MASTER

Performance of displacement ventilation in primary schools
theoretical and experimental study

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PERFORMANCE OF DISPLACEMENT VENTILATION IN PRIMARY SCHOOLS

Theoretical and experimental study

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PREFACE

This report is the final graduation phase of my course Building Services at the Technical University of Eindhoven (TU/e). During the last 5 years of my dual course at the University I also worked at a company in the Building Services sector, namely BAM Techniek regio West.

This report is the result of a one year research into displacement ventilation in primary schools. I like to express my gratitude to the members of the supervising committee: Prof. Ir. Wim Zeiler, Prof. Dr. Ir. Jos Lichtenberg, Ir. Ing. Gert Boxem and Ruud van Zijl. I thank Wim, Jos and Ruud for their stimulation and positive attitude with respect to my research. Further I thank Gert for his extensive assistance during this thesis.

Without the help of the staff members of the laboratory Wout van Bommel and Erwin Smits the experiments, with all measurements, would not have been completed this way.

I am grateful to BAM Techniek regio West, especially Ruud van Zijl for the offered flexibility, technical- and financial support during this research.

I wish to express my gratitude to the primary school director Miss Jenny Sol, the children and the teachers of group 7/8 for participating in this project. Also my thanks extend to the sponsors who supported me by delivering different parts of the experimental setup.

Finally, I thank my family, especially my girlfriend Celesta for her patience and support during the last phase of my course.

Dennis Schuiling

Eindhoven, 10 December 2008

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SUMMARY

Most ventilation systems in Dutch primary schools do not provide acceptable indoor air quality (IAQ) and do not achieve thermal comfort requirements. As a result of a lack of necessity or budget these school are provided with natural- or exhaust only ventilation systems. These systems often involve draught problems (especially during winter) with human intervention as a result. Ventilation improves indoor air quality, learning performance and reduces sick leave. Dutch primary schools need a ventilation system which is able to supply and guarantee a large amount of air in a comfortable and efficient way throughout the year. A well maintained and balanced mechanical ventilation system is needed to guarantee a minimal air flow and prevent draught problems. But how to minimize system components to reduce build- and energy costs? One way is to improve the efficiency of ventilation system.

Displacement ventilation (DV) is the most effective way to improve IAQ. Especially school buildings seem suitable for DV because of high occupancy (high amount of air with low air velocity), little room space and children are often the main contaminant sources. But exceeding boundary conditions influences the good performance of the system. Known problems are a high vertical temperature gradient and a high air velocity near the supply diffusers.

The goal of this research is to obtain a good indoor air quality/thermal comfort in primary schools by developing, constructing and validating a "standard" displacement ventilation solution that can be generally applied in primary school environments. Several experiments were formulated (with knowledge from a literature study) to analyse the performance of a DV system in a typical Dutch school and obtain specific knowledge about the boundary conditions. Subsequently experiments were performed in a real (no steady state) classroom.

In general, the findings from the experiments unite with the literature study. The required air flow can be reduced with 23% compared to mixing ventilation with same IAQ conditions. Because of under temperature and the correct velocity the supply air is equally spread along the floor of the classroom. During the experiments, the vertical temperature gradient between ankle and neck doesn't exceed its limits. A textile air diffuser provides a primary zone within the first half meter. The average ventilation efficiency is around 1,3 and the extra benefit from the displacement effect near the body is up to 50% (the air around a pupil contains 50% less contaminants than the air elsewhere at the same height). During the experiments the thermal comfort isn't negatively influenced by the ventilation system.

A DV system also has some disadvantages. The supply air can't be heated above room temperature because of shortcut of the air flow which decreases the air flow dramatically. The air supply diffuser needs a primary zone and may not be blocked at floor level. Accurate control of the supply air temperature is needed to prevent draught. The floor needs to be cleaned carefully otherwise contaminants could become airborne.

At the end of the research two options for the implementation of a DV system in a primary school were sketched. One Plug & Play option especially designed for existing schools and another option a centralized system especially designed for new school buildings.

SAMENVATTING

De meeste ventilatiesystemen in Nederlandse basisscholen zijn niet in staat om in een acceptabele luchtkwaliteit en met een thermisch comfort te voorzien. Vanwege een beperkt budget en het niet inzien van de noodzaak van goede ventilatie zijn deze scholen vaak voorzien van te openen ramen of een eenvoudige afzuiginstallatie. Deze systemen veroorzaken, voornamelijk in de winter, tochtklachten met menselijk ingrijpen tot gevolg. Ventilatie verbetert de luchtkwaliteit en leerprestatie en reduceert ziekteverzuim. Een goed onderhouden en gebalanceerd ventilatiesysteem is nodig om minimale ventilatie te garanderen en tochtklachten te voorkomen. Hoe kunnen de systeemcomponenten worden geminimaliseerd om zo bouw- en energiekosten te reduceren? Het verbeteren van de ventilatie-effectiviteit is een wijze waarop dit zou kunnen.

Verdringingsventilatie (VV) is de meest effectieve wijze van ventileren. Vanwege de hoge bezetting (veel ventilatie met lage luchtsnelheid) en doordat kinderen de voornaamste vervuilingsbronnen zijn, lijkt VV juist geschikt voor een school. Echter het overschrijden van randvoorwaarden beïnvloed de prestatie van het systeem. Een hoge verticale temperatuurgradiënt en hoge luchtsnelheden nabij toevoerroosters zijn bekende problemen.

Het doel van dit project is om met een standaard VV oplossing in bestaande basisscholen een zo goed mogelijke luchtkwaliteit te behalen zonder negatieve beïnvloeding van het thermische comfort. Naar aanleiding van een literatuurstudie zijn meerdere experimenten beschreven om zo de prestaties van het VV systeem te verifiëren en de randvoorwaarden te formuleren. Vervolgens zijn de experimenten uitgevoerd in een bestaand klaslokaal onder werkelijke (turbulente) condities.

Over het algemeen sluiten de bevindingen van de experimenten aan bij de literatuurstudie. Zo kan de benodigde ventilatielucht, in vergelijking tot mengventilatie met identieke uitgangcondities, worden gereduceerd met 23%. Vanwege de juiste (onder)temperatuur en snelheid verdeelt de toegevoerde verse lucht zich gelijkmatig over de vloer van het klaslokaal. De maximale temperatuurgradiënt tussen enkel en nek wordt tijdens de experimenten niet overschreden. Een textiele luchtverdeelslang zorgt voor een primaire zone van ongeveer een halve meter. De gemiddelde ventilatie-effectiviteit van de testopstelling is 1,3 en het verdringende effect langs het lichaam zorgt voor een extra verbetering van 50% (de direct langs het lichaam stromende lucht bevat 50% minder verontreinigingen dan de lucht elders op dezelfde hoogte). Tijdens de experimenten heeft het ventilatiesysteem geen directe negatieve invloed gehad op het thermische comfort.

Een VV systeem kent ook een aantal nadelen. Verwarming van de toegevoerde lucht boven de ruimtetemperatuur dient vanwege kortsluiting van de luchtstroom (drastische afname van de ventilatie-effectiviteit) te worden voorkomen. Toevoerroosters hebben een primaire zone en het rooster mag niet worden geblokkeerd op vloerniveau. Een nauwkeurige regeling van de toegevoerde luchttemperatuur is noodzakelijk om tochtverschijnselen te voorkomen. Ook dient de vloer grondig te worden gereinigd om opwaaiende (vervuilde) deeltjes te voorkomen.

Aan het eind van het rapport worden twee opties, voor de implementatie van een VV systeem in basisscholen, voorgesteld. Een Plug & Play optie ontwikkeld voor bestaande scholen en een centraal ventilatiesysteem voor nieuw te bouwen basisscholen.

NOMENCLATURE

ACR	Air change rate per hour (N)	
AHU	Air Handling Unit	
CAV	Constant Air Volume	
CO_2	Carbon dioxide	
DV	Displacement ventilation	
DCDV	Demand controlled displacement ventilation	
GGD	Municipal Health Service (Gemeentelijke Gezondheidsdienst)	
IAQ	Indoor Air Quality	
MV	Mixing ventilation	
PMV	Predicted Mean Vote	
PPD	Predicted Percentage Dissatisfied	
PS	Person Simulator (which is used in this research)	
SD	Standard Deviation	
TNO	Dutch Organisation for Applied Nature Scientific Research Nederlandse organisatie voor Toegepast Natuurwetenschappelijk Onderzoek)	
VAV	Variable Air Volume	
VOC	Volatile Organic Components	
RH	Relative humidity	[%]
ppm	Parts per million	
I_{clo}	Clothing Insulation	[clo]
T	Temperature	[°C]
M	Metabolic rate	[W/m²]
ε	Efficiency	[-]
$\varepsilon_c/\varepsilon_v$	Ventilation efficiency	[-]
C	Contamination concentration	[ppm]
q_v	Air flow rate	[m³/h]
L	Length	[m]
H	Height	[m]
t	Time	[s] or [h]

Subscripts

r	Radiant
oz	Occupied zone
s	Supply
e	Extract
exp	Personal exposure
v	Ventilation
T	Temperature

1. INTRODUCTION

Nowadays the indoor climate of primary schools is a hot item in the Netherlands. Despite the fact that this situation is going on for years, there's a strong increase in scientific research and more focus on this problem. People (parents' en health specialists) become aware of the negative influence of a bad indoor climate on the learning performance. The pressure on the public institutions to undertake some action is rising. The GGD (Habets et.al. 2006), TNO (De Gids et.al. 2007) among others the Technical University of Eindhoven (Joosten, 2004) (Bruchem, 2005) already conducted research (including field studies) to the indoor climate in Dutch primary schools. Problems like draught and poor air quality are very common in primary schools (Joosten, 2004). Beside the fact that pupils feel uncomfortable, poor indoor climate also influences the performance, work productivity and sick leave (Myhrvold et. al., 1996 and Wargocki et. al., 2005)

To obtain a good indoor climate, a large airflow is needed in the highly occupied classrooms without negatively influencing the thermal comfort. In the Netherlands, most existing (and even new constructed!) schools are provided with windows which can be opened to stimulate natural ventilation in the classroom. These measures are easy to implement at low costs. Several studies (Joosten, 2004) (Bruchem, 2005) indicate that this ventilation method isn't sufficient to achieve a good indoor air quality without causing draught problems. Besides poor fresh air distribution these solutions are strongly user- and weather dependent. The teacher can only consider a good indoor air quality at the expense of a poor thermal comfort or vice versa.

As a successor of the window based ventilation system more and more Dutch schools are equipped with a mechanical (local or central) exhaust ventilation system combined with a natural air supply through openings (e.g. air supply grilles or dauerlüftung) in the facade. The main benefit of this system is the user independency of the ventilation system and fresh air seems to be guaranteed. On the other hand most air supply grilles can (and will) be closed during the heating season. They are depending on wind speed and orientation of the building. Generally the fresh air through facade openings isn't equally spread throughout the classroom and often draught problems still occur.

Dutch primary schools need a ventilation system which is able to supply and guarantee a large amount of air in a comfortable and efficient way throughout the year. Earlier research conducted by Bruchem (2005) concluded that a displacement ventilation system could be able of supplying a large amount of air with a low velocity (no draught problems). Although this system seems to have a high potential as ventilation system in primary schools, more research is needed to obtain a better understanding of the critical factors of applying such system in a typical Dutch (primary) school environment.

According to Skistad et.al. (2004) a displacement ventilation (DV) is in first place meant to obtain a good air quality into the occupied zone. DV is suitable in rooms where the main heat sources are also the contaminant sources (like pupils); a classroom is a good example. A displacement ventilated classroom needs less fresh air (when compared to often applied mixing ventilation) to gain the same indoor air quality. This involves an energy reduction (see paragraph 2.2).

Mattsson (1999) conducted research on the performance of DV systems in classrooms under laboratory conditions. It seems that for example people movement demolishes the displacement effect, but the displacement flow pattern was re-established fairly quickly after ceasing the activity. In all test cases of his study he found that the air quality in the breathing zone of seated occupants remained significantly better than that at perfect-mixing conditions.

In order to study the performance of DV systems a literature study (See Chapter 2 and Schuiling, 2007) was conducted to get knowledge about the state of the art principles of this type of ventilation. The most important findings are worked out in the literature study and are evaluated in this final thesis with measurements on an experimental setup. The most important findings/expectations of the literature study are:

- Displacement ventilation holds an ventilation efficiency * between 1-1,3 so that ~30% less air (and less energy) is needed to obtain the same IAQ as mixing ventilation (Skistad et. al., 2004 and Etheridge and Sandberg, 1996);
- Displacement effect near the body of pupils is an extra advantage (up to 70% better) to obtain an better air quality (Etheridge and Sandberg, 1996);
- The supply air is equally spread throughout the classroom (Skistad et. al., 2004 and Mattsson, 1999);
- The vertical temperature gradient could easily cause comfort problem (Skistad et. al., 2004);
- The primary zone near the supply diffusers is a critical zone concerning thermal comfort. Draught problems can occur; (very) low air velocities are needed (Skistad et. al., 2004);

1.1. OBJECTIVES

The objective of this research is to obtain a good indoor air quality/thermal comfort in primary schools by developing, constructing and validating a "standard" displacement ventilation solution that can be generally applied in primary school environments

Main question: How can the displacement ventilation principle be implemented to improve indoor air quality and thermal comfort in Dutch primary schools?

To found this main question some particular sub questions can be formulated which can be answered through measurements on an experimental setup:

- To what extent does the DV system meet the expectations of the literature study?
- What are the main requirements of a displacement ventilation system when it's applied in (existing) primary school buildings?

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* *The ventilation efficiency is often expressed by ε_c (contamination removal efficiency) and indicates how fast contaminants are removed out of a room. This value is 1 at MV and could be better (higher) with DV*

1.2. STRUCTURE

The structure of this final thesis is divided in five phases as shown below.

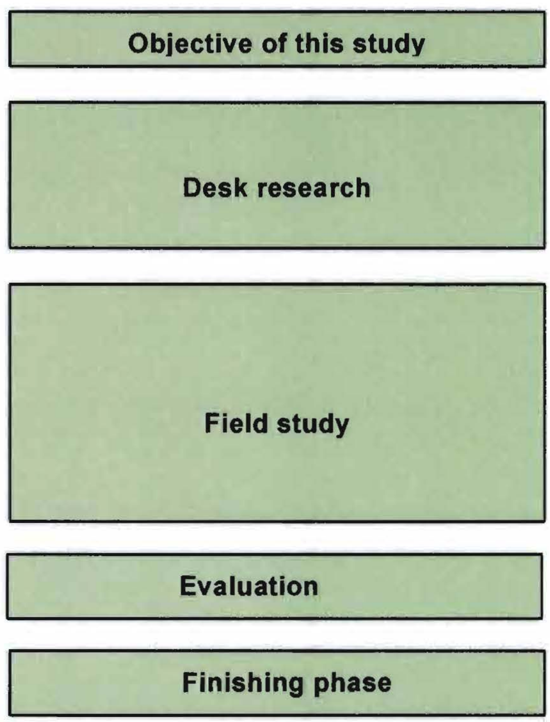


Figure 1.1 The structure of this study

Phase 1: Objective of this study, chapter 1

An inventory on key factors is made and the purpose of the study is defined.

Phase 2: Desk search, chapter 2 and 3

By means of a desk research background information is obtained about:

- Indoor air quality, human health and thermal comfort
- Existing standards and guidelines for school ventilation
- Principles, requirements, key factors, advantages/disadvantages displacement ventilation
- System components and their dimensions

Phase 3: Field test, chapter 4

A representative Dutch primary school building from 1970 is selected and an experimental setup is constructed in the classroom of group 7/8. Several measurements were performed to found the main objective and to answer the sub-questions. Also an enquiry is held with an IAQ questionnaire, two times with system on and off. The methods and the results of the research are explained in this chapter.

Phase 4: Evaluation, chapter 5

As a search for improvement the experimental setup is evaluated and suggestions are made for implementation of the system in existing classrooms (with a simplified Plug & Play solution). A specification of the capacity and the used materials are made.

Phase 5: Finishing phase, chapter 6

Methods used in this study are discussed as well as the results. Conclusions are drawn followed by recommendations for further research.

2. LITERATURE SURVEY

In an earlier stage a preliminary literature survey (Schuiling, 2007) was conducted to obtain basic information of the relation between ventilation, health and thermal comfort. Also the basic principles of displacement ventilation were evaluated in this document.

2.1. INDOOR CLIMATE: IAQ, THERMAL COMFORT, HEALTH AND VENTILATION

Indoor Air Quality

The Indoor Air Quality (IAQ) in classroom affects health and learning performance of children. The IAQ depends on the contaminant sources, the ventilation rate and the quality of the outdoor air. IAQ can be described as good when contaminants aren't present in the room air at hazardous concentrations. Exposure to contaminants isn't only related to the concentration of the contaminant but also the duration of the exposure and the susceptibility of the person. Besides human related contaminants/residues (e.g. CO_2, moisture, body heat, aromatic substances and micro-organisms) there are chemical- (e.g. Ozone, Radon, VOC's and Formaldehydes), microbiological contaminants (e.g. mites, mould spores, bacteria and bio-aerosols) and particles (e.g. fine dust and fibres) which also influence the IAQ of a classroom. Although non human related contaminants could cause health problems, this research focuses on the human related contaminants/residues because they are often the main source. Through sufficient ventilation and reductions of contaminant sources these contaminants can be diluted or removed (Boerstra et. al., 2006). Insufficient ventilation results in a variety of health problems like headache, irritation of the mucous membranes, fatigues symptoms, concentration loss, infectious disease, allergic reactions and aromatic inconvenience.

As a result of the high occupancy in primary school classrooms, the CO_2 concentration is often used as an important indicator of the IAQ (thus required amount of fresh air). Obviously this doesn't mean that other contaminants couldn't cause IAQ problems but it gives a good indication of the required amount of fresh air (Joosten, 2004). According to the Dutch building regulation maximum acceptable indoor CO_2 concentration is 1200 ppm. Because of health issues several agencies advise to obtain CO_2 concentrations around 1000 ppm or lower (Boerstra et. al., 2006).

Myhrvold et. al. (1996) stated that there's a direct link between the measured CO_2 concentration and the study performance of pupils. A higher concentration results in a reduced performance. Recent research performed by De Gids et. al. (2007) also concluded that cognitive study performance increase when a demand controlled mechanical ventilation system is applied. Scandinavian research from Wargocki et.al (2005) indicated that a doubling of the ventilation rate from 19 m^3/h to 35 m^3/h increased some elements of the study performance by 15%.

Thermal comfort

Pupils thermal sensation is mainly related to the thermal balance of her/his body as a whole. This balance is influenced by the physical activity (Metabolism), heat resistance of clothing, room air temperature, mean radiant temperature, air velocity and the air humidity. When these factors are estimated or measured, the thermal sensation for the body as a whole can be predicted by calculating the predicted mean vote (PMV) as described in ISO 7730 (2005) and developed by Fanger. Thermal discomfort could occur in situations with radiant asymmetry, draught (local cooling effect of the body due to air movement), vertical temperature differences and cold or warm floors.

Joosten (2004) found that the thermal sensation of a pupil differs from an adult. When the thermal sensation is compared at the same level of activity, a pupil's sensation is less warm than an adult. To obtain an equal thermal sensation an operative temperature of 24°C is needed.

According to Havenith (2007) the metabolism rate of children with an age of 10-11 is 62 W/m^2 which result in a more negative PMV as well (see table 2.1). The corresponding operative temperature with a neutral PMV appreciation is almost 23°C. The PMV calculations made in this report are based on an adult with a metabolic rate of 70 W/m^2 and a clothing insulation value of 0,97 to obtain a realistic and comparable PMV judgement.

Table 2.1 Predicted mean vote comparison between children and adults at the same activity level (Havenith 2007)

	Children 9-10 yrs	**Children 10-11 yrs**	**Adults**
M [W/m^2]	53	62	70
I_{clo} [clo]	0,97	0,97	0,97
T_r [°C]	21	21	21
T_i [°C]	21	21	21
v [m/s]	0,05	0,05	0,05
RH [%]	50	50	50
PMV	**-0,95**	**-0,43**	**-0,13**

Under normal school circumstances a comfortable air temperature and relative humidity is between 18°C-22°C and 40-70% (Haans et. al., 2004). Thermal discomfort could cause negative health effects for the pupils and teacher of a classroom. According to Deplancke et.al. (2005) the intellectual performances of pupils decrease when the average temperature exceeds 26°C. The optimal temperature for brain activity is around 20°C.

Van Bronswijk (2005) stated that low relative humidity (RH) can give cause for fast dehumidification of human tissues. These dry tissues could easily become liable to infections. Beneath a RH of 30% there's also a high risk for irritated mucous membranes and above 70% RH the growth of mites and mould is stimulated.

Ventilation

According to the Dutch Building code and standard NEN 1089 a ventilation rate of 5,5 l/s per pupil is required to obtain a CO_2 concentration lower than 1200 ppm in a classroom with an occupation of 0,5 person per m^2. The TVVL (a Dutch society for building services) performed a preliminary study (Boersta et.al. 2006) which includes a suggestion for three performance categories, namely: category A "Acceptable" (5,5 l/s per pupil and <1200 ppm), category B "Good" (8,3 l/s per pupil and <1000 ppm) and category C "Very Good" (12,5 l/s per pupil and <800 ppm). These three categories also include other parameters for thermal comfort and noise (see Appendix I).

In spite of the available legislation on this subject it is obvious that continuing of the actual ventilation rate doesn't lead to an acceptable indoor climate without a mechanical ventilation component. And if there's a mechanical ventilation system commissioning and maintenance of the system are very important to guarantee the minimal ventilation rate (Boersta et.al. 2006). From a health perspective it is advisable to aim at the climate category B with a minimal ventilation rate of 8,4 l/s per pupil.

2.2. GENERAL CHARACTERISTICS OF DISPLACEMENT VENTILATION

Displacement ventilation (DV) is a ventilation principle where fresh air is supplied with low velocity, low turbulence level and little under temperature at floor level. In contrast to mixing ventilation, DV creates little disturbances of the room air and thereby only little mixing takes place. The air within the room is then transported by natural convection plumes and their entrainment of the surrounding air. The upwards raising plumes take along contamination, especially when the main contaminants are produced by the heat source itself (e.g. people). The heated and contaminated air is extracted outside the room.

One of the most important benefits of displacement ventilation principle is its efficiency. Because of the use of natural convection as a driving force DV is 10-30% more efficient than mixing ventilation. The most commonly used definitions to indicate the ventilation efficiency of a room are the **contamination removal efficiency ε_c** [1] and the **personal exposure index ε_{exp}** [2]. The contamination removal efficiency of complete mixing ventilation is 1 and if the convection and contamination sources are the same the contamination removal efficiency in a displacement ventilated room can be higher than 1 (AIVC, 1991). The contamination removal efficiency formula is given below.

$$\varepsilon_c = \frac{(C_e - C_s)}{(C_{oz} - C_s)} \quad [-] \qquad [1]$$

C_e	contamination concentration in the extract air	[ppm]
C_s	contamination concentration in the supply air	[ppm]
C_{oz}	average contamination concentration in the occupied zone	[ppm]

The contamination concentration at breathing height around a person isn't the same elsewhere in the room at the same height. This is because of the entrainment of fresh air from beneath along the body of a person. The personal exposure index gives the relation between these concentrations.

$$\varepsilon_{\exp} = \frac{(C_e - C_s)}{(C_{\exp} - C_s)} \quad [-] \qquad [2]$$

Where:

C_{exp}	exposure contamination concentration in the occupied zone (close to the body)	[ppm]

Etheridge and Sandberg (1996) found a relation between the ventilation flow per person and the improved efficiency between the displacement effect around a person versus elsewhere in the room at the same height (see figure 2.1).

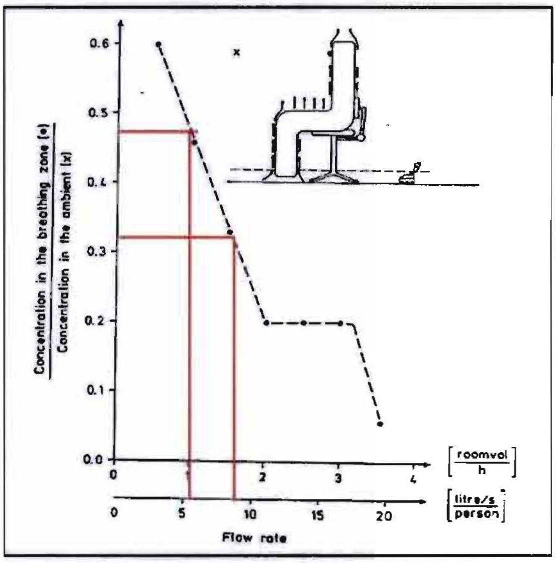


Figure 2.1 *Proportion of the quality of the inhaled air related to the environmental air at the same height in a displacement ventilated room (Etheridge and Sandberg, 1996)*

C

When a room is ventilated with an airflow of 5,5 l/s per pupil the contamination concentration near the body is only **40-50%** of the concentration at the same height elsewhere. With higher ventilation rates this percentage is even lower for example: almost **30%** with an airflow of 8,3 l/s per pupil.

The most important advantages, disadvantages and boundary conditions of DV are enumerated below:

Advantages

- High ventilation efficiency, less air is needed;
- No induction is needed with displacement supply diffusers;
- Longer use of free cooling. Because of vertical temperature stratification the supplied air is colder than the extracted air at ceiling level. With mixing ventilation the temperature of the extracted air is the same as the temperature elsewhere in the room;
- Ability to supply large amount of fresh with low velocities;

Disadvantages

- Heat supply by air creates a shortcut which decreases the ventilation efficiency dramatically;
- The supply diffuser needs some space and may not be blocked by obstacles like closets. Tables and chairs aren't directly influencing the air flow because the air can pass around;
- No occupation should be allowed within the primary zone of the supply diffuser(s);
- Accurate control of the supply air temperature is needed to prevent draught, especially in combination with VAV-systems;
- The floor needs to be cleaned carefully and regularly otherwise contaminants could become airborne.

Boundary conditions

- Minimal air supply temperature 5K beneath room temperature;
- Maximum air speed of 0,15 m/s in winter and 0,25 m/s during summer period (NEN-EN-ISO 7730). An under temperature of 5K and an air velocity of 0,2 m/s is usual with diffuser selection;
- Vertical temperature gradient maximal 3 K/m between ankles and neck (NEN-EN-ISO 7730);
- In cases where high cooling capacity is needed mixing ventilation prevails because of low supply temperature and high induction;
- The location of the ventilation control sensor is important because of stratification of contaminants and temperature.

In the following chapter a methodological design procedure is conducted on the ventilation systems within a primary school. At the end of the chapter a suggestion for an improved ventilation system is made.

2.3. DISPLACEMENT VENTILATION CONCEPT

In an earlier study (Schuiling, 2007), a methodical design approach from van den Kroonenberg (Siers, 2004) is used to evaluate the ventilation concept for primary schools. See also Appendix II for the complete report. This design approach is used to create structure in the design process. Several design aspects can be ordered to create an overall view of the design problem. The methodical design method can be divided into four main segments:

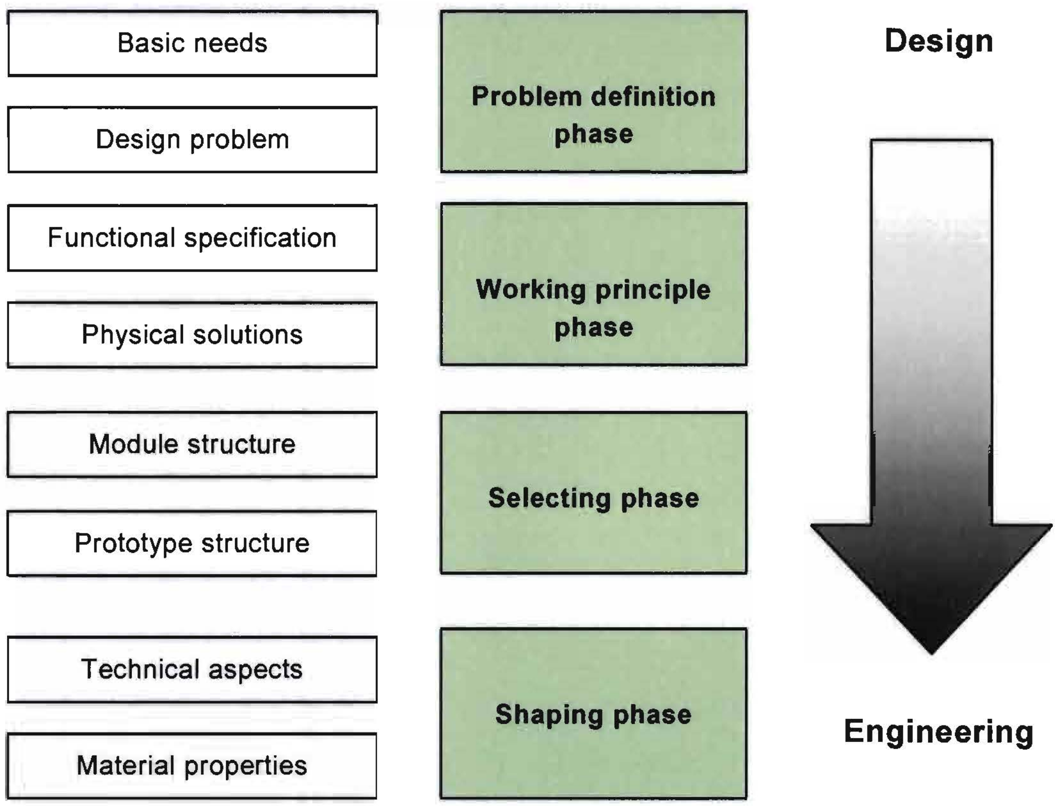


Figure 2.2 The methodical design procedure, divided into four phases

The methodical design process starts with an abstract problem definition and it will end with a definite solution to the design problem. Each phase has different levels of abstraction hierarchy which starts with the primary needs and ends with a suitable concept to fulfil these needs.

