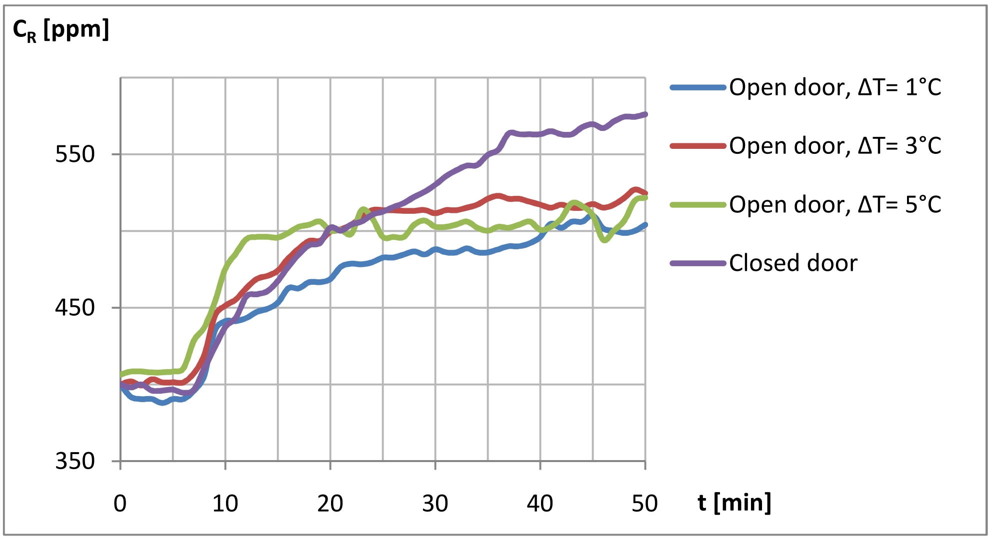


Figure 4.12. Tests with an airflow rate of two 1/h and open door, with a varying differential temperature between the test room and the test facility. These graphs are compared to the tests where the door was closed. The results are from test 21, 38, 39 and 41.

4.4 How to use the measured indications for control and regulation of the indoor climate

The four main parameters that have been evaluated for a feed-forward regulation system are presence, temperature, vapour content and carbon dioxide concentration. Important features for the use are to get significant and reliable response of the measured parameter. The carbon dioxide concentration is the factor that has shown best compliance, according to the previous described result, with the desired properties. A further investigation to motivate this fact follows in this chapter.

4.4.1 Relative change of measured parameters

It is desirable that the parameters are changed rapidly when presence is detected in the room (presence is always detected after five minutes of testing). The parameter that has the earliest and most obvious response should be evaluated further for the use in feed-forward regulation system. To compare the measured parameters, their relative change in percent is shown in figure 4.13 and 4.14.

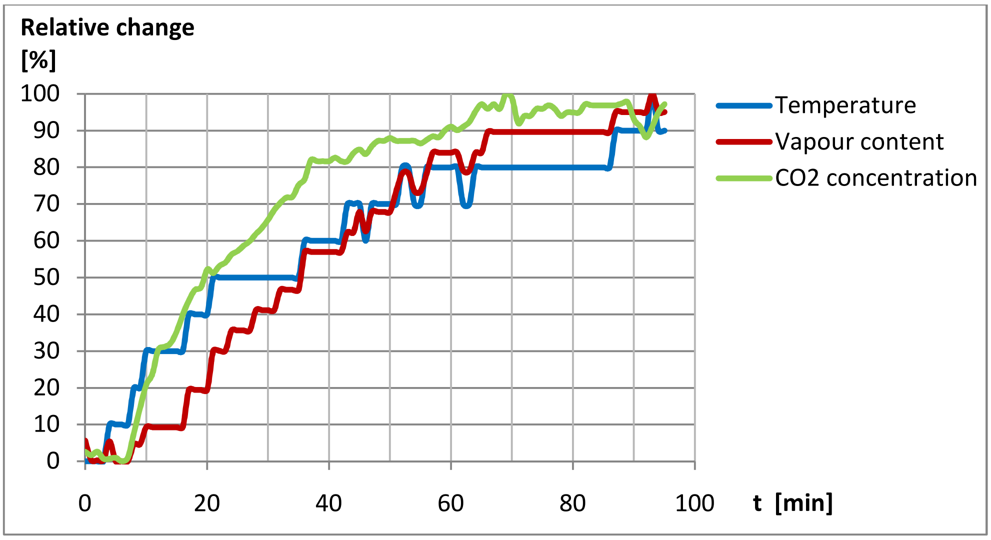


Figure 4.13. Test 21: Two 1/h with two persons present in the room. The diagram shows the relative change of the parameters.

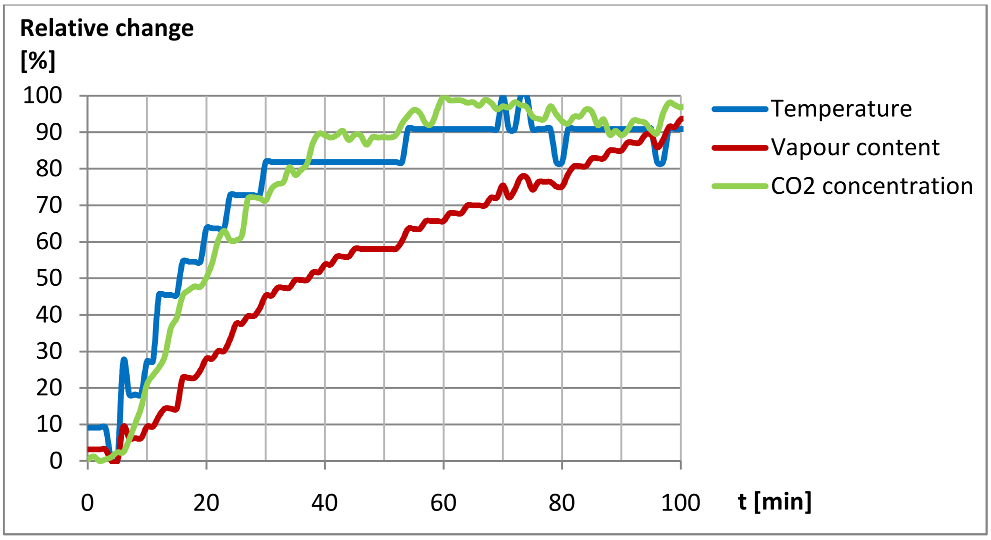


Figure 4.14. Test 40: Two 1/h with three persons present in the room. The sensor positions are the same as in figure 4.13, but the shape of the curves are not the very similar to the test performed with two occupants instead of three.

The graphs in the diagram above show almost the same behaviour, but the first parameter to respond varies between different tests and it is hard to find a clear relation of the response time and the room conditions. However, it is worth to consider the magnitude of the changes, e.g. in test 21 the total change in carbon dioxide is 195 ppm while the total temperature and vapour content changes are 0,9 °C and 0,29 g/m^3.

The magnitude of the changes cannot be seen in the graphs, since only a percentage change is shown. Therefore, it is hard to determine the importance of each parameter. To begin with, the air in the room takes up the emitted heat, vapour and carbon dioxide from the test persons, but with time the inertia of the building envelope reduces the increase of temperature and vapour content, while the concentration of carbon dioxide is not affected by this. Another important aspect to consider is if there is a relationship between the number of people and the increase of a certain parameter. This means that an increase of a certain parameter should be able to give an indication of the number of people present and thereby change the supply conditions.

4.4.2 Sufficient changes to ensure indications

MATLAB has been used to create a program that accumulates measured changes until a preset level is reached and the time to this change can be read in the achieved plots. The level which has to be reached to give a certain change differs depending on which parameter is investigated. The levels are set depending on the natural supply variation and the measurement noise given by the sensors. It is also important to both get reliable results and a short response time for the sensors, to fulfil the demands for the use of feed-forward regulation to control the indoor climate. The standard deviation, measured noise, for carbon dioxide is, about 2,4 ppm for low concentrations and about 4,7 ppm for high concentrations according to noise tests. The corresponding measurement noise for temperature and vapour content variations is much smaller compared to the carbon dioxide concentration, both due to the measurement accuracy and the variation speed. The following figures illustrates the time it takes to achieve the preset level needed to confirm an indication for controlling the system. The indication time depends mainly on the airflow rate and the internal loads.

The first diagram, figure 4.15, shows the result when the airflow rate is two 1/h and two persons are present in the room. The required temperature change for the case is 0,5 °C, while the corresponding change for carbon dioxide concentration is 50 ppm and 0,5 g/m^3 for the vapour content.

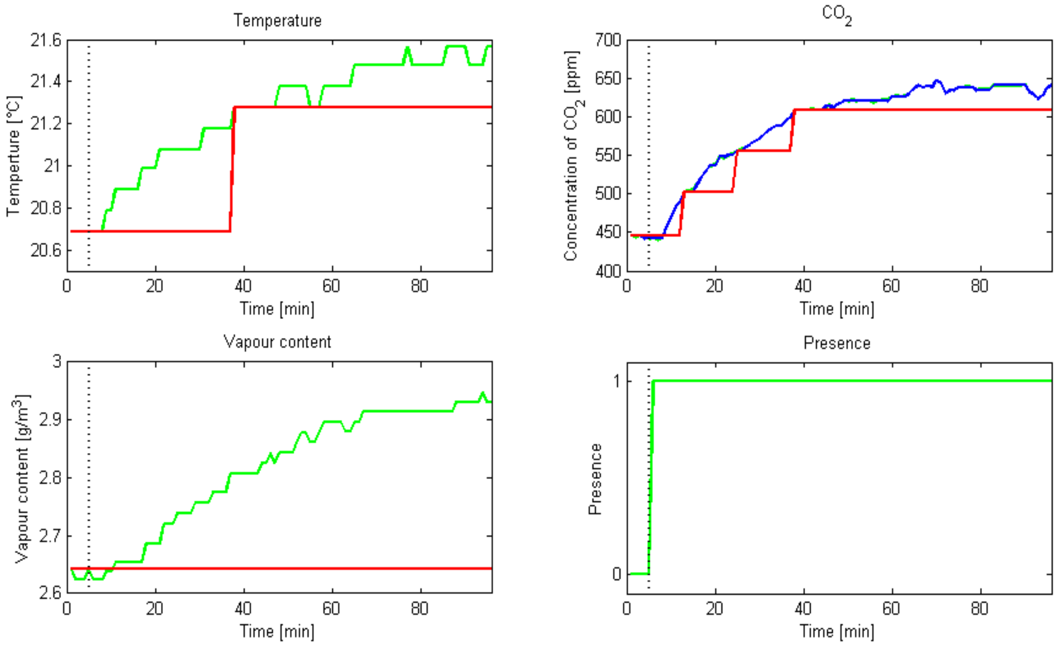


Figure 4.15. Test 21: The required changes are set to be 0,5 °C, 50 ppm and 0,5 g/m^3.

It can be seen that the carbon dioxide sensor indicates that someone enters the room after approximately twelve minutes, while the same indication for the temperature occurs after almost 40 minutes. With the determined settings, there is no indication at all from the sensor that measures the vapour content and no regulation will occur if this parameter would been used in a regulation system. Notice that, as it can be seen in the diagram with the presence sensor, the persons enter the room after five minutes.

Figure 4.16 also illustrates the time to response for the sensors, but with lower required changes. The temperature step is set to 0,1 °C, the carbon dioxide concentration to 10 ppm and the vapour content to 0,1 g/m^3. It is obvious that this settings leads to possibilities for faster regulation, but it also means high demands on accuracy of the sensors to avoid mistakes. The carbon dioxide sensor is still the one that indicates a change first, but the time for the thermometer is considerably shorter compared to the previous case. With a lower required change of the vapour content, there exists two clear changes, but this parameter reacts considerably slower than the other and does not seems to be favourable for feed-forward regulation of the indoor climate.

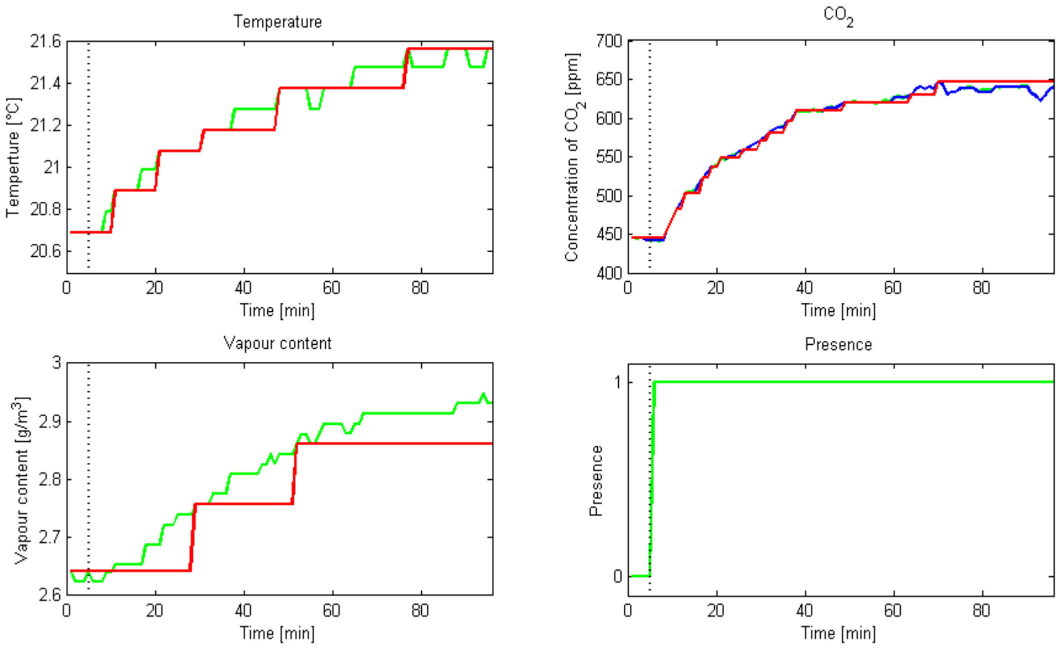


Figure 4.16. Test 21: The required changes are set to be 0,1 °C, 10 ppm and 0,1 g/m³.

If the required changes should be higher, to improve the possibility for correct regulation, it means longer time to response and risk of unnoticeable changes. An example of this is illustrated in figure 4.17, where the changes have to reach 1 °C, 100 ppm and 1 g/m^3 before an indication can be confirmed. For this situation, neither the vapour content or temperature sensor indicates that someone has entered the room and the carbon dioxide concentration sensor reacts after 20 minutes. The presence sensor gives clear information that someone enters the room, but without any information regarding the number of people or if someone leaves the room. Another disadvantage with this sensor is the risk of mistakes if there is a person in the room with very low activity level. It is also important to remember that it takes some time for the sensor to notice if people leave the room. However, the decay of the parameters is not within the scope of this thesis.

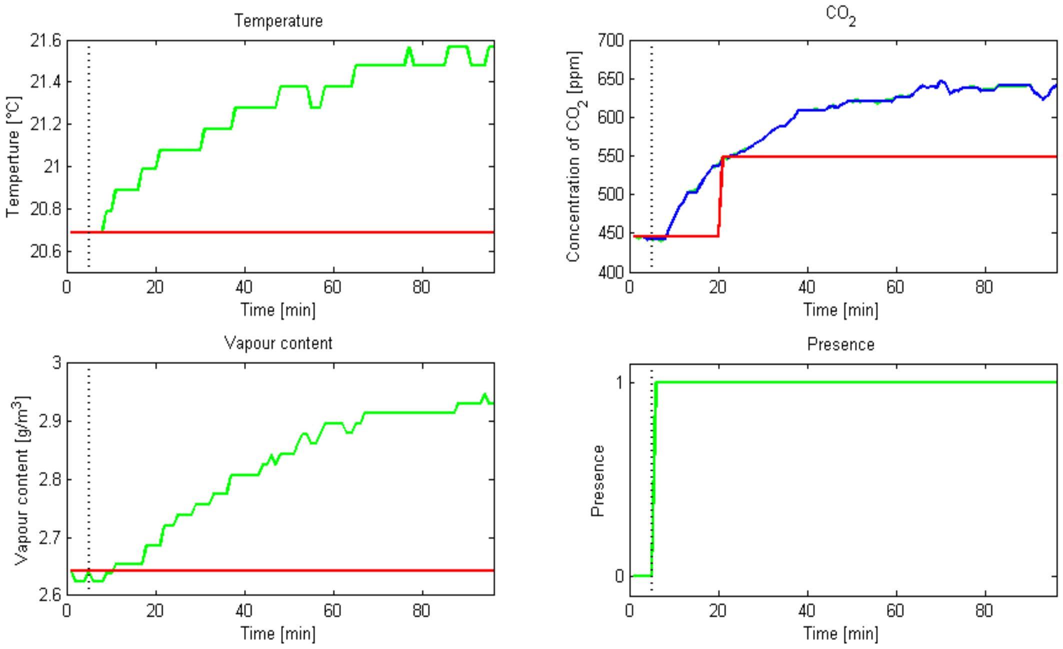


Figure 4.17. Test 21: The required changes are set to be 1 °C, 100 ppm and 1 g/m³.

Since the time to response is of great importance for a feed-forward regulation system, the required change of the parameters that is applied in the rest of the report is set to be the same as in figure 4.16, i.e. 0,1 °C, 10 ppm and 0,1 g/m^3. Figure 4.18 shows that the settings are applicable also when the number of occupants is increased from two to three persons, all other settings are kept unchanged. The time to response is very short for the sensors measuring the temperature and carbon dioxide concentration, while it still takes longer time for the vapour content to reach a change that is big enough for the use in a regulation system.

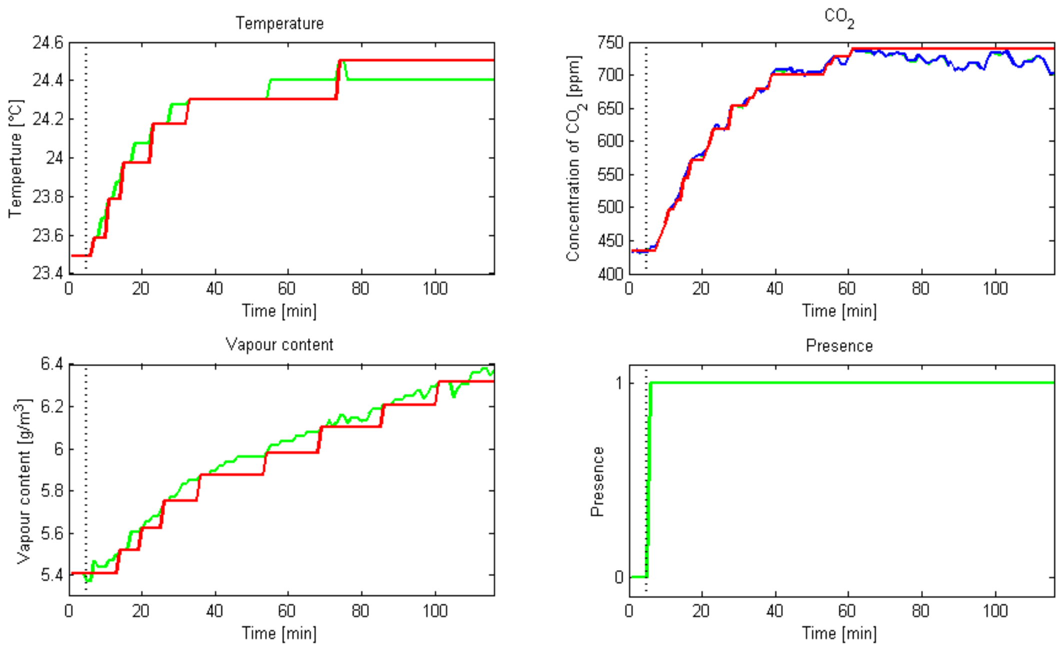


Figure 4.18. Test 40: The required changes are set to be 0,1 °C, 10 ppm and 0,1 g/m³.

Figure 4.19 illustrates the variations when there are two persons present from the fifth minute and an extra person entered after an hour. The thermometer indicates a change before anything has happened, i.e. after two minutes, which probably is because of the natural variations in the ambient caused by e.g. solar radiation or non-reached steady state. That is not good in a regulation control point of view, since the first indication of the thermometer cannot be considered as correct and it indicates presence in the room when it still is empty. This occurs due to the small required changes. The step-changes for the temperature are rather uniformly distributed, which makes it hard to detect that a third person has entered. On the other hand, there are many step-changes for the carbon dioxide concentration and there is a clear increase when the last person entered. Regarding the vapour content, the measurements shows a gradual decay when an increase was expected. This enhances the tendency that the parameter is unfavourable to use in a regulation system for control of the indoor climate.

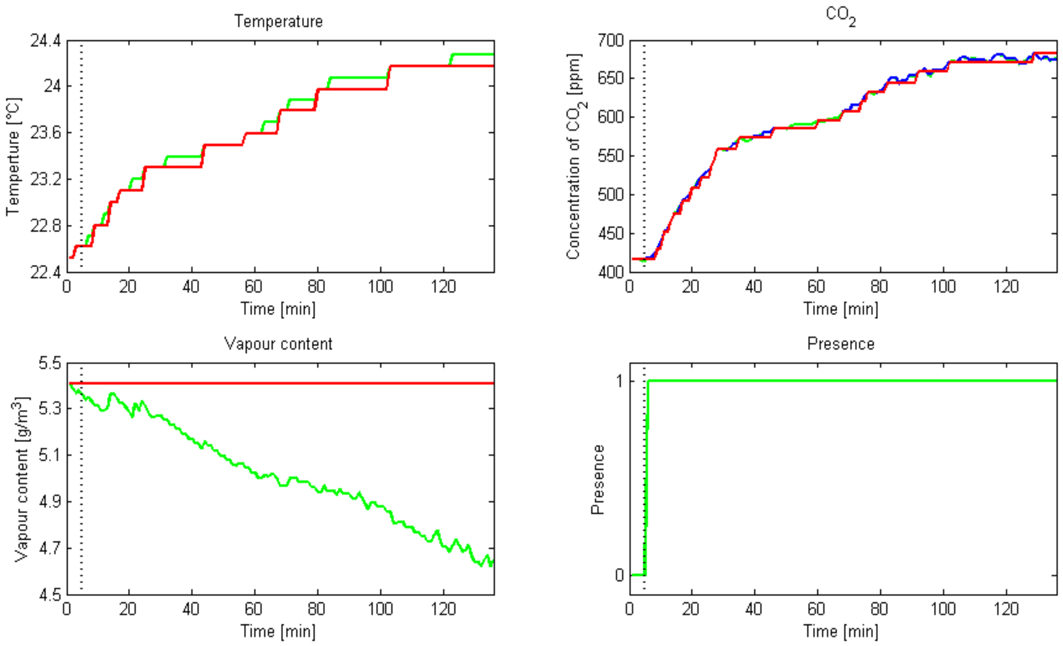


Figure 4.19. Test 42: The required changes are set to be 0,1 °C, 10 ppm and 0,1 g/m3.

Further results can be found in the appendix 1, but without any required step-changes for the use in a regulation system. By the figures above, it is clearly shown that the carbon dioxide concentration is the parameter that has both fastest and most reliable response and it will therefore be the only parameter that is evaluated further to find a regulation strategy.

4.4.3 Regulation strategy based on measured indications depending on person equivalents

It is desirable to get fast response on the measured change of carbon dioxide concentration, to be able to predict the future climate. Therefore, the concentration of carbon dioxide has been investigated and the inclination of the increase for the first few minutes, after the test persons' entrance, has been evaluated and compared for different situations. The differing inclinations have been used to create boundaries for tests with different number of test persons for the same airflow rates. When a concentration of carbon dioxide is measured, the measured value should be compared to the boundaries and the number of persons entering the room can be predicted since the airflow rate already is known. An illustration of the resulting boundaries, with an airflow rate of one 1/h, is shown in figure 4.20. The red lines corresponds to the inclination of the carbon dioxide concentration increase during the first two minutes, where the solid line represents tests with two test persons, the dashed line corresponds to three persons and the dotted line to four persons. The different boundaries for the number of persons have an upper and lower limit, which creates zones for each situation, illustrated by different grey shades. The brightest grey area illustrates the boundary for the dotted line, i.e. four occupants in the room. The upper limit is just an approximation, which is five percents above the lower limit, since no tests have been performed with more than four test persons. The dark grey area corresponds to the case where there are up to two occupants in the room, while the middle grey area means three occupants. The grey areas are created by using the mean values of the upper and lower value for each situation, i.e. number of occupants, achieved from the test results.

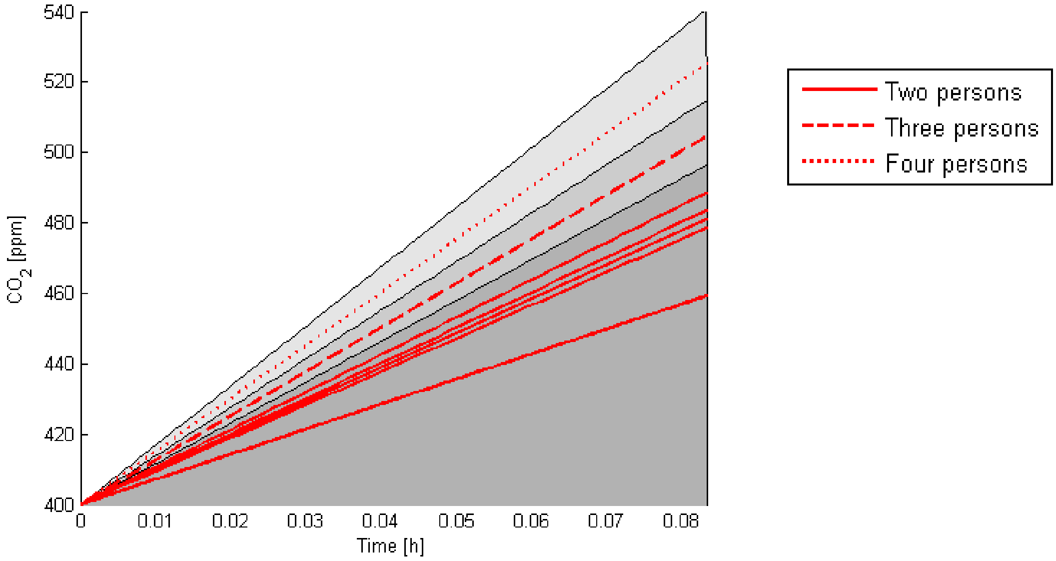


Figure 4.20. This model is valid for an airflow rate of one 1/h, the diagram illustrates the inclination for the change of carbon dioxide concentration during the first few minutes. The requirement is that a change of eight ppm should be noticed for four minutes. All values are normalized to 400 ppm.

The use of the inclination for the first few minutes means that presence in the room can be identified rather early, which is desirable for a feed-forward regulation system in buildings. On the other hand, there is a risk for mistakes, i.e. disturbances make the system to believe that there are another number of people in the room than it really are. A case where the measurement gives the wrong start indications is presented later in this chapter. To verify the number of people, a comparison to the analytical solution might be used after the regulation has started. Then it is possible to make adjustments or accept the already started regulation of the climate. The verification model for the one 1/h can be seen in figure 4.21. The analytical solution in the verification model is based on the dilution equation, but with two extra factors to fit to the actual measured results. This model shows relative change of the carbon dioxide, while the graphs in figure 4.20, the one with that presents the inclination, is normalized towards 400 ppm.

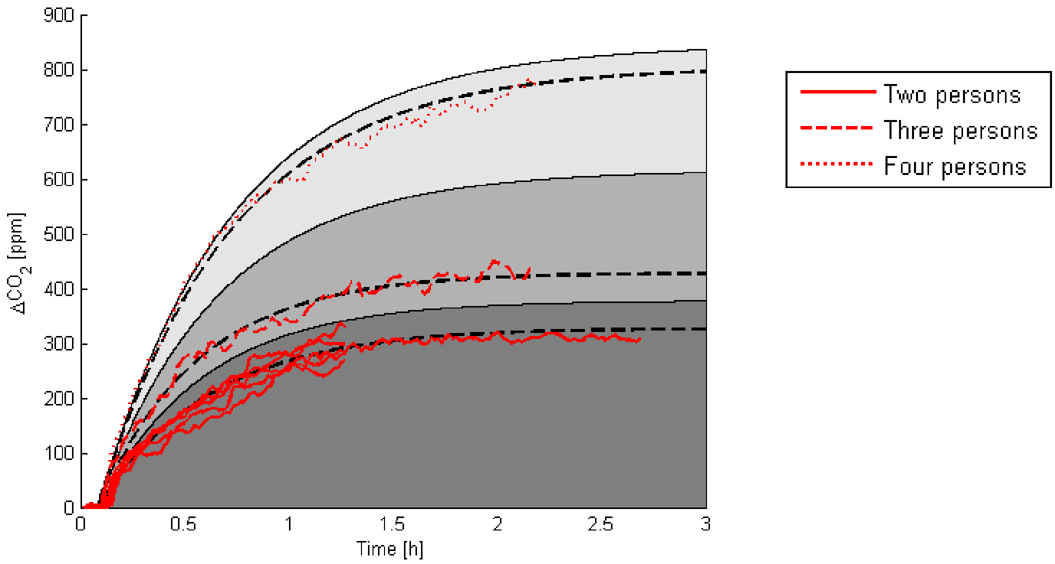


Figure 4.21. The diagram illustrates the use of a verification model when the airflow rate is one 1/h. The grey zones correspond to boundaries that are connected to the number of people in the room. Furthermore, the red lines are the measured carbon dioxide concentration where the solid, dashed and dotted lines corresponds to two, three and four occupants in the room respectively. The dashed black lines are analytical solutions, adapted for each situation. All curves starts at zero ppm, since the diagram presents the concentration change.

The resulting inclination for the change of carbon dioxide concentration has been calculated for three different airflow rates. Figure 4.22 shows the result for two 1/h and it should be read in the same way as figure 4.20, with one 1/h. It is worth to notice that there is an extra zone in this diagram, since a test also has been performed with only one person in the room. The consequence is that the lower zone is divided into two, for one and two occupants in the room respectively. Logically, the inclination of the slopes gets lower when the airflow rate is increased.

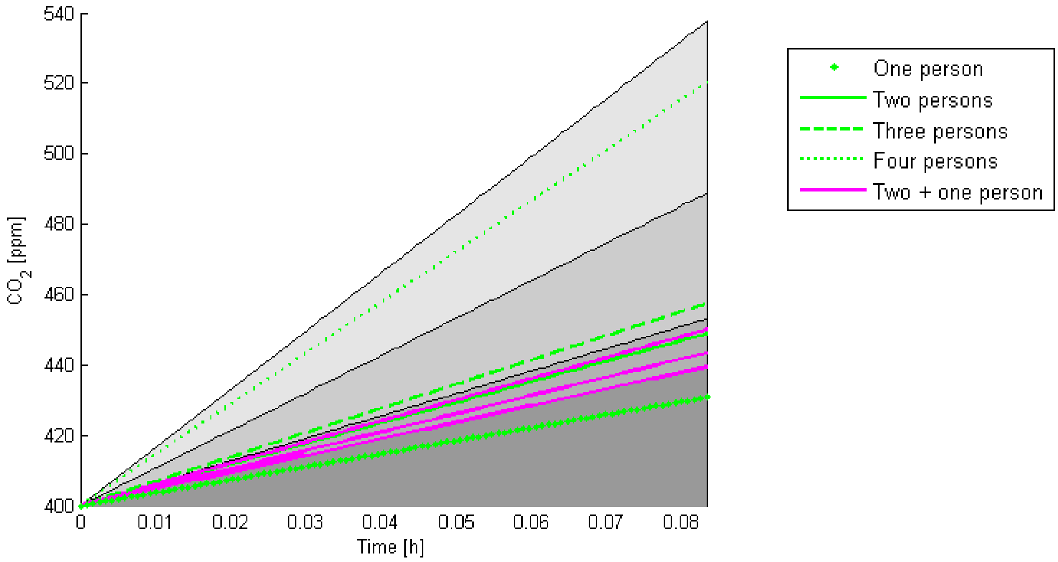


Figure 4.22. This model is valid for two 1/h. The different lines and the corresponding zones represent one, two, three and four persons in the room.

Figure 4.23 presents the verification model for the case with an airflow rate of two 1/h. The purple solid lines represent the performed tests where an extra person has entered the room after a while. It can be seen that the boundary zones still are valid, even though it takes some time to reach the 'new' steady-state level.

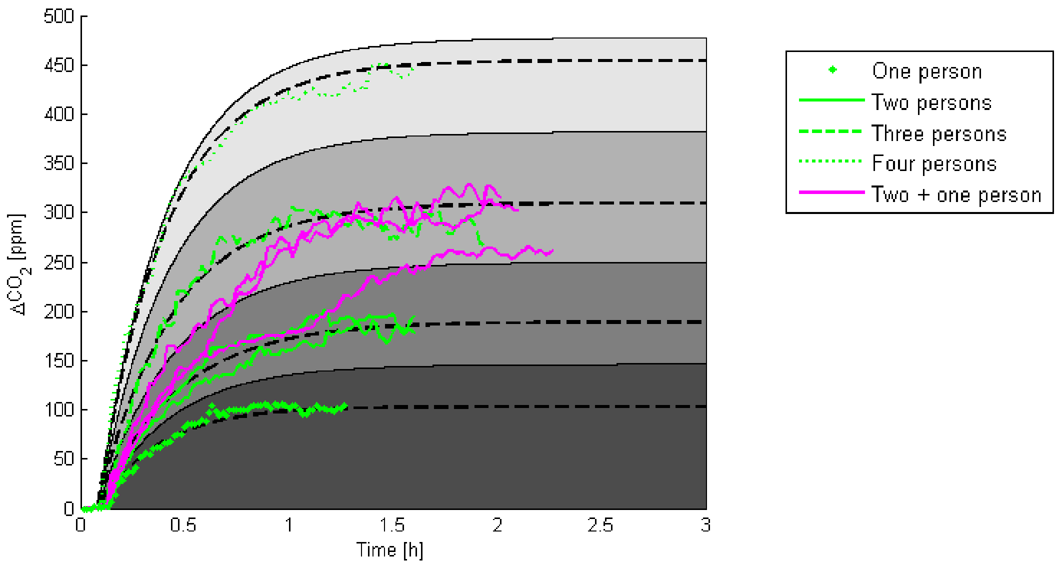


Figure 4.23. The verification model when the airflow rate is two 1/h. There are one zone for each occupancy situation, i.e. one, two, three and four persons in the room. The purple lines correspond to tests where there were two persons in the room from the start and an extra person entered after a while. These tests show that the model is applicable also for such situations.

The third airflow rate that has been investigated regarding the slope of the initial concentration is three 1/h and the results from this are shown in figure 4.24. As for the previous airflows, the scales on the axes are not very important since the trend has been developed for very few minutes and then assumed to have a constant linearly inclination.

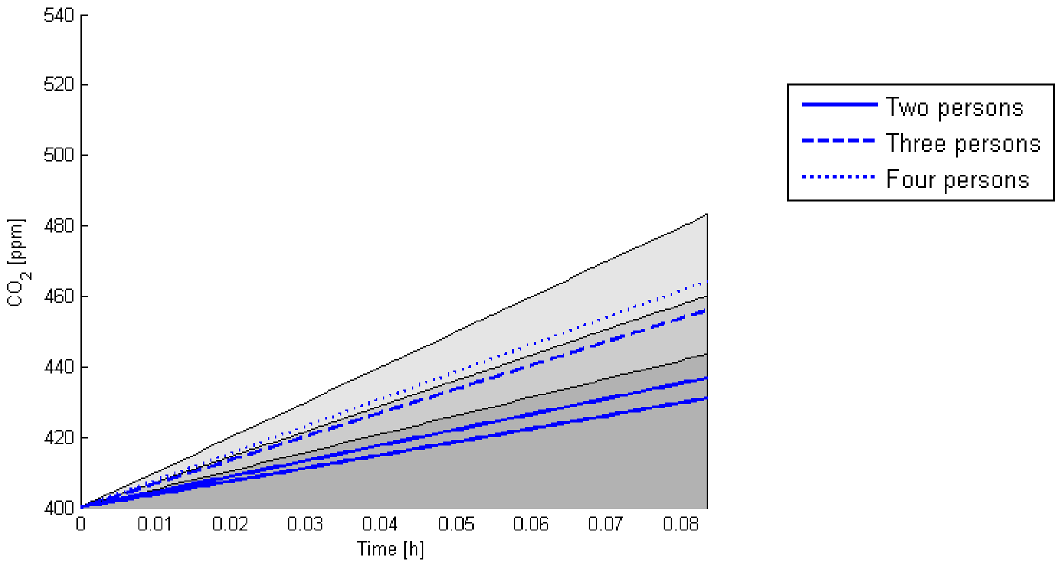


Figure 4.24. This model is valid for three 1/h and there are zones for zero to two, three and four persons in the room.

The verification model for three 1/h is shown in figure 4.25. Unfortunately, very few tests have been performed with this setting and to really use the model, there is a need to perform more tests to ensure that the measured values are correct. However, the idea is to clarify the principle of how the result may be used in a regulation system and that is probably rather clear by the graphs of these three airflow rates.

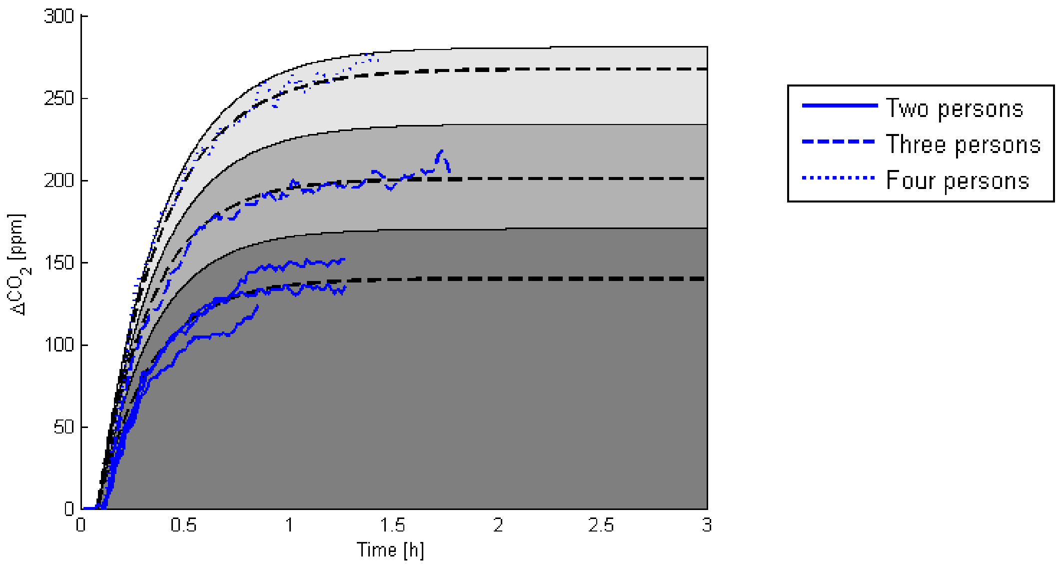
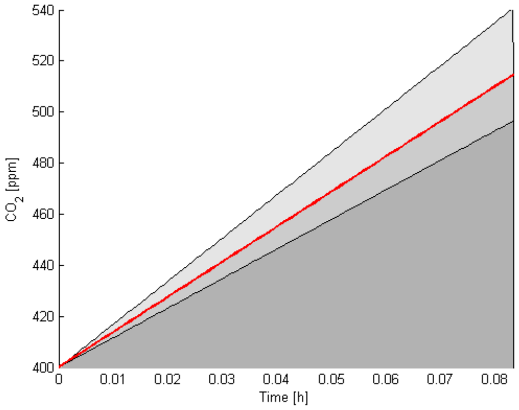


Figure 4.25. The verification model corresponding to three 1/h.

In some situations, the inclination of the change during the first few minutes for the carbon dioxide concentration does not correspond to the reality. An example of this can be seen in figure 4.26, where the airflow rate is one 1/h but the resulting inclination lies between the zones for three and four persons. It is in situations like this there is a need of the verification model, shown in figure 4.27. The system will start to regulate the climate for three to four persons, which apparently is wrong, until the verification model deny that supposed situation is correct. This can be done after almost thirty minutes in this situation, which means that the system has been regulating according to the false situation for a while. It might be considered as rather late for the use of feed-forward regulation, but on the other hand, if a feedback system would be use nothing would have happened in the beginning.



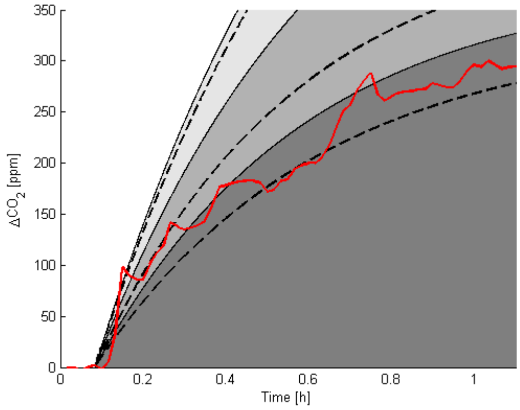


Figure 4.26 (left). The inclination of the carbon dioxide concentration for the first minutes is shown. There are two persons present in the room and the red line would therefore be in the zone with the darkest grey colour, but that is not the case in this test.

Figure 4.27 (right). The verification model is important when the carbon dioxide concentration inclination does not indicate the real situation.

4.5 Evaluation and relations of the measured carbon dioxide concentrations

In this chapter some comparisons between the measured results are performed to see if there is any relationship between the initial increase of carbon dioxide and the later achieved value. Furthermore, it is also of interest to find a relationship between varying number of test persons and altering ventilation rates. Several diagrams have been created to get an overview of the results and to be able to compare different situations. Some of the resulting diagrams are shown and discussed in this chapter, additional diagrams can be found in appendix 2. Moreover, the diagrams presented in this section represent the methods which were evaluated to give the best relationships between different conditions, since they give a possibility to find a common factor. This might be used further to hopefully find some relationships, which can be used to control the indoor climate.

4.5.1 Generation rate of carbon dioxide

Figure 4.28 shows the carbon dioxide generation five minutes after presence in the room has been registered plotted against the mean carbon dioxide generation, which has been calculated from the tenth minute after presence is detected until the end of the test. The reason to not calculate the mean generation from the beginning of the test is that the initial change of carbon dioxide concentration is not representative for average value. The calculations are based on the same formula used to find the carbon dioxide concentration in the room after a certain time (the dilution equation for carbon dioxide), by the assumption that the steady state level has been reached. After achieving the test results, the carbon dioxide concentration are known (measured value) and the generation rate is calculated. This is used to eliminate the person dependence, since it takes care of the fact that people produces different amount of carbon dioxide, i.e. an alternative way to find the internal heat load caused by humans.

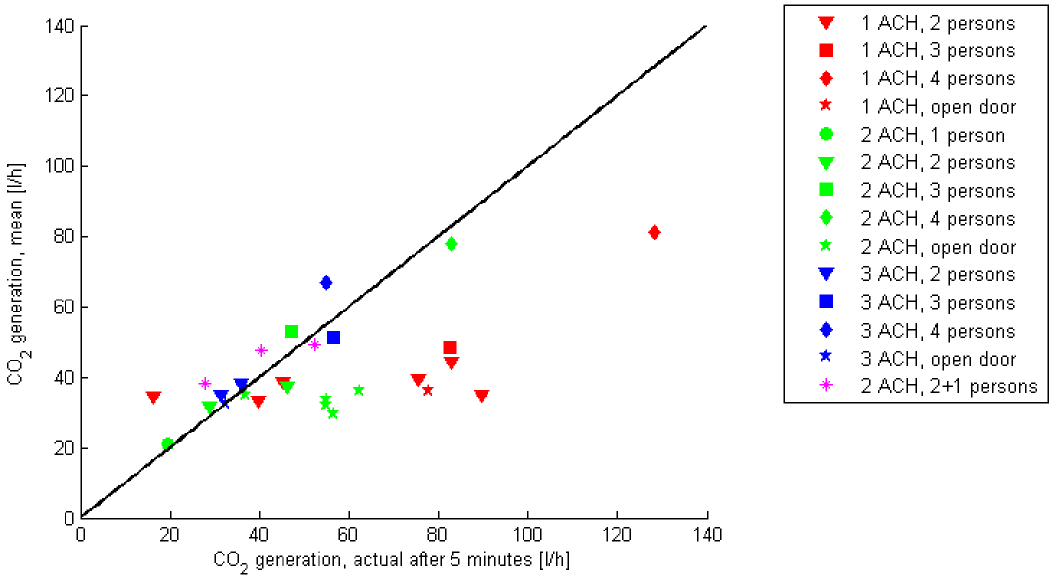


Figure 4.28. The mean carbon dioxide generation five minutes after presence detection against the mean generation of carbon dioxide.

In both figure 4.28 and figure 4.29 a black line can be seen, this line symbolizes the ideal situation. This means that the generation of carbon dioxide after a number of minutes equals the mean generation of carbon dioxide. As discussed earlier, the analytical solution does not perfectly match the measured values and it gives that the carbon dioxide generation is much higher in the initial stage (a few minutes after the test persons have entered). This can be seen if comparing figure 4.28 and figure 4.29, where the values are more spread and further away from the black line in figure 4.28, showing the relationship after five minutes. Naturally, the actual values after five minutes are higher than the mean generation, since it has not decreased yet after the initial peak. This can be seen in figure 4.30.

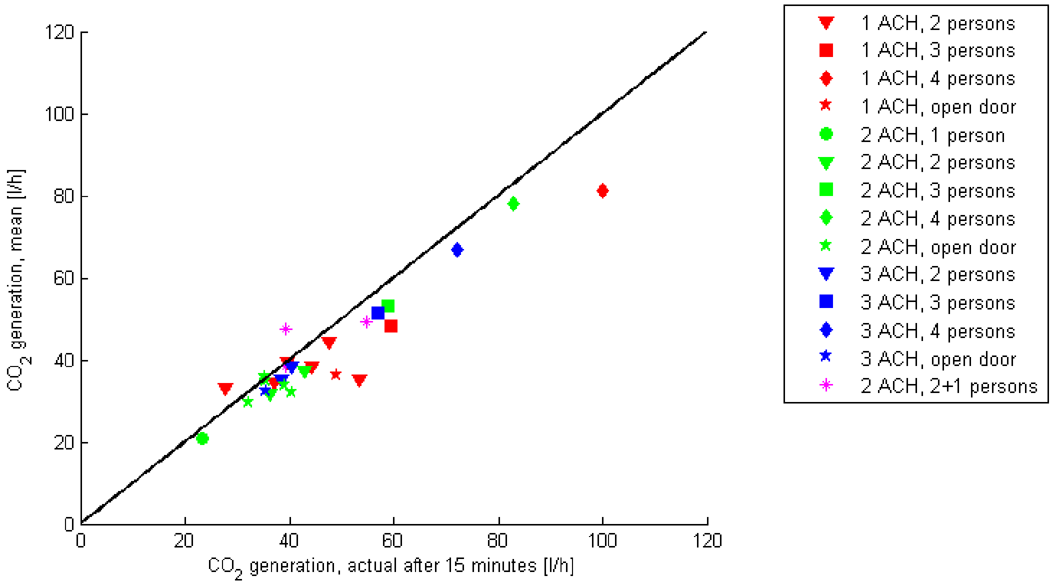


Figure 4.29. The mean carbon dioxide generation 15 minutes after presence detection against the mean generation of carbon dioxide.

The initial generation of carbon dioxide, according to the analytical solution, can be seen in figure 4.30 where the peak occurring in the beginning varies for the different tests. This makes it hard to do a reasonable comparison, especially since all tests do not have any clear peak but gradually rise to the steady state concentration.

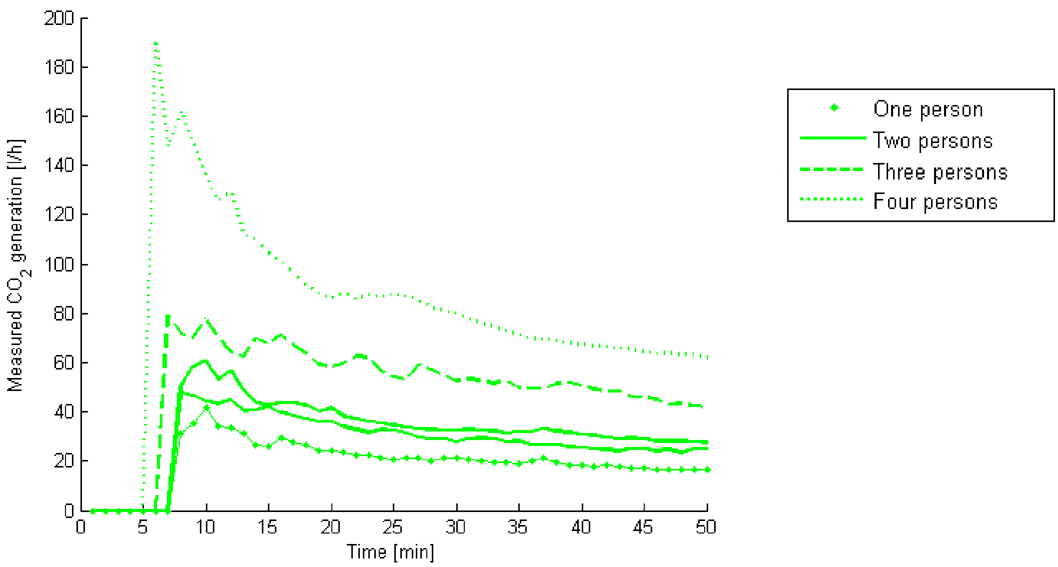


Figure 4.30. The peaks in generation of carbon dioxide for tests with two 1/h and a varying number present test persons. The line with the lowest y-values corresponds to a test with one person and the remaining lines corresponds to two, three and four persons the less dense the lines become.

4.5.2 Dead time for the sensors

Another way to use the results from the measurements to find relationships between the different tests has been to compare the dead time to the total carbon dioxide raise in a test i.e. until steady state is reached. A clear trend between the dead time of the carbon dioxide sensor and the total carbon dioxide increase can be seen in figure 4.31 when the airflow rate is two 1/h. The dead time becomes shorter when the number of present persons is increased. The dead time is around one minute for a four person test and four minutes for a one person test. Moreover, figure 4.31 also shows tests with two test persons and a third test person entering the room after a while. These tests fit quite well to the linear trend in contrast to the tests with the door opened. A possible explanation of this might be that the tests performed with the door open have a significantly lower steady state level. This means that the total change is small and these values will therefore get a low value on the y-axis, which probably is the reason why the results from these tests deviate from the trend. The test with open door does though have faster response compared to the other tests with two persons. This might depend on an increased amount of air being sucked towards the door opening, which is located behind the sensor in the exhaust device.