Problem definition phase

The first phase describes the primary needs of the users and the specific design problem(s). Afterwards, a list of requirements can be generated. The requirements can be divided into two groups. One group contains all the requirements regarding the functionality of the design. The other group contains all the requirements that are important for the realization of the design. These functional requirements are chance of draught, room temperature, efficiency of heat extraction, indoor air quality, individual adaptation, noise level and user dependency. The realization aspects are ease of implementation, flexibility, costs, energy use, reliability and maintenance.

Working principle phase

This phase describes the functions that need to be fulfilled. These functions can be represented by function blocks. Next several physical solutions for each function are collected in a morphological overview. At the end of this phase the best solutions for each function are connected and the total design concept is achieved. Sometimes the total design concept is better if a less optimal solution is chosen for an individual function. To see if a solution is feasible it can be checked with all the functions and the requirements. If not, another solution must be examined or the functions need to be adjusted. Often multiple variants of design concepts appear to be suitable. Therefore these variants are compared with each other in detail in the next phase.

Selecting phase

This phase is to judge which variant fits best. The variants are judged on basis of the desired values in the list of requirements. This is difficult because al lot of requirements are quantitative and part qualitative. Each requirement is evaluated and judged according to the Kesselring method and listed in an overview for a clear and objective discussion. These results are visualized by an S-graph with a realize and a function axis. The S-diagram shows the strengths and the weaknesses of realization or functioning of the design. With the S-graph it is easy to see if improvements must take place on the functional or the realization side. The best variants lie near the diagonal line and have high scores in both aspects.

Shaping phase

In the last phase the details and materials of the best variant are determined. The finally used material depends on several aspects (e.g. safety, easy to use/clean). Also the several components of the design concept are figured out.

Final results

At the end of the methodological design process a ventilation concept for existing primary school buildings is presented.

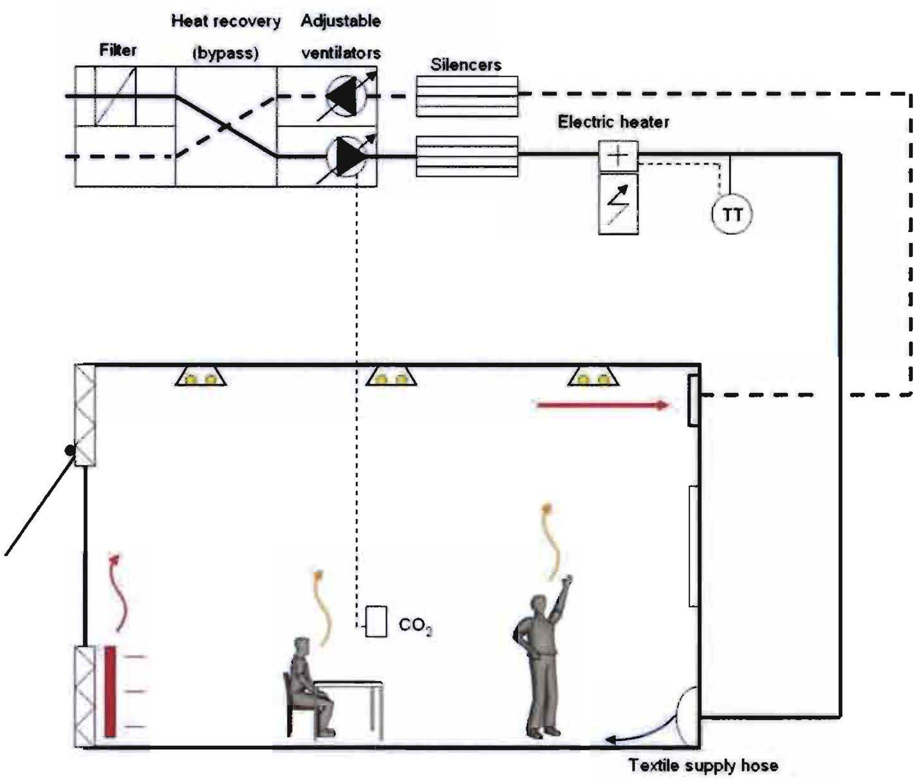


Figure 2.3 An optimized ventilation concept for existing primary schools

Additive information for the chosen concept:

- Silencers are added because it's difficult to obtain a sound level around 35 dB (A) in the classroom without any silencers;
- Filters can have a surplus value for a child who has asthma and is thus desired. Filters need to be replaced once a year, the maintenance intensity increases;
- Occupied classrooms produce an excess amount of heat, thereby a cross flow heat exchange system (efficiency of 50-70%) with a low pressure drop is sufficient to heat up the supply air for a large period of a year. In winter a extra electric heater is available to heat up the supply air to the desired air supply temperature;
- Normal ductwork is capable of transporting air into and out of the classroom in standard situations. When individual adjustability is desired a raised floor could applied to create an extra space for individual adjustment equipment;
- Air is spread into the breathing area with a textile duct system. This hose is safe, easy to clean and relatively cheap compared to low velocity diffusers;

- The air supply temperature, which is kept constant by the (electrical) heater, is determined above the critical value to prevent draught problems in winter;
- The amount of air supplied by the ventilation system is measured by a CO_2 sensor which is located at 1,1 meter above the floor surface.

Advantages of methodological design

- Methodical design approach is an effective way to create a design concept. The designer is forced to perform research on the design problem in a structural way. Complex design problems can be divided into sub problems of a more manageable size;
- Decisions that are made during the design phases can be evaluated and reproduced. Other designer can look into the design concept and improve it wherever they want;
- The morphological overview is a way to express and structure solutions/possibilities during the design process;
- The design requirements of a project need to be set up by a design team and not only by an individual architect. By this way the requirements of the design task becomes more objective and complete;
- The Kesselring graph (S-graph) is a fast and effective way to visualize shortcoming or superiority of design variants;
- The methodical design process is an open process which leaves space for individual interpretation of the design problem or approach strategy.

The full report of the methodological design process can be found in Appendix II. The next chapter describes a field study based on the methodical design of a school ventilation system as a product from this chapter.

3. FIELD TEST WITH DISPLACEMENT VENTILATION

3.1. INTRODUCTION

The objective of this research is to obtain a good indoor air quality in primary schools by developing, constructing and validating a "standard" displacement ventilation solution that can be generally applied in these schools. In spite of the fact that a laboratory environment is commonly used for measurements to validate ventilation systems (because of the controlled steady state conditions that can be achieved) it is important to prove the efficiency of the ventilation system in an existing classroom environment. Several depending and dynamic physical variables need to be examined and monitored to obtain a reliable judgment of the DV system.

With the help of measurements the following aspects of a DV system were formed:

- The current status of the IAQ and thermal comfort (reference conditions without a ventilation system) and perception of the users with respect to IAQ and thermal comfort (with a survey);
- The considered reduction of the required fresh air flow at a fixed CO_2 concentration as a result of the high efficiency of a DV system. And also the extra benefit of the displacement effect near the body to obtain an even better air quality;
- The primary zone of the textile supply diffuser. The primary zone is the distance from the supply opening where draught problems are expected;
- The spreading of the (fresh) air throughout the classroom, the so called air flow path;
- The vertical temperature composition throughout the classroom (vertical temperature stratification);
- The actual ventilation efficiency factor ε_c of the experimental setup;
- The thermal comfort of the pupils at several setting of the ventilation system;

The reference conditions were measured during the winter (March 2008) to look for draught problems which are very common in existing primary school buildings. Whereas in summer the only negative comfort factor to be expected is a high room temperature (and corresponding vertical temperature stratification).

The measurements which are necessary to found out effects of the ventilation system on a existing primary school classroom are investigated and documented in this chapter.

3.2. EXPERIMENTAL SET-UP

The measurements are carried out in a full-scale classroom (in use) approximately the size of a typical classroom in the Netherlands (see picture 3.1 and 3.2). The floor area of the classroom is 7,72 x 7,3= 56,4m^2 with a ceiling height of 3,13 m and a total space volume of 176 m^3.

Figure 3.1 *Orientation of the school building, constructed June 1970*

Some steady state measurements are performed in an empty classroom and others are performed in an occupied classroom to obtain buoyancy sources in accordance with normal classroom activities. The classroom is used by 26 pupils from group 7/8 (age 10-12 years) in standard school conditions. The façade has eight windows of which four can be opened by the teacher. The opposite wall contains six windows (four bordering the outdoor climate) of which none can be opened. See Appendix III for more drawings of the classroom and the constructional details.

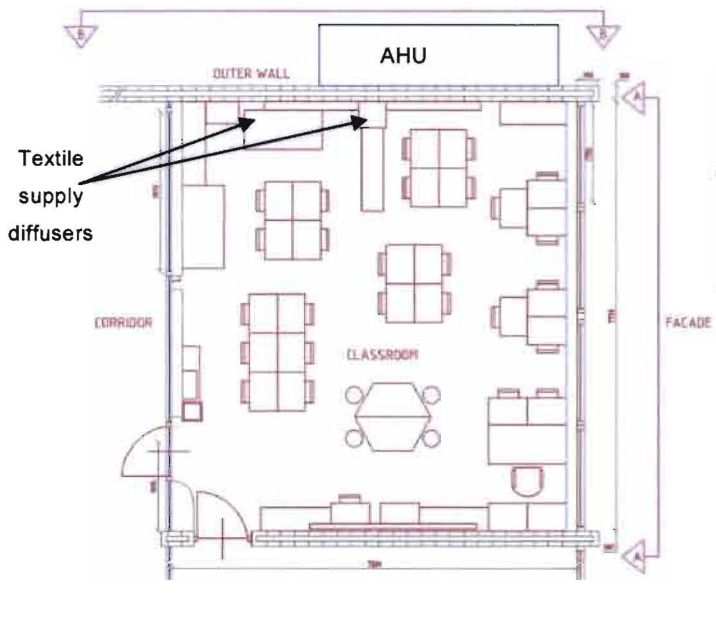
The classroom has two doors, one to the classroom nearby (isn't used) and one door to the corridor. The indoor blinds system (four sections) can be lowered by the teacher to avoid direct sun radiation in the morning.

Existing installations

Three existing radiators with a total capacity of 23500 W (at 90/70°C) provide heat to warm the classroom to the desired air temperature. The radiators are provided with manually controlled radiator valves to adjust the room temperature. Fresh air could be supplied into the classroom by the windows in the façade. In winter this could result into draught problems.

New ventilation system

An air handling unit is mounted on the outer wall of to the classroom. The unit is protected by rain and cold weather by an isolated, water tight casing (see also picture 3.3). The air handling unit is provided with a plate heat exchange system to recover sensible heat from the exhaust air. The air is transported by a duct system which is mounted above the lowered ceiling in the classroom. An additional electric heater is placed which is connected to a temperature sensor nearby the supply diffusers, to obtain a minimal supply temperature of 18°C in winter (only for fine tuning of the air supply temperature). The ventilation flow can be adjusted by a control panel which communicates with electronically commutated ventilators in the air handling unit and is fine-tuned with control valves. The air flow can be measured by prefabricated measuring instruments in the supply and the extract duct system. The air supply temperature is regulated by an electrical heating battery which is connected with a temperature sensor in the supply duct system. Two semicircular textile air diffusers (so called air socks) for displacement ventilation are mounted on the wall, at floor level of the backside of the classroom. The main supply duct is vertically placed in the middle of the wall at the backend of the room. An air distribution box is placed at the end of the duct at floor level to divide the air flow over the textile air diffusers. The textile air diffusers have a length of 1,7 meters with a zipper at 0,5 meter to shorten the length (to 1,2 meter) and increase the supply velocity. Next, two exhaust grilles are mounted in the lowered ceiling on the opposite side of the classroom (see figure 3.3).



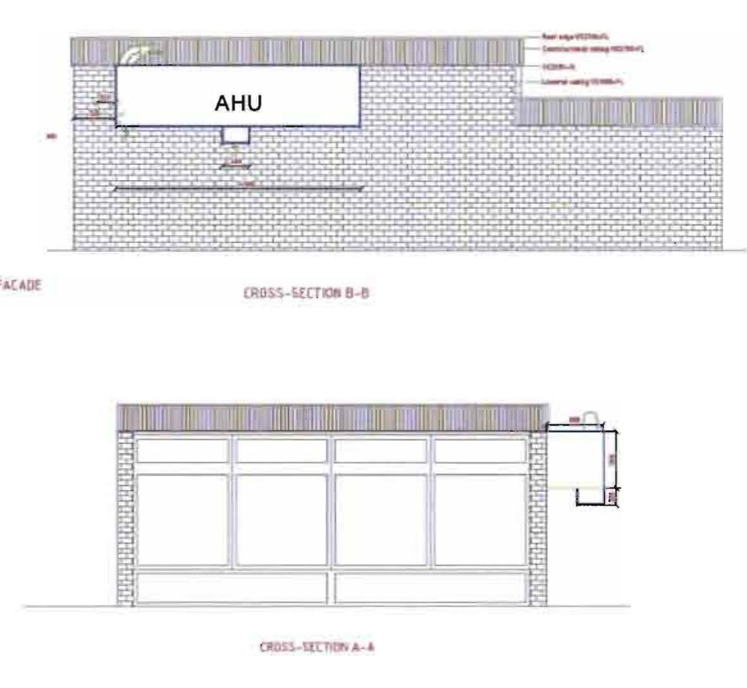


Figure 3.2   Layout of the classroom

The ventilation system of the classroom consists of:

- 1 Air handling Unit: nom. capacity 1000 m^3/h at 300 Pa with electronically commutated ventilators with free set point;
- 1 electrical heating battery, capacity 1500W;
- 5 silencers: 3x Ø 250 mm in the supply duct and 2x Ø 250 mm in the return duct;
- Duct system Ø 250 mm, maximum velocity 5,5 m/s ;
- 2 measuring instruments provided with 12 measuring point to measure the average air velocity over the entire duct in conformance with ISO standard;
- 2 horizontal displacement diffusers made of fire retardant textile;

See also Appendix III for figures and product specification of the main components.

Figure 3.3 *Upper left: The supply duct system and the measuring tripod*

Left below: The textile air diffusers (air socks)

Upper right: Extract grille

Right below: Water tight construction at the outer wall

3.3. EXPERIMENTAL EVALUATION OF THE DV SYSTEM

3.3.1. REFERENCE CONDITIONS OF THE ORINAL CLASSROOM

To quantify the performance of the new ventilation system first the reference conditions (classroom without a mechanical ventilation system) of the examined classroom must be determined. The reference conditions experiment exist of an IAQ quality measurement based on the CO_2 concentration in the classroom; thermal comfort measurements using the parameters and model of Fanger (ISO 7730) and an air change rate measurement. The measurements took place during one week and the air change rate measurements were performed on the Wednesday afternoon when no lessons take place. The classroom is evaluated with a normal occupation of pupils; the teachers were asked to ventilate as usual. No microbiological or chemical samples were taken or examined.

Indoor air quality and thermal comfort measurements

To measure the reference conditions of the mean air quality of the classroom several CO_2 sensors are placed on strategic locations. Also the level of comfort, as described in chapter 2.1, is measured. By using these parameters the predicted mean vote (PMV) can be calculated. The correction for the metabolism, clo-value of pupils and teachers and the measurement error is already discussed in chapter 2.1 of this thesis report. The locations of the sensors in the classroom are shown in Appendix IV. During the measurement period the ventilation behaviour of the teacher and pupils is described in a logbook to relate variations of the measured parameters to the behaviour.

Air change rate measurements

The air change rate of the classroom is measured by a tracer gas measurement. The concentration decay method is a frequently used measurement method and is suitable for rooms where a uniform distribution of tracer gas can be achieved (Innova). This includes both naturally and mechanically ventilated spaces. A commonly used tracer gas is Sulphur Hexafluoride (SF_6). A small amount of SF_6 is thoroughly mixed with the room air until a uniform concentration is obtained. The source of the tracer gas is then removed and the decay of the tracer-gas concentration in the classroom is measured (at six locations) until the tracer gas concentration is reduced to zero or until exponential decay is achieved at all locations. To obtain an indication of the maximum air flow in the winter period a situation is simulated where no windows are opened as usual in the winter period.

The gas analyser (see Appendix IV for measurement locations and Appendix IX for specifications of measurement equipment) is connected to a sampler box with five sampling channels. The minimum time interval between measurements/channels is approximately one minute.

3.3.2. REDUCTION OF THE AIR FLOW WITH DV

Generally displacement ventilation is a more effective way to ventilate a room and therefore needs less air compared to mixing ventilation. In order to validate the benefits of this system in a primary school environment the CO_2 concentrations (as an indicator of the indoor air quality) is measured during a period of several weeks. During this measuring period each week the average CO_2 concentration is derived at different air flow rates and occupation. During the measuring period several variables, which could have an important influence on the efficiency of the ventilation system, were examined:

- Outdoor conditions (air temperature, relative humidity, CO_2 concentration);
- The heat loads in the classroom. The amount of pupils, lighting, heating system;
- The air supply temperature;
- The temperature gradient (measured between ankle 10 cm and head 110 cm);
- The predicted mean vote (PMV) in the occupation zone. By measuring the air velocity, air temperature and the radiant temperature;
- The amount of ventilated air flow (and air change rate);
- The pupil activities (college or gymnastics);

Influence factors that can't be controlled or documented:

- Air movements by pupils;

To determine the minimum amount of supply air to obtain a good indoor air quality, the ventilation flow is changed and reflected to the preliminary study of the TVVL (Boerstra, 2006). According to the TVVL study a CO_2 concentration lower than 1000 ppm gives a good indoor air quality. With mixing ventilation 30 m^3/h per person is needed to obtain this concentration (400 ppm outdoor concentration). Theoretically displacement ventilation only needs ~23 m^3/h per person! (See Appendix V for formula) To underpin this theoretical assumption indoor air quality measurements were performed during a couple of weeks.

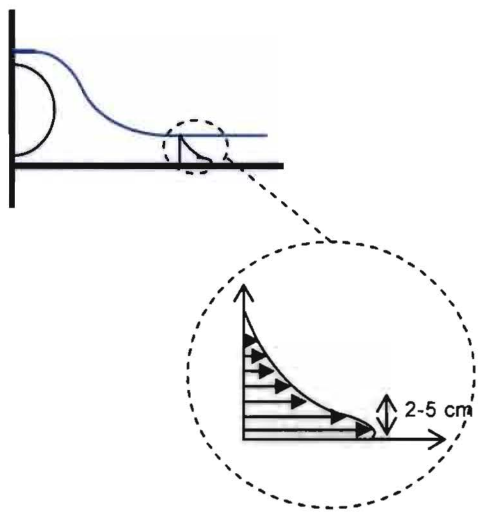
The ventilation flow was adjusted several times and the CO_2 concentration in the classroom was monitored a couple of weeks. The ventilation flow was measured by a measuring station in the supply and extract duct according to the ISSO 31 (1995) guidelines. The desired amount can be adjusted/fine-tuned by a control valve in the same duct system. The ventilation flow could was validated by a Pitot tube measurement.

Windows were kept closed and doors are only opened during the (lunch/toilet) breaks. The air supply temperature was kept constant (~18°C) when outdoor conditions were below 18°C.

3.3.3. PRIMARY ZONE SUPPLY DIFFUSER

High velocities nearby a supply diffuser could cause draught problems. Pupils cannot be seated within the critical primary zone otherwise thermal discomfort could occur. Therefore it is important to analyze the primary zone of the supply diffuser to determine the needed distance from the diffusers.

The velocity profile around the supply diffusers can be measured with an omni directional anemometer perpendicular to the textile air diffuser. A velocity measurement line is chosen to measure the velocity at a fixed path (see Appendix VI). The velocities are measured 2 cm above floor level within the distances every 10 cm within the first meter and also 1,5 meter, 3 meter, 4 meter, 5 meter and 6 meter. According to the theoretical velocity profile, the highest velocity will be measured within 2 to 5 cm above floor level (see picture 3.4).



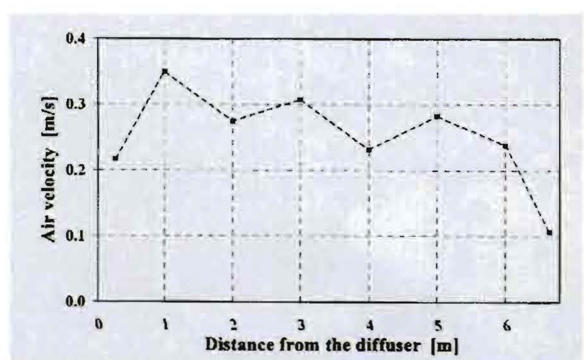


Figure 3.4 Theoretical velocity distribution around a displacement diffuser, Skistad et al (2004)

Figure 3.5 Measured velocity distribution around a conventional displacement diffuser, source: Mattsson (1999)

The primary zone of the displacement supply diffusers can be determined in the maximum flow situation. As the air flow through the diffuser decreases the primary zone also decreases. Thereby low velocity diffusers are suitable for variable flow systems.

The textile displacement air diffuser can be shortened from 1,7m to 1,2 m to increase the maximum air supply velocity from approximately 0,165 to 0,234 m/s at maximum flow situation (theoretically). After the air velocity is measured at the mentioned locations and with different air flows and textile diffuser length, a graph with the velocity versus the distance can be generated (see figure 3.5).

3.3.4. VISUALISATION AIR FLOW PATH

The theoretical air distribution through a displacement ventilated room is shown in figure 3.6. First, cool air is supplied in the classroom and is evenly spread along the room surface area. The air reflects at the opposite wall and returns with a lower velocity. A part of the air current is entrained along the heat sources and warm walls. In the upper part of the classroom a recirculation zone is generated and the air is extracted through exhaust grilles located close to the ceiling. Air near cold surfaces can be cooled down and drops along this surface.

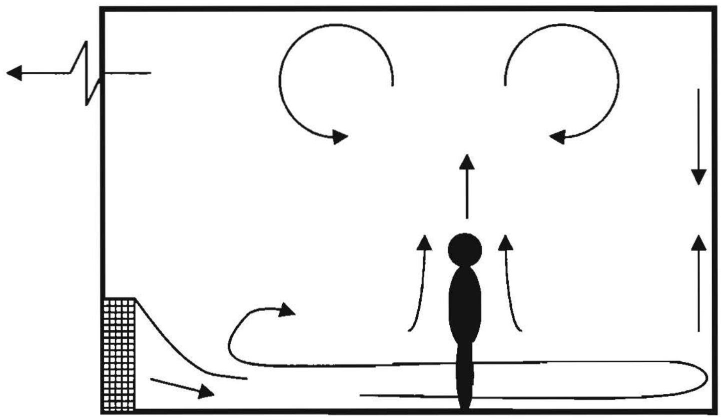


Figure 3.6 Theoretical air distribution in a displacement ventilated room, Brohus (1997)

The flow path is visualized by smoke from a smoke generator which injects smoke near the supply of the ventilation system (along the air sock). The smoke is spread all over the classroom by the air socks. To increase contrast to the surrounding area, the background is covered in black cloths and the smoke is lighted. The smoke visualisations are recorded by a video camera.

3.3.5. TEMPERATURE STRATIFICATION

One of the characteristics of displacement ventilation is the large vertical temperature gradient. A large temperature gradient indicates the displacement system is working properly. Theoretically the 50% rule* gives a good prediction of the vertical temperature gradient for a room with moderate ceiling heights. On the other hand several factors (like: heat sources, air flow, supply air temperature, floor temperature, air movements, etc.) cause disturbances to this theoretical gradient. In order to determine the exact vertical temperature gradient, measurements were performed. Therefore a cable is mounted from floor to the lowered ceiling and resistance thermometers (NTC's) are placed along a cable with the measuring heights 0, 2, 5, 10, 20, 30, 70, 110, 150, 190, 230 and 315 cm.

Air supply temperature and air flow is kept constant. Outdoor climate conditions are evaluated and radiators are monitored by placing temperature sensors on the supply and return pipe of the central heating system.

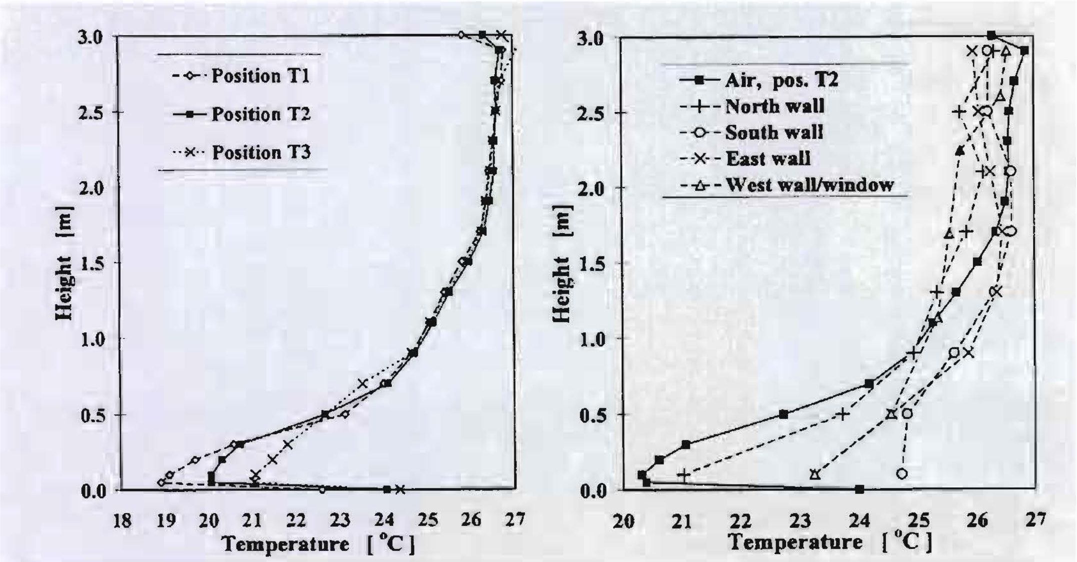


Figure 3.7 *Example of a typical vertical temperature profile (room air temperature and the surface temperature) of a displacement ventilated room, source Mattsson (1999)*

After the measurements are taken a vertical temperature profile can be created (for example see figure 3.7). To calculate the amount of extracted heat a temperature sensor is placed in the supply and extract duct.

* *According to the 50% rule of Skistad (2004) in rooms of moderate height, half of the temperature difference between the exhaust and the supply air is evened out at the floor level and that in the room a linear gradient is formed for the rest of the difference*

The formulas below calculate the actual temperature ratio "50% rule method" (ε) and the temperature efficiency (ε_T) from Skistad et. al (2004):

$$\varepsilon = \frac{T_{floor} - T_{supply}}{T_{extract} - T_{supply}} \times 100 \quad [\%] \qquad \varepsilon_T = \frac{T_{extract} - T_{supply}}{T_{extract} - T_{oz}} \quad [-] \qquad [3]$$

The temperature ratio ε describes the relation between the floor temperature and the total vertical temperature difference. In displacement ventilated rooms the ε percentage is mostly ≤ 50% depending on the ceiling height and heat sources. This means that 50% of the total temperature rise in a room is added at floor level. The percentage will be much lower than 50% in case of a high ceiling where temperature rise of the supply air (due to the floor temperature) is low and the heat is accumulated in the upper part of the room. The temperature efficiency ε_T gives the relation between the temperature in the occupied zone related to the total vertical temperature difference. This indicates how much heat is located in the upper zone of the classroom. Mattsson (1999) found that the vertical temperature profile is almost equal throughout the ventilated room; there is a bigger temperature difference near the floor. According to Skistad et. al. (2004) heat sources in the lower part of the room (like sitting persons, desk lamp, etc) generate a big temperature difference within the first meters from the floor. On the other hand when the heat sources are located in the upper part of the room (lamps at ceiling, roof heated by the sun, etc.) the temperature difference is small in the lower part of the room and high at ceiling level.

3.3.6. VENTILATION-EFFICIENCY

The ventilation efficiency ε_c and the displacement effect near the body ε_{exp} can be calculated (see also formulas in paragraph 2.2) by measuring the CO_2 concentration in the extract grille, the outdoor environment* , the concentration at breathing height and the concentration at the body of a pupil. Due to the fact that placing sensors on a pupil isn't desirable, a person simulator is created to simulate a pupil of 10-12 years old. Three CO_2 sensors are placed within the breathing height of 1,1 meter: at a tripod, at the person simulator and on the side- or front wall of the classroom.

To increase the reliability of the measurements it's important to measure the efficiency and displacement effect outside the overlapping deviation area of the CO_2 sensors (see appendix VI for deviation of the CO_2 sensors used in this research. To obtain a significant difference (displacement effect) the ventilation system is shut down for an hour till the concentration is stabilized and subsequently turned on for 50%. The decay curve can be observed until the CO_2 concentration is stable again at all locations. The different phase shifts and amplitudes between each location give an indication of the age of the air. At the end the ventilation effectiveness can be calculated in each measuring point.

* *The contamination concentration in the supply air is equal to the outdoor concentration because no air re-circulated. The average outdoor CO_2 concentration of the environmental situation was between 400-500 ppm.*

Person simulator

The air quality near the body of a human in a displacement ventilated room is verifiable better due to thermal buoyancy which stimulates fresh air supply from beneath. The buoyancy forces near the person simulator (PS) are used to validate (better) air quality in the breathing zone. Mattsson (1999) already used a person simulator to measure the displacement effect near the body. The PS in this research is made of round 250mm duct material (see figure 3.8). The dimensions of the PS are determined by the furniture of the classroom and the average body surface of the pupils.

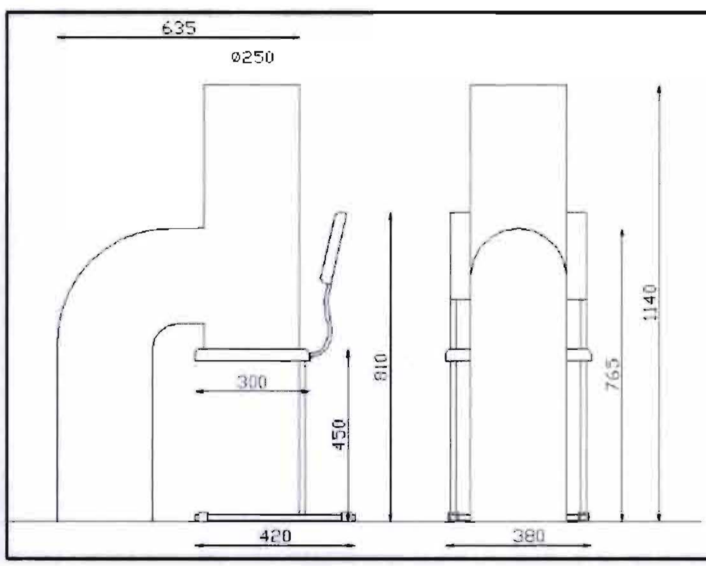


Figure 3.8 left: undressed person simulator, right: dimensions of the person simulator

Table 3.1 Average body surface of pupils between 1,5 and 16,5 years old. Bremmer (2000)

Age [yr]	Average body surface [m²]	SD
1,5	0,520	0,062
2,5	0,616	0,062
3,5	0,690	0,076
4,5	0,762	0,081
6,5	0,902	0,093
9,5	1,13	0,13
12,5	1,40	0,15
13,5	1,51	0,16
16,5	1,75	0,16

Table 3.2 Metabolic rate of pupils at different activities (category B: age 10-11 years old). Havenith (2007)

Primary school	Average body surface [m²]	Air temp. [°C]	Metabolic rate [W/m²]
1 Drawing	0,520	21,5	62
2 Calculus	0,616	22	64

The metabolic rate of a pupil depends on the activity and age. According to Havenith (2007) the metabolic rate of pupils with the age of 10-11 years is equal to 62 W/m^2 when performing a writing task (see table 3.2). The corresponding average body surface between 9,5-12,5 years old pupils is 1,27 m^2 (see table 3.1), which returns a total heat production of 79W per pupil.

Lamps are installed inside the PS to simulate the metabolism rate of a child of 10-12 years of age. Three lamps which holds a total capacity of 80W (1x40W feet part, 1x 25 W upper leg part, 1x 15W head part) are mounted in the PS. The lamps are connected to a 24 V (AC) current for safety. The PS is dressed with a fire retardant textile (see figure 3.9).

The PS is used to mount on resistance thermometers and CO_2 sensors. The resistance thermometers are mounted on the outside of the PS to measure the cooling effect of the passing air. Also the temperature gradient between ankle and head is observed. The function of the CO_2 sensors is already mentioned.

Figure 3.9

Upper left: dressed person simulator

Upper right: thermo graphical photo of the PS

Lower right: thermo graphical photo of human

Thermo graphical pictures were made to compare the surface temperature of the PS with a real human. A comparison is made between the surface temperature of the PS and a real human being. The surface temperature of the PS (25-29°C) is, in contrast to the human being (22-33,6°C), equally spread from toe to head. The exposed skin of the human head was relatively high (32-34°C). The extra heat loss (per unit area) of the head, caused by high temperature, was to some extent compensated on the PS by its larger head area.

4. RESULTS

4.1. REFERENCE CONDITIONS OF THE ORIGINAL CLASSROOM

Air change rate measurements

The measurements were taken on Wednesday afternoon 25th February 2008. During the tracer gas measurement the outdoor temperature was around 10°C. The first period of the tracer gas measurement indicates insufficient ventilation (see table 4.1). The ventilation rate as a result of infiltration through the façade is calculated. As expected the average ventilation rate is very low, approximately 32 m^3/h. More detailed information can be found in Appendix IV.

In the first period all windows were closed (see figure 4.1 for average decay curves). Due to the slow decay curve two upper windows were opened during the second period. The ventilation rate increased to an average value of 301 m^3/h. Although ventilation flow is quite high, this situation is improbable in the winter period due to comfort problems.

Table 4.1 Tracer gas measurement results

Period 1						
	Ch. 1	Ch. 2	Ch. 3	Ch 4	Ch 5	Average
Air change rate [h^{-1}]	0,21	0,21	0,21	0,22	0,19	0,18
Period 2						
Air change rate [h^{-1}]	1,78	1,62	1,78	1,46	1,91	1,71

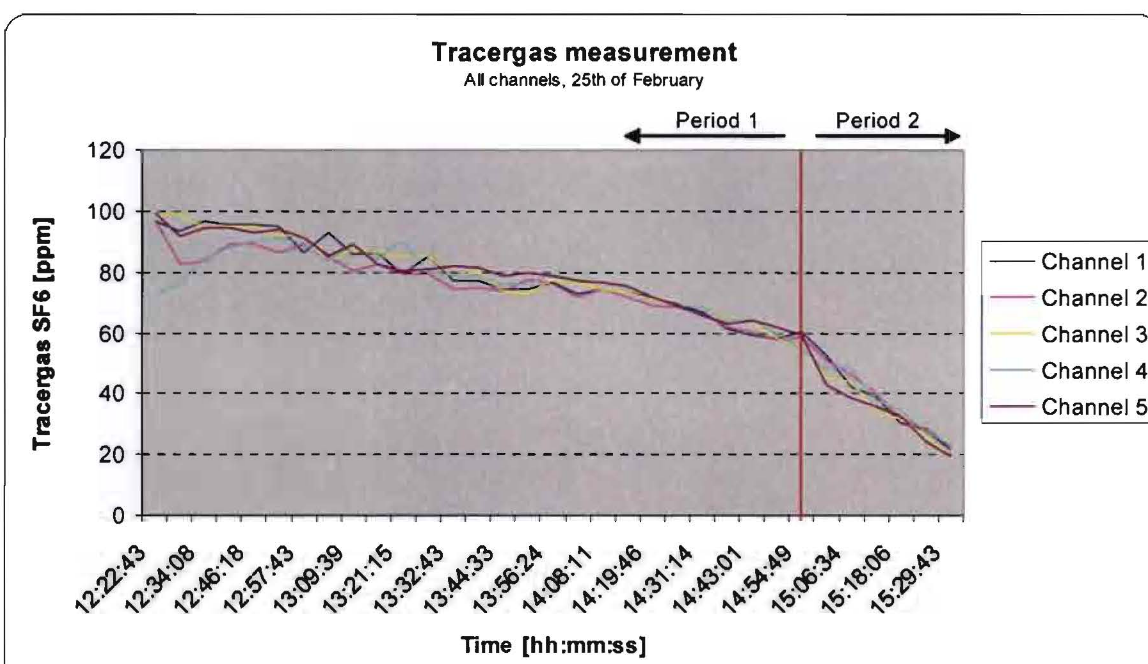


Figure 4.1 Tracer gas decay curve. First period before red line, second period after red line

IAQ and thermal comfort measurements

The measurements took place during one week from 3rd till 7th of March. The mentioned values are measured within the school lessons. For time table and more detailed information see Appendix IV. The average values of the temperatures, relative humidity and the CO_2 concentration are shown in table 4.2.

Table 4.2 Mean temperature, relative humidity, CO_2 concentration and occupation with SD

Day	Mon	Tue	Wen	Thu	Fri
T_{indoor} [°C]	21,1 ±0,7	20,2 ±0,6	20,1 ±0,5	19,9 ±0,5	20,3 ±0,5
RH_{indoor} [%]	44 ±2	41 ±3	41 ±3	50 ±4	50 ±2
$T_{outdoor}$ [°C]	8,3 ±0,4	7,9 ±2,4	4,7 ±1,8	8,0 ±0,7	9,3 ±0,7
$RH_{outdoor}$ [%]	57 ±7	61 ±10	72 ±7	89 ±6	74 ±6
$CO_{2\ tripod}$ [ppm]	1870 ±321	1740 ±333	1770 ±409	1870 ±304	1750 ±316
$CO_{2\ wall}$ [ppm]	1850 ±336	1720 ±326	1730 ±433	1860 ±321	1680 ±316
$CO_{2\ outdoor}$ [ppm]	430 ±15	480 ±27	490 ±20	440 ±6	420 ±6
Amount of pupils [-]	24	24	22	23	18

Throughout the week the average indoor room temperature is reasonably constant, approximately 20°C. Also the relative humidity is reasonably well with an average value between 40-50%. The indoor air quality, which is measured by the CO_2 concentration, exceeds the limit of 1200 ppm by 55% and the desired value of 1000 ppm by 86%! (See also appendix IV). This is unacceptable but unfortunately recognizable within Dutch primary schools. In the winter period, when the outdoor temperatures are relatively low, the windows of the classroom of group 7/8 are kept closed. As a result of the closed windows the indoor air quality exceeds the general accepted limit of 1200 ppm and thus insufficient. At high outdoor temperatures the windows were sometimes closed because of traffic noise produced by the nearby roadway. The windows aren't sufficient to obtain a good approach on the general limit of 1200 ppm most of the time!

The thermal comfort of the classroom during the measuring week is experienced slightly cold with an average PMV of -0,13 till -0,38. The percentage dissatisfied (PPD) varies from 6,1% on Monday to 8,3% on Thursday and sometimes temporarily increases to 20% (see also table 4.3 and figure 4.2). Despite the fact that the windows were opened sometimes, the PMV values are quite good. A PMV value of -1 to -3 would have to be expected.

Table 4.3 Calculated PMV and PPD

PMV	Mon	Tue	Wen	Thu	Fri
Mean	**-0,13**	**-0,37**	**-0,38**	**-0,38**	**-0,28**
Median	-0,09	-0,35	-0,37	-0,34	-0,26
Min	-0,87	-0,76	-0,78	-0,85	-0,68
Max	0,38	-0,13	-0,25	-0,23	-0,08
SD	0,19	0,13	0,11	0,13	0,14
PPD [%]					
Mean	**6,1**	**8,2**	**8,2**	**8,3**	**7,1**
Median	5,3	7,6	7,8	7,5	6,4
Min	5,0	5,3	6,3	6,1	5,1
Max	20,9	17,1	17,9	20,1	14,8
SD	2,6	2,2	2,1	2,6	2,3

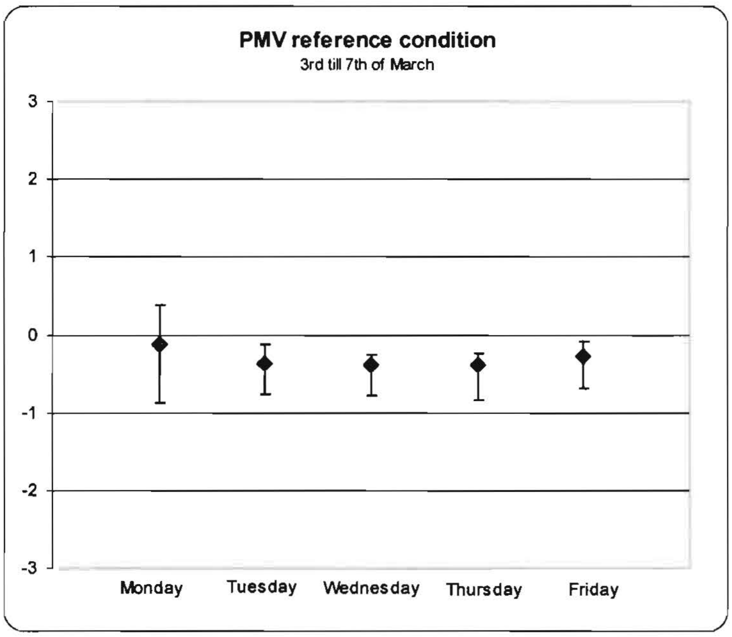


Figure 4.2 mean PMV per day with SD

Enquiry results

To obtain an indication of the IAQ and thermal comfort perception of the pupils an enquiry is performed at the end of this research. Two times the enquiry was executed, one before and one after the ventilation system was turned on. The interval between each enquiry was one month. The pupils were asked to judge the indoor climate based on the last two weeks according to a 7-point scale. Subsequently, the perception of the pupils is weighted (according to the 7-point scale). The scores from the 7-point scale are weighted from negative -3 and +3 with a minimum appreciation to neutral 0 with a maximum appreciation. The average score between 0-10 is calculated by dividing the actual score to the maximum score.

Figure 4.3 shows the perception of the pupils with respect to the IAQ and thermal comfort aspects. The scoreboard is scaled with 10 as an optimal situation. Two experiments are shown, the ventilation system turned off and the system turned on. On almost all aspects the ventilation system performs better working than not working. It's remarkable that pupils feel the same at the "Satisfying IAQ", "Comfort classroom" and the "Odours" aspect. The "Overall feeling" is even better when the ventilation system stays off. The pupils experience more "annoyance of noise" which is probably produced by the ventilation system. In spite of the measurements indicating more significant values, the pupils' opinion of the ventilation system is slightly better than when the ventilation system is turned off and the windows are opened sometimes.

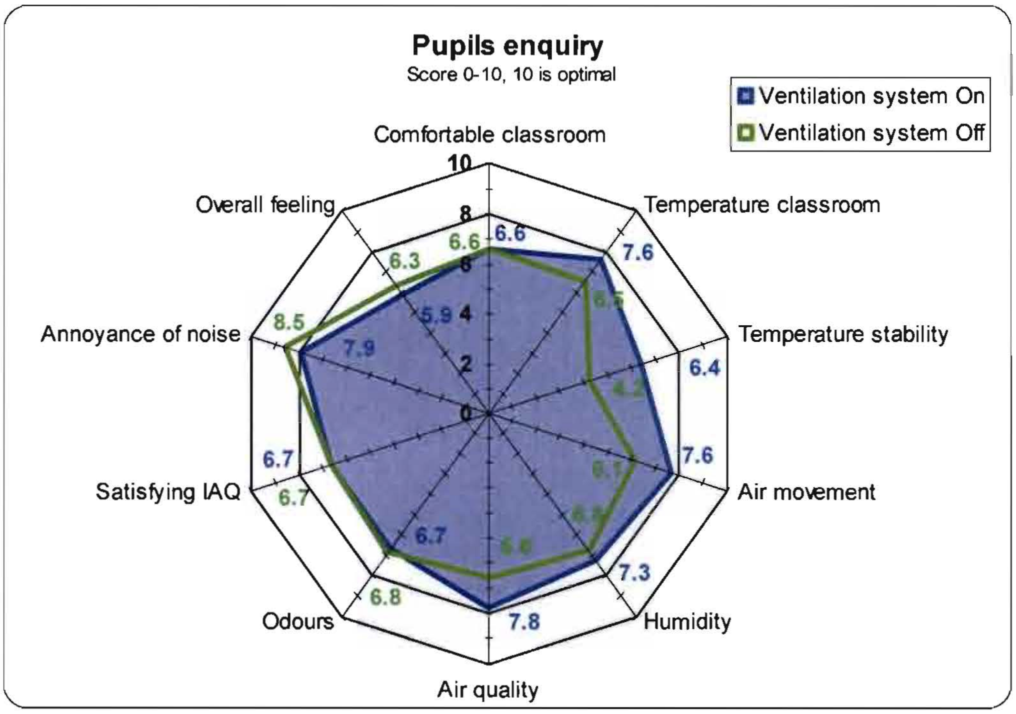


Figure 4.3 Average opinions of pupils for several aspects on a scale from 0 to 10. The perception of the pupils could be influenced and not representative.

The health complaints (see figure 4.4) are judged in the same way and no really significant improvements can be found. Only the stuffed-up nose, irritated eyes and tiredness are much better than before. The expectation of the ventilation system were much higher because of the dramatic IAQ at the reference conditions, a significant difference could be expected.

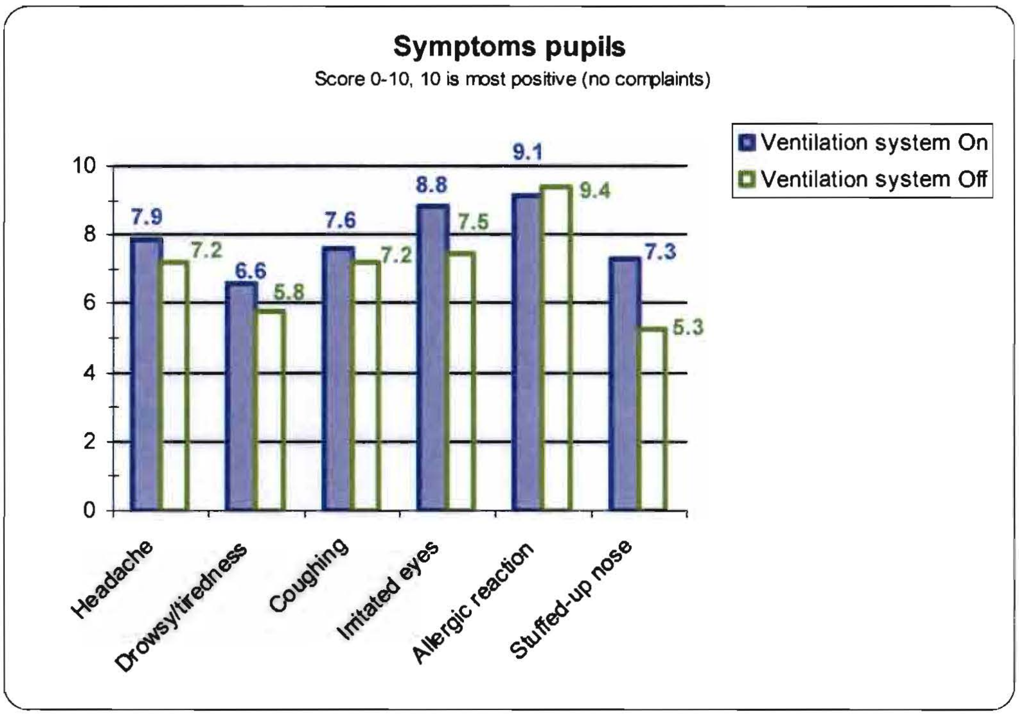


Figure 4.4 Average opinions of pupils for several health symptoms on a scale from 0 to 10. The perception of the pupils could be influenced and not representative.

A critical note to this outcome is the fact that two day before the last enquiry (ventilation system was turned on) the weather was warmer than the weeks before. This could have a distortion on the outcome of the score because the pupils incline towards a judgement based on the last moment and not the two last weeks (as asked).

4.2. REDUCTION OF THE AIR FLOW WITH DV

After the logger data of the preceding weeks was analysed, two experiments were performed to determine the CO_2 concentrations at several air flow rates. Because the CO_2 is strongly dependant of the occupation, air flow rate and time (CO_2 build-up) the final CO_2 concentration is determined with the median value when the CO_2 concentration was reasonably stable (most of the time just before morning/lunch breaks).

Experiment 1

At the first experiment, the total air flow rate was constant and the occupation changed every day (so that the air flow per pupil changed). See table 4.4 and also appendix V for location of the sensors and more detailed information. The table below (table 4.4 and also figure 4.5) shows the comparison between the theoretical values of mixing ventilation (MV), displacement ventilation (DV) and also the measured values of the DV system with a total air flow of 497 m^3/h.

Table 4.4 Comparison between theoretical and measured CO_2 concentration, experiment 1

Day	Pupils (and teacher)	Air flow per person [$m^3/h.pp$]/ [l/s.pp]	CO_2 outdoor [ppm]	CO_2 theoretical MV [ppm]	CO_2 theoretical DV [ppm]	CO_2 measured DV tripod (accuracy) [ppm]	CO_2 measured DV wall (accuracy) [ppm]
Monday	26+1	18.4 / 5,1	528	~1506	~1280	1224 (±97)	1184 (±97)
Tuesday	26+1	18.4 / 5,1	524	~1502	~1276	1188 (±97)	1145 (±97)
Wednesda	24+1	19.9 / 5,5	507	~1413	~1204	1177 (±97)	1043 (±97)
Thursday	22+1	22 / 6,1	495	~1328	~1135	1145 (±97)	1004 (±97)
Friday	20+1	23,7 / 6,6	513	~1273	~1098	1129 (±97)	1051 (±97)

<u>Measurement conditions and calculation:</u>

Median supply temperature 18,1°C SD ± 0,77, CO_2 production pupil 18 l/h (also used for teacher), air sock length 2x1,7 meter, measuring height CO_2 sensor at (breathing area) 1,1 meter

The theoretical values are based on the measured outdoor CO_2 concentrations and the actual air flow per person. Using the formula in Appendix V, the theoretical calculation* of the DV system is based on an efficiency factor ε_v of 1,3. As can be seen in the table the difference between the theoretical DV values and the measured values is within the bandwidth of the accuracy of the CO_2 sensors (marked green). At the wall the measured values are even lower than the theoretical values which means an even better ventilation efficiency ε_c>1,3.

* *Note: It seems the theoretical method of approach is quite accurate with a deviation of the average measured value of maximum -13,3% (lower measurement) and +2,9% (higher measurement)*

The difference between MV and DV is decreasing with a rising air flow rate. For DV a increasing air flow rate results in a declining ventilation efficiency. This is quite logical because the CO_2 production stays constant while the air flow increases. Thus the CO_2 concentration at breathing height becomes more and more the same as the exhaust concentration. The measured CO_2 concentration at the tripod (blue) crosses the theoretical DV line (yellow) at approximately 21,5 m^3/h. At the wall (magenta) the concentration decays parallel to the theoretical calculations.

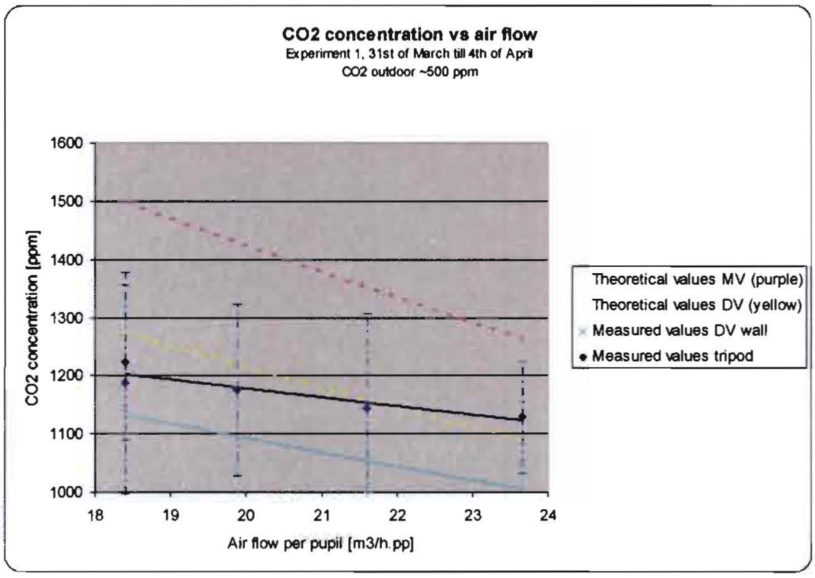


Figure 4.5

The exponential trend lines of the theoretical (dotted lines) and the measured values (continuing lines) of DV compared to MV with SD

The comparison can also be visualized by a graph (figure 4.6) which gives a good impression of the improvement of DV related to MV. The comparison is set up by dividing theoretical mixing value with the measured displacement values. This graph also includes error bars with the accuracy of the CO_2 sensors.

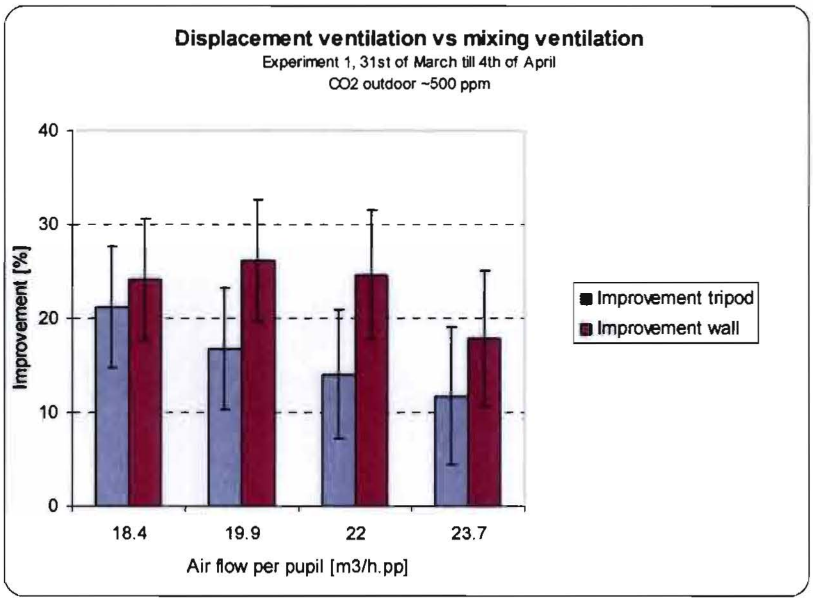


Figure 4.6

Improvement of IAQ DV versus MV with accuracy bars (no ventilation efficiency)

Experiment 2

On the second experiment the air flow rate was set on 800 m^3/h on Tuesday and Wednesday and 508 m^3/h on Thursday and Friday. Also an extra day is added because this day has reliable data and a typical air flow rate (557 m^3/h) and occupation of 22 pupils. Further on, during the week, the occupation changed every day. There is a noticeable difference in CO2 outdoor concentration, in the first experiment the concentration was around **500 ppm**. In the second experiment the concentration was around **400 ppm**. The table below (table 4.5 and also figure 4.7) shows the comparison between the theoretical values of mixing ventilation (MV), displacement ventilation (DV) and also the measured values of the DV system.