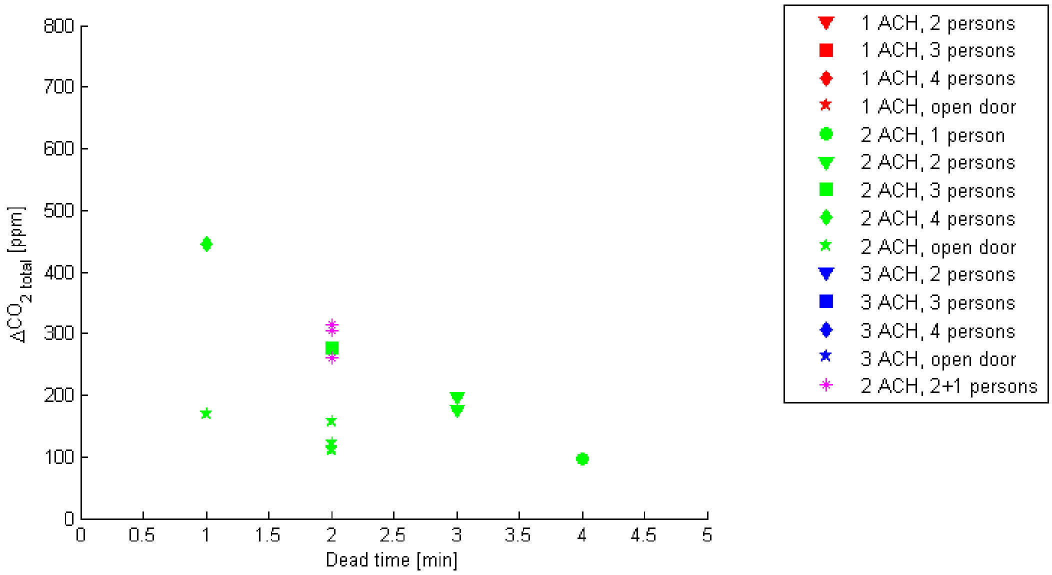


Figure 4.31. Tests performed with an airflow rate of two 1/h, where the measured total carbon dioxide change is plotted against the obtained dead time.

In figure 4.32, three different airflow rates are shown with the same unit on the axes as in figure 4.31. This diagram clarifies that the same relationships can be found also in tests performed with one and three 1/h, even though the relation is not as linear as it is for tests performed with two 1/h. The figure also shows that the carbon dioxide sensor in the exhaust air duct has quite fast response time and does not show that large differences between the different tests. Other sensor positions and their dead time can be seen in appendix 2. It can be stated that the dead times are rather spread for the sensor in the center of the room (position 5), while the dead time is very short if the sensor is located in the corner behind the occupants close to the supply air device (position 13). Furthermore, it is worth to point out that the sensor in the exhaust air is exactly the same for all tests and the dead times can be compared to each other. Different sensor types cannot be compared since there is a risk that the time to response depends on the feature of the sensor and not to the sensor location.

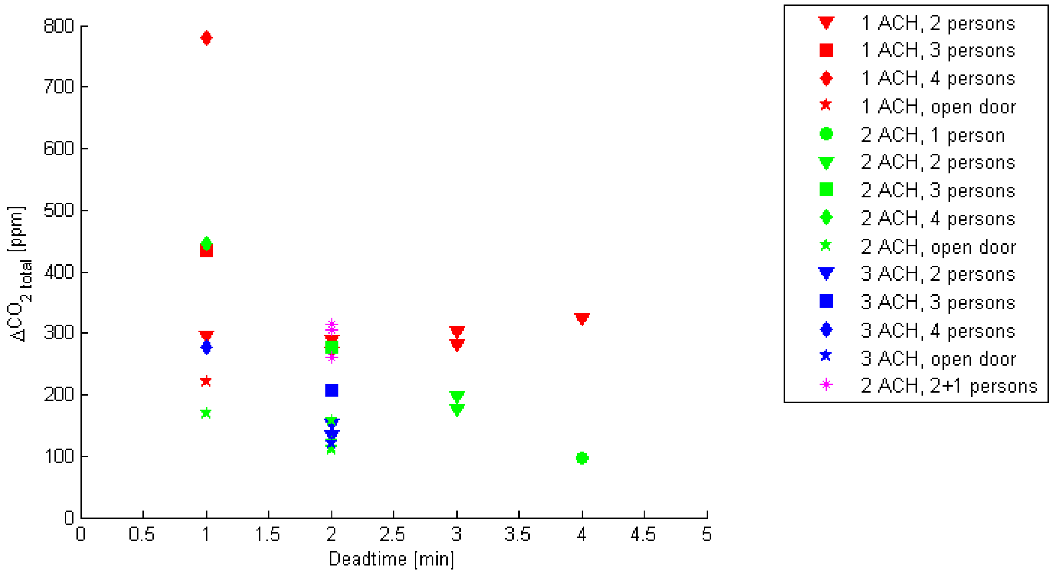


Figure 4.32. The dead time plotted against the total change in carbon dioxide during a test. The plotted values represent all performed tests which have been considered as successful.

4.5.3 Mean concentration of carbon dioxide

The tests can also be compared to get relationships by plotting the average change (increase) of carbon dioxide during a certain time against the total change of carbon dioxide. This can be seen in figure 4.33, where the average carbon dioxide change, on the x-axis, is set to five minutes from the first noticeable increase in carbon dioxide concentration. The figure shows that the values are quite gathered and a relationship is starting to appear, but without being clear enough to avoid mistakes in the conclusions.

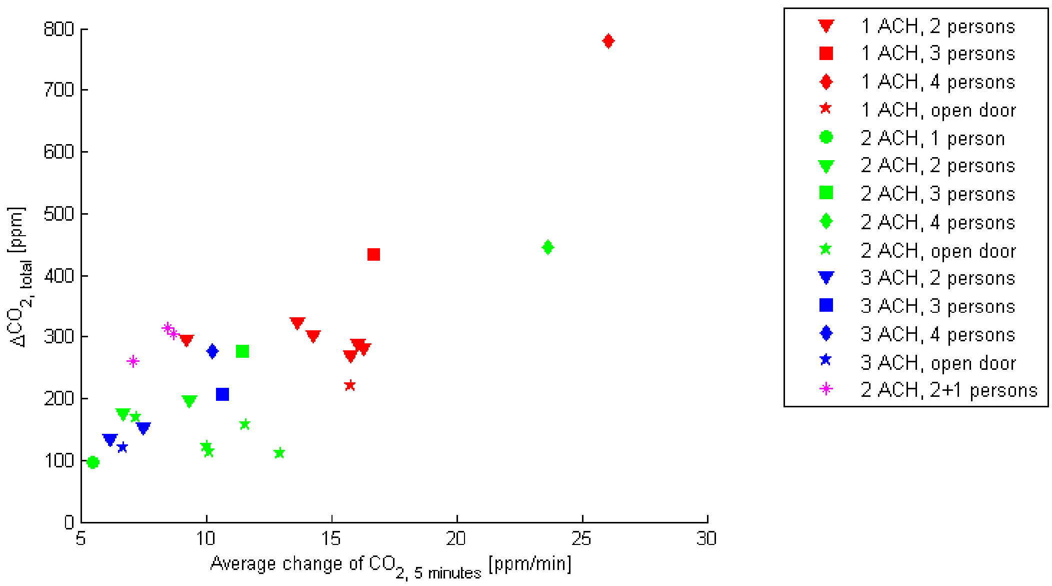


Figure 4.33. The average change in carbon dioxide during five minutes plotted against the total change in carbon dioxide until reaching steady state. It can be seen that a relationship between the values is starting to form.

Figure 4.34 shows the same comparison as figure 4.33, but the average change of carbon dioxide is set to 15 minutes instead of five. Here, the relationship between the different tests, with various settings, appears to be even more obvious. Although some extreme values exists, e.g. the red and the green diamonds on the right hand side, but since they are four persons test it is logical that the changes are larger than in the other tests.

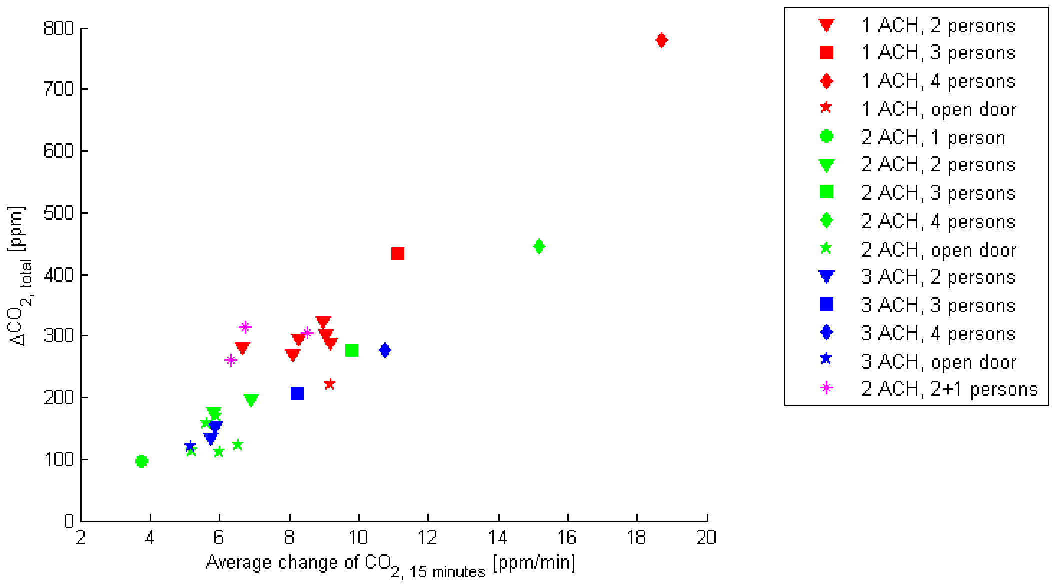


Figure 4.34. The average change in carbon dioxide during 15 minutes plotted against the total change in carbon dioxide until reaching steady state. The relationship is even clearer here, since the results are less spread and they become even more gathered the longer the average change is check for.

4.6 Candles as a substitute to humans in tests

To either confirm or dismiss a myth, that a candle is comparable to a human's combustion, concerning heat and carbon dioxide generation, a test with candles has been performed. Figure 4.35 and 4.36 shows the measured results from the candle test, where two candles where placed in the test room with an airflow rate of two 1/h. The results from the candle test are compared to some of the earlier performed tests with people present, to investigate if the temperature and carbon dioxide generation corresponds to any of them. Figure 5.35 shows the concentration of carbon dioxide and two candles corresponds to the same source flow of carbon dioxide as one person. The heat emitted from two candles, see figure 4.36, does not correspond to one human as for the concentration of carbon dioxide; instead it corresponds to three humans. Therefore, at least according to our tests, the myth can be considered as busted.

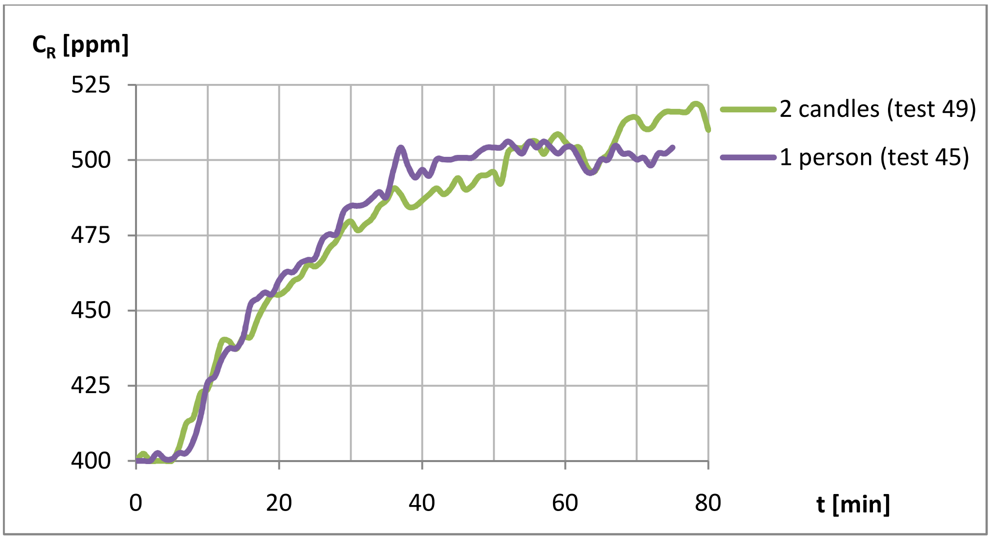


Figure 4.35 Carbon dioxide concentration with two candles in the test room. The values are normalized to 400 ppm to simplify the comparison.

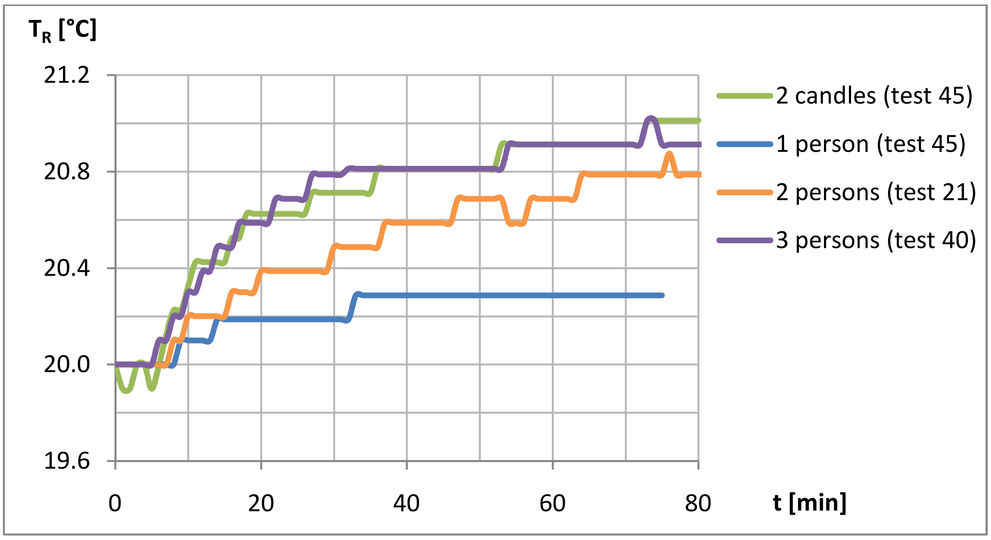


Figure 4.36. Temperature variation with two candles in the test room, to be comparable with one, two and three occupants. The values are normalized to 20 °C.

4.7 Sources of error

All tests are performed with the same procedure, so as few circumstances as possible differs between the tests, otherwise the tests would be inconsequent and not comparable. The only changed factors between the performed tests are the airflow rate, the number of present people and the ambient conditions. The most severe of these is the ambient conditions, since it is harder to control than the rest of them. The ambient conditions affect the room by parameters that can be controlled from the control computer, such as the ventilation rate and the supplied heat. The higher the ventilation rate is, the more influence has the ambient air on the indoor air. The same thing applies for the supplied heating; the system is rather slow and an increase of the outdoor air temperature might cause a higher indoor temperature since the water temperature in the heating coil changes to slow due to the thermal properties of the water. The ambience also affects the room by parameters that are uncontrolled; this regards leakage through the walls and thermal conduction through both the façade and to the surrounding rooms. The driving potentials are either temperature or concentration differences. The concentration of substances in the surrounding rooms often varies more than the outdoor ambient, since it often is occupied by a various number of people, e.g. in the test facility. This also concerns the test persons' behaviour before entering the test room, some adjustments and documentation regarding the test needs to be done and this is performed in the control room located next to the test room. When performing these activities a buffer of carbon dioxide might be created and it is a risk that this can be brought into the test room when starting the test.

The way of entering the test room may influence the results, even if the test persons enters the room at very precise times and goes to the same position with the same activity in all tests, the number of persons creates different mixing of the air on the way to the seats. The measurements may also be affected due to the position of the sensors, since the portable sensor sometimes turns itself off and needs to be restarted during the test. This could cause both undesired mixing of the air and unreasonable high measurement from the sensor, since a person needs to get close to the sensor in order to turn it on again.

Another parameter that might affect the results is the inertia and general storage capacity of the walls; this mostly regards heat and vapour, but also the air, since it takes a while for the air to be exchanged and the gases to disperse. Therefore, it is very important to await steady state conditions for all parameters that should be evaluated, before performing any tests.

The analytical solution for the room concentration of carbon dioxide fits the measured values until a certain point where steady state occurs for the test room, this occurs significantly earlier than the analytical solution indicates. The difference between the theoretical and the measured values might depend on leakage; this is why the analytical solution mostly needs to be multiplied with certain factors to get an appropriate curve fit in the regulation control. The factors depend on the air exchange rate and it is also probable that stratification of the air matters. The analytical solution is based on a certain source flow of carbon dioxide per person and this value is a standard value for low activity performed in an office (1,2 met). The value might not represent the real situation in all cases, since it depends on factors such as the size and physical condition of the person and this might affected all tests with more than two test persons. In the figure shown below, figure 4.37, an example of this is illustrated. Both tests have been performed with the same airflow rate and three test persons and the only difference is that one of the persons has been changed, where person 1 has a higher body mass index than person 2.

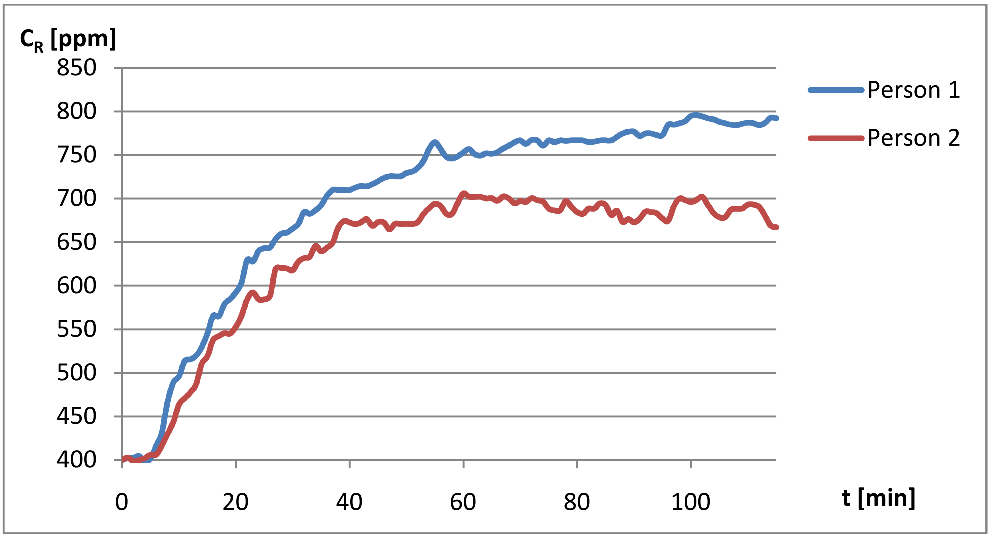


Figure 4.37. There is a difference of carbon dioxide generation rate due to the size of the test persons. The diagram presents the carbon dioxide concentration in test 32 and 40, which is exactly the same except for the fact that one of the test persons is substituted. The airflow rate is two 1/h and the values are normalized to 400 ppm.

No theoretical model of the temperature has been established due to lack of information about the wall construction, regarding both the inertia and the U-values. The model was done for the carbon dioxide concentration to ensure that the test conditions were correct; no confirmation of the test room regarding temperature has been performed.

5 Conclusions

The idea of this master thesis has been to perform measurements and evaluate them in order to find a relationship between parameters that can be used to regulate the indoor climate by a feed-forward control and regulation system. 49 tests have been performed in total and it can, according to the results, be concluded that a forthcoming temperature change can be identified by measuring other parameters than the temperature.

The sensor that has been found to give the fastest indication of occupancy in a room is the presence sensor. Despite this fact, it is not recommended to (only) use this parameter as the main signal in a feed-forward regulation system due to the lack of information regarding the number of occupants. Instead, the measurements have shown that it might be a good idea to use the carbon dioxide concentration for indoor climate control in such a system. The inclination of the carbon dioxide concentration change during the first few minutes can be used to determine the number of persons that have entered the room. Because of this, it is also possible to derive the internal heat load, caused by humans, since the amount of exhaled carbon dioxide are linearly connected to the combustion process that generates heat. This gives that the carbon dioxide concentration can be used to indicate both the air quality, which it is already used to, and a forthcoming temperature rise caused by human generated internal heat. The heat loads from machinery etc. have already been evaluated in previous research.

By the developed method that is based on the inclination of carbon dioxide concentration change in a room it only takes a few minutes to identify the number of occupants that have entered a room. The measurements can sometime give unreliable result, which needs to be verified and this can be done by another developed model. Both the inclination principle and the verification model are dependent on the airflow rate, which already is a known variable. The disadvantage with this personal dependent model is that it does not consider the fact the all people do not exhale the same amount of carbon dioxide, or neither emit the same amount of heat. The physical condition and size of the persons have a major impact on the carbon dioxide concentration in the room. It would be desirable, from a control and regulation point of view, to register the weight and length of the persons entering the room. Unfortunately, that would not be possible in practise for an office building. On the other hand, there are normally adults that occupy an office and what really matters is the metabolic rate (even though this often is connected to the size of a person). Furthermore, to control the climate, the regulation system only needs to get information about how big the needed airflow is and the number of occupants may therefore be stated as personal equivalents, rather than number of persons. One personal equivalent could for example correspond to 100 W emitted heat and 18 l/h generated carbon dioxide or the measured carbon dioxide could be directly connected to the generated heat.

A combination of different sensors might be an alternative way to find out the number of present persons in a room. This is probably the only way to use sensors measuring the relative humidity in a regulation system; it is too unreliable and not enough accurate to be used alone. However, the advantages with the parameter are that people always produce vapour and it is not affected by combustion processes in the neighborhood, as the carbon dioxide might be.

There will always be a certain delay in noticing presence if it is to be detected by sensors measuring either the vapour content, temperature or carbon dioxide concentration. The transport delay for the investigated parameters is very similar to each other without any clear variations. However, the magnitude of the changes differs significantly between the sensors and the change of carbon dioxide concentration is the most apparent.

The performed tests have shown that the sensors in the room do not indicate faster change of carbon dioxide concentration than the sensor in the exhaust air. This does not correspond to the observations from the smoke test, but the result is favorable since there is a risk that sensors mounted on the wall will be locally affected by persons visiting the area in front of it. Moreover, a sensor mounted in the exhaust air will probably give a more stable result compared to a sensor located in the room, since it measures an average value of the room condition, which is desirable in control and regulation systems.

Short dead time is another desired property, together with fast and clear response. The dead time for the sensor in the centre of the room (position 5) is significantly longer than in the exhaust air and in the corner behind the supply air device (position 13). The time to response is rather spread for this sensor and it is clear that it represents the average situation in the room, while the short distance from the supply device to the sensor in the corner means clear airstreams and it is therefore affected directly. The sensor in position 13 and the one in the exhaust air has about the same dead times. Moreover, the dead times for the sensor in the exhaust air shows a linear relation to the carbon dioxide concentration level in the room, i.e. the generated amount in the room, depending on the airflow rate.

Another factor that was expected to affect the measured carbon dioxide concentration in the room was airstreams to surrounding rooms. This was tested by keeping the door to the test room open, while varying the differential temperature between the rooms and the supplied airflow. According to the measurements, this did not have any substantial impact on the concentration of carbon dioxide in the room, neither if the supplied airflow rate or temperature gradient between the rooms were changed.

Some relations has been carried out to find better ways for indicate presence. The problem with using the average change for a while or calculate the generation rate compared to the mean generation is that it takes some time to get a stable and representative situation in the room. The lower changes that are needed in the control and regulation input signals, to be able to create a comfortable indoor climate, the faster the climate can be adjusted. On the other hand, small changes mean a higher risk of incorrect indications. More values would improve the assurance of the results, since diverge variations of single values can be neglected. The logging interval in the performed tests was one minute, this time might be shortened to improve the capacity for fast and correct response. Moreover, there is no need to store the measured values for more than half an hour, at least from a control and regulation aspect according to the test results.

The feed-forward system can preferably be used together with a feedback system, to get an even more secure climate control strategy. It will not contribute to the attempt of creating faster response, but it could be used in order to improve the accuracy and avoid incorrect predictions. It might be a good idea to use the feed-forward regulation to prepare the system and make a rough estimation, while the feedback control still could be used for the accurate calibration.

Finally, it can be concluded that there is a potential of feed-forward systems for controlling and regulating the indoor climate. It could either be used by lowering the supply air temperature or increase the supplied cooling to avoid a forthcoming temperature rise. This complies with either hydronic systems, airborne systems or a combination of them, where the climate in each room can be adjusted. There is also a possibility to use the feed-forward system to improve the amount of supplied air, so the building is neither over nor under ventilated.

However, there is still some work that needs to be done before it can be applied in practise. First of all, more tests needs to be performed in order to verify the measurements that the developed models are based upon. Moreover, this thesis has focused on what happens when people enter the room, but it is also important to study the decay when people leave the room. This is outside the limits of this report, but might be a subject for further research. Furthermore, to improve the indoor climate and lower the energy need, a model similar to the adjusted dilution equation for carbon dioxide concentration should be developed for temperature variations.

If further research will be performed to complete the work that has been started, it is of great importance to verify the test procedure and to reach steady state condition of measured parameters before a test is started.