Table 4.5 Comparison between theoretical and measured CO_2 concentration, experiment 2

Day	Pupils (and teacher)	Air flow per person [m^3/h.pp]/ [l/s.pp]	CO_2 outdoor [ppm]	CO_2 theoretical MV [ppm]	CO_2 theoretical DV [ppm]	CO_2 measured DV tripod (accuracy) [ppm]	CO_2 measu DV wall (accuracy) [ppm]
1: 30-05-08	25+1	19,5 / 5,4	437	~1358	~1146	995 (±92)	1152 (±92) f
2: 29-05-08	24+1	20,3 / 5,6	431	~1317	~1112	999 (±88)	1074 (±88) f
3: 24-04-08	21+1	25,3 / 7,0	420	~1131	~967	908 (±97)	894 (±97) si
4: 28-05-08	24+1	32 / 8,9	418	~980	~851	660 (±77)	839 (±77) si
5: 27-05-08	22+1	34,8 / 9,7	422	~940	~821	802 (±79)	886 (±79) si

During the measurements two types of CO_2 sensors were used and the air sock length was changed from 2x1,2 meter to 2x1,7 meter. For more detailed information about the measurements also look at Appendix V.

On the first and second day of experiment 2, the wall CO2 sensor was located at the front of the classroom next to the school board in stead of the sidewall. It is obvious that the CO_2 concentration at the front wall is slightly higher (approximately 70-150 ppm higher, uncorrected) than the side wall when compared to the tripod values. There's an indication of a gradient between the back- and the front side of the classroom. The air socks are long and the air flow is low (508 m^3/h) during these days.

Figure 4.7 shows similar results as the graph of the second experiment. Notable is the lower outdoor concentration compared to the first experiment (which results in better average concentrations). This is why a ventilation rate of 24 m^3/h per pupils results in an average value of 1100 ppm at the first experiment and 1000 ppm at the second experiment.

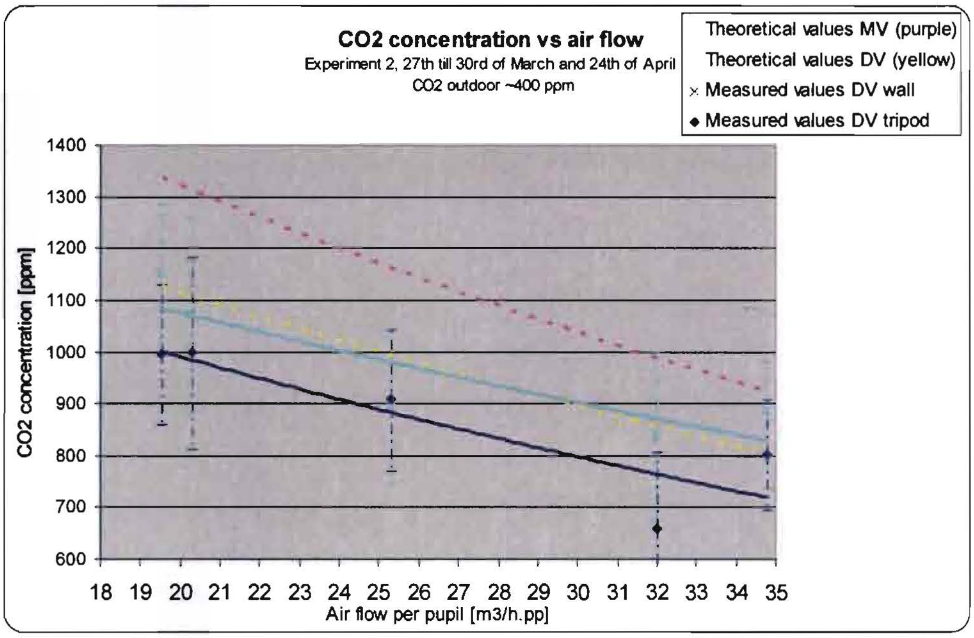


Figure 4.7 *the exponential trend lines of the theoretical (dotted lines) and the measured values (continuing lines) of DV compared to MV with SD*

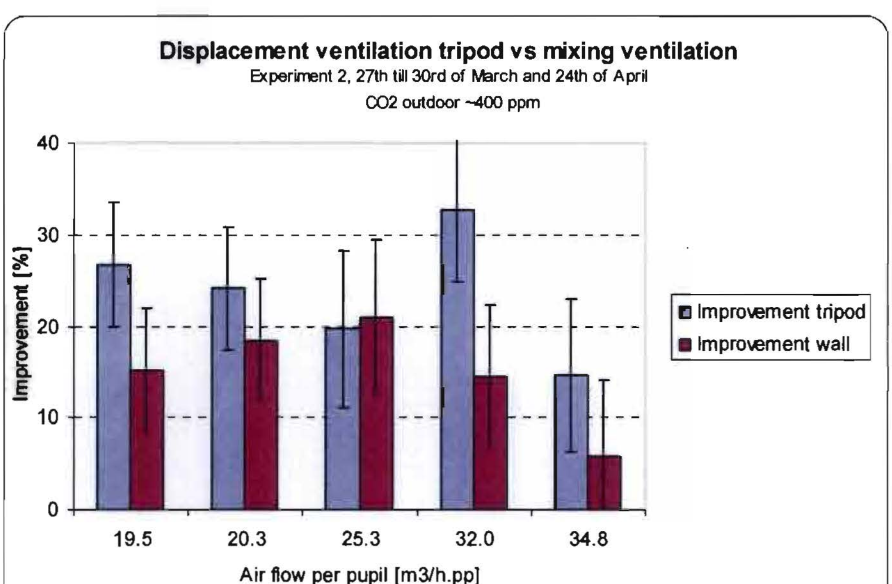


Figure 4.8

Improvement of IAQ DV versus MV with accuracy bars (no ventilation efficiency)

As earlier mentioned, the increasing air flow rate results in a decreasing improvement (efficiency) of the displacement system and the performance approaches the theoretical MV (see also figure 4.8).

The theoretically, the DV system needs an air flow rate of 23 m^3/h per person to obtain a stabilized CO_2 concentration of 1000 ppm (with 400 ppm outdoor concentration). In reality this is almost identical; the system only needs 24 m^3/h per person, while a MV needs 31 m^3/h per person to reach a good indoor air quality at the same outdoor conditions. This gives a reduction of the needed air flow of **23%!** Where MV needs 25-26 m^3/h per pupil to obtain a maximum CO_2 concentration below 1200 ppm, the DV system needs only 18-19 m^3/h per pupil. This reduces the needed airflow by approximately **27%**!

Although the benefit of DV (efficiency) decays with the air flow rate, the system keeps a higher performance than a MV system.

4.3. PRIMARY ZONE SUPPLY DIFFUSER

In order to determine the primary zone of the textile air diffusers the air velocity is measured at different distances and air flows. Measurements took place every 5 seconds and after 5 minutes the air flow was changed. The first and the last minute of the measuring period were ignored because of irregularity due to changing the measuring position. The standard measuring height was fixed on 2 cm above floor. Both air sock lengths were measured (1,7 and 1,2 meter). The distance of the omni directional anemometers were changed within referred distances from the air sock (see picture 4.9). After all the distances were measured, a graph with the velocity distribution at several distances can be generated, see figure 4.10.

Figure 4.9 Measuring line up with anemometers at several distances from the textile air diffuser

These measurements took place with a sock length of 2x 1,7 meter and an air flow of approximately 550 m^3/h (ventilation system set on 55%). Within close distance to the air sock the air velocity was relatively low. As a result of the gravitation effect of the cold air, the velocity increases until the highest velocity is reached at approximately 1 meter. After the 1 meter distance the velocity decreases almost linear with distance to and average end-value of approximately 3-5 cm/s at the front of the classroom. The primary zone ($L_{0,2}$) is in this case around 2,5 meter from the air sock. Table 4.6 shows a summary of the primary zone of all the cases which were measured. The velocity distribution of all the investigated cases (see also Appendix VI for more details and logbook) show rough similarities to the findings of Mattsson (1999) from graph 3.5.

Table 4.6 Primary zone at different lengths of the textile air diffusers and different air flows

Length air sock [m]	Air flow [m^3/h]	Length primary zone [m] h= 2 cm
2x1,2	~500	1,3
	~550	3,1
2x1,7	~450	1,1
	~550	2,5

Ing. D.J.B.W.Schuiling
10 December 2008

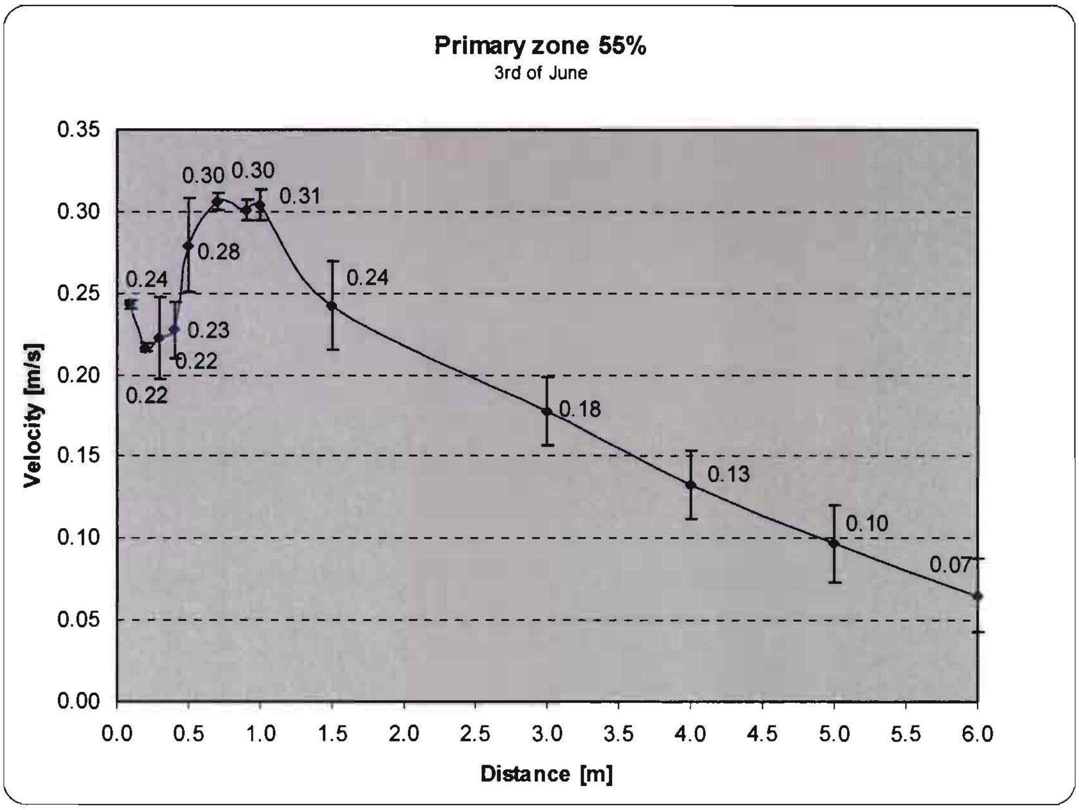


Figure 4.10 *Distance from the textile air supply diffuser into the classroom versus the measured air velocity at 2cm above floor level with SD. Primary zone (v=0,2 m/s) at approximately 2,5 meter from textile air diffuser. Average air flow 550 m^3/h.*

Measuring data

T_{room}	23,1	[°C]
T_{supply}	20,7	[°C]
ΔT	2,4	[K]
$T_{extract}$	24,4	[°C]
$q_{vsupply}$	550	[m^3/h]
$q_{vextract}$	532	[m^3/h]
Sock length	2x1,7	[m]
$L_{0,2}$	2,5	[m]

The measured air velocities are mostly (too) high within the first meters, so it is important to investigate the velocity distribution further in the vertical plane. The ankle height of 10 cm is an important height as a draught indication height. Therefore the omni-directional anemometers were positioned vertically at the distances of 2 cm, 5 cm, 10 cm, 15 cm, 20 cm and 30 cm from the floor surface (see also picture 4.11 and 4.12). In these cases also the air sock length, the air flow were and the measuring distances were changed (see also Appendix VI for logbook).

Figure 4.11 Measuring line up with anemometers at several heights and distances from the textile air diffuser

It is remarkable to see that the velocity distribution above 5 cm is almost constant at all the measured distances. Only the 0,5 meter line show a fluctuation within the 5-30 cm height. The highest velocity is measured at 2 cm above floor level and the velocity almost divide into halve at 5 cm. This is an important finding because it can be expected that no draught problems could occur when the air flow is at least 550 m^3/h (which is the minimal required amount of fresh air to obtain a good air quality). The last three rows of the boundary conditions table show that the height at which draught problems might occur **is always below the 5 cm height**. Only the measurements with short air sock and an air flow of approximately 550 m^3/h show that the air velocity exceeds its limits at 8 cm height and 1,5 meter from the air sock. The highest velocity is 0,4 m/s at 2 cm height at this distance.

At the end of the velocity measurements obviously **no draught problems** would be expected to occur because the maximum velocities are around 0,4 m/s at 2 cm height results in a velocity of 0,13 m/s at 10 cm height.

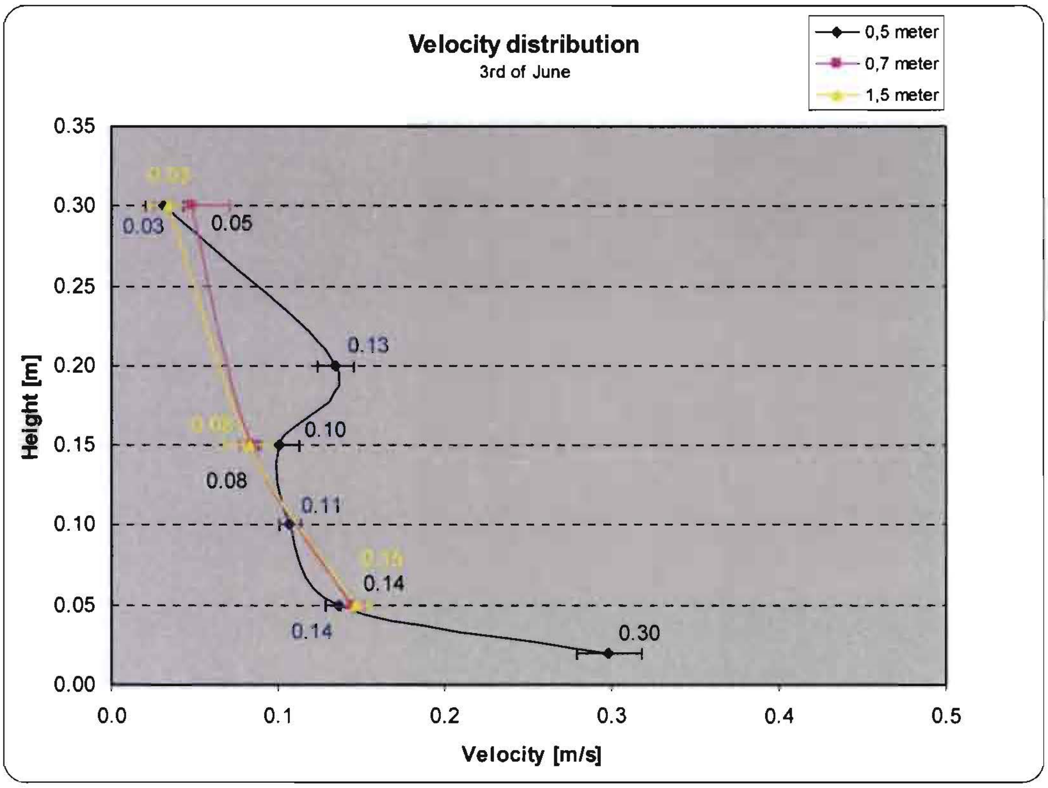


Figure 4.12 Several measuring heights (at three distances from the textile air supply diffuser) versus the measured air velocity with SD. Primary zone (v=0,2 m/s) all within 0,5 meter from the textile air supply diffuser at 10 cm height. Average air flow 550 m³/h.

Measuring data

T_{room}	22,9	[°C]
T_{supply}	20,2	[°C]
ΔT	2,7	[K]
$T_{extract}$	24,1	[°C]
$q_{vsupply}$	550	[m^3/h]
$q_{vextract}$	532	[m^3/h]
Sock length	2x1,7	[m]
$H_{0,2 @ 0,5m}$	<0,05	[m]
$H_{0,2 @ 0,7m}$	<0.05	[m]
$H_{0,2 @ 1,5m}$	<0.05	[m]

4.4. VISUALISATION AIR FLOW PATH

The buoyancy near the person simulator was investigated with the help of a smoke generator. As expected the smoke rises to the ceiling as a result of locally heated air.

Also the smoke was injected in the suck in opening of the air handling unit. The smoke enters the room through the air sock and is obviously and equally spread along the floor surface. Because the smoke has the same temperature as the air supply temperature of approximately 18°C (and an average room temperature between 20-21°C), the smoke stays low along the floor for a while (see also figure 4.13) because no natural heat sources were available. As soon as heat sources were introduced, the upwards convection stream builds up. These smoke tests are in line with the prediction of Brohus (1997) figure 3.6 in paragraph 3.3.4.

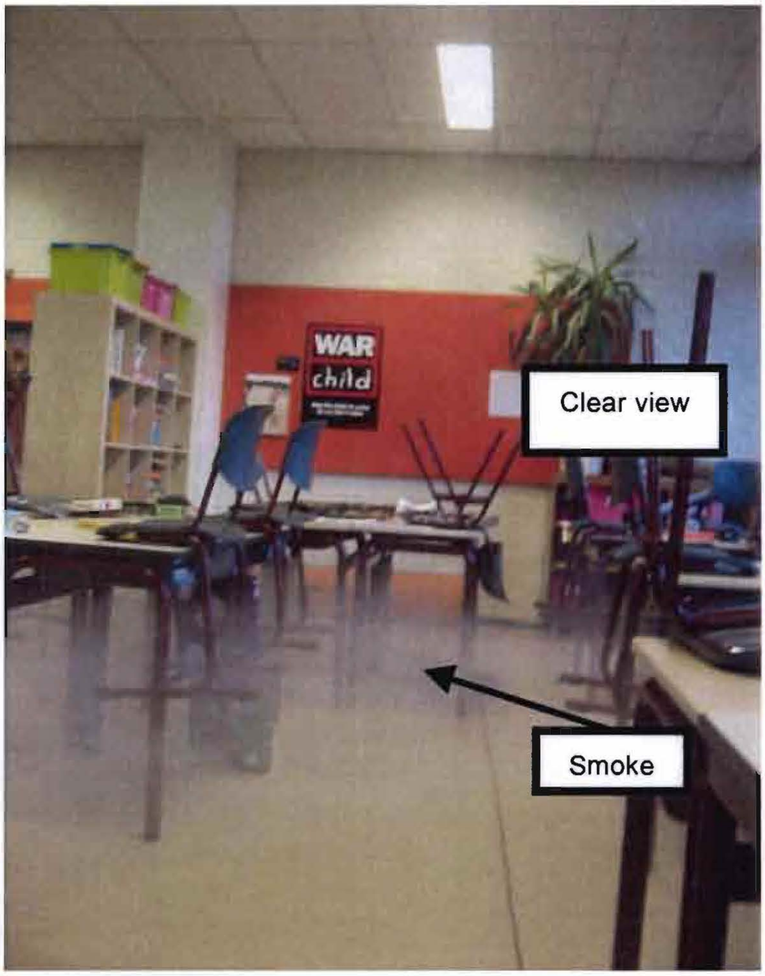


Figure 4.13 Smoke tests: smoke stays low

4.5. TEMPERATURE STRATIFICATION

The vertical temperature gradient is assumed to be constant throughout the room (except at surfaces), the gradient was measured one location (see picture 4.14 and Appendix VII for more information).

Figure 4.14 Vertical temperature gradient measurements at one location (marked red)

The temperature gradient was measured during a couple of weeks and peak values were evaluated. Figure 4.15 shows a comparable build-up of the vertical gradient as figure 3.7 from Mattsson (1999). The stratification height is on approximately one meter (near the breathing height of the children) above floor level where there almost isn't any temperature rise anymore. The dotted red line indicates the turn over point between the big gradient below one meter and the small gradient above one meter height.

There's only a small difference between the supply temperature of 18,4 °C and the floor surface temperature of 19,2 °C and therefore the 50%-rule isn't quite accurate in this situation. The real temperature ration ε is 21,6%, thus only 1/5 of the temperature difference between the supply and the exhaust air is added at floor level. The maximum temperature gradient during the experiment is used as an example, the gradient between ankle and head was 2,8 K. The total temperature gradient was 3,7K.

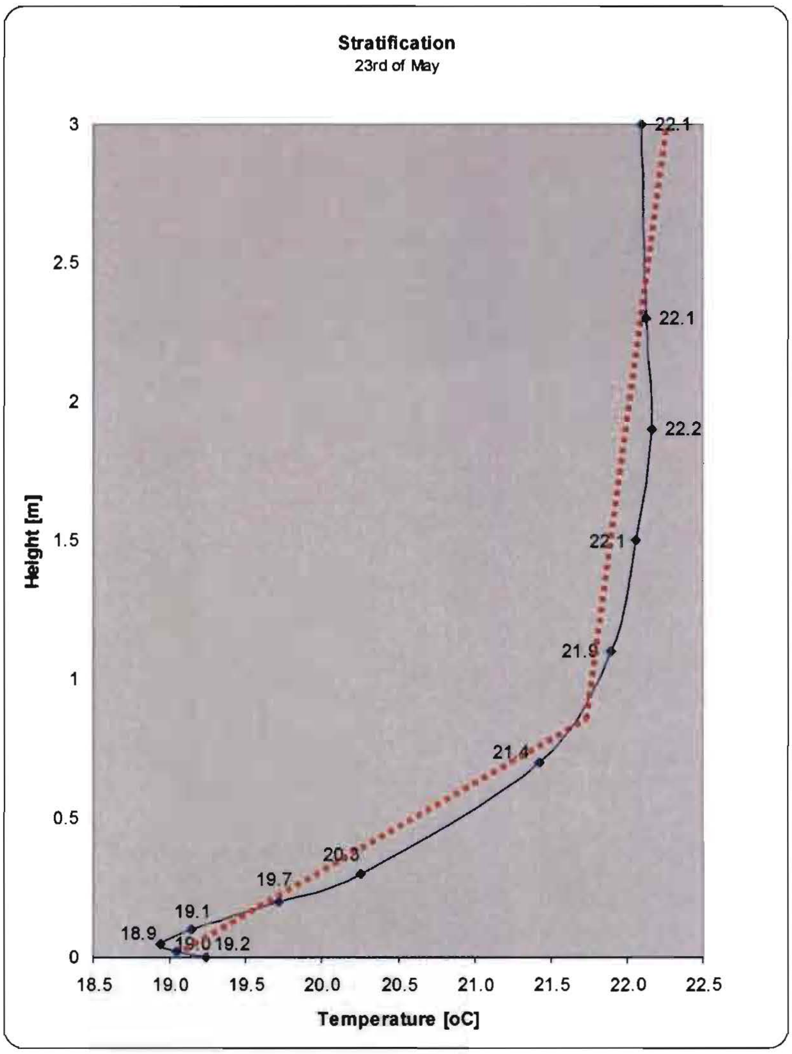


Figure 4.15 Vertical temperature gradient, height versus the temperature. The stratification height at approximately one meter. Total temperature gradient of 3,7 K.

Measurement data

T_{supply} (T_s)	18,4	[°C]		
$T_{outdoor}$	17,9	[°C]	26 pupils	
$T_{extract}$ (T_e)	22,1	[°C]	Supply air flow	550 [m³/h]
$T_{occupied\ zone}$ (T_{oz})	21,9	[°C]	Extract air flow	532 [m³/h]
T_{floor}	19,2	[°C]	Extracted heat	680 [W]
ε_T	1,06	[-]	dT (0,1 meter – 1,1 meter)	2,8 [K]
ε, real percentage	22	[%]		

Also three other cases were selected based on the occupation and air flow at the moment, see table 4.7. The accuracy of the used NTC's (see also Appendix IX) is high ±0,05K and therefore the accuracy of the temperature efficiency ε_T isn't mentioned in this table.

Table 4.7 Temperature stratification at different cases

Case	T_o [°C]	T_s [°C]	T_f [°C]	T_{oz} [°C]	T_e [°C]	ε_T [-]	ε_C [-]	Air flow [m³/h]	Occup. [-]	Ex. heat [W]
1: 23-05-08	17,9	18,4	19,2	21,9	22,1	1,06	n/a	550	26	680
2: 27-05-08	16,6	18,5	18,4	20,9	21,1	1,08	1,15±0,08	800	23	695
3: 28-05-08	18,0	20,2	19,4	21,4	21,7	1,25	1,33±0,08	800	25	400
4: 29-05-08	18,1	20,5	20,3	22,3	23,1	1,44	1,24±0,07	508	25	440

During all cases the maximal vertical gradient between ankle and head didn't exceed the maximum value of 3 K/m.

The ventilation efficiency ε_c is added in the table to compare it with the temperature efficiency ε_T , see formula [1] in paragraph 2.2. The ε_c of the tripod is used because this sensor is the closest to the temperature stratification line up. As expected there is a relation between the ventilation- and the temperature efficiency (case 2, 3 and 4). The polluted air is heated due to the body surface (also exhaled air) and is carried upwards by the buoyancy stream near the body. However, the efficiency values aren't exactly the same due to influence factors like for example: measuring location, CO_2 gradient in the horizontal plane and the accuracy of the CO_2 sensors. In all the considered cases the ventilation efficiency ε_c and the temperature efficiency ε_T were higher than 1 (mixing ventilation) varying from 1,06 to 1,44. See also formula [3] in paragraph 3.3.5.

The temperature difference is high in the lower part of the room due to the pupils as heat sources, this conclusion unite with the findings of Skistad (2004). According to Skistad (2004) the fresh air flow per person must be more than 20 l/s (72 m³/h to balance with the natural convection flows and obtain a stratification height above the heads of the pupils. Although the stratification height is at the breathing height of the pupils, the displacement effect near the body could provide a better inhaled air quality. This aspect of displacement ventilation is discussed in the next paragraph 4.6.

4.6. VENTILATION EFFICIENCY

The efficiency measurements took place on a normal school day with morning and a afternoon session (see figure 4.16). The occupation was constant with 23 persons and when the ventilation system turned on the air flow per person was 22 m^3/h (6,1 l/s).

Before the start of the school day (first period) the ventilation system was turned off. After one hour the CO_2 concentration was between 1700 and 1900 ppm just before the ventilation system was turned on. Within the first three minutes the CO_2 concentration at the PS sensor was decreasing. After twelve minutes the CO_2 concentration at the wall- and the tripod sensor were decreasing. It is plausible that the displacement effect at the PS causes the extract sensor to decrease earlier than the wall- and tripod sensors (after six minutes).

The second period started after the morning break at 10:45 when the system was turned off again. After three quarter of an hour the CO_2 concentration was build up again to a value between 1500-1750 ppm. Subsequently the ventilation system was turned on and the sensor of the PS again decreased within the first three minutes. The other sensors follow after twelve minutes except for the extract sensor with an obvious decrease after six minutes. Just before lunch break the CO_2 concentration was around 1000 ppm at the PS sensor and between 1200-1300 ppm at the other sensors (and declining).