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Appendices

Appendix 1 – Test results p.A1

Appendix 2 – Presentation of comparisons p.A23

Appendix 1 - Test results

This appendix presents data from the test results used in the thesis. The results are presented test by test and they are divided into four categories; tests with one to four occupants in the room and with different ventilation levels, tests when the door has been opened during the test, tests when an extra person has entered the room after certain times and finally a noise test and a test to investigate if people can be replaced by candles to perform the tests. The presented data in the appendix includes temperature variation, carbon dioxide concentration and vapour content. All these parameters are measured at the same location and with a logging interval of one minute. The results are illustrated by graphs in order to make it easy to clarify and identify trends. Unfortunately, some tests lack data of any of the parameters, because of troubles with the sensors or unreasonable results. Regarding the concentration of carbon dioxide; the analytical solution assumes a source flow of 18 l/h. Please notice that all values in the diagrams are normalized towards the supply air condition. An overview of the performed tests are presented below, in table A1.

*Table A1. Summary of the conditions for the performed tests. The * means that all tests with the same number should have identical conditions, the only difference is the position of the sensors.*

Test number	ACH [1/h]	Number of occupants	Time [h]	Positions of the portable sensors	Comments
15	1	2	2:45	5, 6	*[1]
16	1	2	1:15	11, 13	*[1]
17	1	2	1:15	8, 9	*[1]
18	1	2	1:35	5, 10	*[1]
19	1	2	1:15	5, 6	*[1]
20	2	2	1:35	5, 6	*[2]
21	2	2	1:35	9, 13	*[2]
22	0,6	2	2:15	9, 13	*[3]
23	0,6	2	2:15	5, 6	*[3]
24	3	2	1:15	5, 6	*[4]
25	3	2	1:15	9, 13	*[4]
27	1	2	1:05	9, 13	*[1]
28	1	2	3:25	6, 13	Full mixing

29	1	0	2:15	Between 5-10	Noise test
30	2	4	1:35	5, 13	
31	3	4	1:25	5, 13	
35	3	3	1:45	5, 13	
36	3	2	0:50	13, test facility	Open door, ΔT=1 °C
37	2	2+1	2:00	5, 13	Third person entered after t=30min
38	2	2	0:50	13, test facility	Open door, ΔT=1 °C
39	2	2	0:50	13, test facility	Open door, ΔT=3 °C
40	2	3	1:55	5, 13	
41	2	2	0:50	13, test facility	Open door, ΔT=5°C
42	2	2+1	2:15	5, 13	Third person entered after t=60min
43	2	2+1	1:25	5, 13	Third person entered after t=11min
44	1	2	1:05	13, test facility	Open door, ΔT=1 °C
45	2	1	1:15	5, 13	
46	2	2	0:55	Test facility	Open door, ΔT=1 °C
47	1	4	2:10	5, 13	
48	1	3	2:10	5, 13	
49	2	0	1:20	5	Candles

1-4 test persons with different airflow rates

One test person, two air exchanges per hour (Test 45)

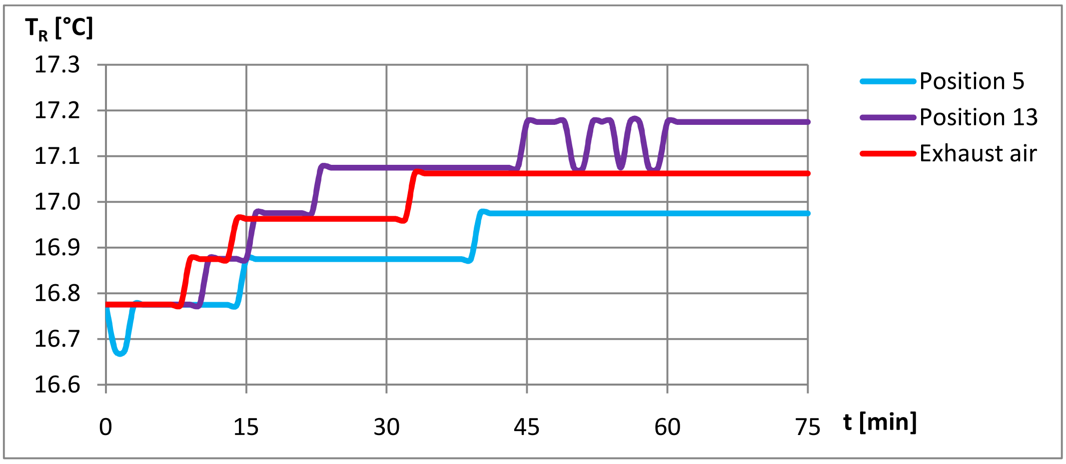

Figure A1. Test 45, temperature variations at three different locations.

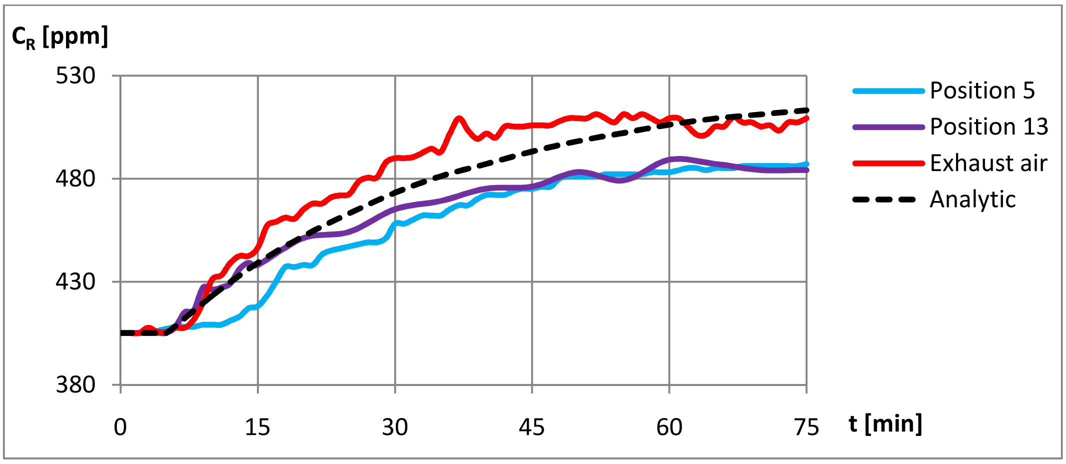

Figure A2. Test 45, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

Two test persons, one air exchange per hour and full mixing of the indoor air (Test 28)

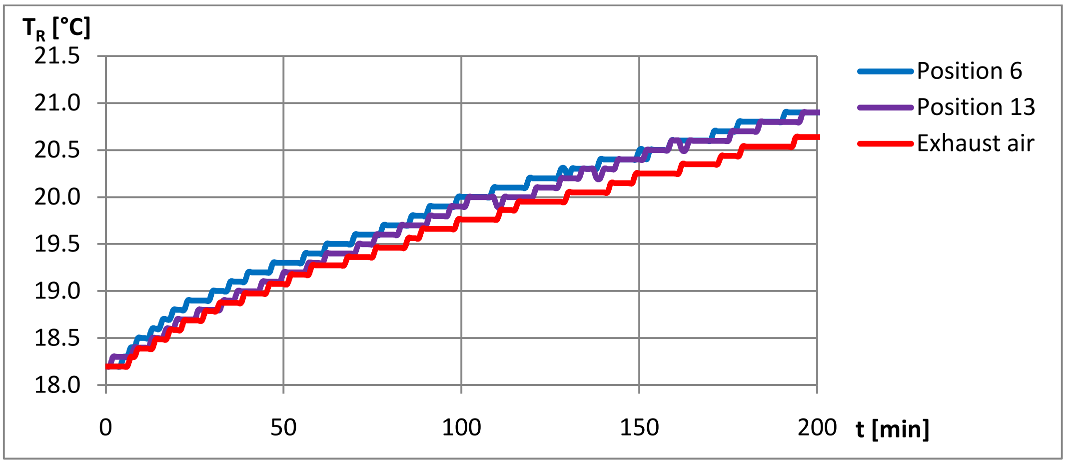

Figure A3. Test 28, temperature variations at three different locations.

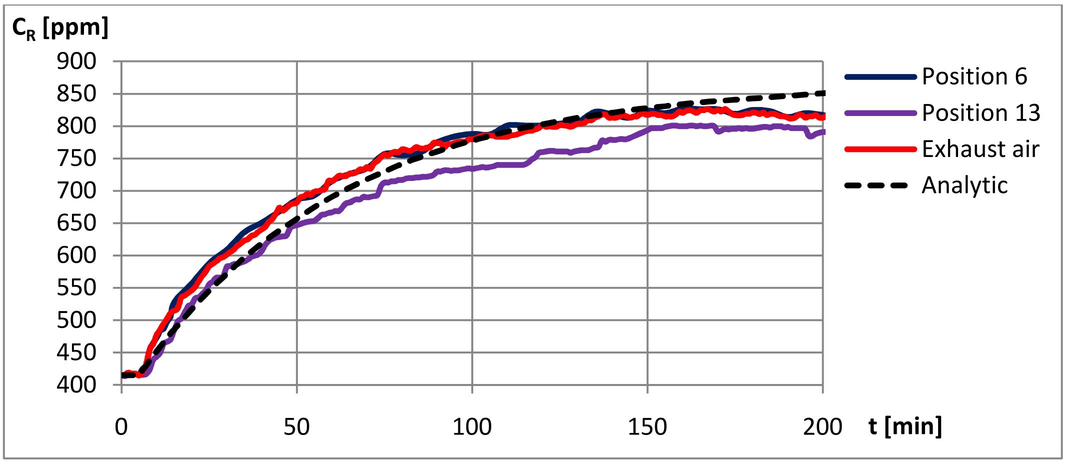

Figure A4. Test 28, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

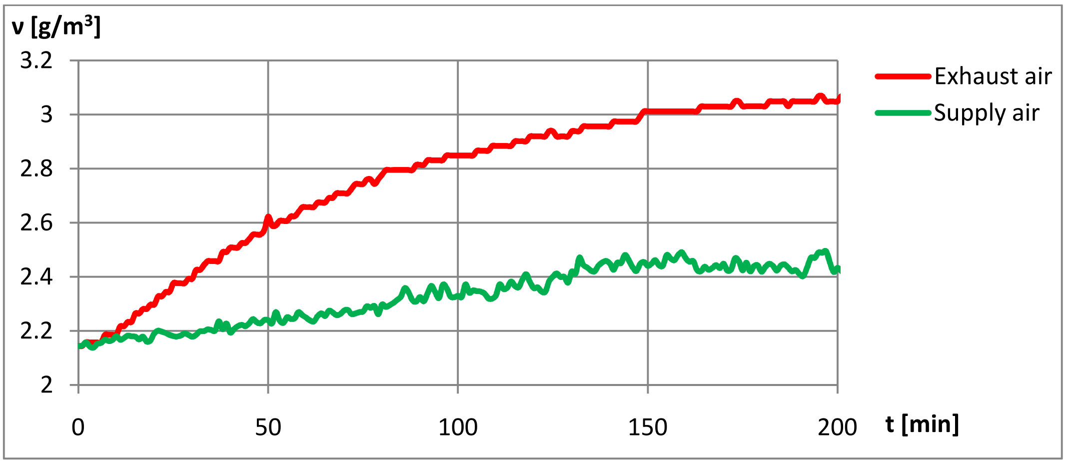

Figure A5. Test 28, variations of the vapour content in the supply and exhaust air.

Two test persons and 0, 6 air exchanges per hour (Test 22, 23)

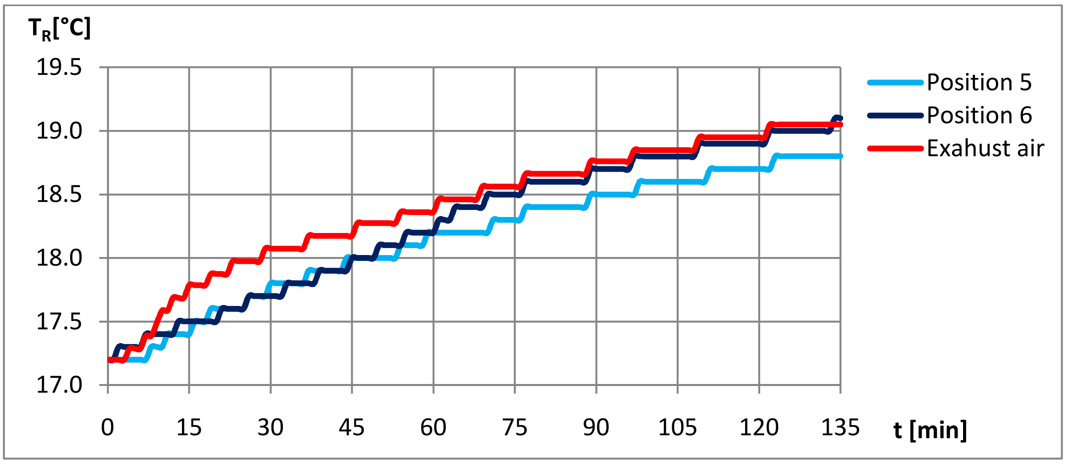

Figure A6. Test 23, temperature variations at three different locations.

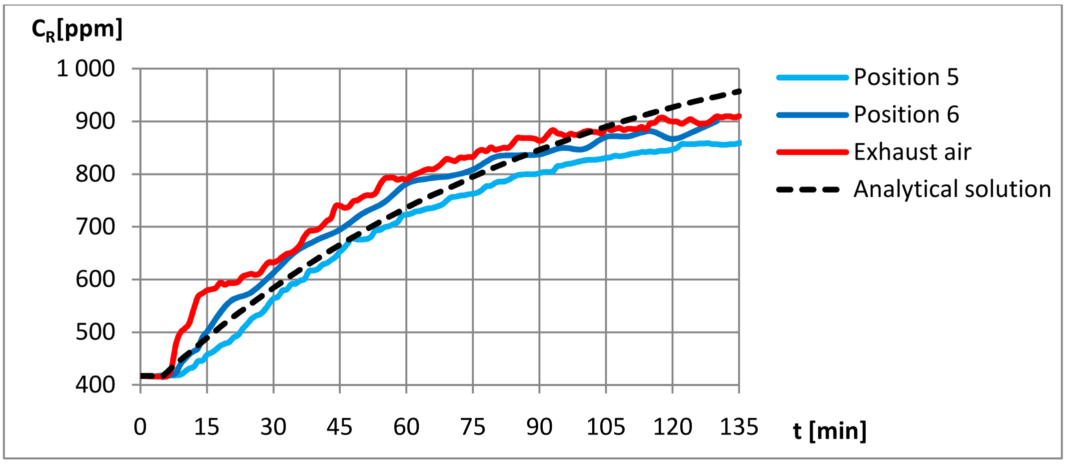

Figure A7. Test 23, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

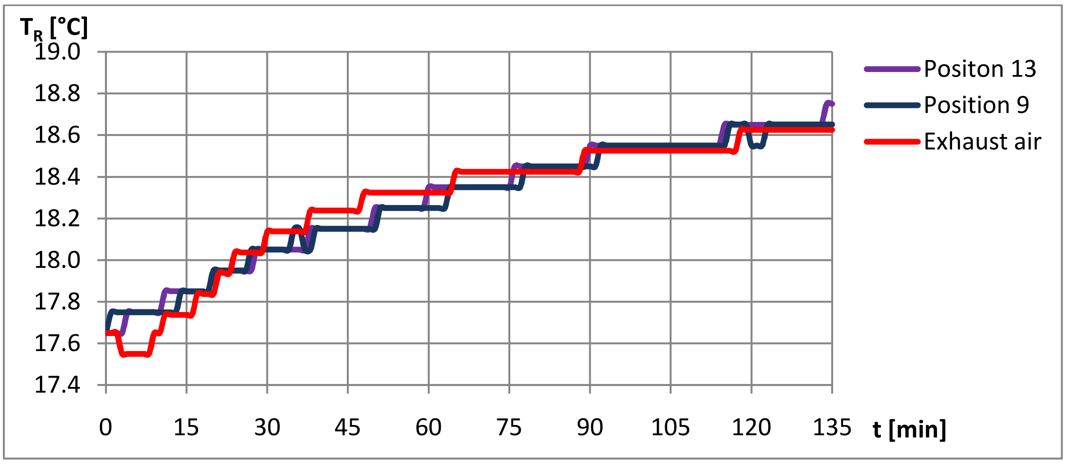

Figure A8. Test 22, temperature variations at three different locations.

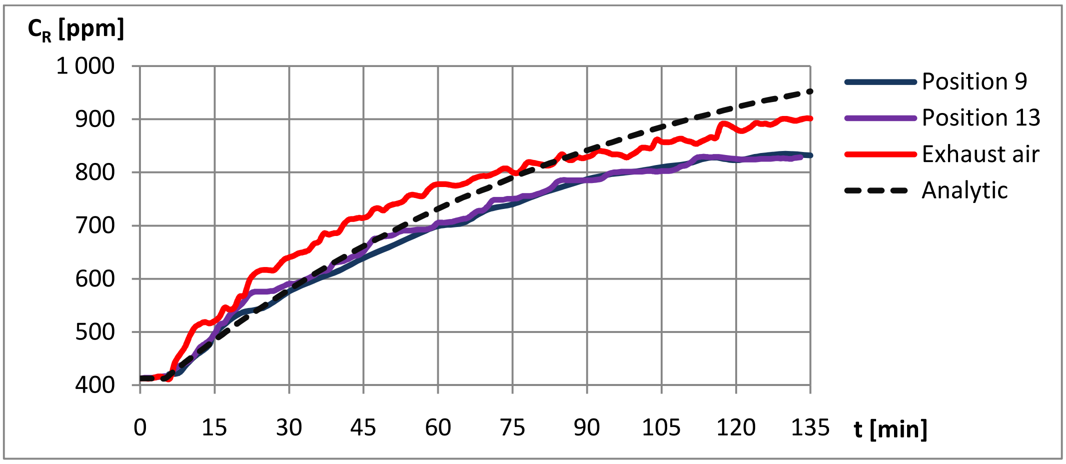

Figure A9. Test 22, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

Two test persons and one air exchanges per hour (Test 15, 16, 17, 18, 27)

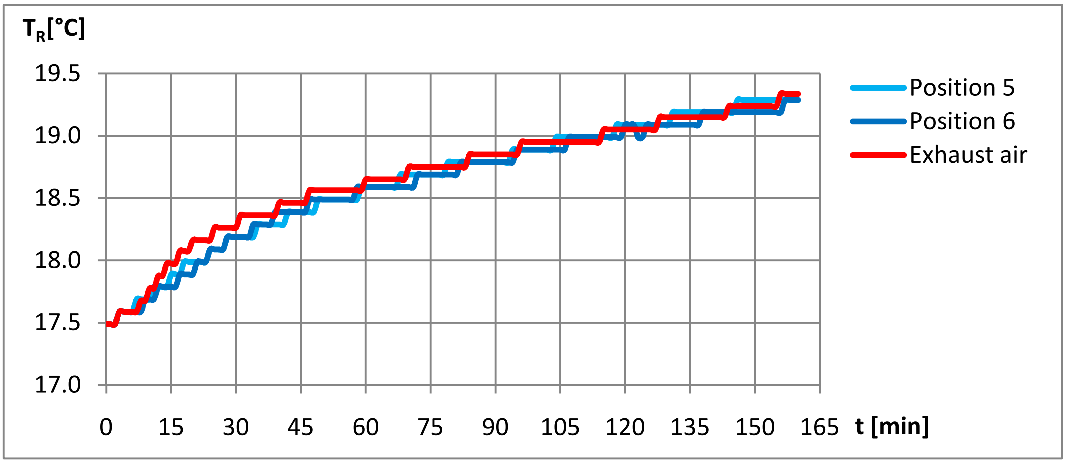

Figure A10. Test 15, temperature variations at three different locations.

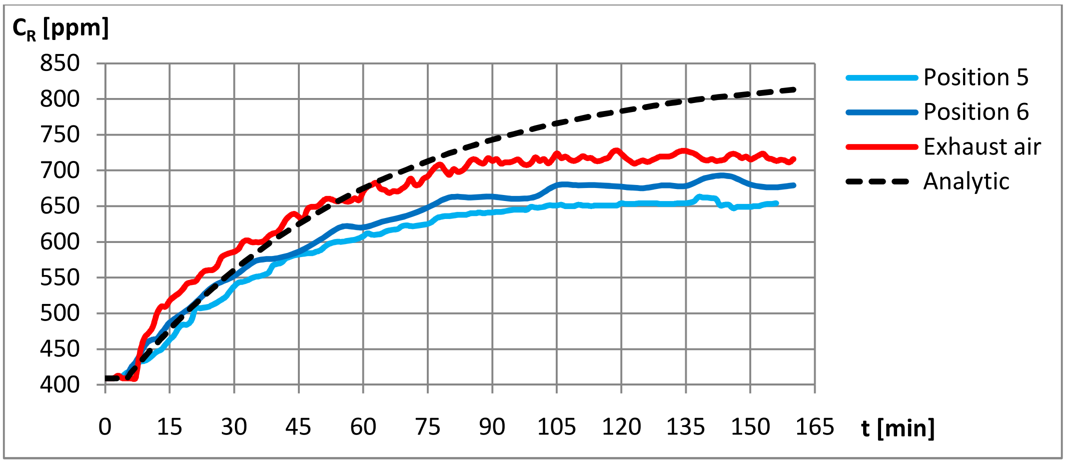

Figure A11. Test 15, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

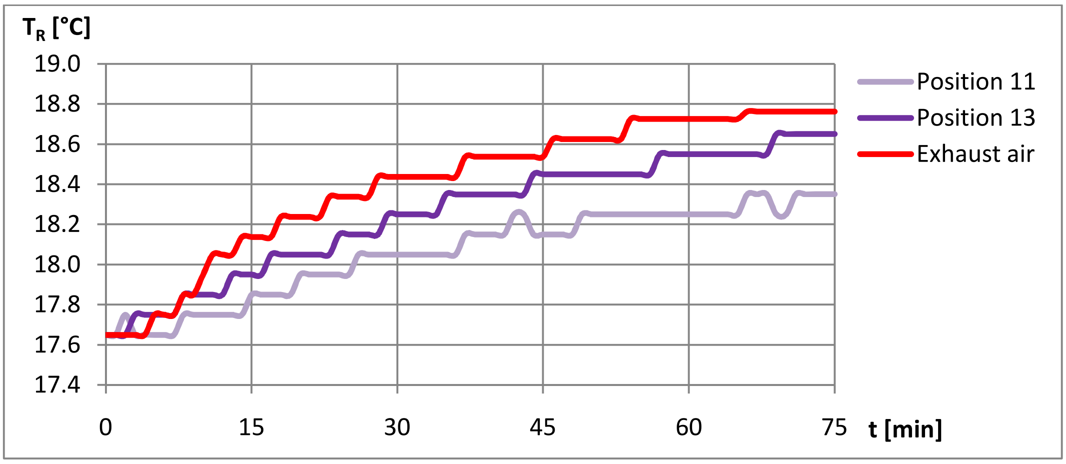

Figure A12. Test 16, temperature variations at three different locations.

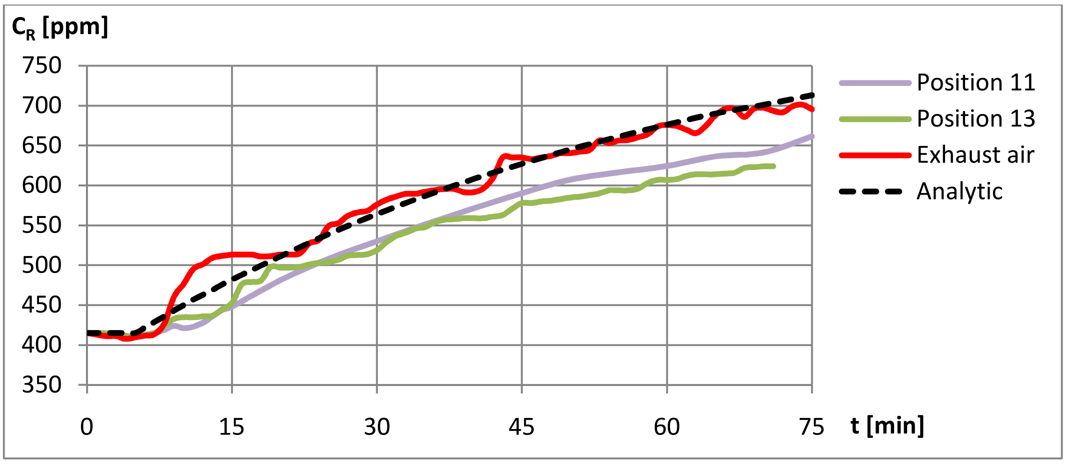

Figure A13. Test 16, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

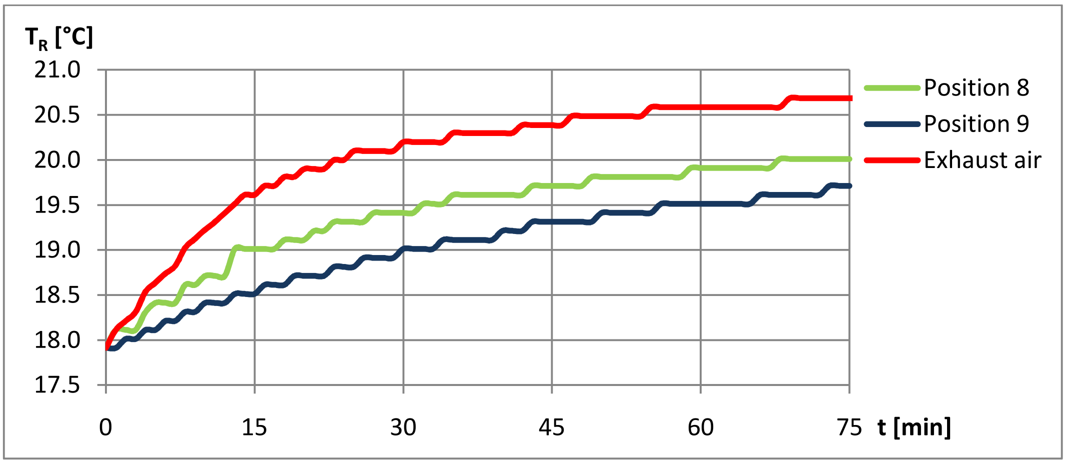

Figure A14. Test 17, temperature variations at three different locations.