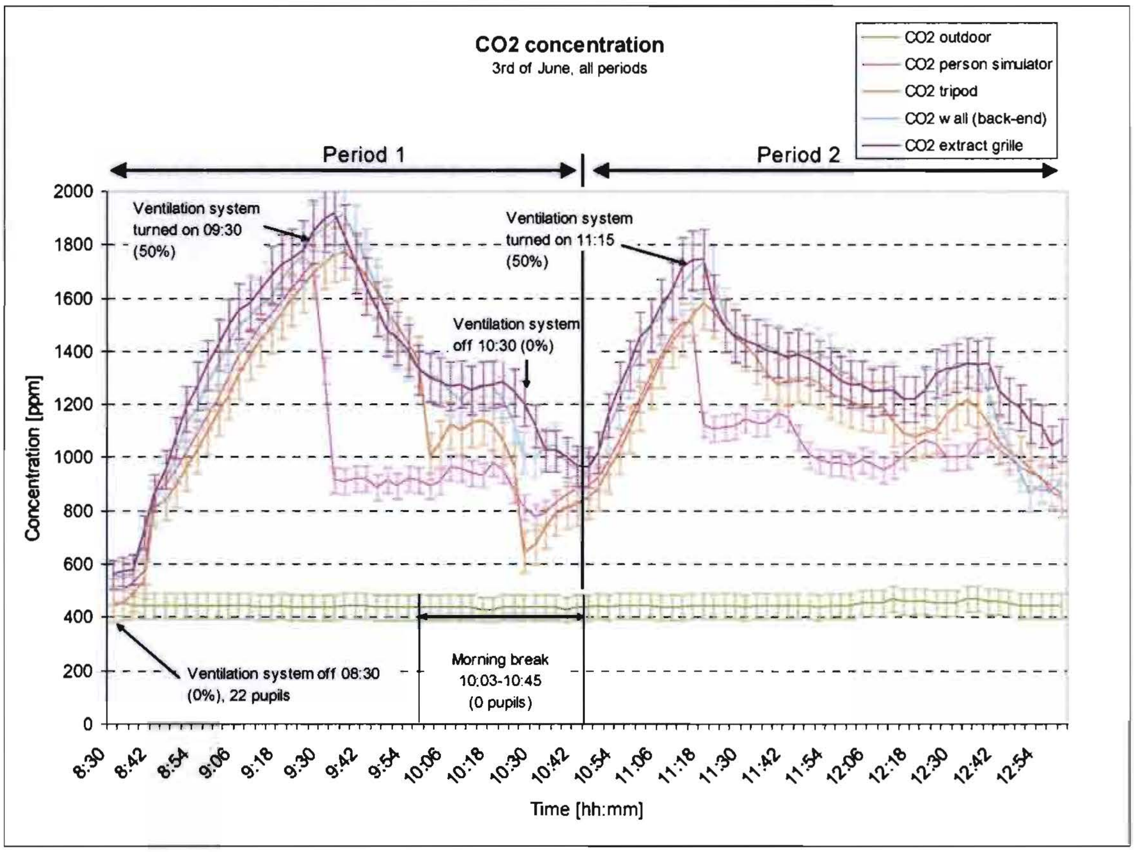


Figure 4.16 CO_2 concentration curves of the efficiency measurement. At 9:30 and 11:15 the air quality at the PS improves quickly, the other measuring points follow later.

More detailed information about the second period can be found at Appendix VIII.

A closer look at the first period gives a good impression of the displacement effect and the ventilation efficiency, formula [1] and [2] in paragraph 2.2. The displacement effect is the difference between the concentration at the tripod and the PS is marked with green arrows in figure 4.17. In the first hour the error bars of the tripod and PS curves cross each other. However, after turning on the ventilation system the error bars do not longer cross and a significant improvement is made.

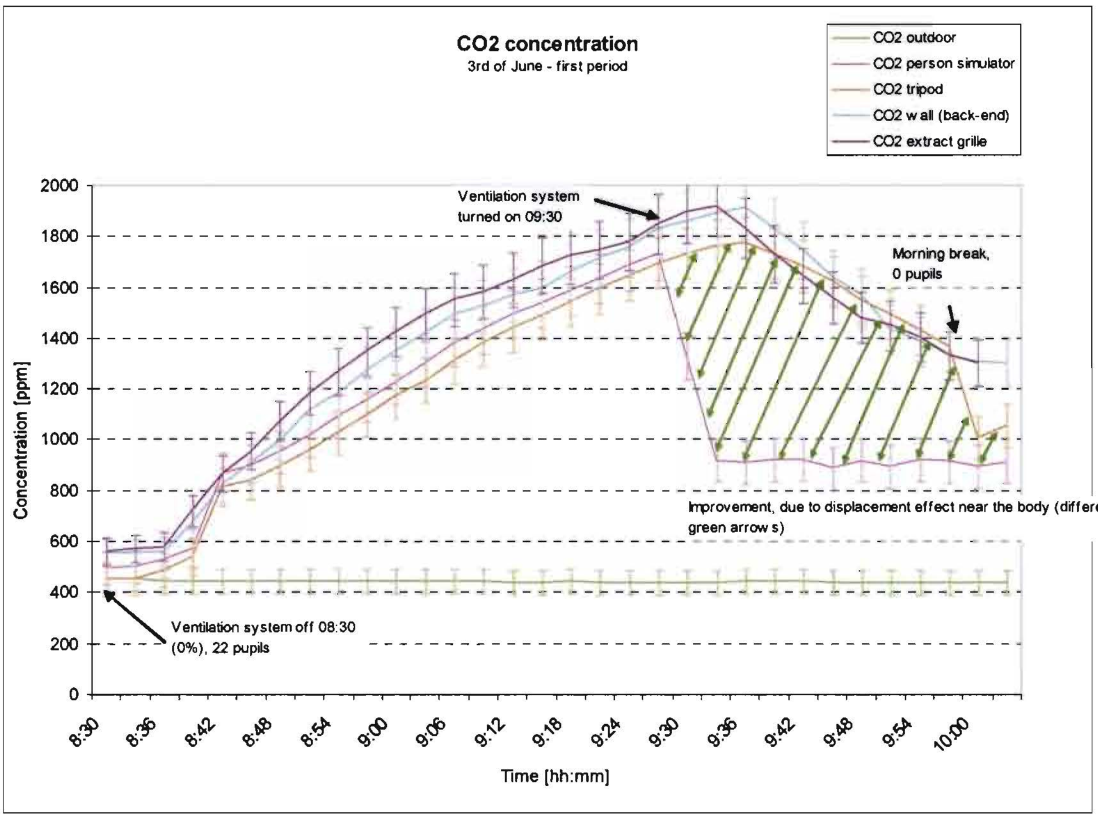


Figure 4.17 CO_2 concentration curves of the first period, displacement effect is marked green. The improvement (difference between PS and other locations) is significant.

Before the ventilation system is turned on it's clear that the ventilation efficiency is higher than one. That's because the warm air rise to the ceiling in a natural way (this is also visible in figure 4.18 where the concentration at the extract grille is always the highest). After the system is turned on, the ventilation efficiency gives an optimistic overshoot. That's because it takes time to displace the old air by new air (nominal time constant* is 21

* *The nominal time constant is defined as the average time it takes for an air particle to flow from the supply opening to the exhaust grille. The inverse of the nominal time constant is the exchange rate of the room per hour*

minutes) and the CO_2 concentration at the ceiling is relatively high at the beginning related to the sensors at breathing height.

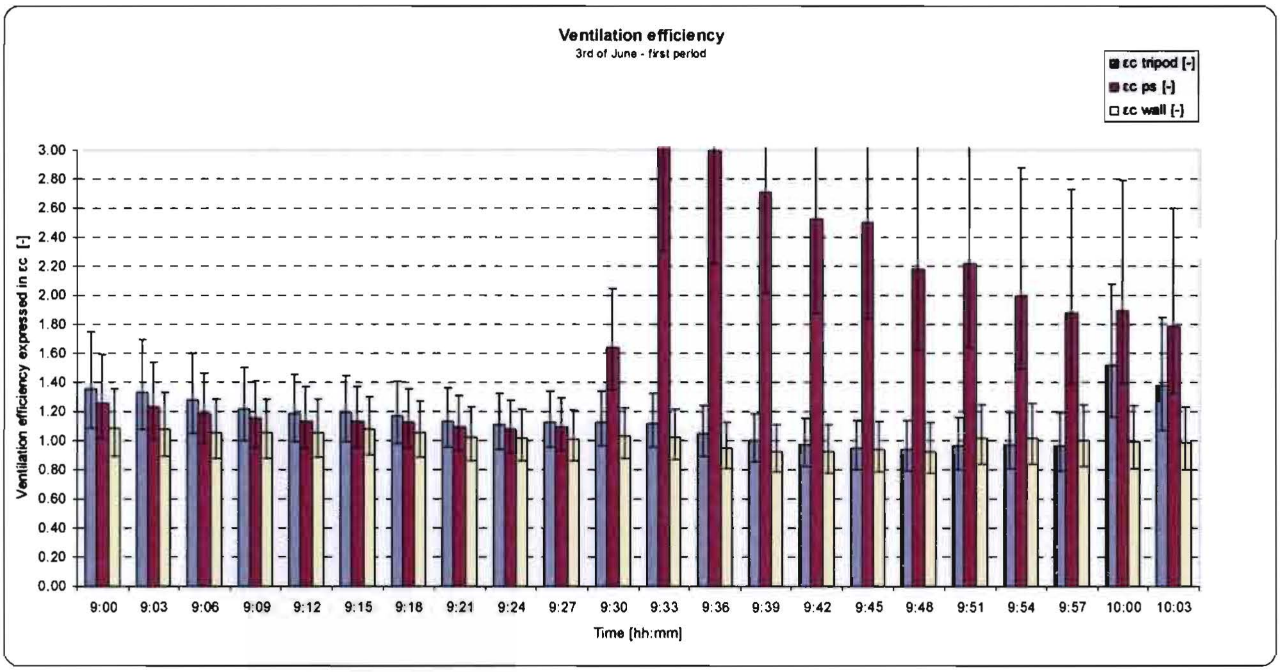


Figure 4.18 The calculated improvement near the body, the so called displacement effect ε_{exp}. When the system is turned on (9:30) the efficiency instantly improves at the PS. After a half an hour (nominal time constant) first the tripod follows with a higher efficiency.

Despite this delay the CO_2 concentration at the **PS stays superior** to the sensor at the tripod where no buoyancy occurs. In this case, the displacement effect near the body gives an air quality improvement up to **50%**.

4.7. ASSESEMENT FIELD EXPERIMENTS

Before evaluating the experiments I would like to emphasize that the measurements were performed in a non steady state situation. Despite the fact that the chosen school is a typical Dutch school building, one should be reserved to draw hard conclusions. A classroom is a turbulent environment; therefore it's difficult to draw definite conclusions. The conclusions of the measurements give an indication of the performance of a DV system. Most of them are significant enough to get a good impression of the potential performance of the DV system and may be generalized.

This paragraph gives an assessment to what extent the findings from the literature study unite with the outcome of the experiments.

Reference conditions of original classroom

As expected, the reference conditions of the examined school building aren't very different from other Dutch school buildings. The indicator for IAQ, the CO_2 concentration, is very high (above 2000 ppm). Despite the fact that windows weren't opened in March, the average indoor air temperature was slightly low varying from 18 to maximum 22 ^{o}C. This results in a PMV between -0,08 to -0,87. The current air change rate isn't sufficient to obtain a good IAQ during the winter period.

The enquiry results aren't very significant compared to the differences of the measured IAQ. It seems people aren't aware or don't engage in the quality of the indoor air. They are used to a bad IAQ in winter and a better IAQ in summer. The perception of the pupils can be influenced by the actual day of the enquiry. Also I can't expect the pupils to be consistent when they fill in the enquiry.

Reduction of the air flow with DV

Theoretically steady state conditions of DV holds an ventilation efficiency (expressed in ε_c) between 1-1,3 so that up to 30% less air is needed to obtain the same IAQ as a MV system. From a range of 19 to 35 m^3/h per person measured for two weeks, the ventilation efficiency is equal or sometimes even better than the theoretical calculated factor (1,3) for displacement ventilation. For this typical Dutch school building the theoretical value gives a good prediction of the IAQ with a displacement ventilated classroom. The accompanying reduction of the fresh air flow of 23% results in an air flow of 24 m^3/h per pupil in stead of 31 m^3/h per pupil when an average CO_2 concentration of 1000 ppm is desired. The extra advantage of the air flow near the body of the PS isn't yet included!

Note: The prediction of the performance of MV is based on a theoretical method of approach described in the practical guideline NPR-CR 1752. No measurements were performed in this study to validate this approach for mixing ventilation and it is assumed to give a reasonably good indication for MV like it does for DV.

Primary zone supply diffuser

At the beginning the primary zone was measured at 2 cm above floor level. The primary zone was very long (e.g. 3 meter) with a long and a short textile air diffuser at the nominal air flow situation (550 m^3/h). Later on it seems useful to measure the velocity at greater distances from the floor, because of the differences of personal thermal sensation in height when repositioning the anemometers. Eventually it turned out that the air velocity reduces by half when the air velocity is measured at 10 centimetres above floor. Since this is ankle height, it's important for possible draught problems. For the observed situations the pupils can be seated at a distance of 0,5 meter from the textile air diffuser without draught problems (or occasionally when airflow changes).

Visualisation air flow path

The smoke from the smoke generator spreads equally across the floor like water. It reaches every corner in the classroom. As soon as a heat source (e.g. person or radiator) is reached the smoke rises to the ceiling. At the ceiling the smoke circulates before it is extracted out of the classroom. No air flow along cold windows or walls was observed. Furthermore the air flows through the classroom as predicted.

Temperature stratification

As expected the temperature efficiency of the DV system is above 1 varying from 1,06 to 1,44 during the experiments. As expected, there is a relation between the ventilation efficiency and the temperature efficiency. The stratification height is also around one meter as predicted. The critical vertical temperature gradient between ankle and neck stays below 3 K/m thus no complaint would be expected. The recorded temperature gradient has been the strongest close to the floor, declining with height. The temperature stratification was only measured at one location because of the statement of Mattsson (1999) that the temperature gradient in the horizontal field is almost constant.

Ventilation efficiency

The ventilation efficiency of the DV system turned out to confirm the theoretical efficiency value between 1-1,3. Despite the turbulent environment the efficiency stays above 1 and therefore performs superior to a MV system. In this research the extra efficiency near the body of a person is proved to achieve its maximum at 50%. This means that the air around the PS contains 50% less CO_2 than a measuring point elsewhere in the classroom at the same height. This reduction of personal exposure may not be used to reduce the fresh air flow even more because this effect can be distorted very easily by movements of the pupils themselves.

Thermal comfort

The thermal comfort measurements with the ventilation system turned on gave good PMV values. However, PMV values between the reference conditions and the measurement with the ventilation system may not be compared because the outdoor temperatures were approximately 10 degrees warmer than the reference conditions. No definite conclusions can be drawn.

5. EVALUATION: IMPLEMENTATION OF A DV SYSTEM

At the end of the field experiments several (physical) parameters came out of the typical Dutch classroom, e.g. air flow per pupil, air supply temperature, system capacity, etc. These parameters are combined with the classification standard B from preliminary study TVVL (2006)* and enumerated in the table below.

Table 5.1 The (physical) parameters extracted from the field experiments

Occupation		
Surface per person	~2	[m^2]
Thermal comfort		
Operative temperature - winter	20-22	[°C]
Operative temperature – summer (excluding school vacations)	23-28	[°C]
Air velocity (draught) - winter	<0,16	[m/s]
Air velocity (draught) - summer	<0,2	[m/s]
Floor temperature (cold/warm feet)	19-26	[°C]
Air Quality and ventilation		
Desired concentration CO_2 (with outdoor concentration of 400 ppm)	1000	[ppm]
Required amount of ventilation air (with ε_v=1; MV)	8,4	[l/s.pers]
Ventilation rate (@ 176 m^3 and 25 pupils and a teacher)	~5,4	[1/h]
Required amount of ventilation air (with ε_v=1,3; DV)	6,7	[l/s.pers]
Ventilation rate (@ 176 m^3 and 25 pupils and a teacher)	~4,3	[1/h]
Supply air		
Minimal air supply temperature (no cooling)	18-19	[°C]
Under temperature compared to occupation zone	1-5	[K]
Length of the primary zone <0,2 at 10 cm height	<0,5	[m]
Noise		
Traffic noise with closed windows	35	[dB(A)]
Installation noise	30 (NR25)	[dB]

To give an indication of a possible implementation of a DV system two options were examined briefly, a Plug & Play and a centralized option.

* *During this research the classification from the TVVL preliminary study is followed by a new publication ISSO 89: Binnenklimaat scholen (2008). The changes made to the classification are evaluated in Appendix I*

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DISPLACEMENT VENTILATION SYSTEM 1: PLUG & PLAY

The first suggested ventilation system is a Plug & Play system especially suitable for existing school buildings. This decentralized system is placed in the classroom at the front or the back of the classroom. Special attention is needed to safety and robustness and sound level of the "ventilation box". The system can be modularly expanded to more classrooms and investment can be spread over a longer time. The ventilation system is not designed for a specific school but can be applied generally. Thereby the system can be reused in other school buildings. The maintenance of the ventilation system is carried out by the facility manager or the teachers themselves. The system can be used temporarily to bridge a period before a new school building is build. Two holes in the ceiling or facade are necessary to enable air supply and air extract.

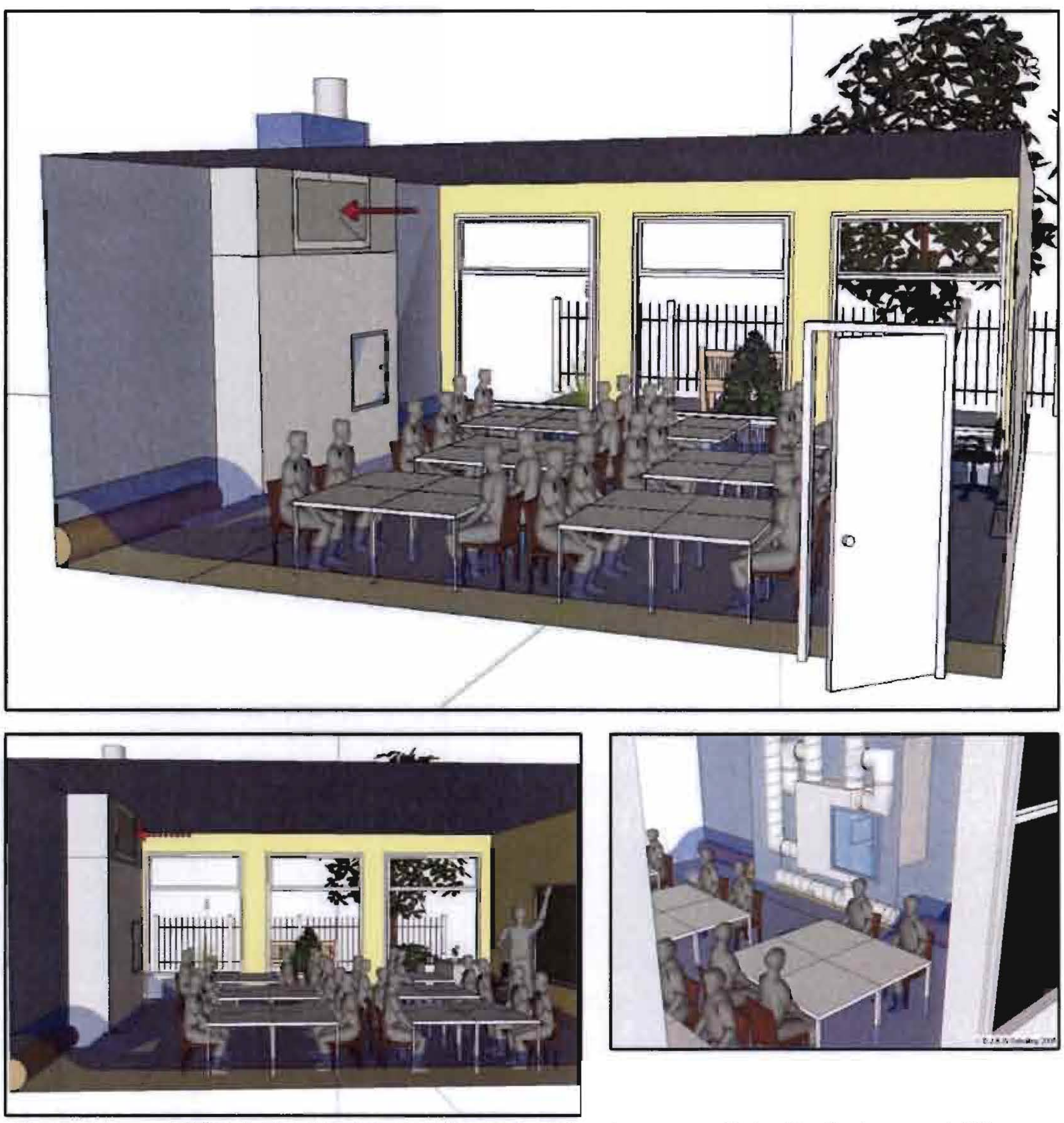

Figure 5.1 A "Plug & Play" prototype at the back of the classroom with textile displacement diffusers on both sides

DISPLACEMENT VENTILATION SYSTEM 2: CENTRALIZED SYSTEM

The second ventilation system is based on a central/combined system and is especially suitable for new school buildings. All classrooms are connected to the central system; therefore the initial costs of the system are relatively high but the system. The maintenance is centralized and therefore less time consuming and this system is less expensive in exploitation costs. A cooling system can be integrated in the system easily. Also afterwards a cooling system can be added when an empty section is reserved for the cooling coil in the air handling unit. Because of the needed air ducts for transportation the implementation of this system in an existing school building is more radical and difficult and therefore less suitable.

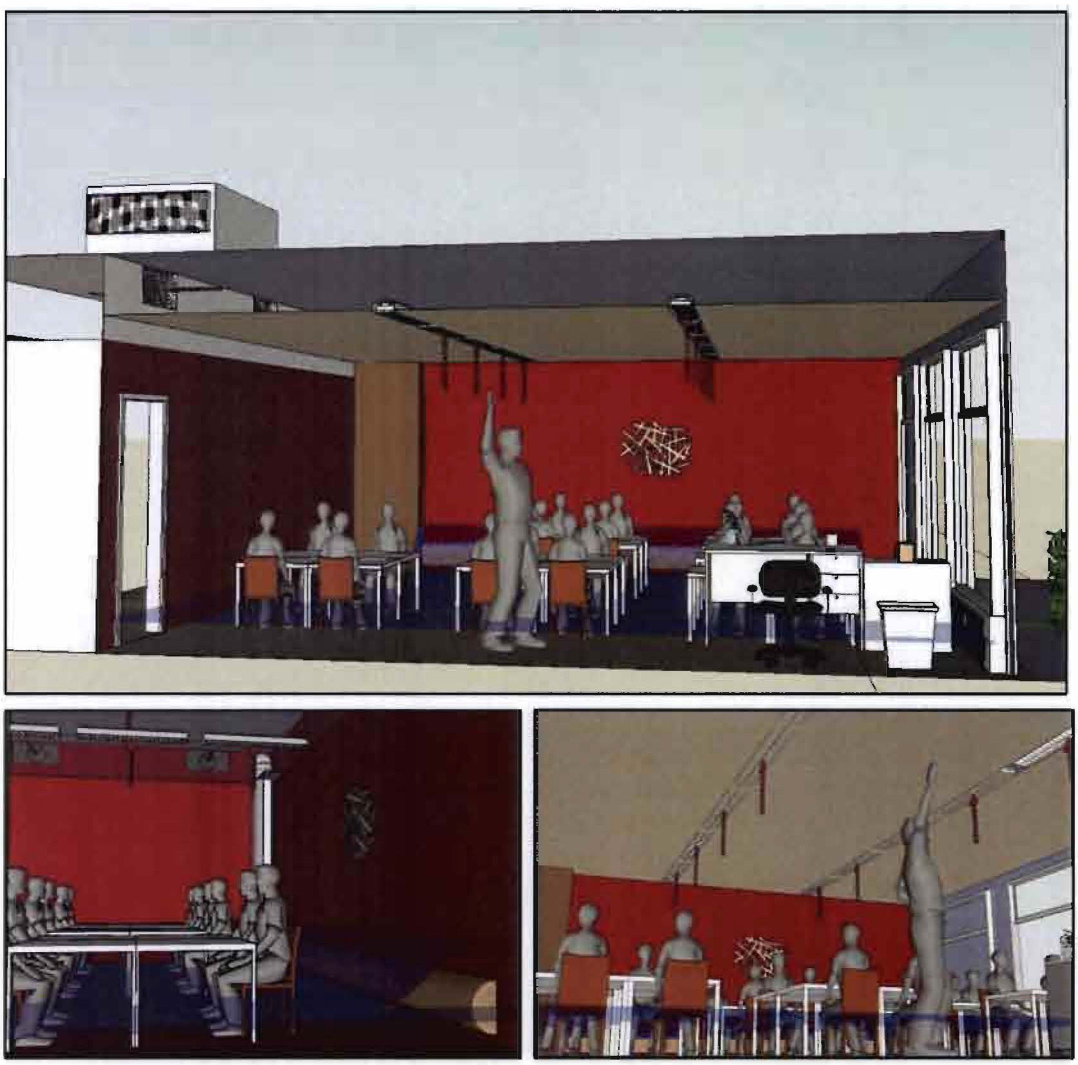

Figure 5.2 *A centralized prototype at the back of the classroom with a long textile displacement diffuser. Air supply ducts behind panels (or a double wall) and extraction through lighting fittings and extract grilles in the corridor wall*

The air ducts can be removed from sight by for example a double wall. To increase the robustness of the textile air diffuser, it can be placed behind a perforated panel inside the double wall. The space between two walls is only 300 mm for a classroom with 25-30 pupils.

Both options are evaluated and several supplements to the systems are described in Appendix X.

Investments

According to ISSO 89 (2008), an indication of the costs of a suggested ventilation system for an existing school building is around €5800,- including balanced demand controlled ventilation with heat recovery. These costs aren't depending on the type of ventilation system. As a logical result one could expect a DV system to be cheaper because of smaller system components. The exact costs of a DV system need to be examined for each situation individually.

These costs seems to be high for the board of a school, on the other hand several other aspects need to be taken into account for a good comparison. Comparatively, if we only take into account the reduction of personnel costs (sick leave, work productivity) of the teachers in a school (€15,-/m^2 per year) with a good IAQ. The pay back time of the investment of the ventilation system of €230,-/m^2 (in a standard classroom) becomes economical feasible (ISSO 89, 2008). Board of schools or municipalities don't realise this positive effect, simply can't pay the initial investment or don't see necessity for a ventilation system.

The school could also outsource the ventilation system without any responsibility. A lease contract with guarantee for a good IAQ enables the school to go into action and purchase a ventilation system without high initial or maintenance costs.

Energy costs

Rough calculations of the energy costs of a DV system with a 80% heat recovery lead to costs of €38,- per classroom per year (see also Appendix XI). These costs aren't higher than a normal natural ventilated classroom with a poor IAQ and thermal comfort problems (in winter). A DV system with a 50% heat recovery consume slightly more thermal energy which result in total energy costs of €62,- per classroom per year. When a classroom is ventilated in a natural way and a good IAQ must be obtained, the total energy costs are €96,- per classroom per year. In this case draught problem could be expected.

6. CONCLUSION

A displacement ventilation system has a high potential in improving the IAQ in primary school buildings without significant negative effect on the thermal comfort in the classroom. When a DV system is implemented control of physical parameters as mentioned in the experiments are essential for DV system to be successful. When these boundary conditions are taken into account a DV system could perform as mentioned in the previous chapters.

- Reduction of the air flow of ~ 23% compared to mixing ventilation at identical CO_2 concentrations;
- Short primary zone around ~0,5 meter, highest velocity measured 2 cm from floor. The maximum velocity almost divide into a third at 10 cm from floor;
- Stratification height around one meter and gradient doesn't exceed its maximal accepted value. Above one meter (stratification zone) the temperature is almost constant;
- Air flow equally spread along floor surface and raises along heat sources;
- Average ventilation efficiency around 1,3 and extra improvement obtained due to the displacement effect near PS of 50%;
- No significant negative influence from the ventilation system to thermal comfort during experiments.

Conclusions from experimental setup

- The ventilation system needs some classroom space, pupils must be seated approximately 0,5 meter from the textile supply diffuser. No obstacle in front of the textile air diffuser or they must be raised with legs;
- The location of the textile supply air diffuser is preferably placed at the front (below the school board) or the backend of the classroom to avoid direct interference with convection flow of radiators or door openings. The supply opening on the diagonally opposite of the extract opening show good results;
- An additional heating system is needed to obtain a good indoor air temperature and to avoid the bypass effect of air heating of a DV system (preferably radiant heating system);
- A clean floor to prevent dust particle to become air borne. Asthmatic children could suffer more from airborne dust particles. But perhaps also particle reach the extract grille are carried away;
- The system needs a control panel to provide human intervention/ preferences to air temperature or air volume. This could improve the mental experience and acceptation of the system.

Regarding the suggested ventilation systems

- The implementation of a DV system in an existing or new school building is possible in a variety of ways. The suggested systems show that some simple (low costs) adjustments are necessary to accomplish the Plug & Play option in a existing school building and a integral design could fulfil the centralized option;
- Energy consumption. (Extra) energy consumption due to ventilation is inevitable. Compared to a natural ventilation system with a poor IAQ, a DV system consumes more electric energy in summer but less thermal energy in winter (when heat recovery of 80% is applied). The total energy consumption (electric and thermal) could be the same as a natural ventilated classroom.
- The costs for a demand controlled mechanical ventilation system, which is able to provide a good IAQ with a good thermal comfort, are estimated around €5800,- per classroom. A DV system should be cheaper because of smaller system components.