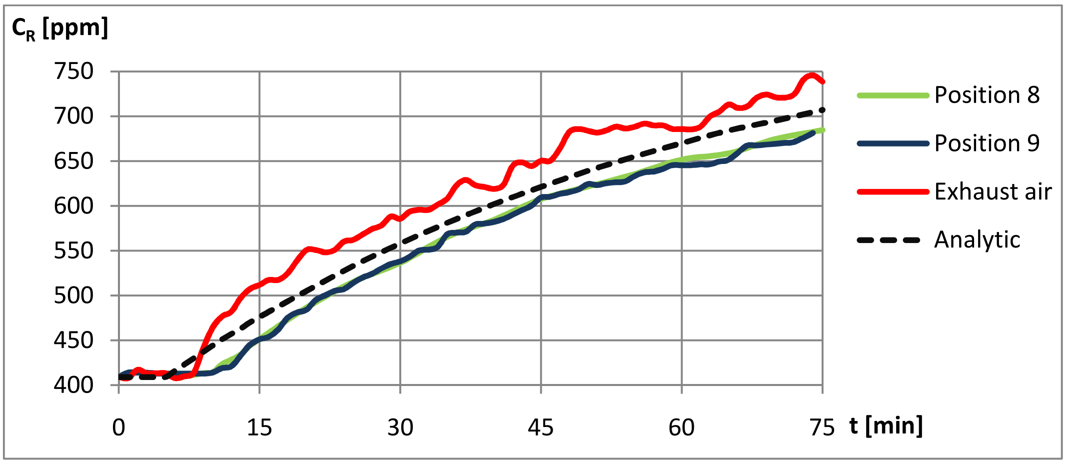

Figure A15. Test 17, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

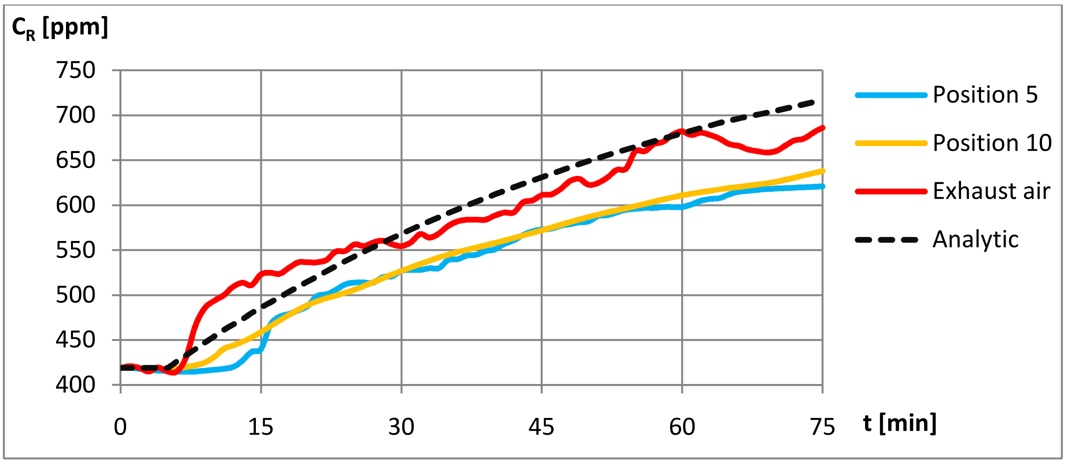

Figure A16. Test 18, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

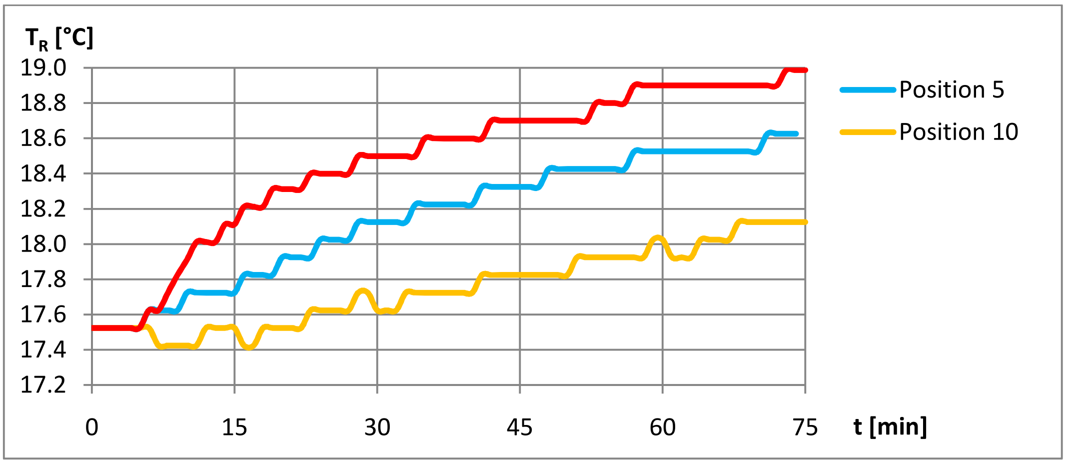

Figure A17. Test 18, temperature variations at three different locations.

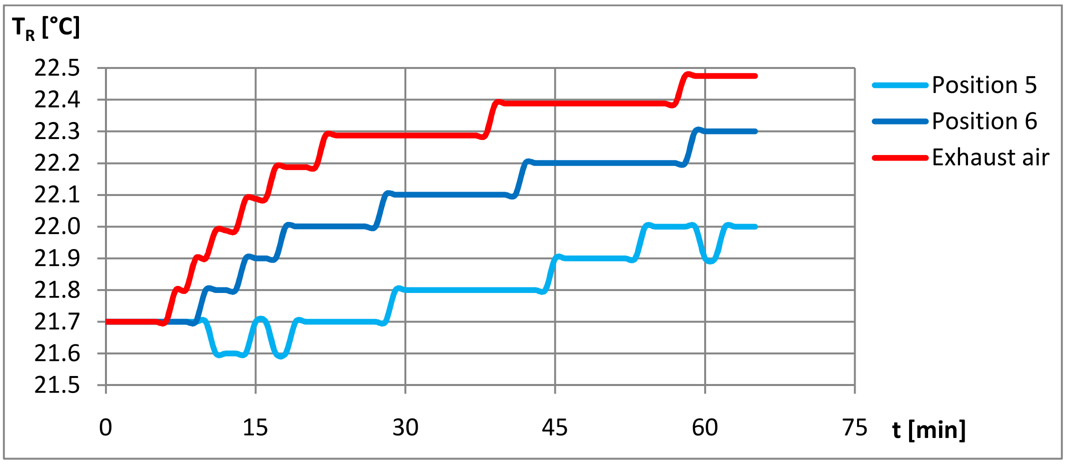

Figure A18. Test 27, temperature variations at three different locations.

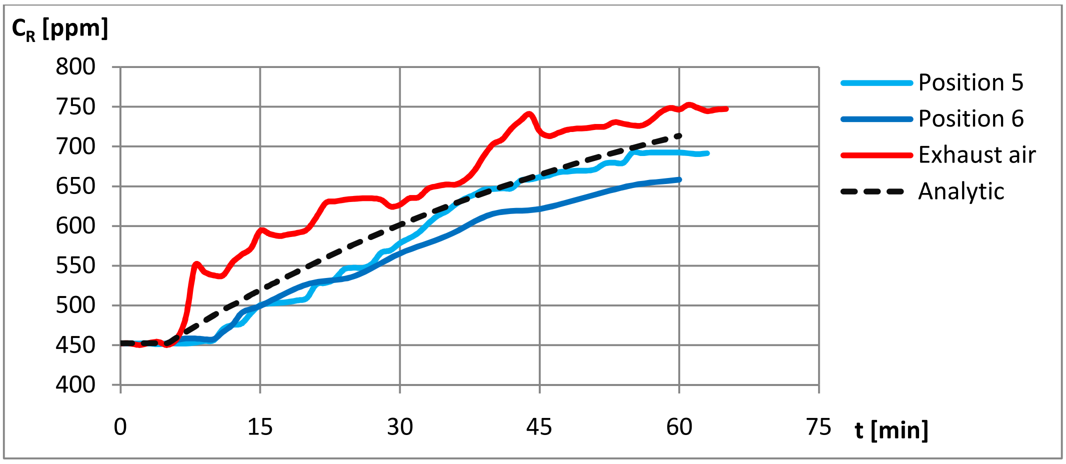

Figure A19. Test 27, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

Two test persons and two air exchanges per hour (Test 20, 21)

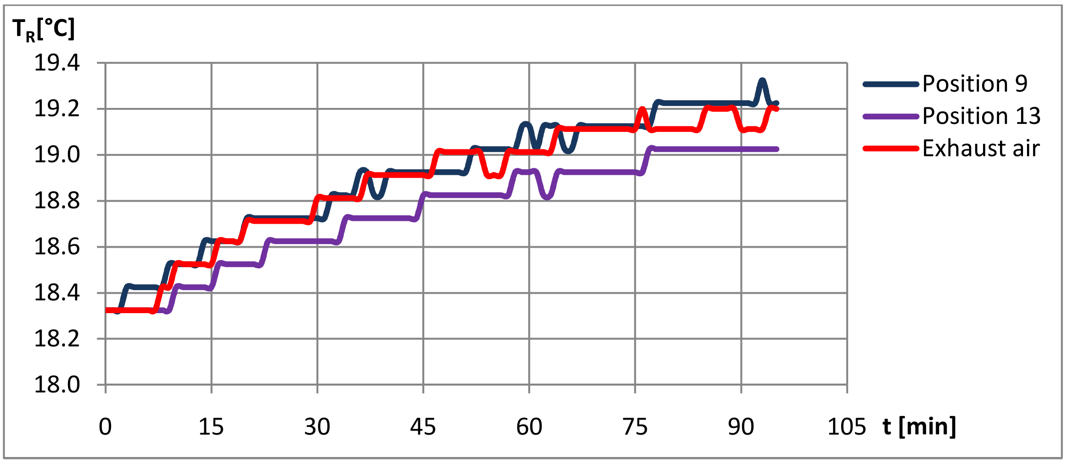

Figure A20. Test 21, temperature variations at three different locations.

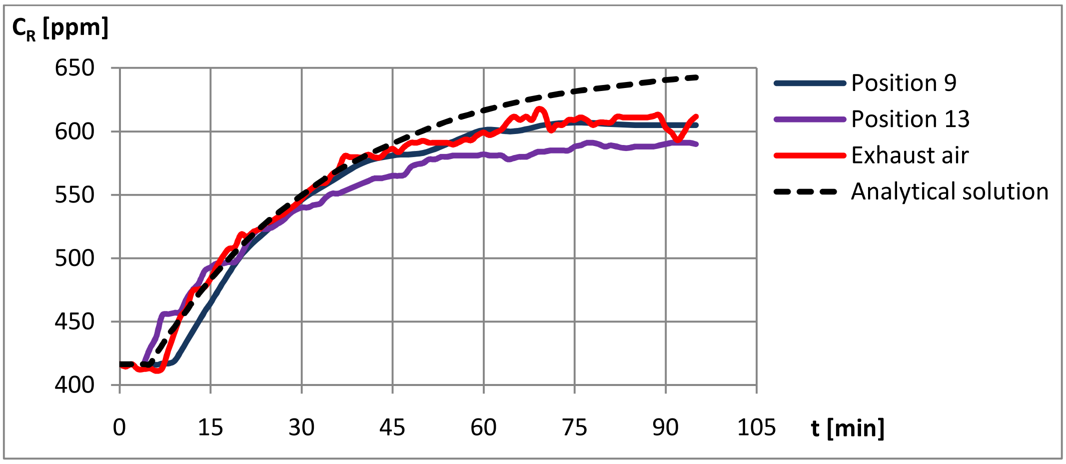

Figure A21. Test 21, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

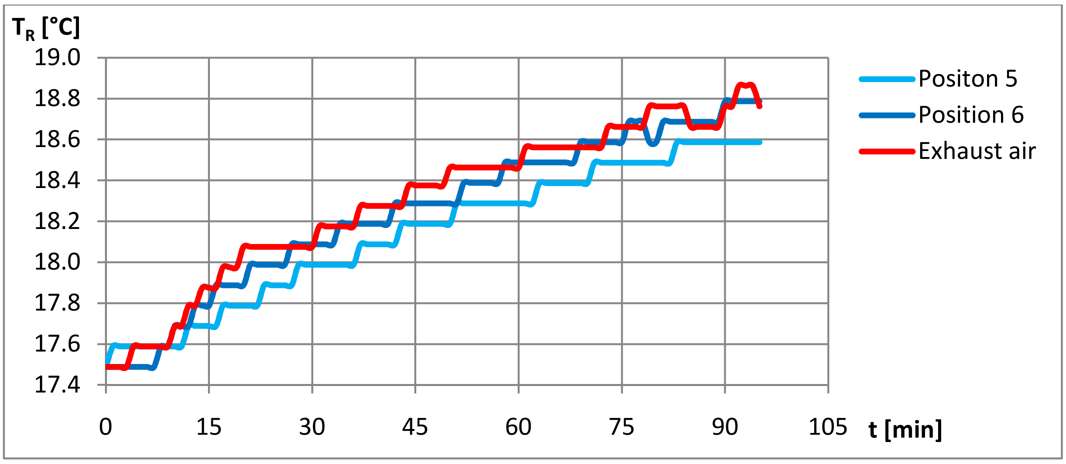

Figure A22. Test 20, temperature variations at three different locations.

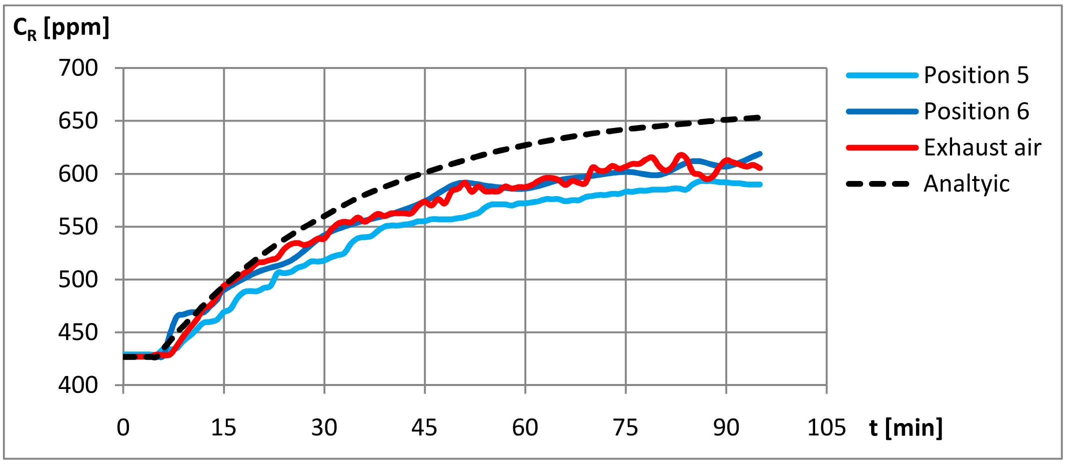

Figure A23. Test 20, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

Two test persons and three air exchanges per hour (Test 24, 25)

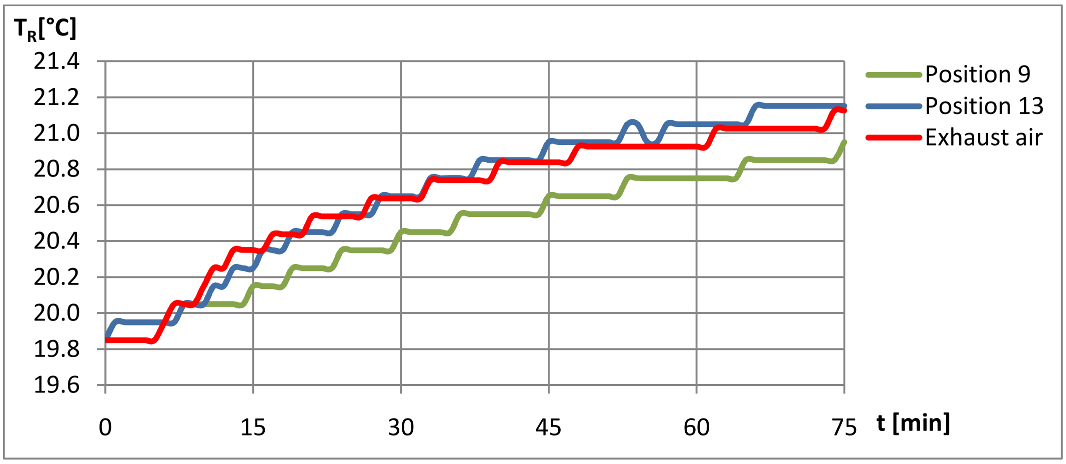

Figure A24. Test 25, temperature variations at three different locations.

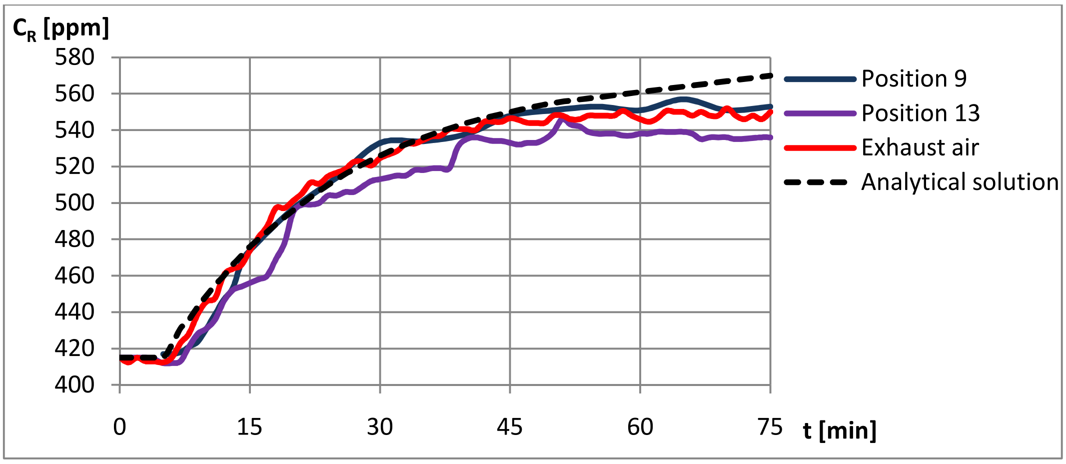

Figure A25. Test 25, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

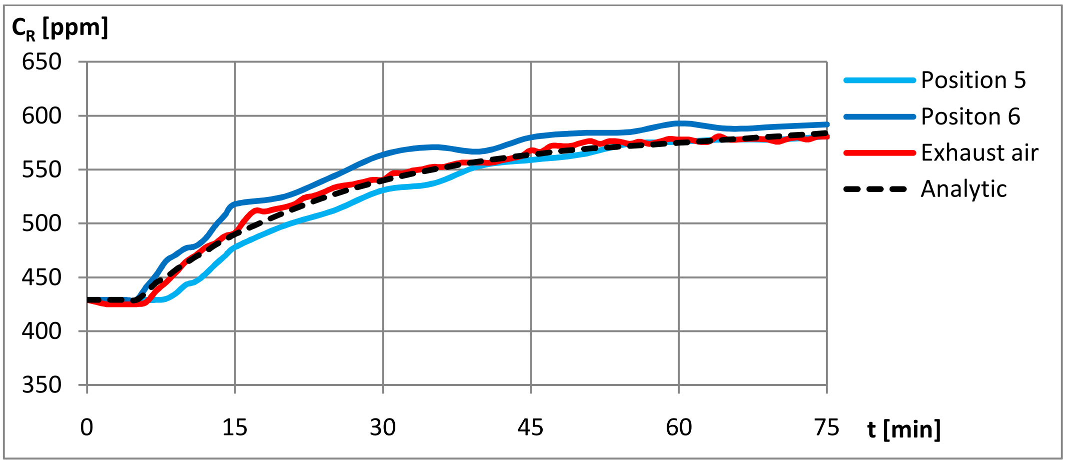

Figure A26. Test 24, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

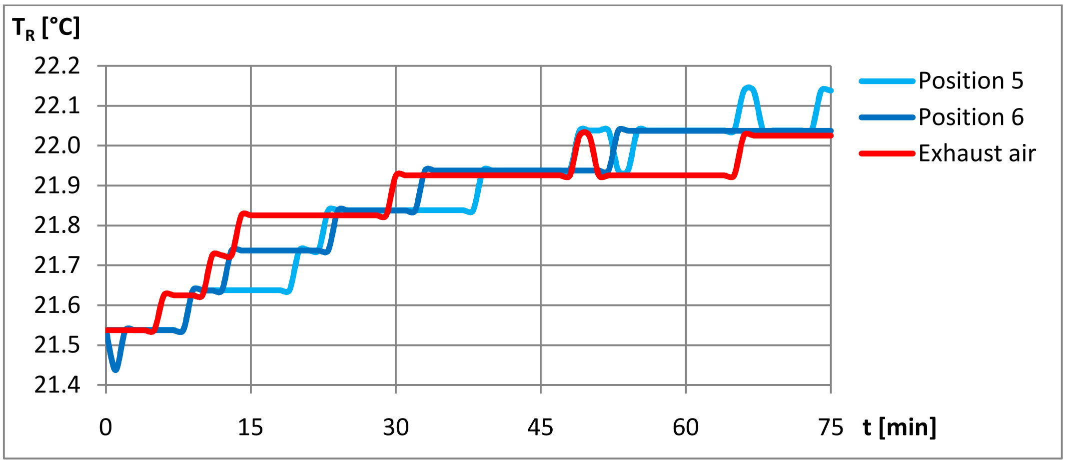

Figure A27. Test 24, temperature variations at three different locations.

Three test persons and one air exchanges per hour (Test 48)

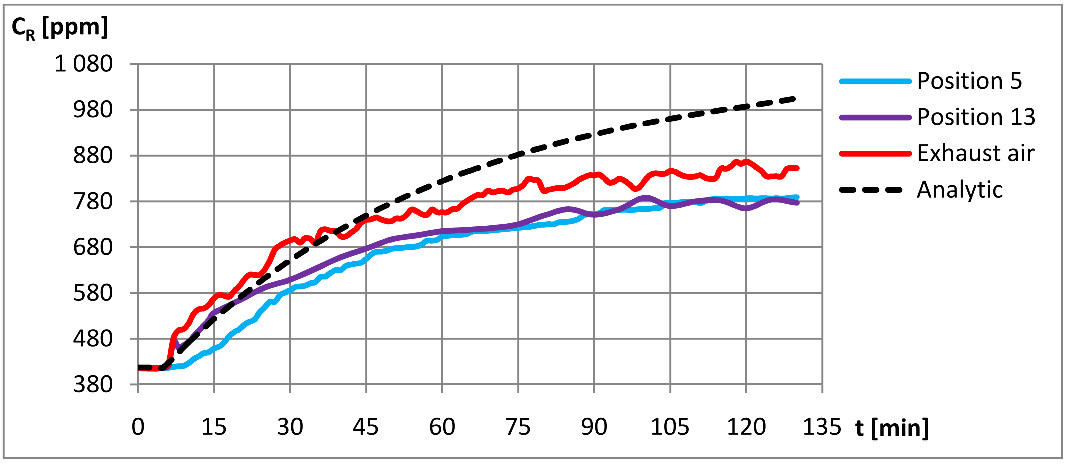

Figure A28. Test 48, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

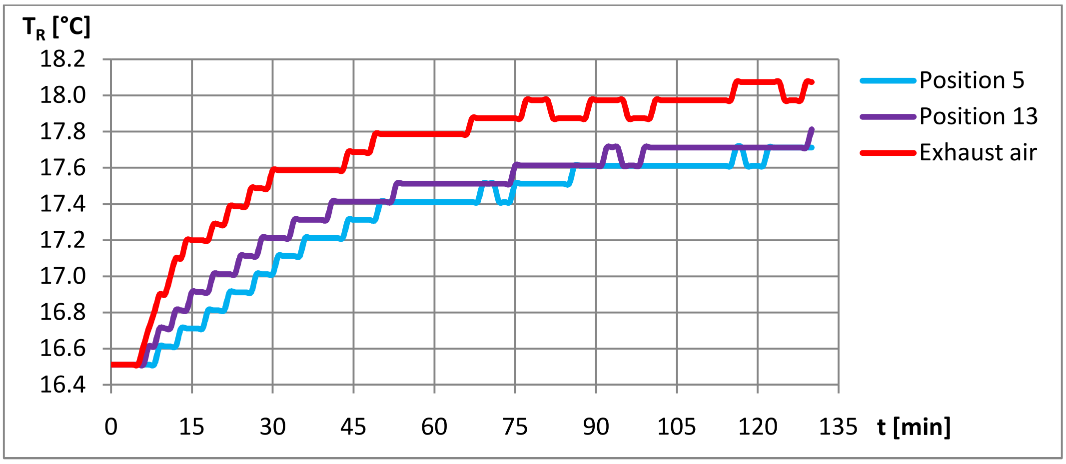

Figure A29. Test 48, temperature variations at three different locations.