6.1. DISCUSSION

Circumstances of experiments

In general the experiments in the field study agree with the literature study. It is difficult to generalize conclusions from a non steady state environment. A reserved attitude to the outcome of the measurements is necessary. But most of the outcomes of the experiments are significant enough to get a good indication of the performance of the system. The measurements were taken on a specific school building, but these comply with typical Dutch school building.

To improve the comparison between a DV system and a MV system it could have been better to adapt the DV system and turn it into a MV system. In this way an exact comparison between the performance of a MV and a DV is possible and no theoretical assumption were necessary.

Human perception of IAQ and thermal comfort

It is unwise to attach high importance to the outcome of the enquiry of pupils. When they are asked to give their opinion of the IAQ and thermal comfort for a longer period of time (e.g. for two weeks), the perception of pupils can be influenced by last moment changes of the indoor climate. The outcome of such a enquiry should be used in a quantitative and not in a qualitative way.

Applicability of the Fanger model on pupils

Input like body surface and metabolism is obtained from Havenith (2007) and the PMV value is calculated. According to the Fanger model pupils need a much higher operative temperature to feel comfortable. Therefore the metabolism of an adult is used in this research to obtain a realistic impression of the thermal experience of the pupils.

Consistence of the logbook

During the reference condition experiment a logbook is used to register opened windows, doors and the amount of pupils with the accompanying time. Generally, the logbook is used with care and the activities were followed consistently. Sometimes the logbook isn't used consistent because of change of teacher, busyness or forgetfulness. This causes unreliable measuring data and therefore the data excluded from the measurement analysis.

Orientation of the classroom

The classroom is orientated to the East; therefore only in the morning sun enters the classroom. The outcome of the experiments could become influenced when the classroom was orientated on the South. On the other hand all school building should be advised to use an external shading system.

Air change rate measurements

During the reference experiment an air change rate measurement was performed. Because of a slow decay curve the upper windows were opened to stimulate air exchange. An extra measurement could be added, simulating a summer period by open all possible windows.

Temperature gradient

Temperature stratification measurements were performed during the Spring season. High outdoor air temperatures could affect the temperature stratification in the classroom, especially when the air is cooled with an air conditioning system. The differences in the horizontal plane weren't measured because it was expected to be quite uniform. An extra test could have been performed to prove this statement.

Air movements

Air flow changes due to people movement (e.g. entering the room) temporarily affect the displacement effect. The displacement effect stabilizes within minutes depending on the nominal time constant. Despite the disruption of the displacement effect the measured ventilation efficiency stays above 1 during the experiments.

Upper windows can be opened when a DV system is applied; especially in summer, when the heat is concentrated along the ceiling, the upper windows could have a positive effect on the thermal comfort.

Person simulator

The person simulator provides a global indication of the entrainment of fresh air along the body. Despite the fact that the total body surface and heat production is the same as an 11 year old pupil, the temperature distribution along the PS isn't the same a real human being. The exact difference should be examined more closely but personally I expect no significant difference in the air entrainment.

6.2. RECOMMENDATIONS FOR FURTHER RESEARCH

- The effect of a lower or higher ceiling height is already examined by Mattsson (1999), however a non steady state could give different outcome of the performance of DV system;
- To examine the best position of a CO_2 sensor for regulating the demand controlled ventilation system. Normally a sensor is placed as far as possible from windows and doors at 1,1 meter above floor level. But is this the best location for adequate response of the DV system?
- To examine the entrainment of fresh air along a real human body in a (non) steady state situation;
- The effect of introducing a cooling system. The cold air in summer leads to a very high temperature gradient with the DV system;
- To analyse if the suggested solutions are ready to put on the market. A SWOT analyses with marketing research should expose the risks and chances of the solutions;
- A ventilation system seems to have an acceptable payback time when compared to personnel costs reduction due to sick leave and production loss. This is an indication and needs to be examined more closely;
- To examine outsourcing possibilities and avoid high initial costs and backlog of maintenance. In this way a good IAQ and thermal comfort could be guaranteed by the building services company.

Epilogue

I would like to thank the following sponsors for the financial support to this research.

- BAM Techniek for providing the assembly team;
- Nijburg groep for the air distribution equipment;
- Air Trade Center for the delivery of the air handling unit
- BLT luchttechniek for the delivery of the textile air diffusers.

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APPENDIX I CLASSIFICATION INDOOR CLIMATE OF SCHOOLS

	Indoor climate classification		
	A 8	B 7	C 5
Thermal Comfort			
Operative temperature – lower limit	20-22 C	20-22 C	19-23 C
Operative temperature – lower limit	20 C	20 C	19 C
Operative temperature – summer except vacations and Tout> 30 C	23-27 C	23-28 C	22-29 C
Operative temperature – upper limit Tout<20 C	23-27 C	23-28 C	22-29 C
Operative temperature – upper limit Tout>20 C	Tout+2 C, max. 27 C	Tout+3 C,	Tout+4 C,
Draught/ air velocity – winter (closed windows)	<0,13 m/s	<0,16 m/s	<0,19 m/s
Draught/ air velocity – summer (closed windows)	<0,16 m/s	<0,2 m/s	<0,23 m/s
Vertical temperature gradient (between ankle and head)	<2 K	<3 K	<4 K
Cold & warm feet / floor temperature	19-26 C	19-26 C	17-29 C
Radiation asymmetry	5/10/14/23 K	5/10/14/23 K	7/13/18/35 K
Individual influence of temperature	± 2 C in summer and winter	± 2 C in winter	± 2 C in winter
Indoor Air Quality			
Carbon dioxide concentration	<800 ppm	<1000 ppm	<1200 ppm
Carbon dioxide concentration		<900 ppm	
Fresh air per person in classroom, 400 ppm outdoors	45 m /h.pp	30 m /h.pp	20 m /h.pp
	12,6 l/s.pp	8,4 l/s.pp	5,6 l/s.pp
Fresh air per person in classroom, 360 ppm outdoors	40 m /h.pp	30 m /h.pp	20 m /h.pp
Fresh air per person in classroom, 500 ppm outdoors	55 m /h.pp	40 m /h.pp	25 m /h.pp
Fresh air per m floor surface (1 person per 2 m)	22,5 m /h.m	15 m /h.m	10 m /h.m
Fresh air per m floor surface (1 person per 2 m)	20 m /h.m		
Wash out ventilation	Open windows	Open windows	Open windows
CO indicator	possibly	yes	yes!
Noise			
Noise from outdoor	30 dB(A)	35 dB(A)	40 dB(A)
Noise from outdoor		33 dB(A)	35 dB(A)
Noise of building services (in classroom)	25 dB (NR20)	30 dB (NR25)	35 dB (NR30)
Noise of building services (in classroom)	30 dB(A)	33 dB(A)	

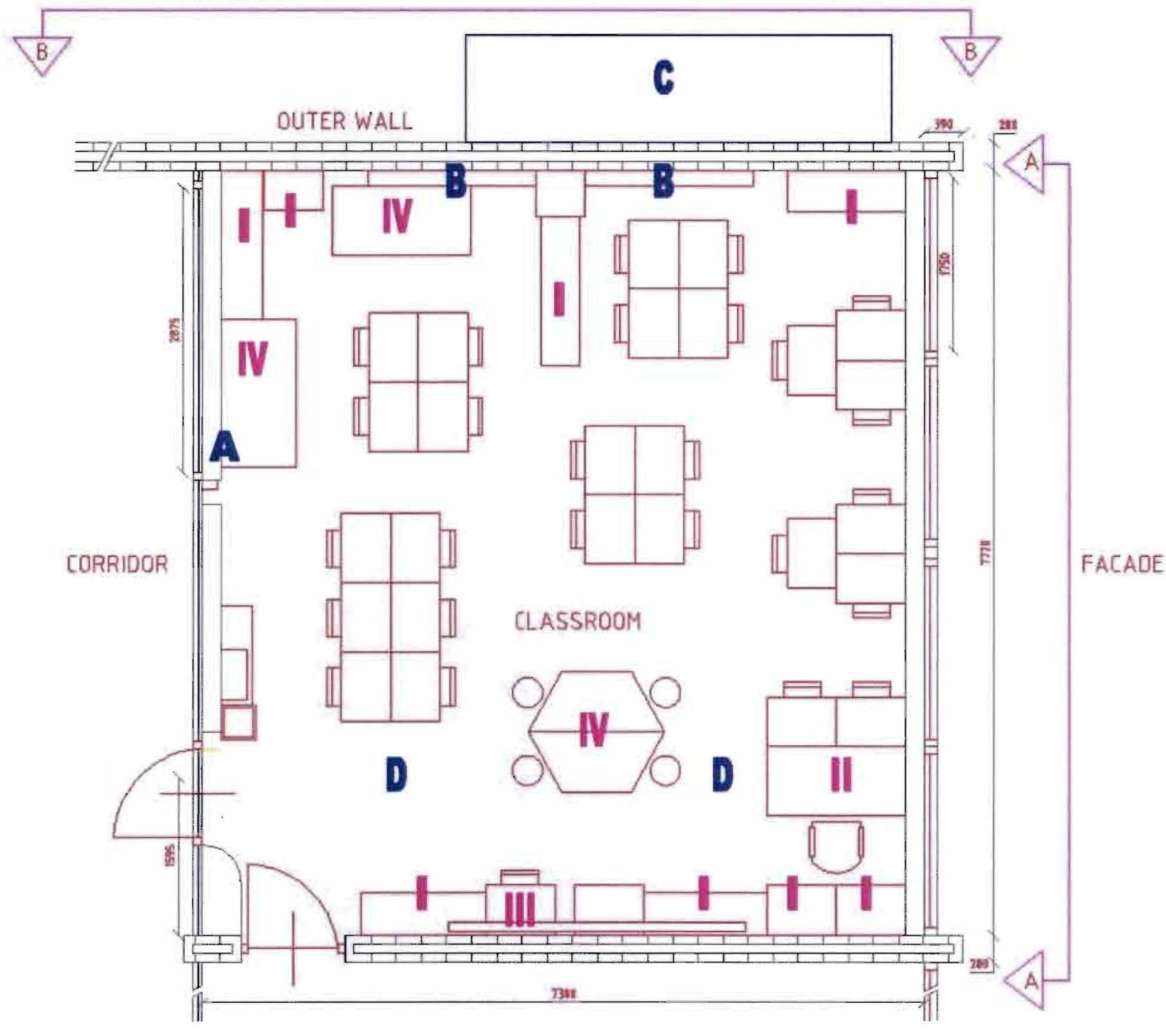
At the time of writing this report a new ISSO guideline "ISSO publicatie 89: Binnenklimaat scholen" was published. This new guideline is a result of an optimisation of the preliminary study of the TVVL from Boerstra et. al. (2006). The indoor climate classification was slightly changed. The values marked dark green replace the orange values. The light green values are unchanged.

APPENDIX II METHODICAL DESIGN FOR PRIMARY SCHOOL VENTILATION

The document "Methodical Design for Primary School Ventilation (2007)" is added as a separate document.

APPENDIX III EXPERIMENTAL SETUP

The figure below shows the floor plan of group 7/8 and two cross-sections on the next page.



Legend 1		Legend 2	
A	Control unit (regulates room temperature, RH and air flow)	I	Closet
B	Textile air diffusers (low at floor level)	II	Teacher
C	AHU with water tide casing	III	School board
D	Extract grilles (at ceiling h=3,1 meter)	IV	Extra table

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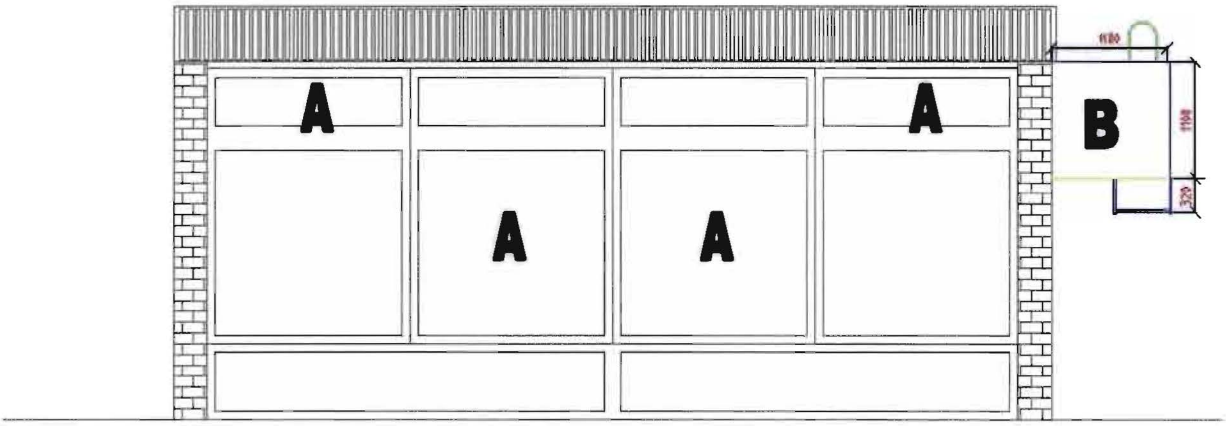
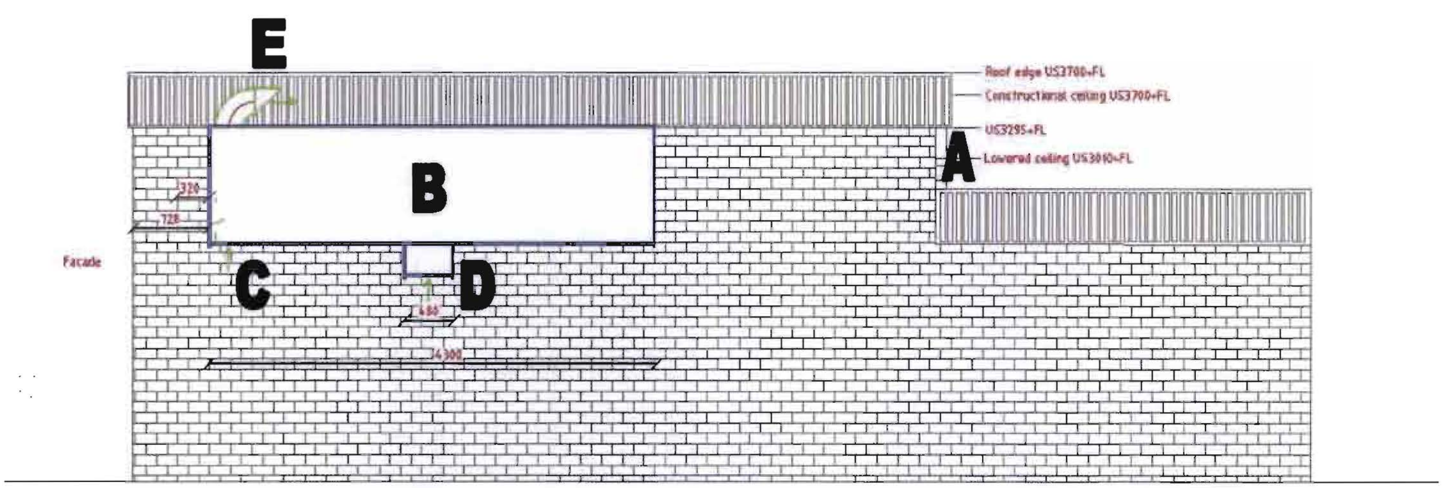


CROSS-SECTION A-A



CROSS-SECTION B-B

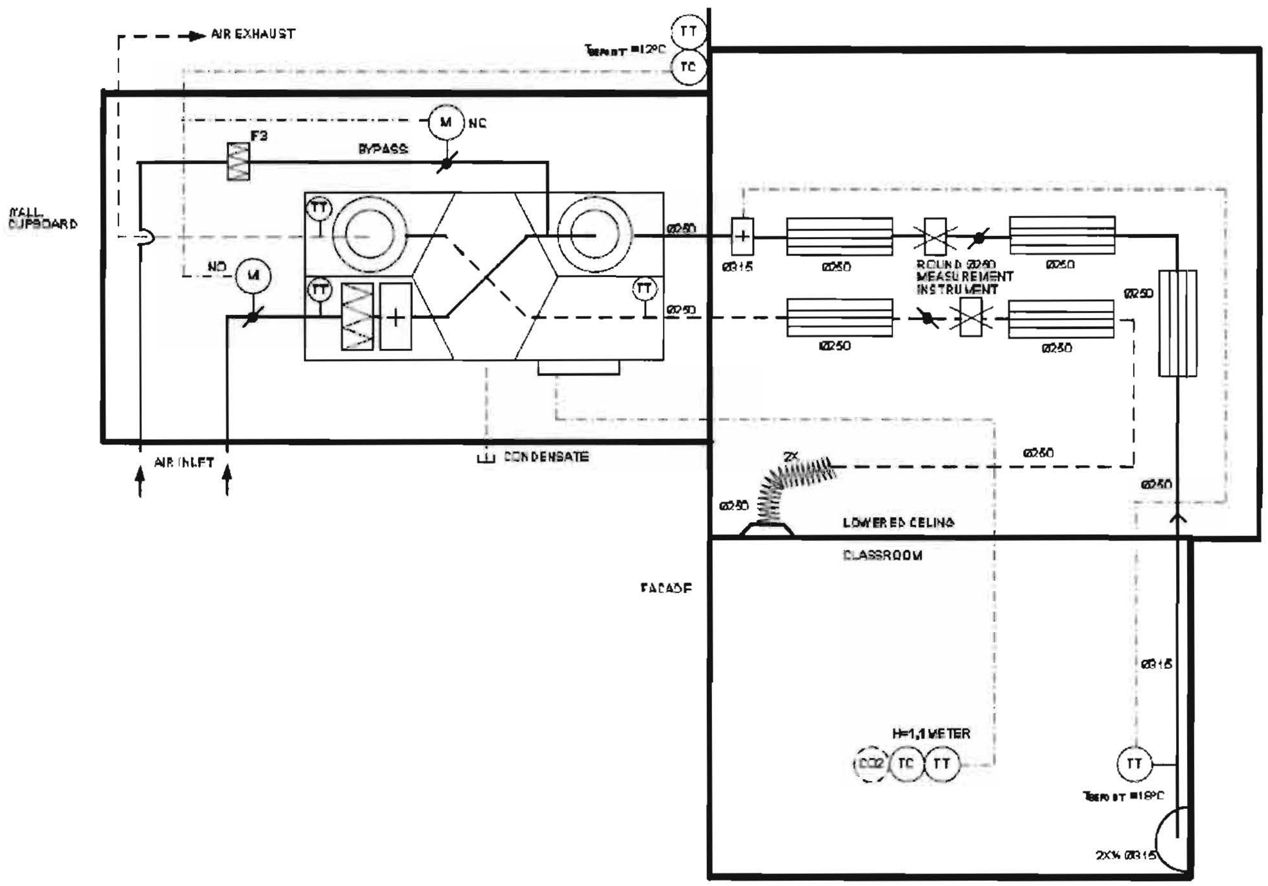
Legend

A	Window for ventilation
B	AHU water tide casing
C	Air supply heat recovery
D	Air supply bypass
E	Air exhaust from classroom

Construction details of the classroom

Construction	Material	Rc-value [m^2K/W]	U-value [W/m^2K]	Surface [m^2]
Façade	Sandwich panels: Trespa and an air layer	0,21		4,32
Façade	Wooden framework around windows	0,36		14,1
Windows façade	Metal framework and single glass		5,72	17,7
Outer wall	Bricks (2 layers) and an air layer	1.32		28,6
Inner wall (along corridor)	Wood and an air layer	0,42		14,5
Windows/door inner wall	Wooden framework and single glass		5,72	6,2
Inner wall (near other classroom)	Bricks (2 layers) and an air layer	0,37		26,9
Roof	Durisol wapened roof panel and 3 layers of bitumen	0,9		56,2
Floor	Concrete and a crawl space	0,11		56,2
Total				~225

Process and instrumentation diagram



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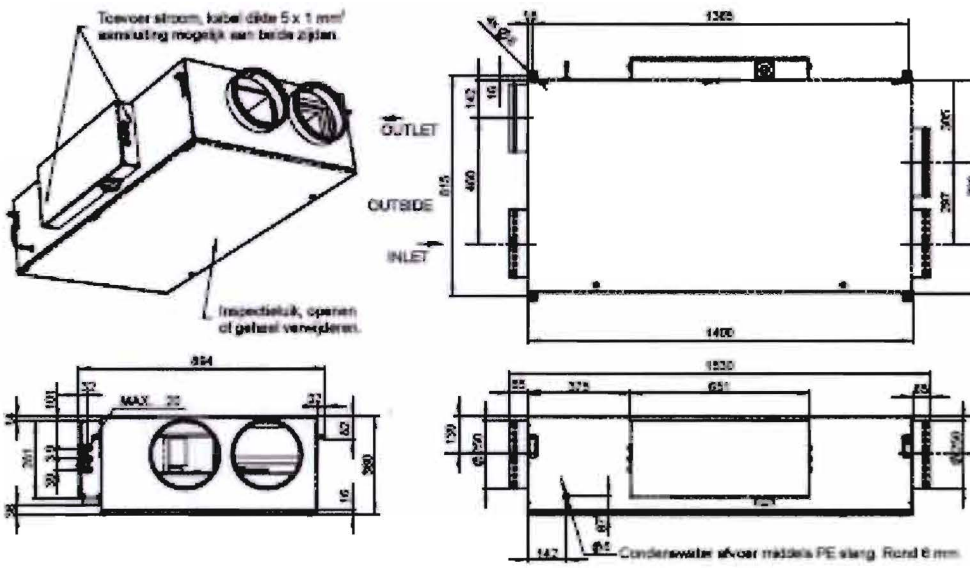
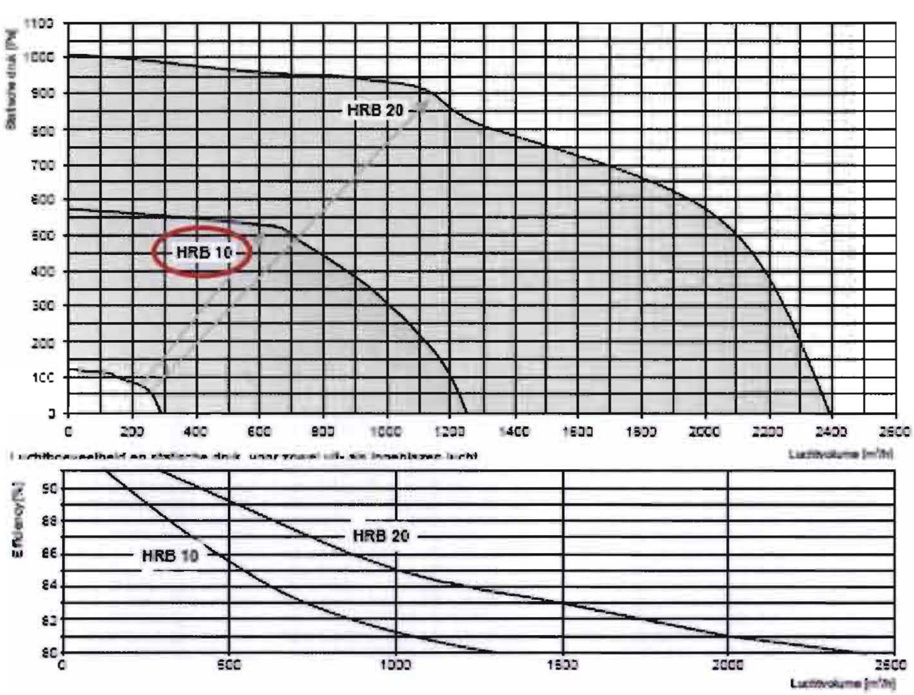
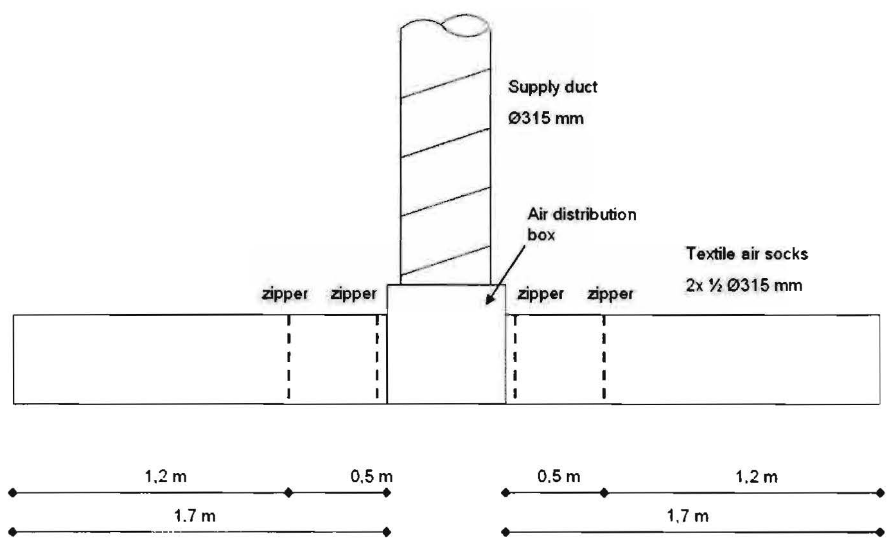
Air handling unit





Inblaas temp ❶ [°C]	Rel. Lucht vochtigheid inblaas ❷ [%]	temp voor WW ❹ [°C]	temp na WW ❺ [°C]	temp na WW ❻ [°C]	WW ❺ [kW]		Voor verwarmer ❻ [kW]		na verwarmer ❼ [kW]	
					HRB10	HRB20	HRB10	HRB20	HRB10	HRB20
-20	90	-11	17,2	17,2	9,50	19	3,30	6,60	1,03	2,05
-15	90	-11	17,2	17,2	9,50	19	1,47	2,93	1,03	2,05
-10	90	-10	17,3	17,3	9,17	18,34	0,00	0,00	0,99	1,98
-5	80	-5	16,9	16,9	7,35	14,69	0,00	0,00	1,14	2,27
0	70	0	16,7	16,7	5,61	11,21	0,00	0,00	1,21	2,42
5	60	5	17,2	17,2	4,11	8,22	0,00	0,00	1,03	2,05
10	50	10	16,1	16,1	2,74	5,48	0,00	0,00	0,70	1,39
15	40	15	19,1	19,1	1,37	2,74	0,00	0,00	0,33	0,66

Textile supply diffuser



	Total airflow	Pressure loss [Pa]	Surface [m²]	Supply velocity
Textile diffuser ½ Ø315mm, length 2x 1,7 meter	1000	90	1,68	0,165
	850	80	1,68	0,14
	500	45	1,68	0,083
Textile diffuser ½ Ø315mm, length 2x 1,2 meter	1000	130	1,19	0,234
	850	110	1,19	0,2
	500	65	1,19	0,117

The textile air diffuser can be shortened by zippers which are marked with a dotted line.