Three test persons and two air exchanges per hour (Test 40)

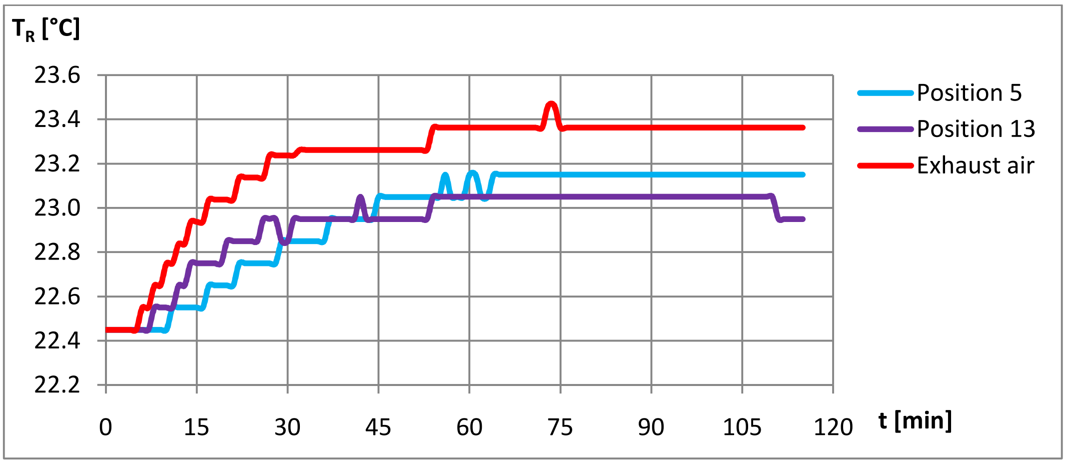

Figure A30. Test 40, temperature variations at three different locations.

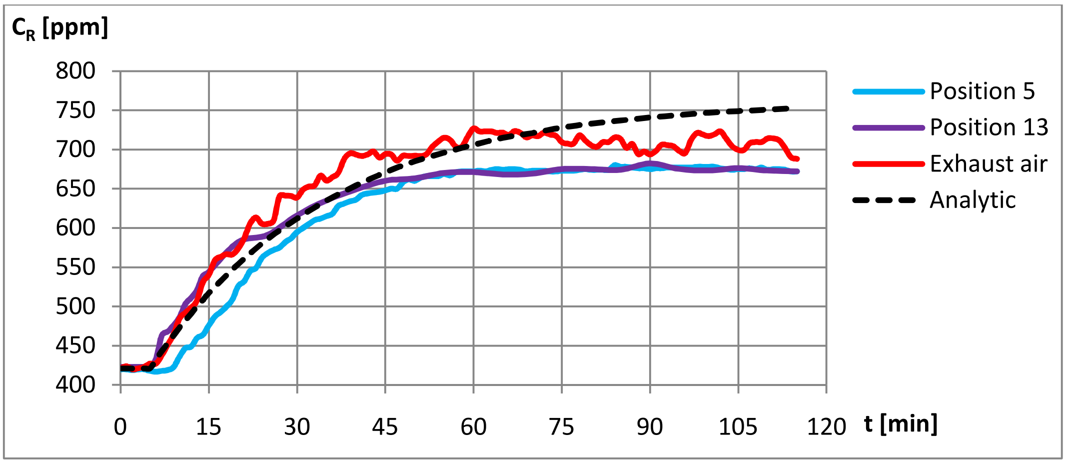

Figure A31. Test 40, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

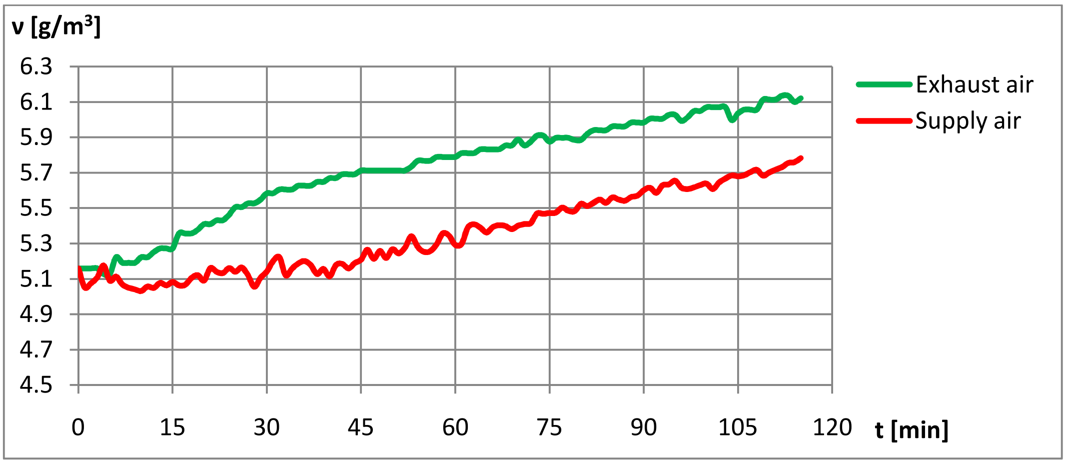

Figure A32. Test 40, variations of the vapour content in the supply and exhaust air.

Three test persons and three air exchanges per hour (Test 35)

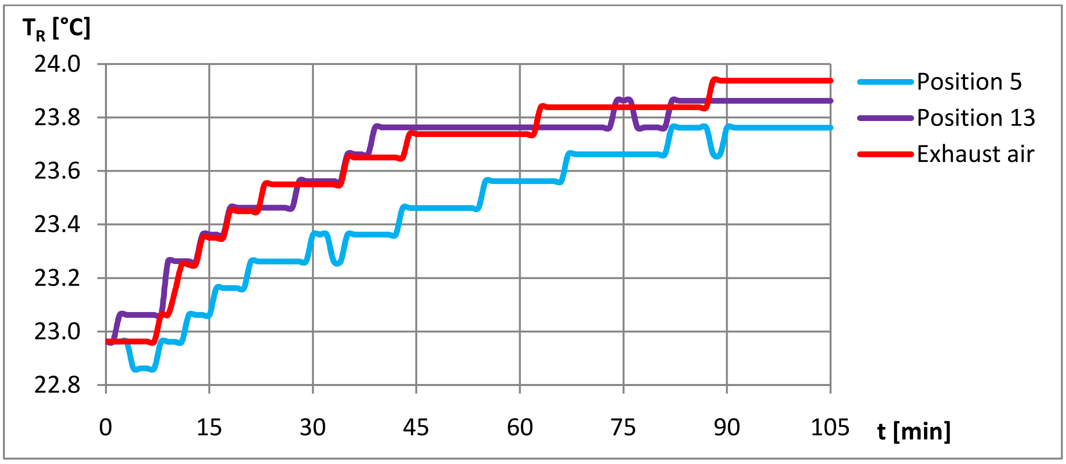

Figure A33. Test 35, temperature variations at three different locations.

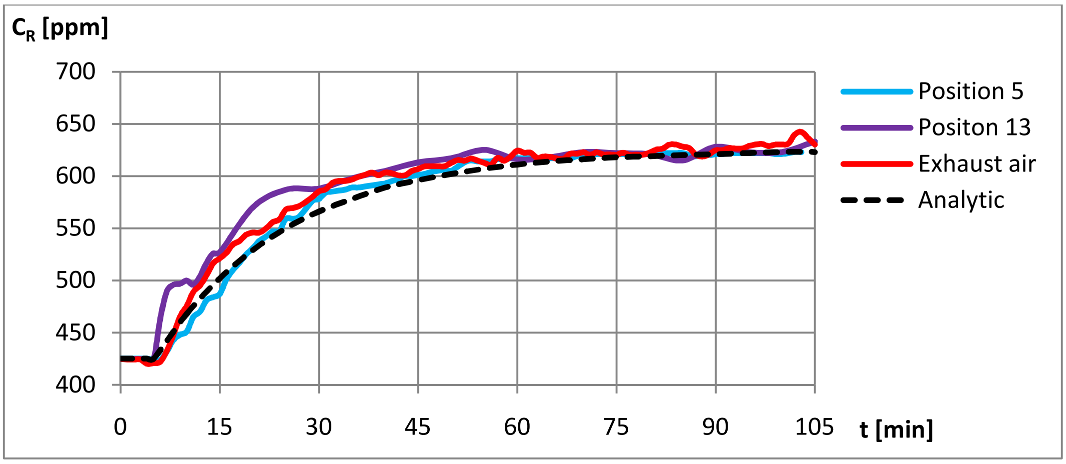

Figure A34. Test 35, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

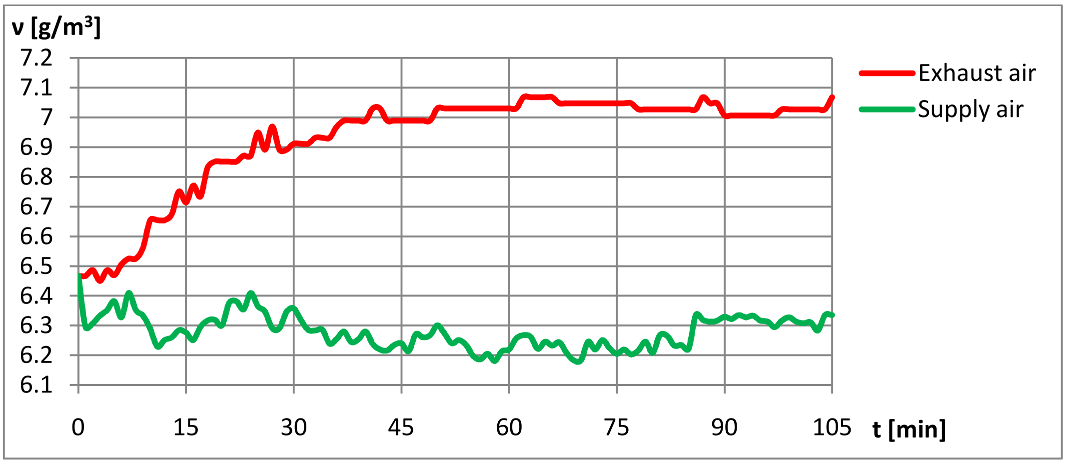

Figure A35. Test 35, variations of the vapour content in the supply and exhaust air.

Four test persons and one air exchanges per hour (Test 47)

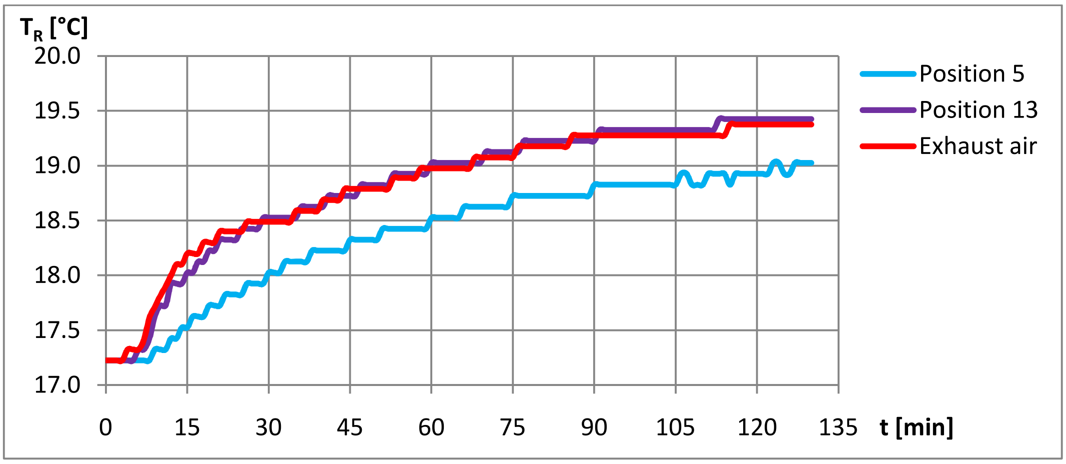

Figure A36. Test 47, temperature variations at three different locations.

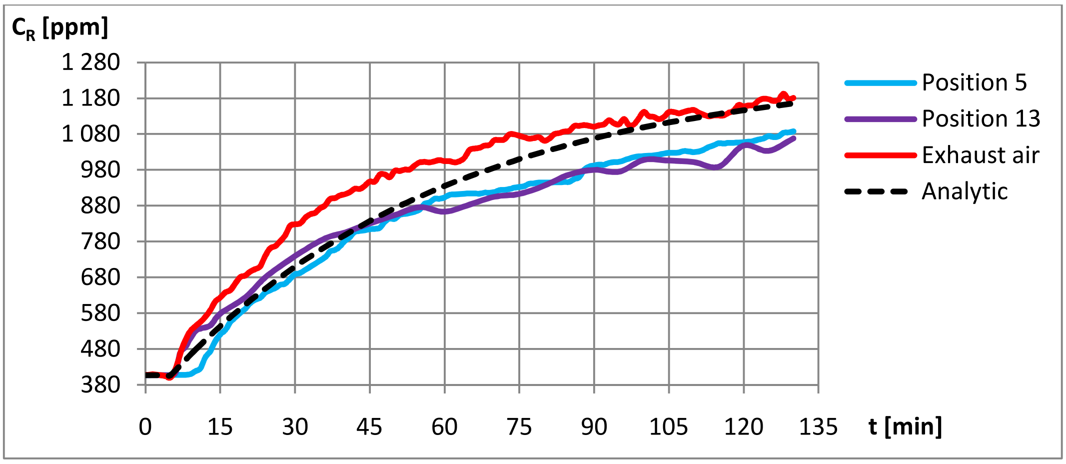

Figure A37. Test 47, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

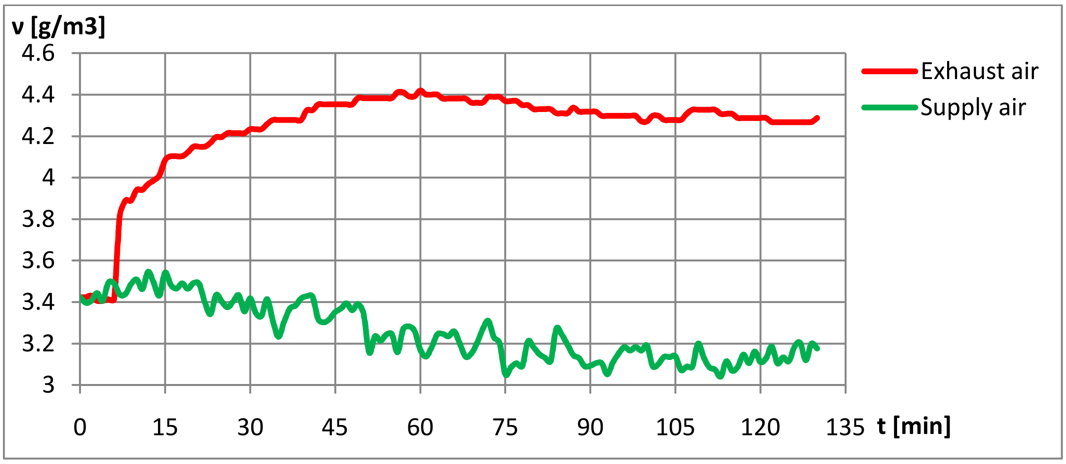

Figure A38. Test 47, variations of the vapour content in the supply and exhaust air.

Four test persons and two air exchanges per hour (Test 30)

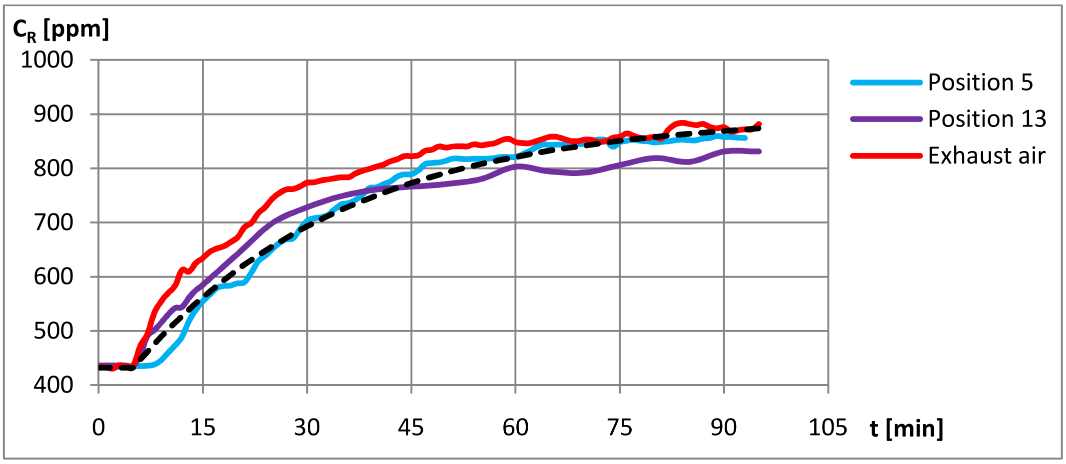

Figure A39. Test 30, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

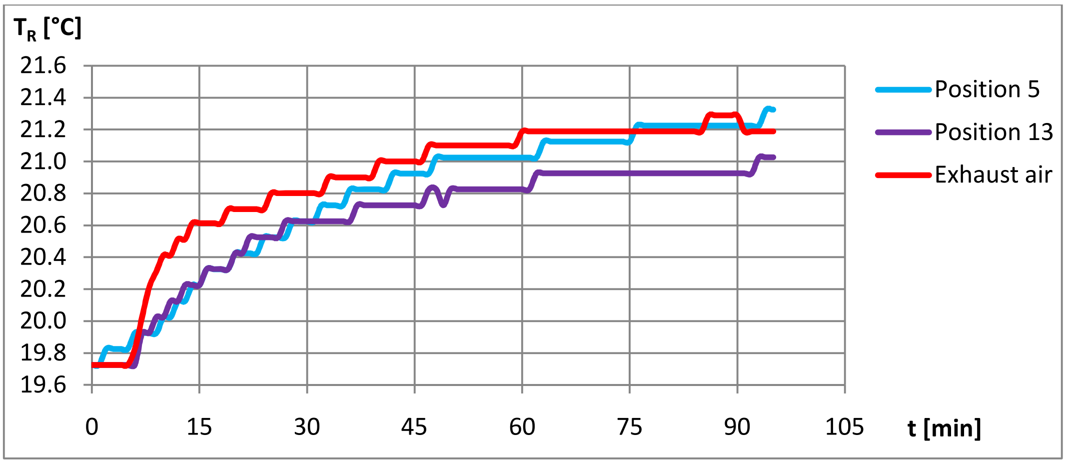

Figure A40.Test 30, temperature variations at three different locations.

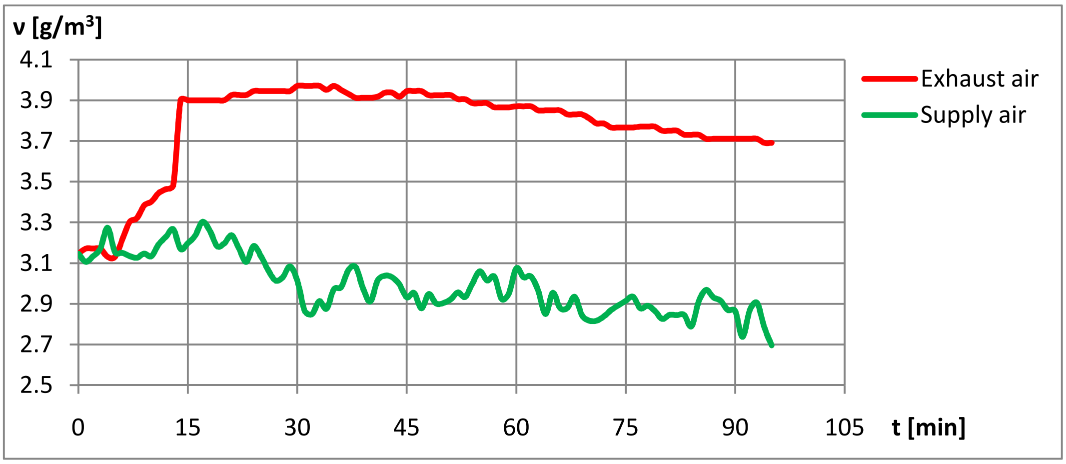

Figure A41.Test 30, variations of the vapour content in the supply and exhaust air.

Four test persons and three air exchanges per hour (Test 31)

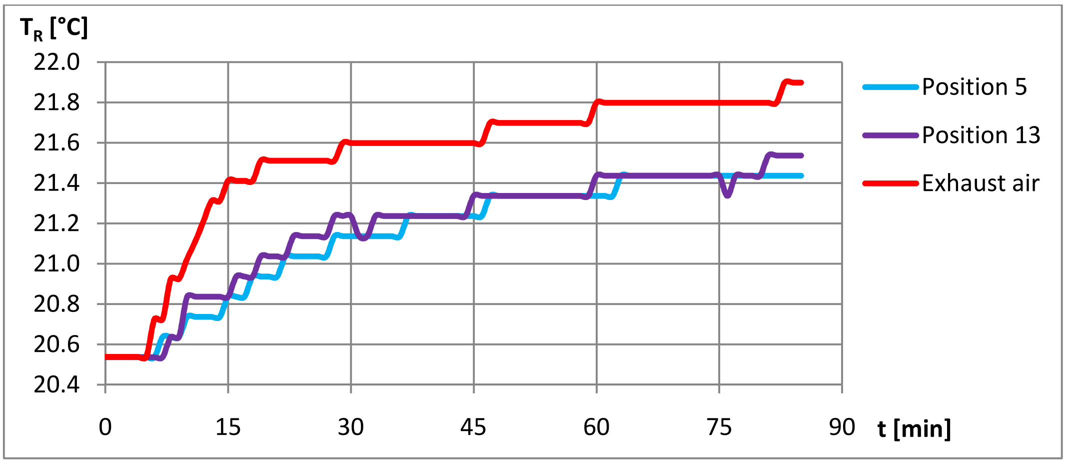

Figure A42. Test 31, temperature variations at three different locations.

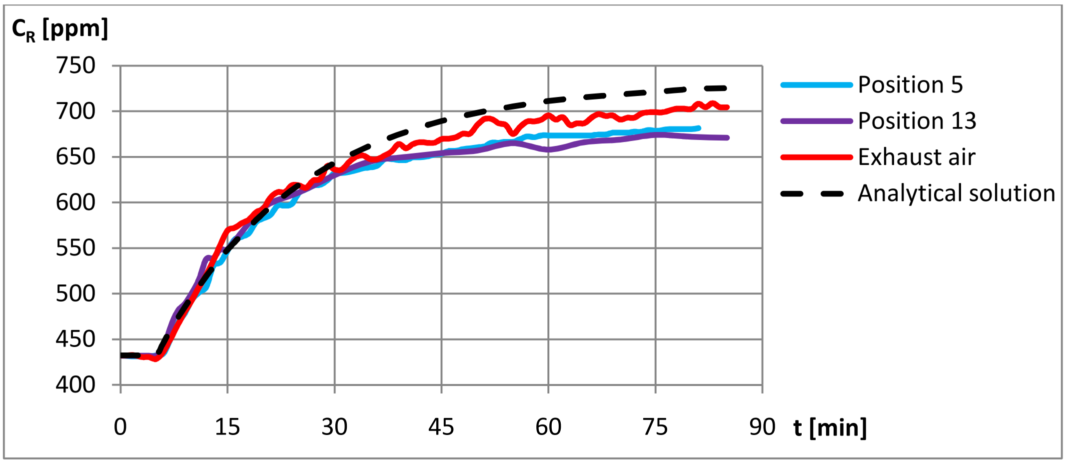

Figure A43. Test 31, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

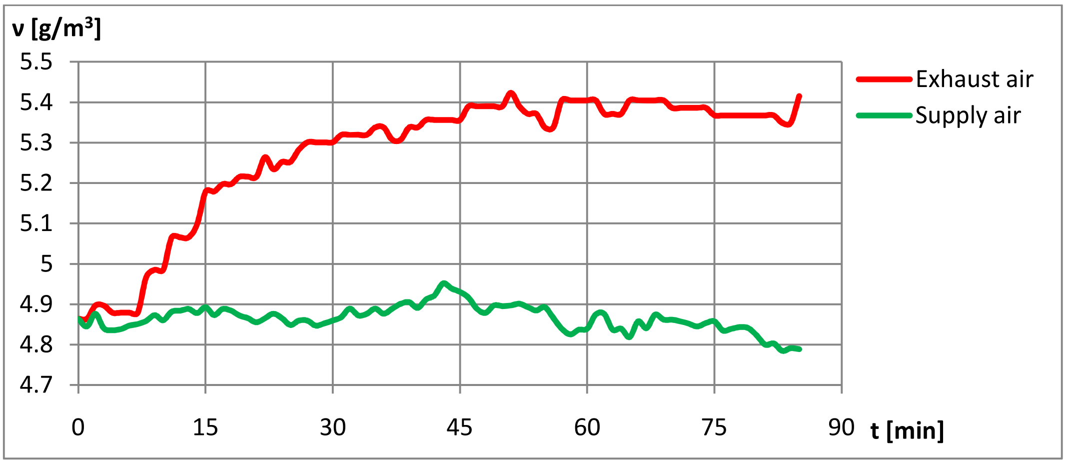

Figure A44. Test 31, variations of the vapour content in the supply and exhaust air.