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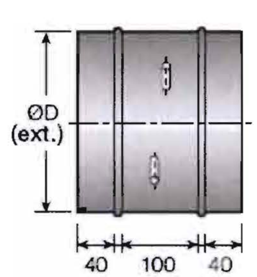
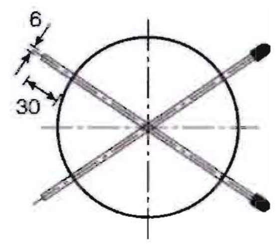
Measuring stations

These instruments provide a reasonably constant pressure signal at 16 measurement points.





$$q = C_v \bullet \sqrt{p}$$

With:

q	air flow	[m^3/h]
Cv	constant correction factor (157,5)	[-]
p	signal pressure measuring station	[Pa]

Measurements D.Schuiling/E.Smits 23rd of April 2008										
Only heat recovery	**15%**	**Δ [%]**	**50%**	**Δ [%]**	**55%**	**Δ [%]**	**60%**	**Δ [%]**	**100%**	**Δ [%]**
Supply dp dyn [Pa]	1.98		9.94		11.8		14.9		25.1	
Airflow [m3/h]	222	48	497	-1	541	-2	608	1	789	-21
Exhaust dp dyn [Pa]	1.23		9.52		11.6		14.3		31.5	
Airflow [m3/h]	175	16	486	-3	536	-2	596	-1	884	-12
Balance difference [%]	27		2		1		2		-11	
Bypass and heat recovery	**15%**	**Δ [%]**	**50%**	**Δ [%]**	**55%**	**Δ [%]**	**60%**	**Δ [%]**	**100%**	**Δ [%]**
Supply dp dyn [Pa]	2.15		10.1		12.5		15.4		38.6	
Airflow [m3/h]	231	54	501	0	557	1	618	3	979	-2
Exhaust dp dyn [Pa]	1.15		8.39		10.3		12.7		29.2	
Airflow [m3/h]	169	13	456	-9	505	-8	561	-6	851	-15
Balance difference [%]	37		10		10		10		15	
Only Bypass	**15%**	**Δ [%]**	**50%**	**Δ [%]**	**55%**	**Δ [%]**	**60%**	**Δ [%]**	**100%**	**Δ [%]**
Supply dp dyn [Pa]	2.05		10.4		12.2		15.6		36	
Airflow [m3/h]	226	50	508	2	550	0	622	4	945	-6
Exhaust dp dyn [Pa]	1.24		8.98		11.4		14.1		31.8	
Airflow [m3/h]	175	17	472	-6	532	-3	591	-1	888	-11
Balance difference [%]	29		8		3		5		6	

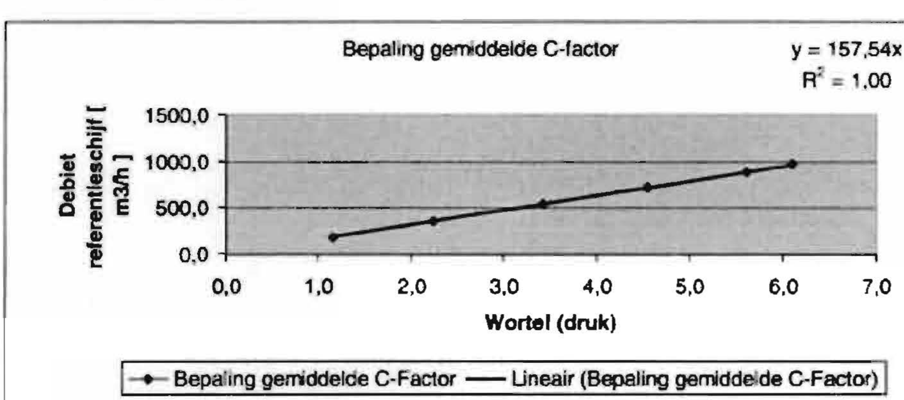
Validation measurements taken by Peutz Zoetermeer (with calibrated measuring equipment)

Calibratie Solid Air meetkruizen

datum	27-2-2006
SA meetkruis diameter	250mm
project omschrijving	Controle
referentie	DN
diameter referentieschijf	92 mm
temp	18 ℃
rv	31 %
druk	1015 mBar

SA 250mm [Pa]	volume debiet [m3/h]	C-factor	Debiet met bijbehorende C-factor [m3/h]	Debiet met gemiddelde* C-factor [m3/h]	Afwijking berekend met gemiddelde * C-factor [m3/h]	Afwijking berekend met gemiddelde * C-factor [%]
1,4	176,0	148,75	176,0	186,4	10,3	5,9%
5,1	349,6	154,81	349,6	355,7	6,1	1,7%
11,6	537,0	157,66	537,0	536,4	-0,5	-0,1%
20,9	714,4	156,26	714,4	720,0	5,7	0,8%
31,8	886,7	157,24	886,7	888,2	1,5	0,2%
37,4	966,9	158,10	966,9	963,2	-3,7	-0,4%
37,3	966,4	158,23	966,4	961,9	-4,5	-0,5%
31,4	885,0	157,93	885,0	882,6	-2,4	-0,3%
20,5	711,2	157,08	711,2	713,1	1,9	0,3%
11,8	540,2	157,26	540,2	541,0	0,8	0,2%
4,9	345,3	155,99	345,3	348,6	3,3	1,0%
1,3	178,0	156,10	178,0	179,6	1,6	0,9%

* Gemiddelde C-Factor bepaald uit grafiek 157,5



APPENDIX IV REFERENCE CONDITIONS

Timetable

Monday/Tuesday/Thursday		
	Group 7	Group 8
08:30-10:15	Lessons	Lessons
10:15-10:30	Morning break	Morning break
10:30-12:00	Lessons	Lessons
12:00-12:30	Lunch break	Lunch break
12:30-14:30	Lessons	Lessons

Wednesday		
	Group 7	Group 8
08:30-09:30	Lessons	Gymnastics
09:30-10:30	Lessons	Lessons
10:30-10:45	Lunch break	Lunch break
10:45-11:45	Lessons	Lessons
11:45-12:30	Gymnastics	Lessons

Friday		
	Group 7	Group 8
08:30-09:30	Gymnastics	Gymnastics
10:15-10:30	Lunch break	Lunch break
10:30-12:30	Lessons	Lessons
12:30-13:00	Lunch break	Lunch break
13:00-14:30	Lessons	Lessons

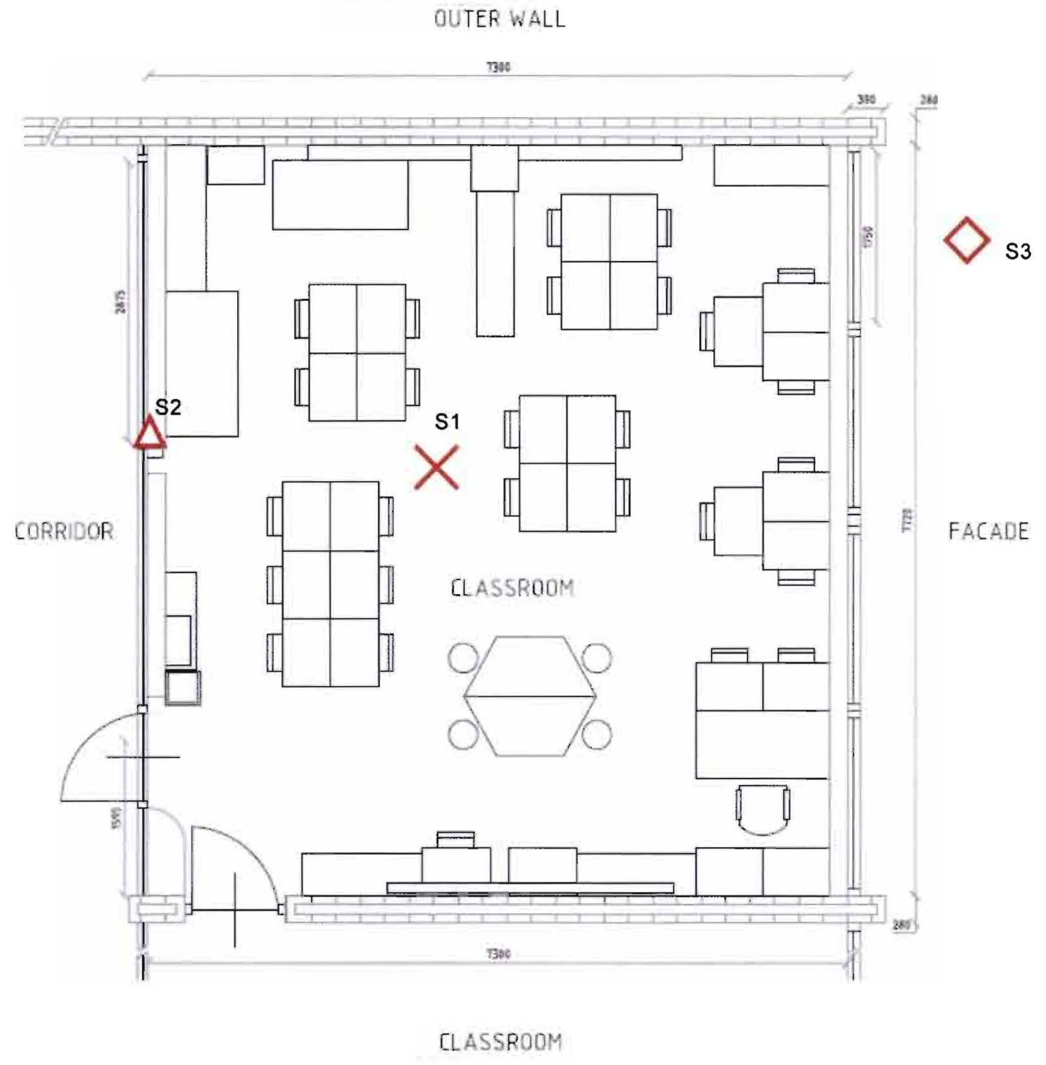
Maximum occupation 26 pupils and a teacher

Nominal occupation 24 pupils and a teacher

Ing. D.J.B.W.Schuiling
10 December 2008

IAQ and thermal comfort measurements

The locations of the different sensors are marked in the floor plan below.



S1 Tripod for comfort measurements provided with air temperature, relative humidity, radiant temperature, local air velocity, CO_2 sensor and temperature gradient between 0,1 and 1,1 meter

S2 Extra CO_2, temperature and relative humidity sensor at 1,1 meter at the wall

S3 Outdoor climate conditions, air temperature, CO_2 and relative humidity at the shade side of the façade

Specification of the temperatures and relative humidity during the IAQ and thermal comfort measurement period

T_{indoor} [°C]	Mon	Tue	Wen	Thu	Fri
Mean	**21,1**	**20,2**	**20,1**	**19,9**	**20,3**
Accuracy	±0,05	±0,05	±0,05	±0,05	±0,05
Median	21,2	20,3	20,2	20,1	20,3
Min	17,8	18,8	18,8	18,1	18,7
Max	22,7	21,4	20,7	20,5	21,3
SD	0,7	0,6	0,5	0,5	0,5

RH_{indoor} [%]	Mon	Tue	Wen	Thu	Fri
Mean	**44**	**41**	**41**	**50**	**50**
Accuracy	±2	±2	±2	±2	±2
Median	44	41	42	51	50
Min	35	34	33	40	45
Max	47	45	45	56	52
SD	2	3	3	4	2

$T_{outdoor}$ [°C]	Mon	Tue	Wen	Thu	Fri
Mean	**8,3**	**7,9**	**4,7**	**8,0**	**9,3**
Accuracy	±0,3	±0,3	±0,3	±0,3	±0,3
Median	8,3	8,1	4,1	8,1	9,5
Min	7,8	4,1	2,4	6,7	7,8
Max	9,2	13,1	8,6	8,9	10,0
SD	0,4	2,4	1,9	0,7	0,7

$RH_{outdoor}$ [%]	Mon	Tue	Wen	Thu	Fri
Mean	**57**	**61**	**72**	**89**	**74**
Accuracy	±3	±3	±3	±3	±3
Median	55	65	75	90	71
Min	48	40	56	80	67
Max	70	73	80	98	85
SD	7	10	7	6	6

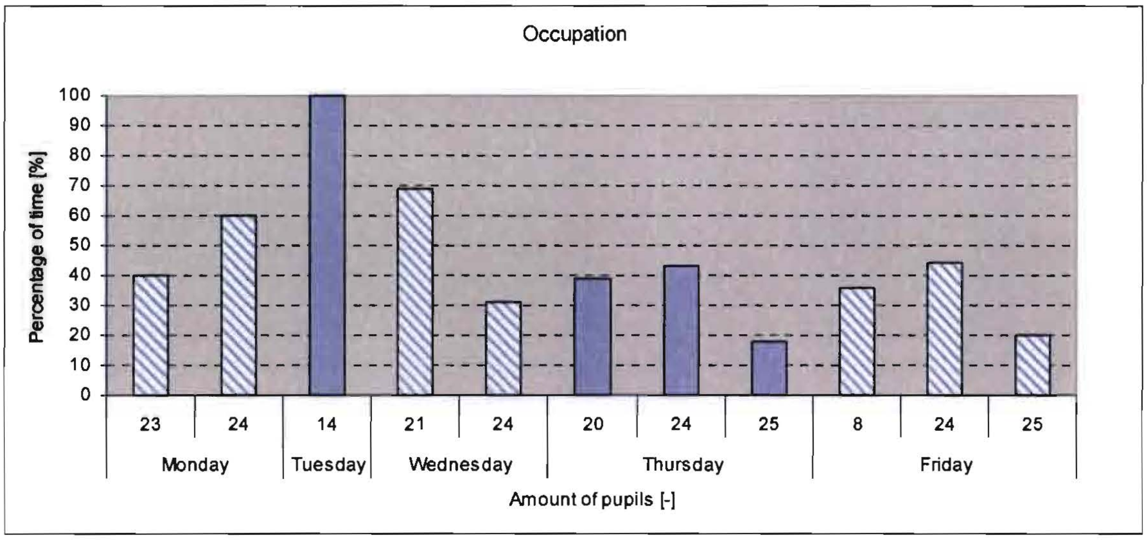
Specification of the CO_2 concentrations during the IAQ and thermal comfort measurements

$CO_{2\,tripod}$ [ppm]	Mon	Tue	Wen	Thu	Fri
Mean	**1870**	**1740**	**1770**	**1870**	**1750**
Accuracy	±130	±130	±130	±130	±130
Median	2000	1840	2000	2000	1880
Min	530	520	620	670	880
Max	2000	2000	2000	2000	2000
SD	321	333	409	304	316

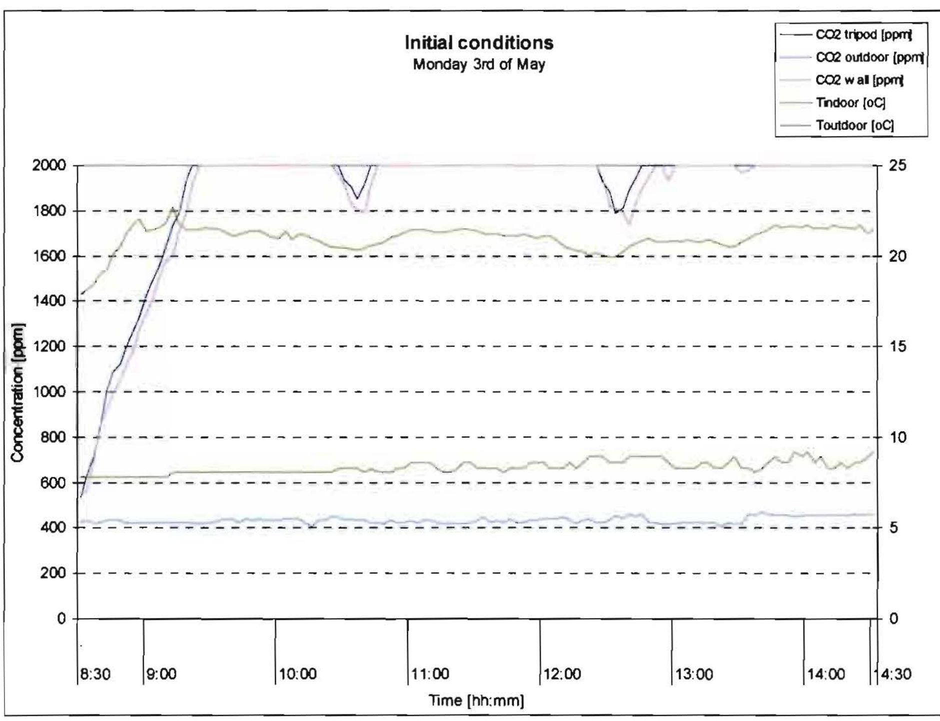
$CO_{2\,wall}$ [ppm]	Mon	Tue	Wen	Thu	Fri
Mean	**1850**	**1720**	**1730**	**1860**	**1680**
Accuracy	±130	±130	±130	±130	±130
Median	2000	1819	2000	2000	1800
Min	540	540	590	640	840
Max	2000	2000	2000	2000	2000
SD	336	328	433	321	318

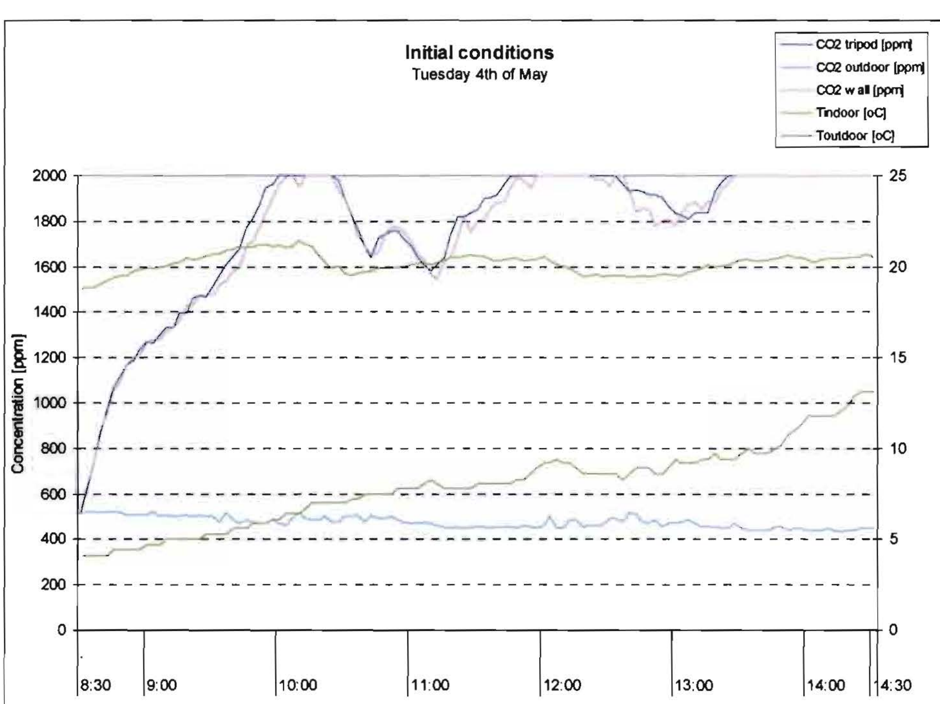
$CO_{2\,outdoor}$ [ppm]	Mon	Tue	Wen	Thu	Fri
Mean	**430**	**480**	**490**	**440**	**420**
Accuracy	±50	±50	±50	±50	±50
Median	410	470	490	440	420
Min	410	430	450	430	420
Max	470	530	530	480	430
SD	15	27	20	6	6

The occupancy during the measurement period



Visualisation of the indoor climate and the indoor air quality





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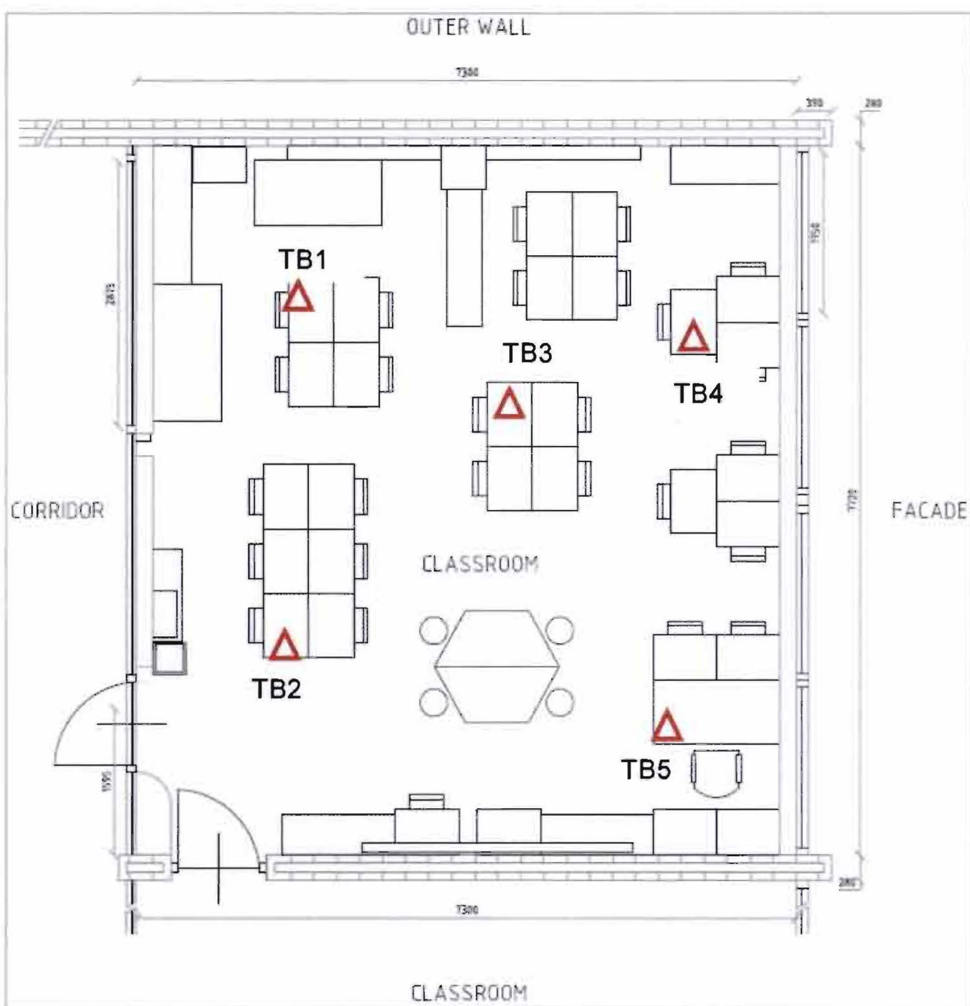
Air Change rate measurements

The figure below shows the location of the sampling tubes (TB1 till TB5) for the air change rate measurements. The tubes were placed at the same height (1 meter).



Conditions and specification air change rate measurement

Bruel & Kjaer 1302	
Five channels switch box	
Delay between each channel: approximately one minute	
Date: 25th of February 2008	
KNMI – Royal Netherlands Meteorological Institute data	
Measured location: De Bilt - Netherlands	
Predominantly wind direction	SW
Wind speed average twenty-four hour [m/s]	3,5
Wind speed highest hourly average [m/s]	5,0
Highest wind blast twenty-four hour [m/s]	11
http://www.knmi.nl/klimatologie/daggegevens/download.cgi	
Logbook	
SF6 injection [hh:mm]	12:20
Start period 1 (windows closed) [hh:mm]	12:22
End period 1 [hh:mm]	14:55
Start period 2 (upper facade windows opened) [hh:mm]	14:55
End measurement/door opened [hh:mm]	15:35

The concentration of tracer-gas exponentially decays in time according to the formula:

$$N = \frac{\ln C(0) - \ln C(t_1)}{t_1}$$

where:

N	air change rate	[h^{-1}]
C(0)	concentration at t_0	[ppm]
$C(t_1)$	concentration at t_1	[ppm]
t_1	measuring period	[h]

The total air flow in the room can be derived from the air change rate by:

$$q_v = V \bullet N$$

where:

q_v	air flow	[m^3/h]
V	room volume	[m^3]

APPENDIX V REDUCTION OF THE AIR FLOW WITH DV

Week 14

T_{indoor} [°C]	Mon	Tue	Wen	Thu	Fri
Mean	**21,6**	**21,8**	**20,9**	**21,2**	**21,5**
Accuracy	±0,3	±0,3	±0,3	±0,3	±0,3
Median	21,7	21,7	20,9	21,1	21,7
Min	21,4	21,7	20,6	20,9	20,9
Max	21,9	22,2	21,7	21,7	22,2
SD	0,15	0,13	0,26	0,3	0,37

RH_{indoor} [%]	Mon	Tue	Wen	Thu	Fri
Mean	**49**	**45**	**44**	**44**	**45**
Accuracy	±3	±3	±3	±3	±3
Median	50	45	44	45	45
Min	48	42	42	43	44
Max	51	48	46	46	47
SD	0,9	2	1	1	1

$T_{outdoor}$ [°C]	Mon	Tue	Wen	Thu	Fri
Mean	**9,1**	**9,2**	**9,6**	**9,1**	**9,4**
Accuracy	±0,3	±0,3	±0,3	±0,3	±0,3
Median	8,9	8,6	9,7	9,2	9,2
Min	8,6	7,8	9,4	8,3	8,3
Max	10,0	11,0	9,7	9,7	10,8
SD	0,31	1,10	0,13	0,43	0,85

$RH_{outdoor}$ [%]	Mon	Tue	Wen	Thu	Fri
Mean	**89**	**82**	**75**	**80**	**80**
Accuracy	±3	±3	±3	±3	±3
Median	90	84	75	81	80
Min	85	75	71	75	77
Max	92	86	79	87	83
SD	2	3	2	4	3

Measuring periods*			
Monday	9:06-10:15	and	10:36-11:00
Tuesday	9:06-10:15	and	10:15-12:00
Wednesday	9:09-10:30	and	10:54-11:30
Thursday	8:54- 10:15	and	10:48-12:00
Friday	9:57-10:15	and	10:48-12:15

* Periods: the measured period is when the CO_2 is build up and reasonably stable. This is usually in the morning until the morning/lunch break starts.

The CO_2 concentration is measured by CO_2 sensors at several strategic locations (see figure on next page):

- Tripod at 1,1 meter breathing height (1 pc, S1)
- Wall at 1,1 meter (1 pcs, S2)
- Outdoor air at 2,5 meter on the façade (1 pc, S3)
- Extraction grille at 3,1 meter (1 pc, S4)
- Person simulator at approximately 1,1 meter (1 pc, S5)

Location of the temperature/humidity sensors:

- Supply duct at 1 meter (1 pc, S6)
- Extraction duct at 3,1 meter (1 pc, S4)
- Outdoor air at 2,5 meter on the shade side of the façade (1 pc, S3)
- Room air at breathing height 1,1 m and ankle height 0,1 m on tripod (2 pcs, S5)

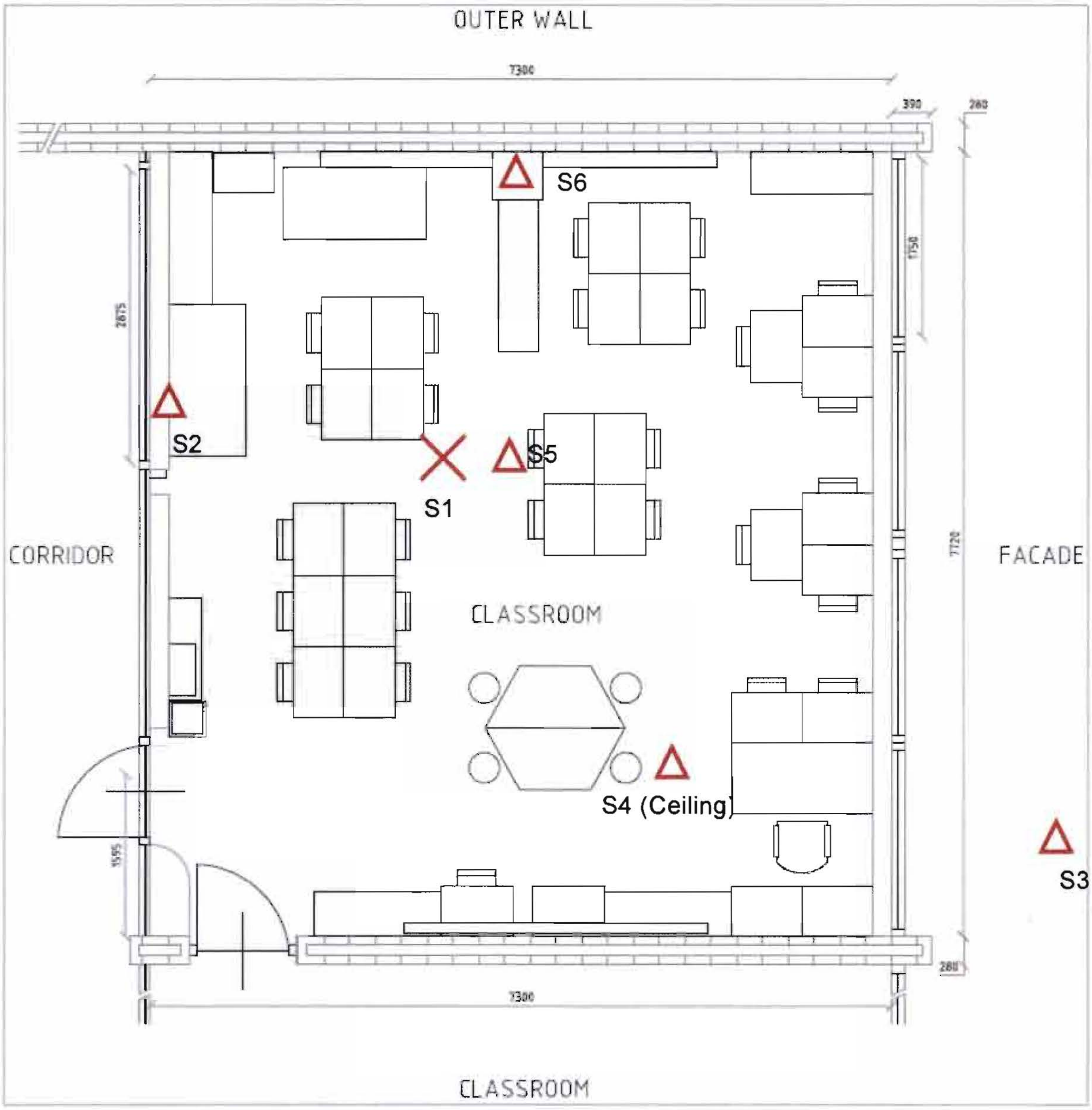
The theoretical CO_2 concentration of the ventilation principle is estimated using the formula from NPR-CR 1752 (1999):

$$q_s = \frac{q_{CO_2}}{\left(c_{CO_2\,\max} - c_s\right) \times \varepsilon_v} \qquad \text{[l/s]}$$

Where:

q_{CO_2}	CO_2 production per pupil	[l/s]
$c_{CO_2\,\max}$	Desired CO_2 concentration at breathing height	[ppm]
c_s	CO_2 concentration of outdoor air	[ppm]
ε_v	Ventilation-efficiency (MV~1, DV~1,3)	[-]

Location of the measuring points

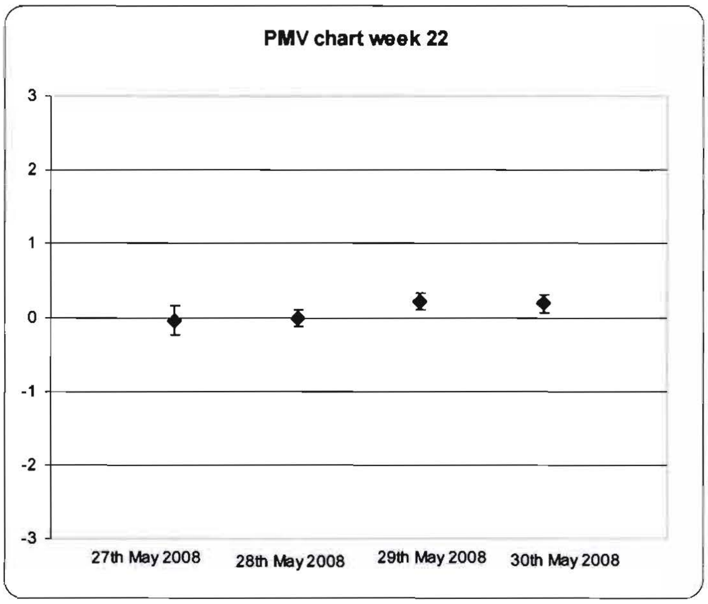


Measuring periods*			
30-05-08	10:06-10:15	and	11:18-12:15
29-05-08	9:00-10:18		
24-04-08	9:03-10:15	and	11:06-12:00
28-05-08	9:12-10:27		
27-05-08	9:12-10:15	and	11:18-12:30

* Periods: the measured period is when the CO_2 is build up and reasonably stable. This is usually in the morning until the morning/lunch break starts.