Tests with open door

Open door ΔT=1 °C, two test persons and three air exchanges per hour (Test 36)

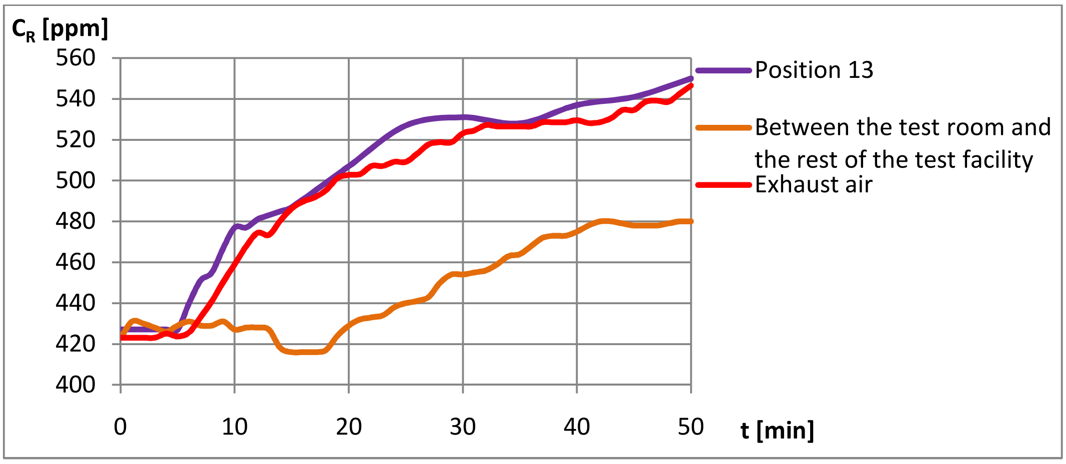

Figure A45. Test 36, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

Open door ΔT=1 °C, two test persons and one air exchange per hour (Test 44)

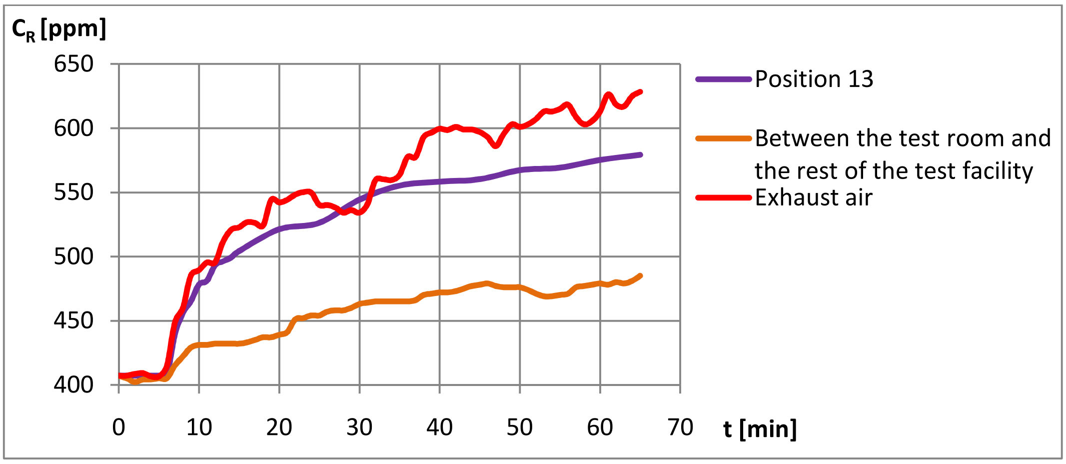

Figure A46. Test 44, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

Open door ΔT=1 °C, two test persons and two air exchanges per hour (Test 46)

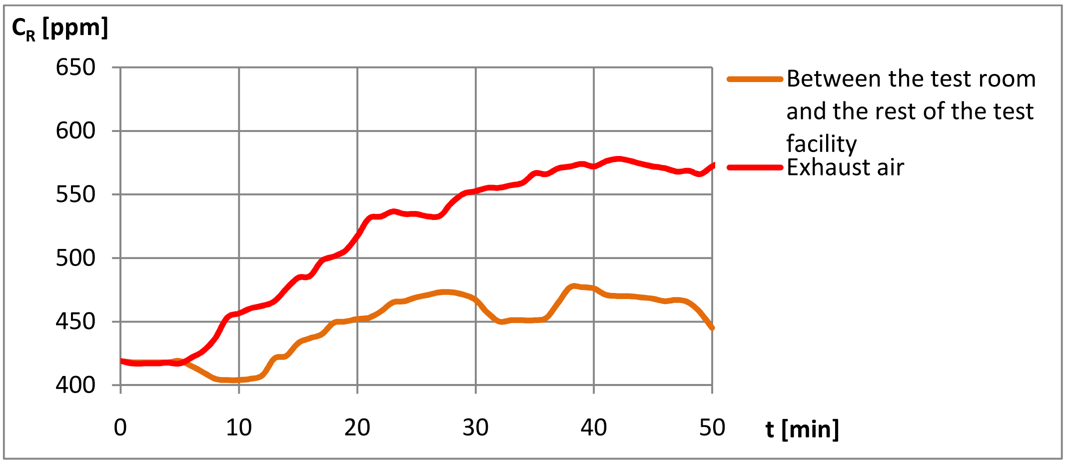

Figure A47. Test 46, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

Open door ΔT=3 °C, two test persons and two air exchanges per hour (Test 39)

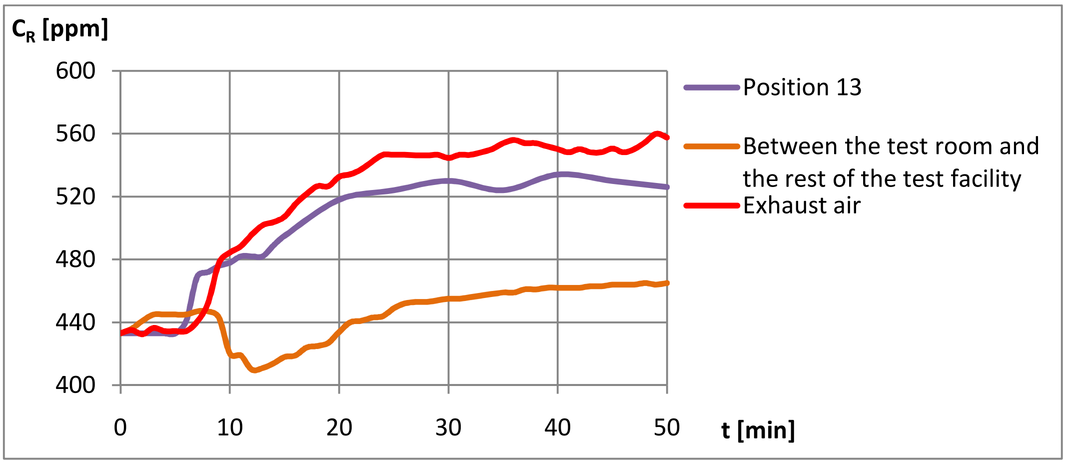

Figure A48. Test 39, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

Open door ΔT=5 °C, two test persons and two air exchanges per hour (Test 41)

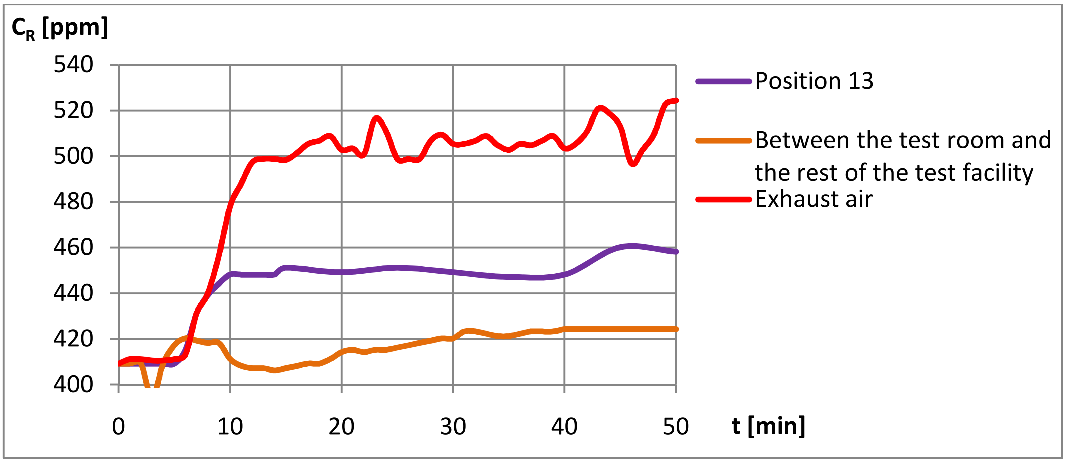

Figure A49. Test 41, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

Persons entering the room after a while

3 (2+1) test persons and two air exchanges per hour (Test 37)

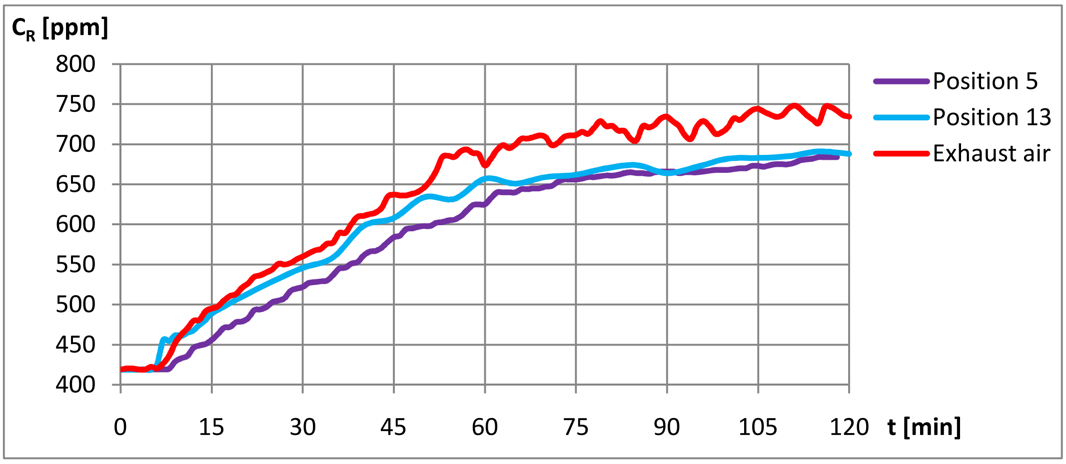

Figure A50. Test 37, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

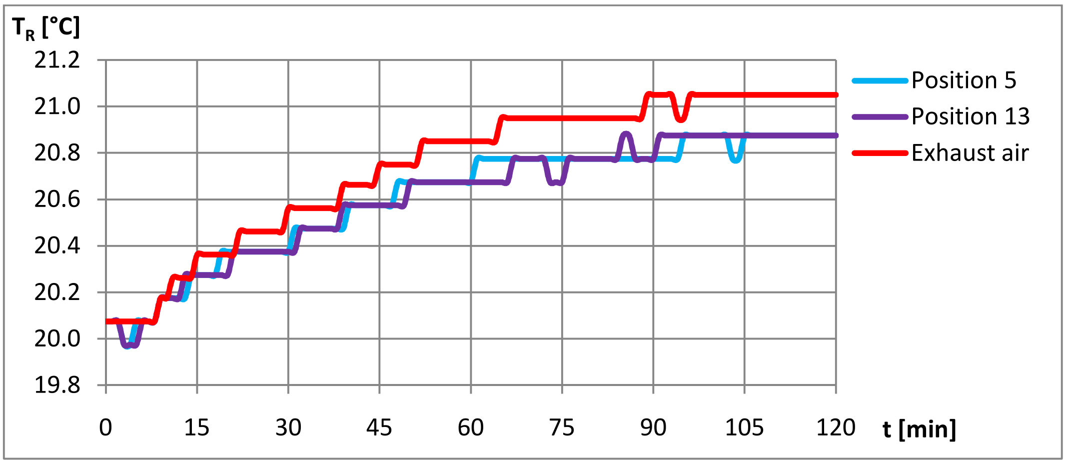

Figure A51. Test 37, temperature variations at three different locations.

3 (2+1) test persons and two air exchanges per hour (Test 42)

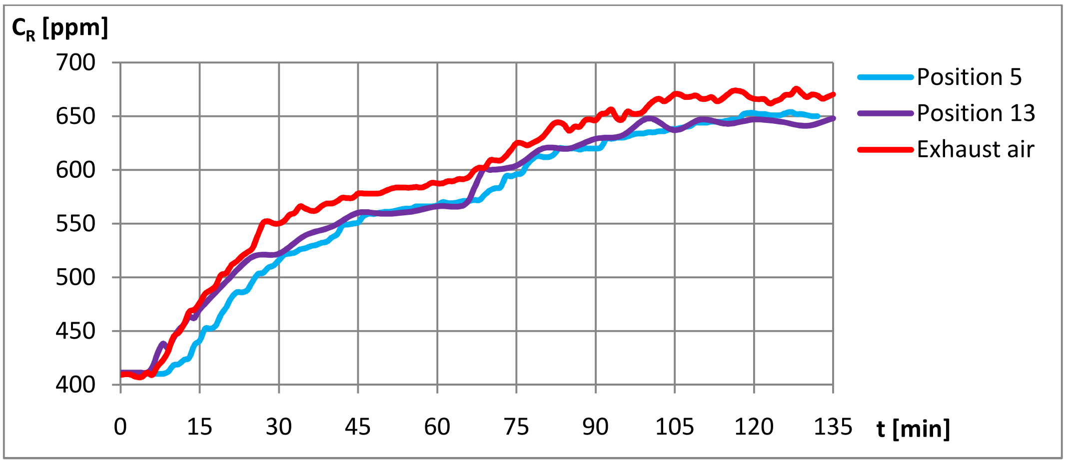

Figure A52. Test 42, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

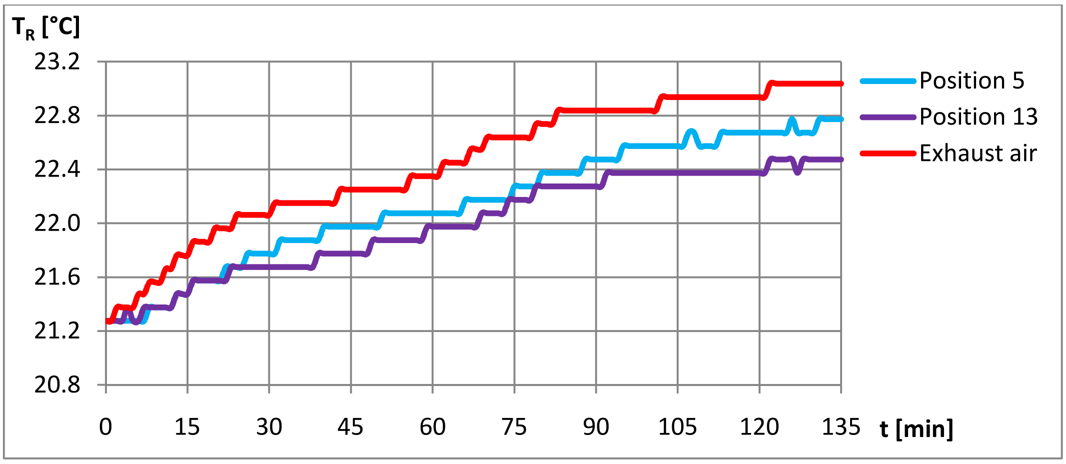

Figure A53. Test 42, temperature variations at three different locations.

3 (2+1) test persons and two air exchanges per hour (Test 43)

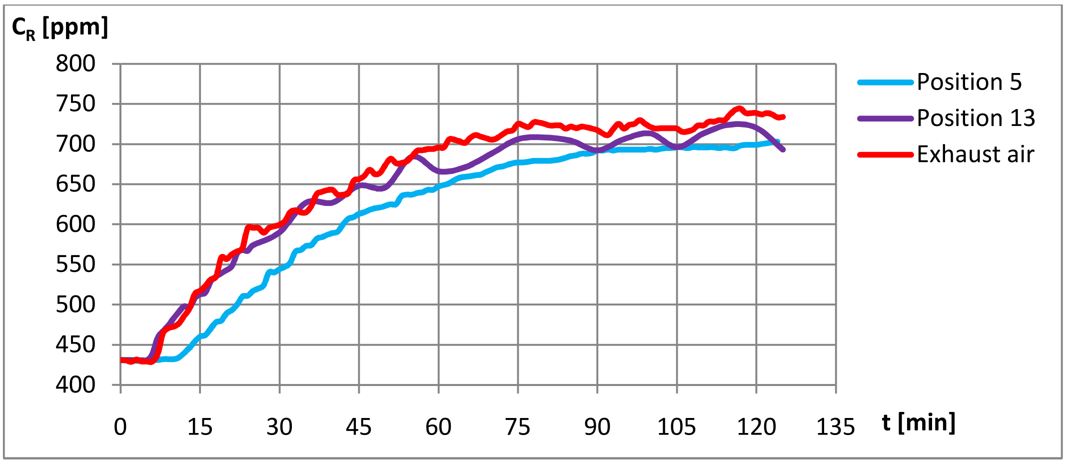

Figure A54. Test 43, variations of carbon dioxide concentration at three different locations to be compared with the analytical solution.

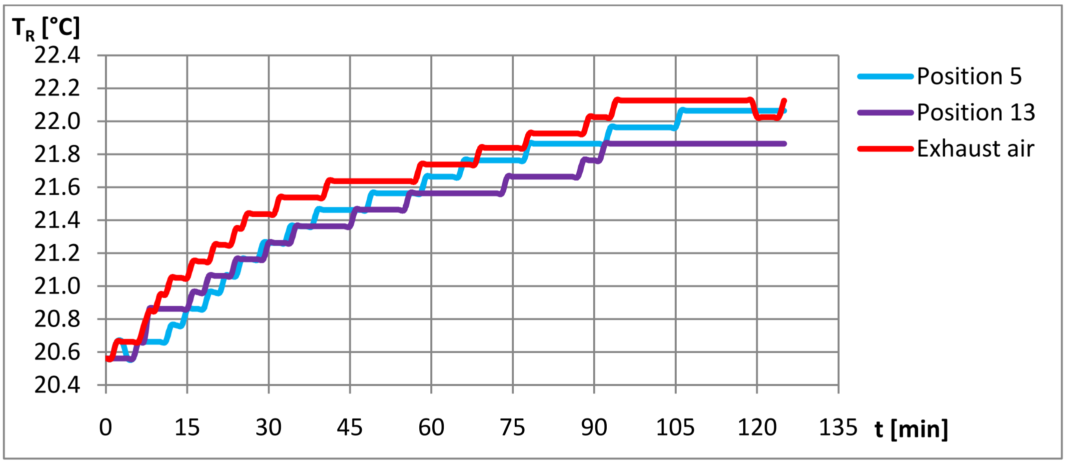

Figure A55. Test 43, temperature variations at three different locations.

Noise test (Test 29)

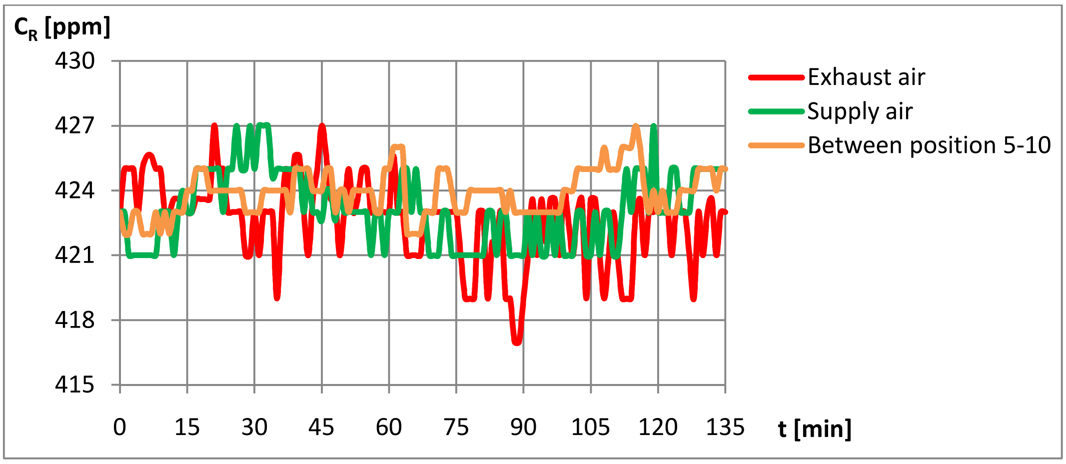

Figure A56. Test 29, variations of the carbon dioxide concentration in the noise test, i.e. no occupants in the room.

Candles (Test 49)

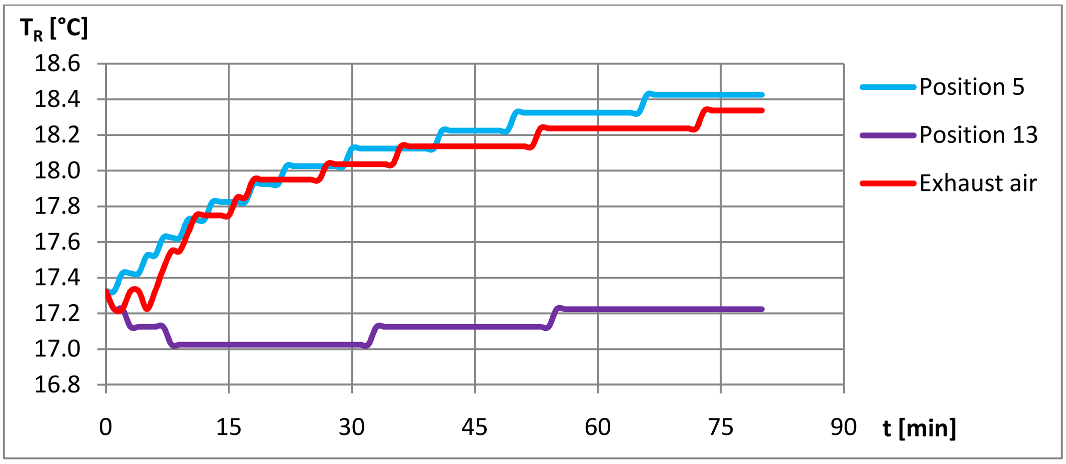

Figure A57. Test 49, temperature variations at three different locations with only two candles present in the room, two 1/h.

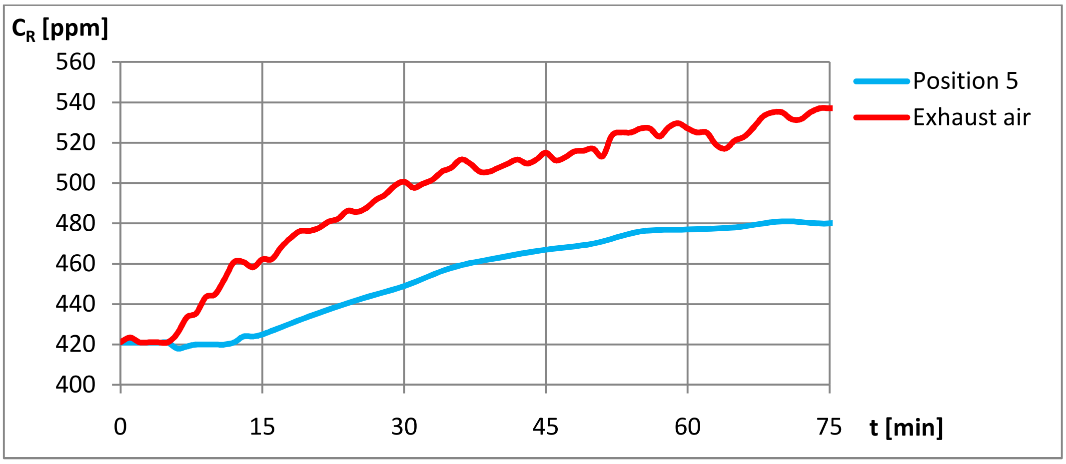

Figure A58. Test 49, variations of carbon dioxide concentration with only two candles present in the room, two 1/h.

Appendix 2 – Presentation of data

This appendix includes a number of illustrations and comparisons to get an overview of the results. This is done as an attempt to find a relation between the internal heat load caused by people in a room and any kind of change in the carbon dioxide concentration. As mentioned in the report, both fast and reliable response is necessary to improve the system by the use of feed-forward. Most of the diagrams in this appendix have the same unit on the y-axis, while the parameter on the x-axis is varied for different cases. The y-axis unit is the total change of carbon dioxide in room from the test has started until its steady-state level is reached, i.e. it is a way to indicate the generation of carbon dioxide in the room.

Dead time

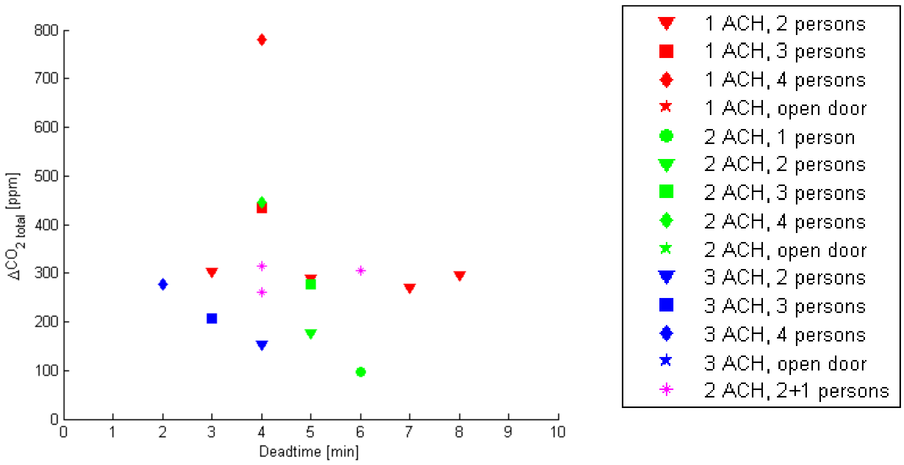

Figure A59. Dead time for sensor 5

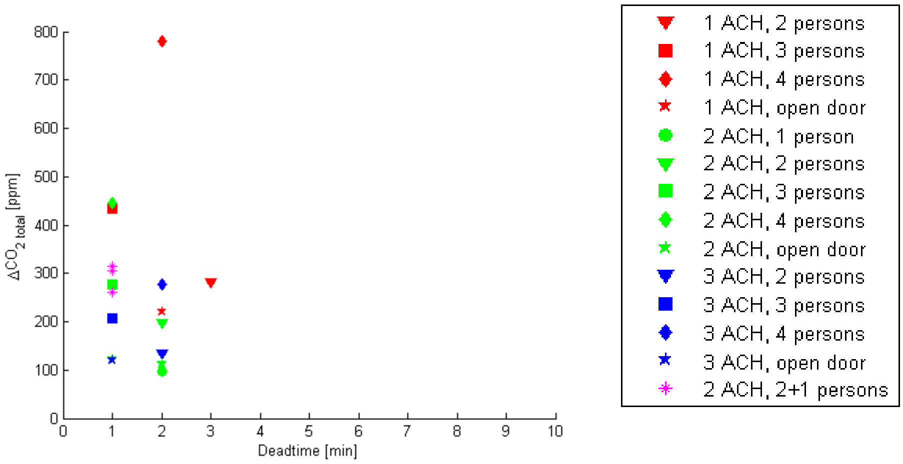

Figure A60. Dead time for sensor 13.

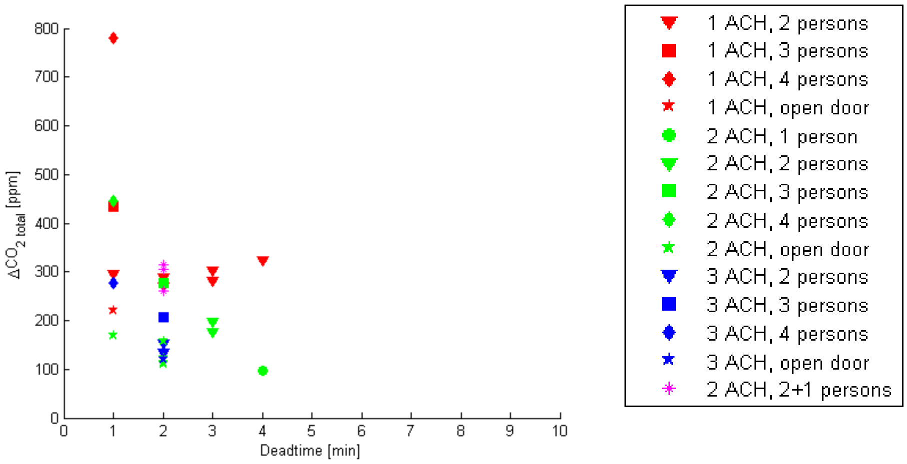

Figure A61. Dead time for the sensor in the exhaust air.

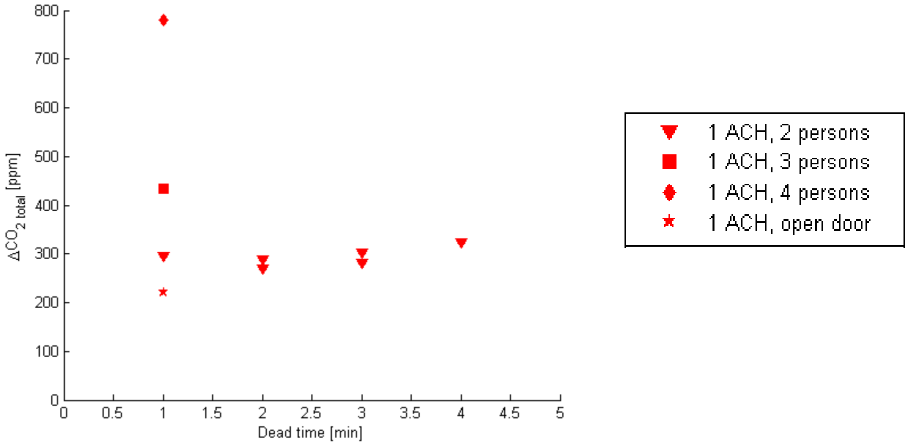

Figure A62. Dead time for the sensor in the exhaust air, 1 ACH.

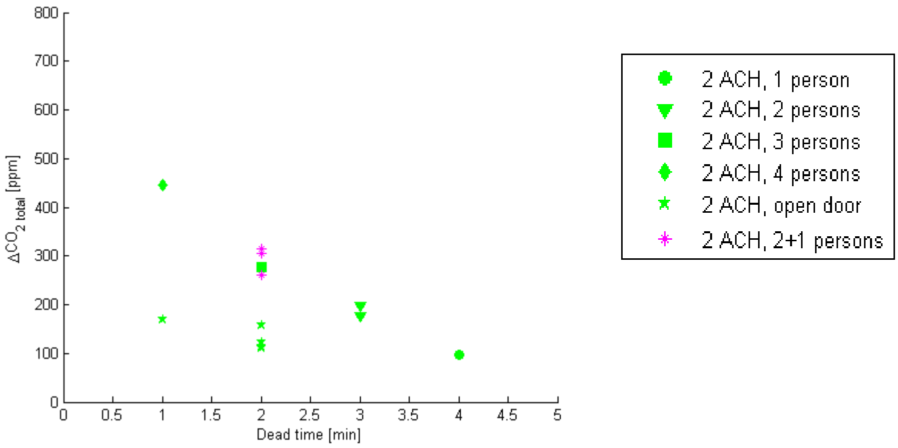

Figure A63. Dead time for the sensor in the exhaust air, 2 ACH.

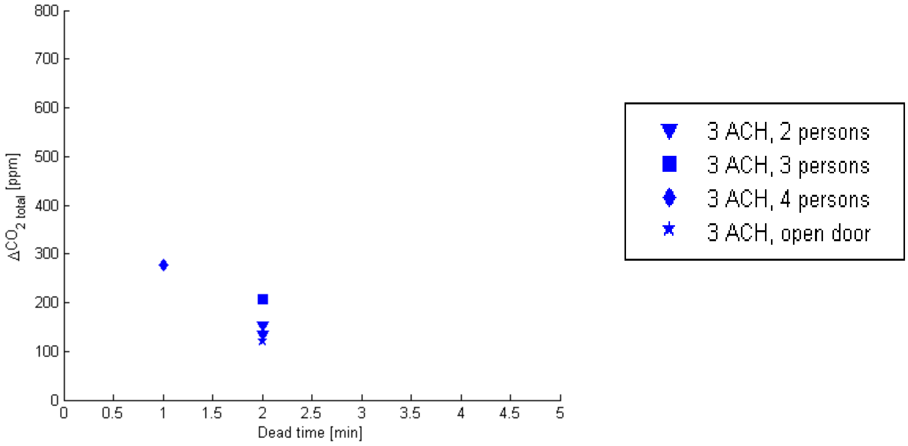

Figure A64. Dead time for the sensor in the exhaust air, 3 ACH.

Mean value and average change

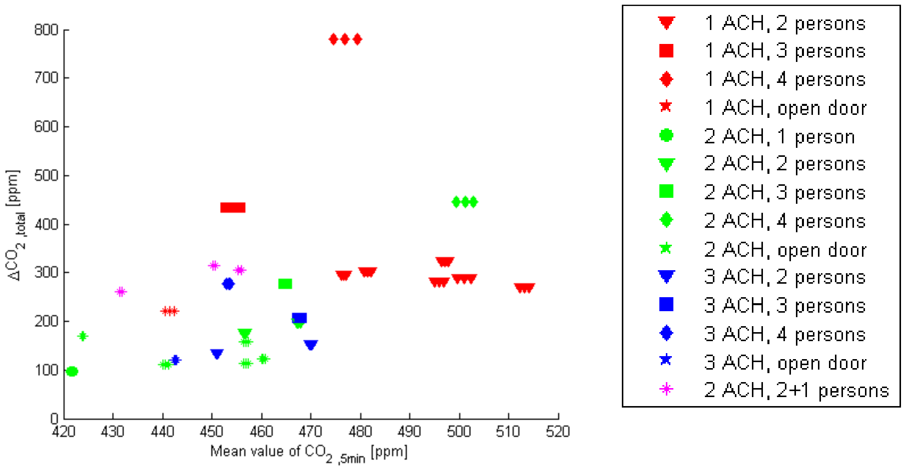

Figure A65. Mean values; Arithmetic, harmonic and geometric (H<G<A). The values are calculated five minutes from the carbon dioxide concentration starts to rise.

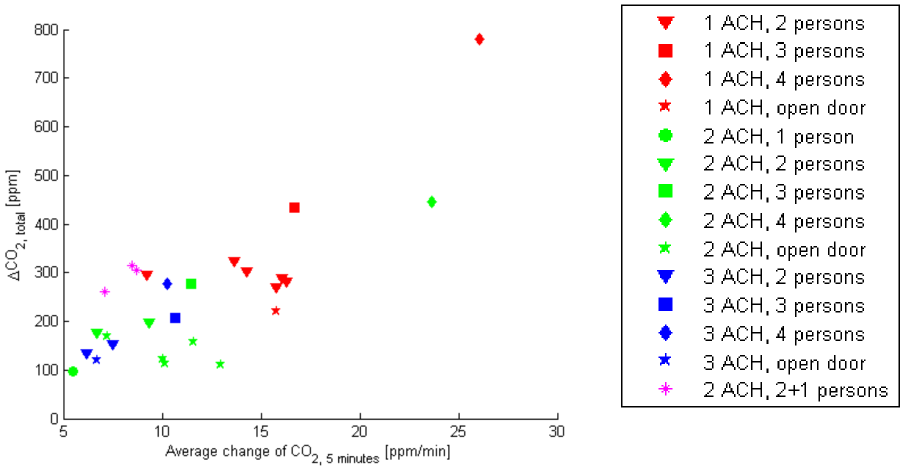

Figure A66. Average change of the carbon dioxide concentration. The values are calculated for five minutes from the carbon dioxide concentration in the room starts to rise.

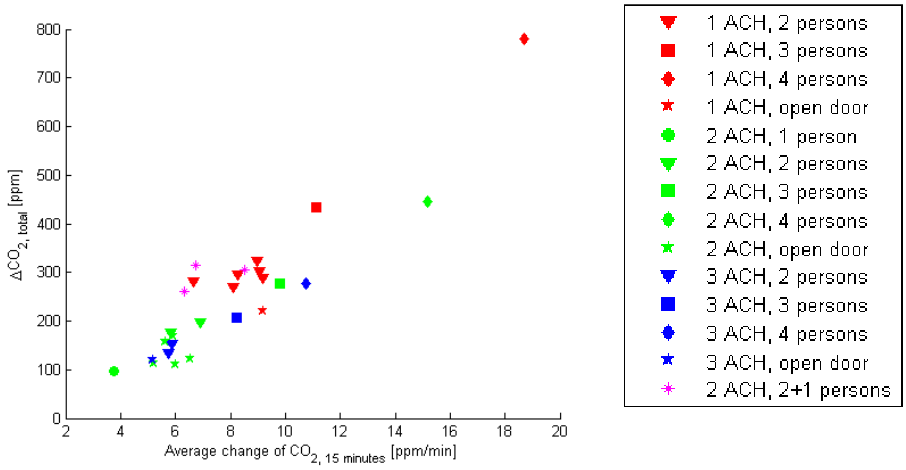

Figure A67. Average change of the carbon dioxide concentration. The values are calculated for fifteen minutes from the carbon dioxide concentration in the room starts to rise.

Initial inclination of carbon dioxide concentration change

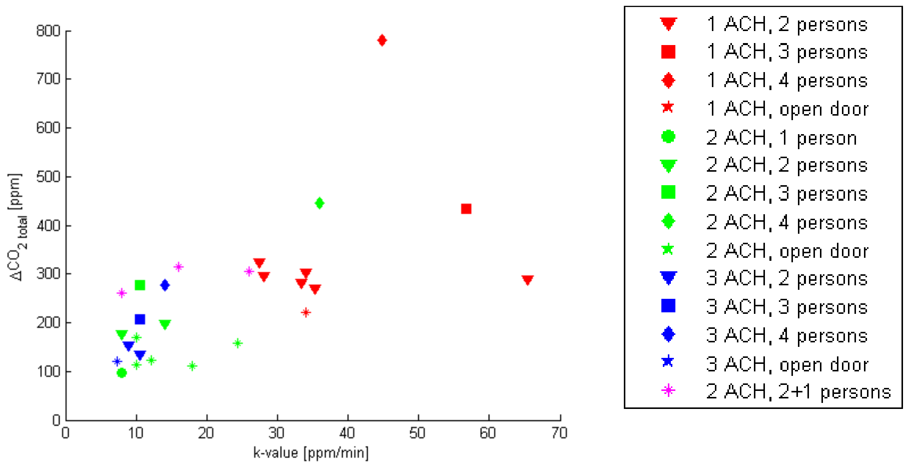

Figure A68. The inclination (k-value) is calculated during the first minute when an initial increase is registered.

Generation rate of carbon dioxide

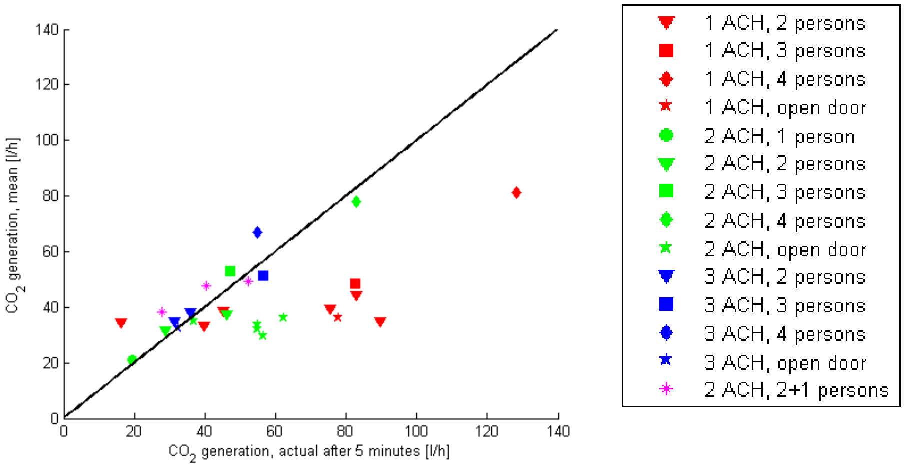

Figure A69. The mean value is calculated from the tenth minute until the end of each test. The actual generation is the measured value five minutes after the presence sensor indicates that someone has entered the room. The black line describes the ideal case, where the actual concentration is equal to the mean concentration for the whole test.

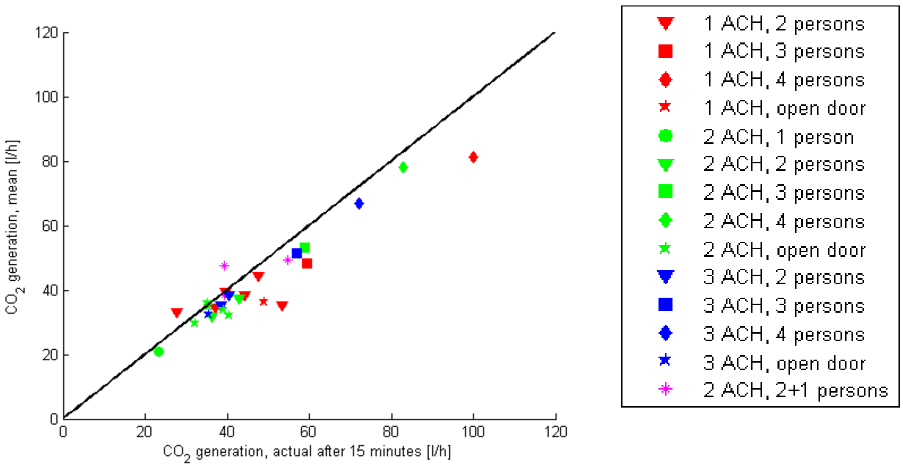

Figure A70. The same as the previous figure, but a longer time after the test person has entered.

Statistical comparisons

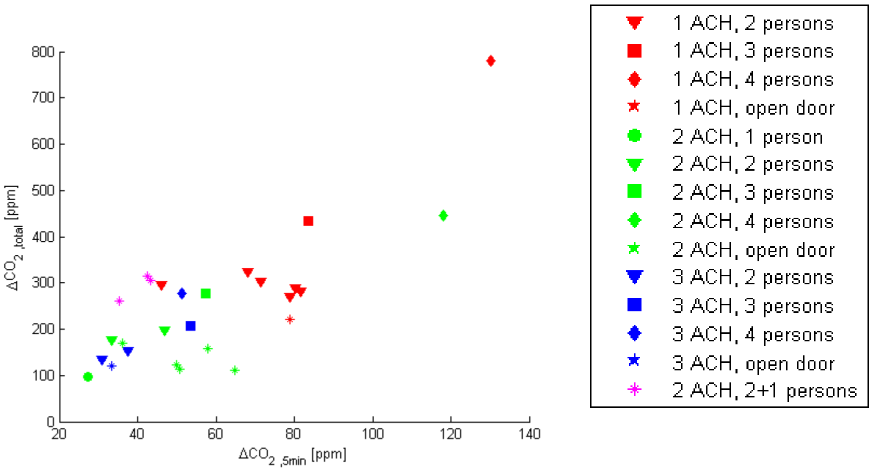

Figure A71. Absolute change of CO_2 during five minutes:

$$AC = Cr(5) - Cr(1)$$

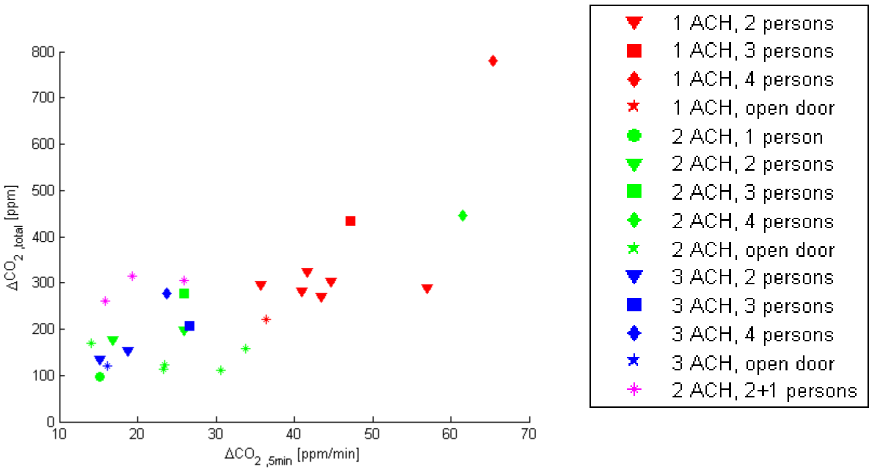

Figure A72. Mean absolute increase of CO_2 during five minutes:

$$MAC = \frac{\sum_{i=1}^{N} AC(i)}{N} = \frac{Cr(1) - Cr(1) + Cr(2) - Cr(1) + \cdots Cr(4) - Cr(1)}{5}$$

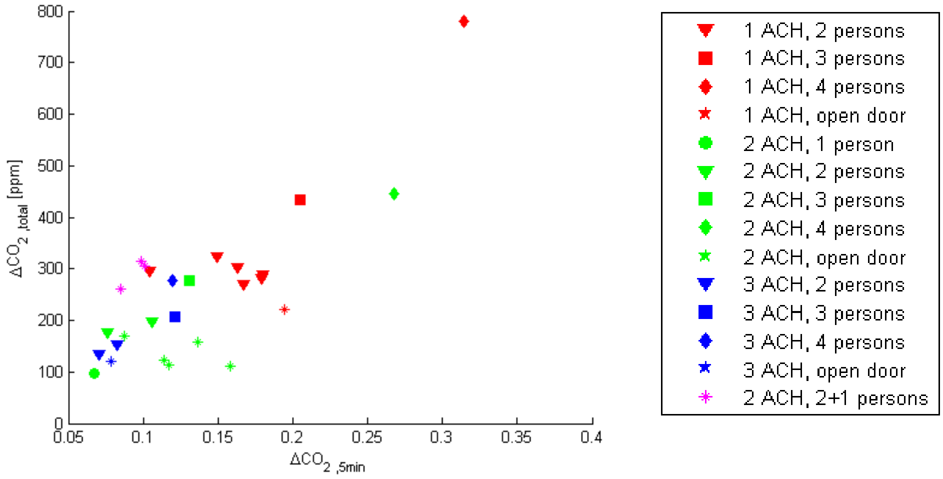

Figure A73. Absolute percentage increase of CO_2 during five minutes:

$$APC = \frac{Cr(5) - Cr(1)}{Cr(1)}$$

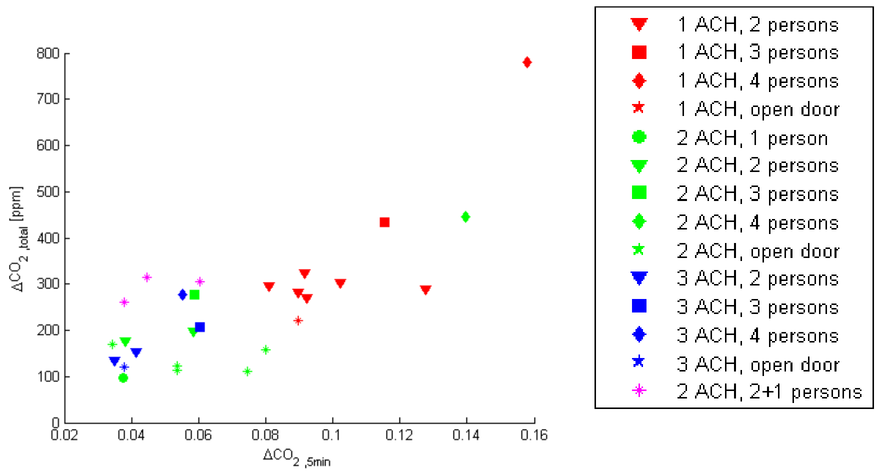

Figure A74. Mean absolute percentage increase of CO_2 during five minutes:

$$MAPC = \frac{\sum_{i=1}^{N} APC(i)}{N}$$

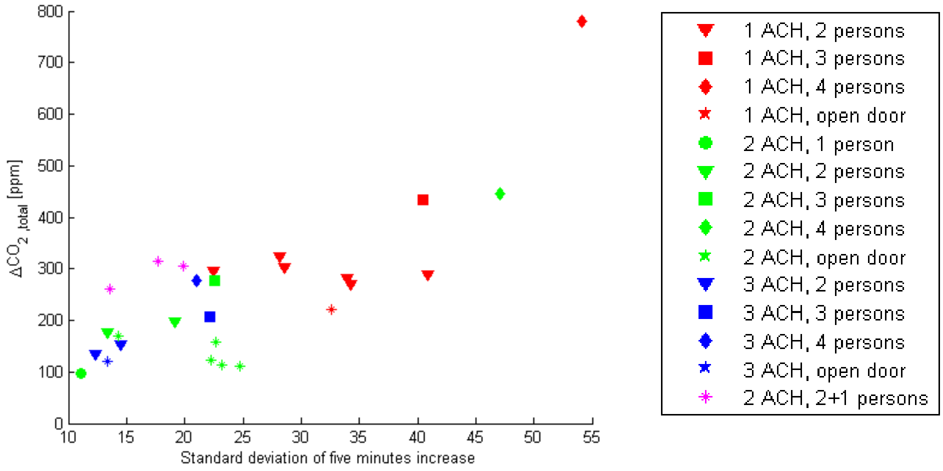

Figure A75. Standard deviation absolute increase during five minutes:

$$Std.AC = \sqrt{\frac{\sum_{i=1}^{N}(AC(i) - MAC)^2}{N-1}}$$

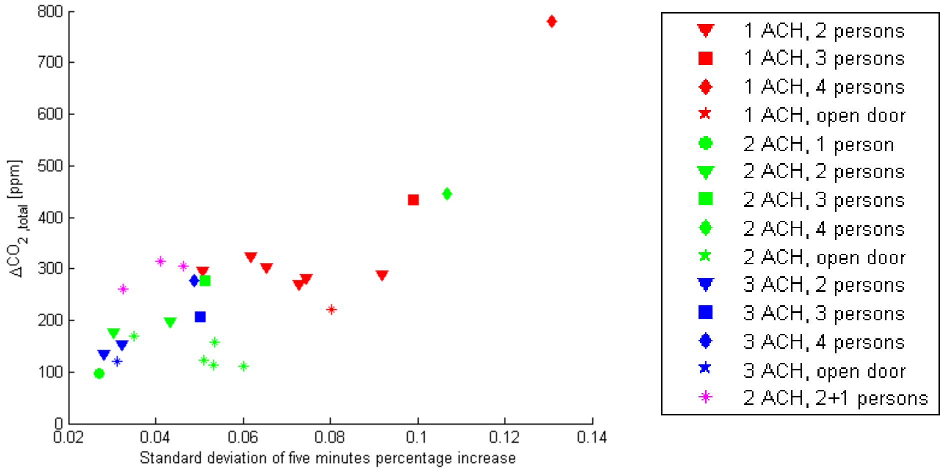

Figure A76. Standard deviation absolute percentage increase during five minutes:

$$Std.APC = \sqrt{\frac{\sum_{i=1}^{N}(APC(i) - MAPC)^2}{N-1}}$$