	30-05-08	29-05-08	24-04-08	28-05-08	27-05-08
T_{supply} [°C]	18,7 ±0,2	20,2 ±0,2	18,3 ±0,3	19,6 ±0,3	18,9 ±0,5
$T_{extract}$ [°C]	22,5 ±0,3	22,8 ±0,2	20,7 ±0,5	21,5 ±0,3	21,6 ±0,5
$T_{outdoor}$ [°C]	15,9 ±0,4	17,9 ±0,2	11,1 ±0,1,1	17,3 ±0,3	17,9 ±0,5
Air sock length	long	long	short	long	short
q_v (total air flow) [m^3/h]	508	508	557	800	800
Type of CO_2 sensors	Escort + EE	Escort + EE	Escorts	Escort + EE	Escort + EE
Location of the wall CO_2 sensor	front wall	front wall	side wall	side wall	side wall

PMV values of week 22



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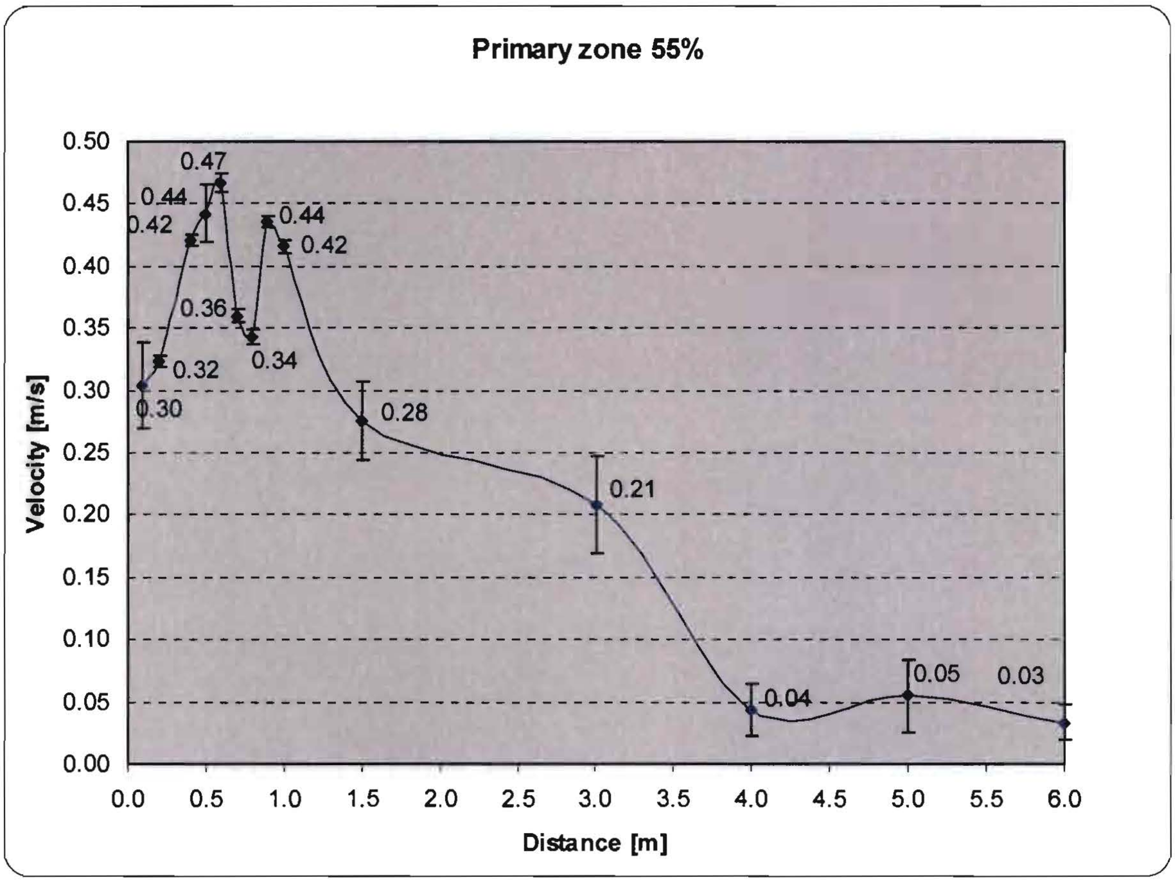
APPENDIX VI PRIMARY ZONE MEASUREMENTS

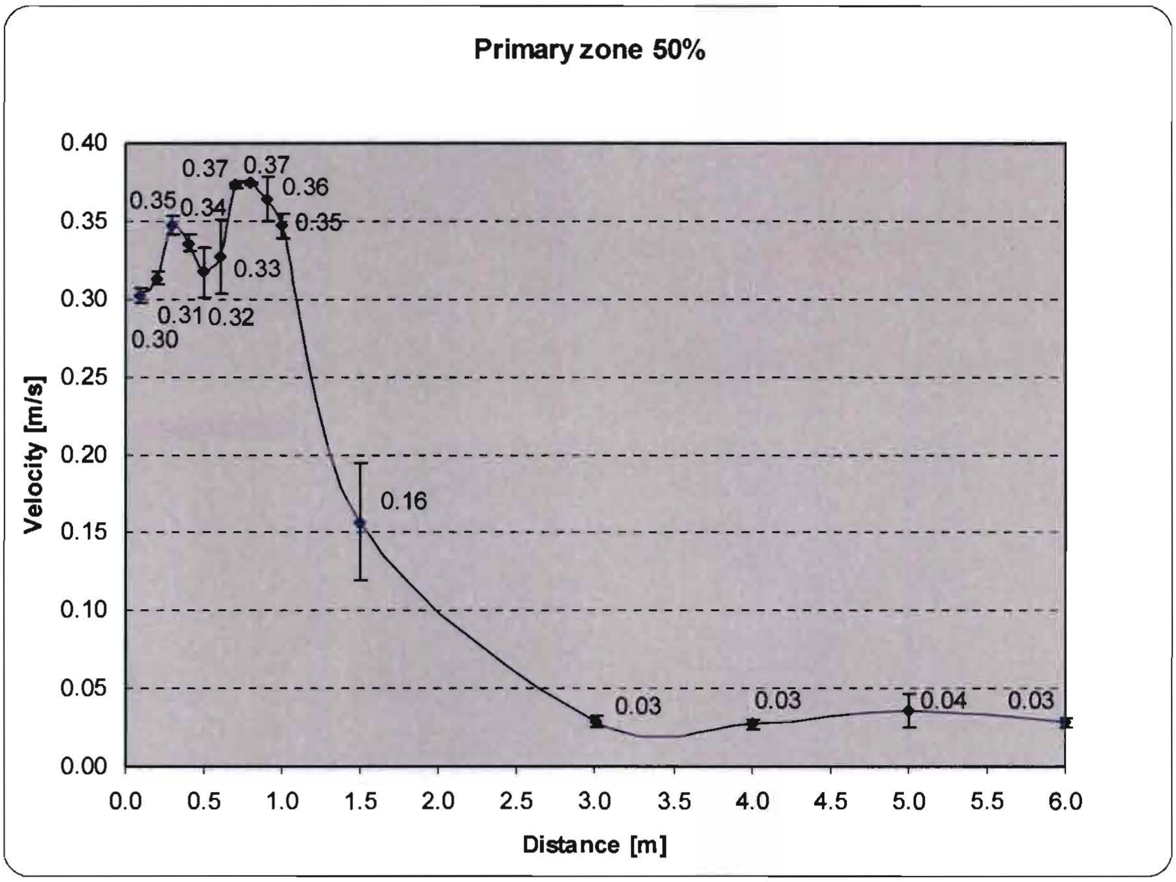
The figure below shows the measurement line of the primary zone measurements. No pupils were in the classroom during the measurements.

The air velocity versus the distance from the (short) textile air supply diffuser. The ventilation system is set on 55%.



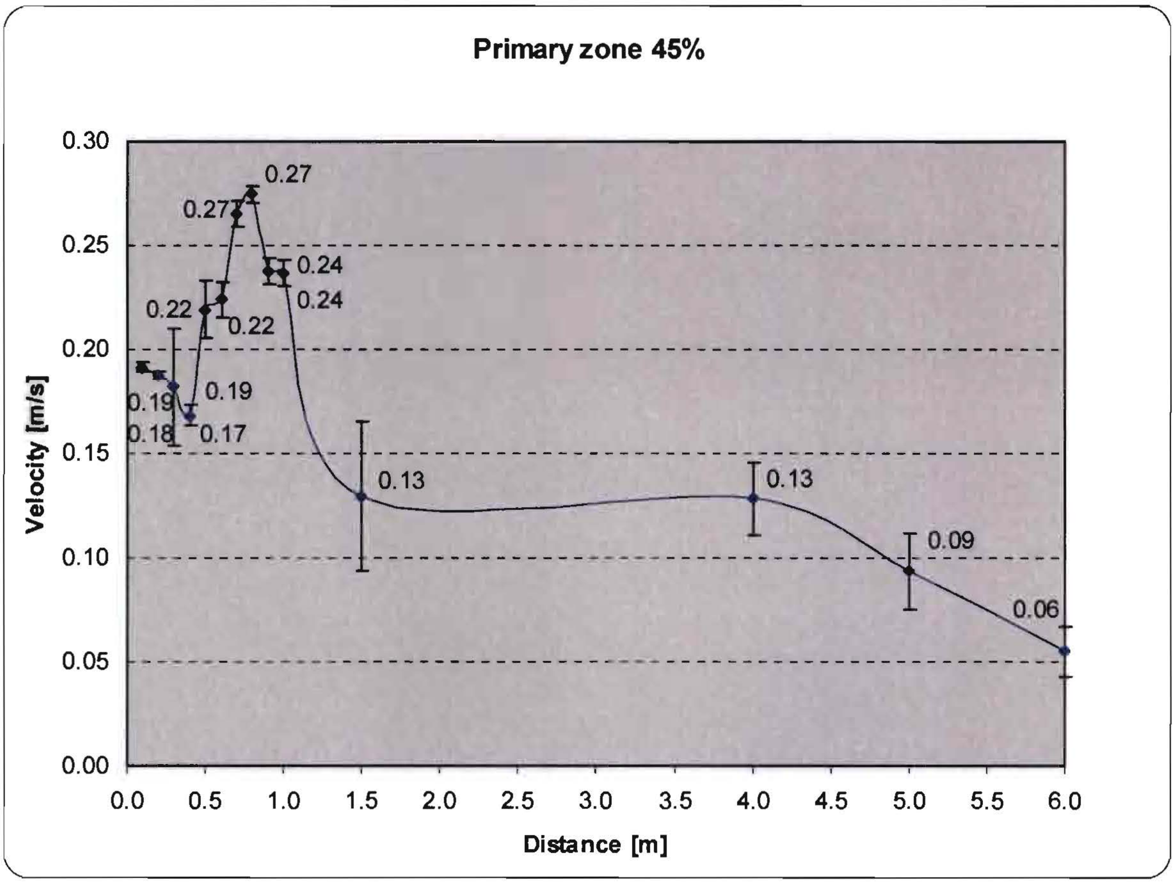
T_{room}	23,4	[°C]
T_{supply}	21,8	[°C]
ΔT	1,6	[K]
$T_{extract}$	24,5	[°C]
$q_{vsupply}$	550	[m^3/h]
$q_{vextract}$	532	[m^3/h]
Sock length	2x1,2	[m]
$L_{0,2}$	3,1	[m]

The air velocity versus the distance from the (short) textile air supply diffuser. The ventilation system is set on 50%.



T_{room}	22,9	[ºC]
T_{supply}	22,1	[ºC]
ΔT	0,8	[K]
$T_{extract}$	24	[ºC]
$q_{vsupply}$	508	[m^3/h]
$q_{vextract}$	472	[m^3/h]
Sock length	2x1,2	[m]
$L_{0,2}$	1,3	[m]

The air velocity versus the distance from the (short) textile air supply diffuser. The ventilation system is set on 45%.



T_{room}	22,9	[°C]
T_{supply}	20,2	[°C]
ΔT	2,7	[K]
$T_{extract}$	24,1	[°C]
$q_{vsupply}$	450	[m^3/h]
$q_{vextract}$	450	[m^3/h]
Sock length	2x1,7	[m]
$L_{0,2}$	1,1	[m]

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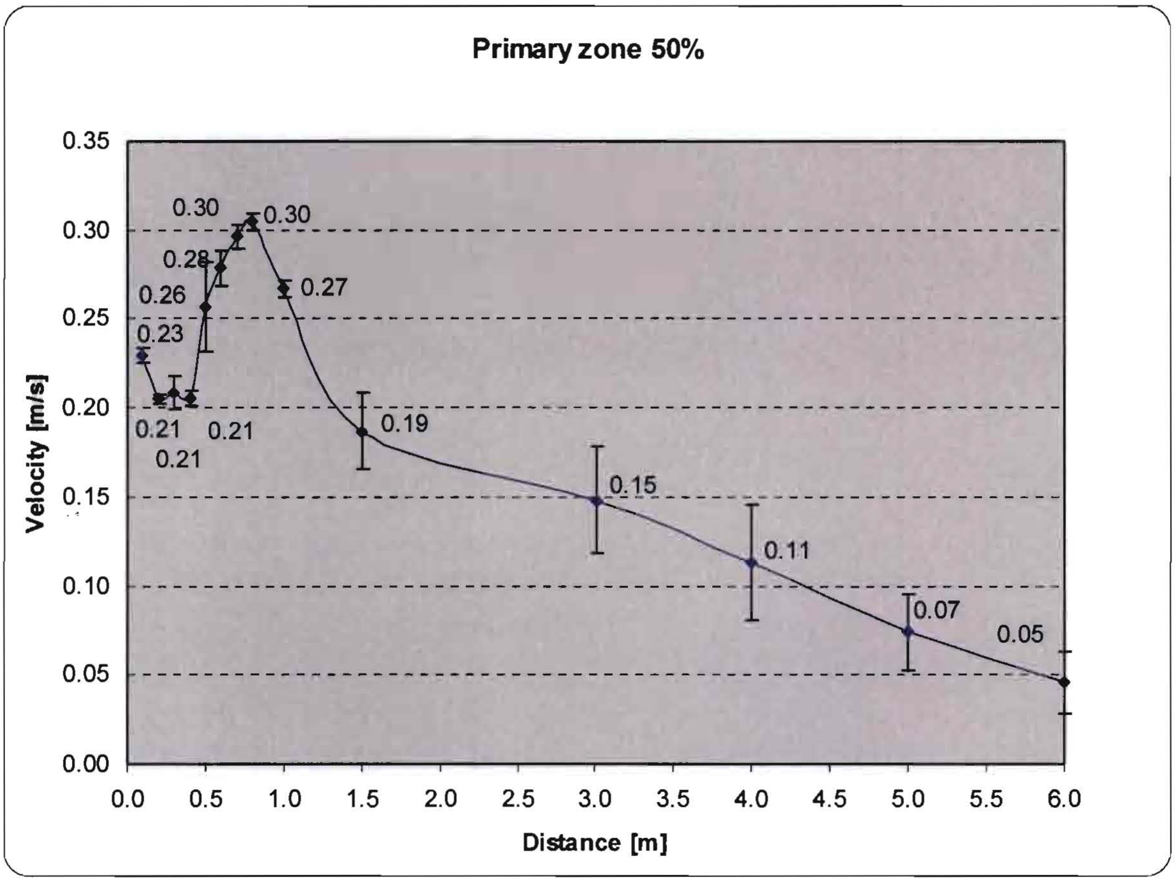
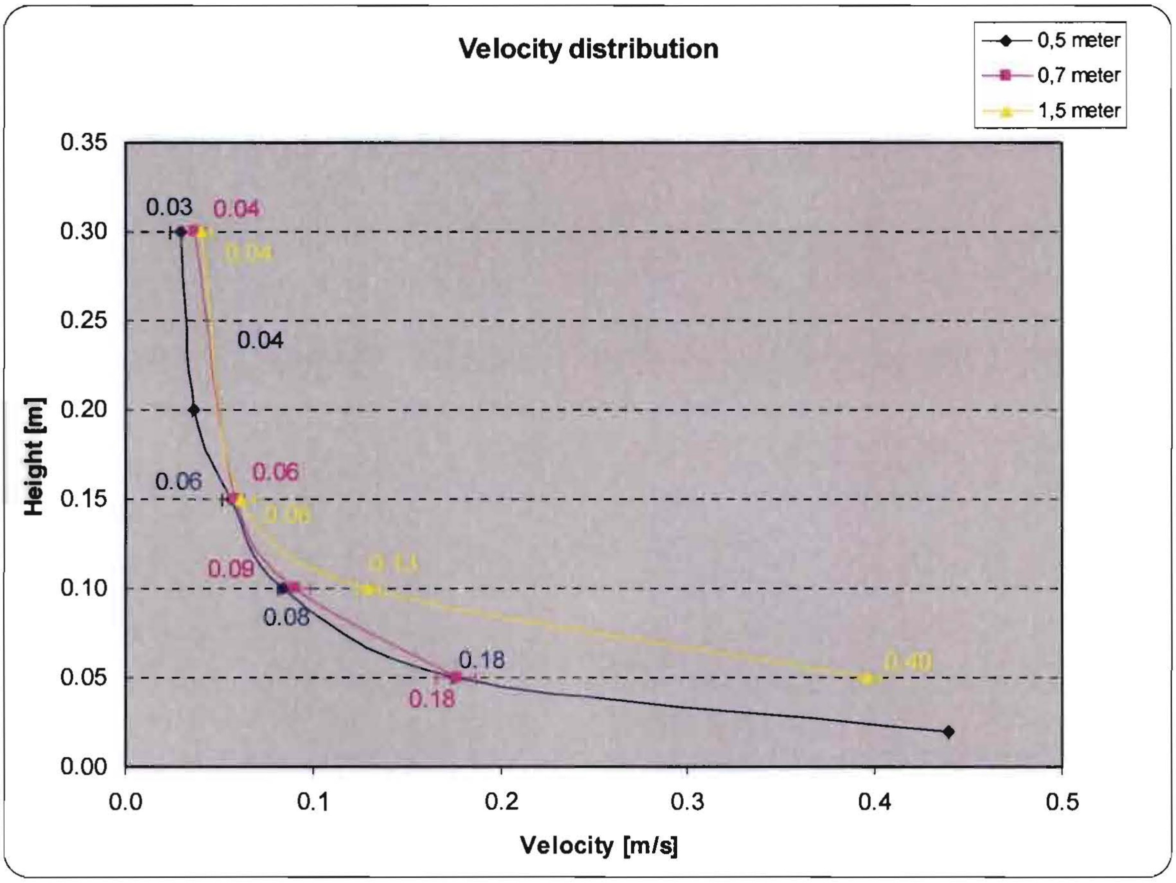
The air velocity versus the distance from the (long) textile air supply diffuser. The ventilation system is set on 50%.



T_{room}	23	[°C]
T_{supply}	20,6	[°C]
ΔT	2,4	[K]
$T_{extract}$	24,8	[°C]
$q_{vsupply}$	508	[m³/h]
$q_{vextract}$	472	[m³/h]
Sock length	2x1,7	[m]
$L_{0,2}$	1,4	[m]

The air velocity versus the height at several distances from the (short) textile air supply diffuser. The ventilation system is set on 55%.



Peak of 0,4 m/s at 5 cm and the highest velocity can be expected at 2 cm height.

T_{room}	22,8	[°C]
T_{supply}	21,7	[°C]
ΔT	1,1	[K]
$T_{extract}$	24	[°C]
$q_{vsupply}$	550	[m^3/h]
$q_{vextract}$	532	[m^3/h]
Sock length	2x1,2	[m]
$H_{0,2\ @\ 0,5m}$	<0,05	[m]
$H_{0,2\ @\ 0,7m}$	<0.05	[m]
$H_{0,2\ @\ 1,5m}$	<0,08	[m]

Logbook Primary Zone (1)

Measurements with a short textile air diffuser on the 28th of May. The velocities were measured at three distances or heights at a time. Temperature difference between supply air and at 1,1 meter height is among 1,5 and 3 K.

Distances

Time [hh:mm]	Air flow [m^3/h]	Distance location 1 [m]	Distance location 2 [m]	Distance location 3 [m]
22:27	541	0,1	1,6	0,3
22:30	541	0,2	1,65	0,4
22:35	541	0,7	1,9	0,9
22:40	541	0,8	1,9	1
22:45	541	4	0,5	5
22:50	497	4	0,43	5
22:55	497	0,1	1,6	0,3
23:00	497	0,2	1,6	0,4
23:05	497	0,7	1,7	0,9
23:10	497	0,8	1,8	1

Heights at several distances

Time [hh:mm]	Air flow [m3/h]	Distance all locations [m]	Height location 1 [cm]	Height location 2 [cm]	Height location 3 [cm]
23:35	541	0,5	2	10	20
23:20	541	0,5	5	15	30
23:25	541	0,7	5	15	30
23:30	541	1,5	5	15	30

Logbook Primary Zone (2)

Measurements with a long textile air diffuser on the 3rd of June. The velocities were measured at three distances or heights at a time. Temperature difference between supply air and at 1,1 meter height is among 1 and 3 K.

Distances

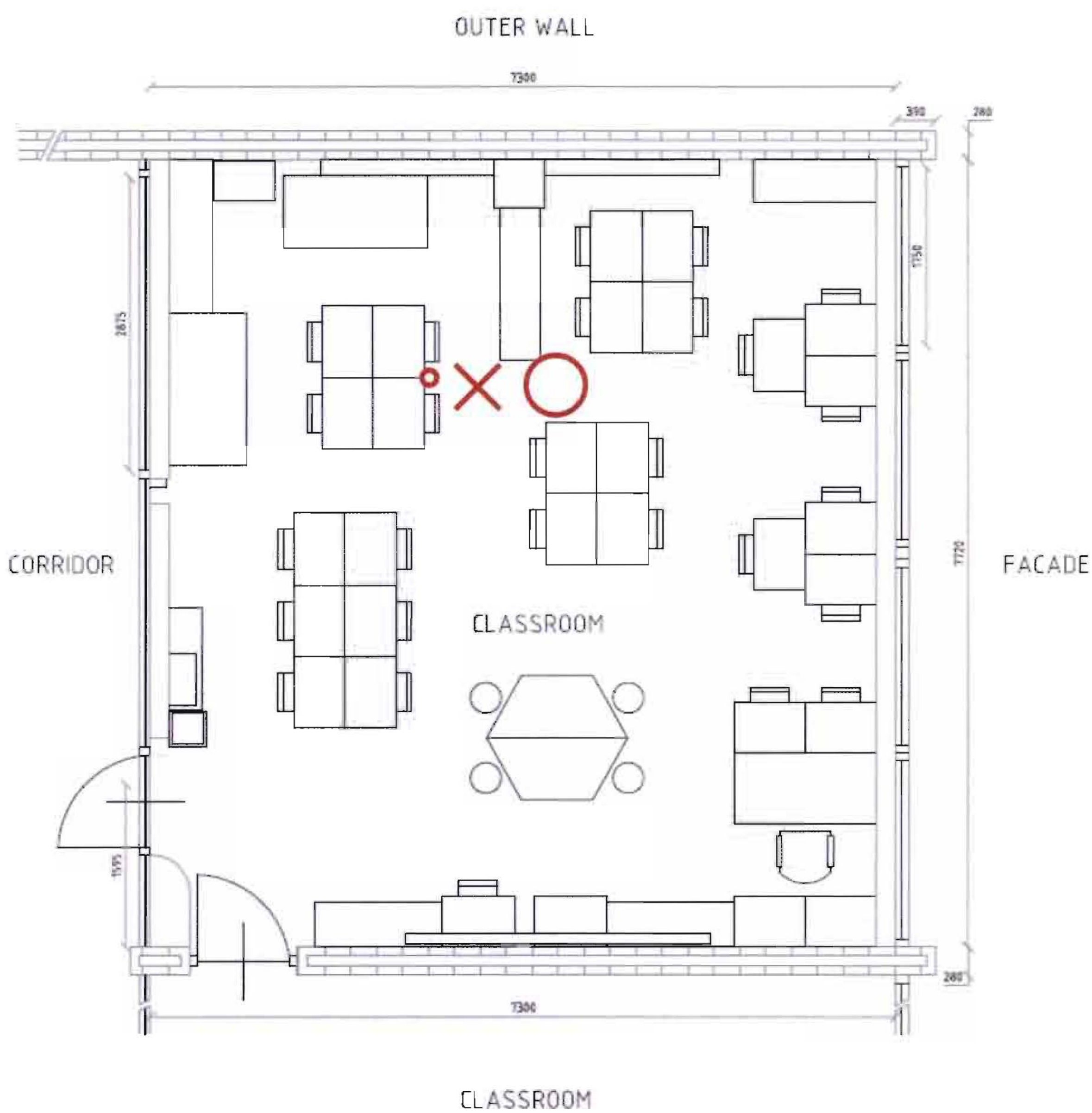
Time [hh:mm]	Air flow [m^3/h]	Distance location 1 [m]	Distance location 2 [m]	Distance location 3 [m]
20:50	497	0,1	0,3	0,5
20:55	497	0,2	0,4	0,6
21:00	497	0,7	0,9	1,5
21:05	497	0,8	1	3
21:10	497	4	5	6
21:15	541	4	5	6
21:20	541	0,8	1	3
21:25	541	0,7	0,9	1,5
21:30	541	0,2	0,4	0,6
21:35	541	0,1	0,3	0,5

Heights at several distances

Time [hh:mm]	Air flow [m3/h]	Distance all locations [m]	Height location 1 [cm]	Height location 2 [cm]	Height location 3 [cm]
22:15	497	0,5	2	10	20
22:40	497	0,5	5	15	30
22:45	497	0,7	5	15	30
22:50	497	1,5	5	15	30
22:20	541	0,5	2	10	20
22:25	541	0,5	5	15	30
22:30	541	0,7	5	15	30
22:35	541	1,5	5	15	30

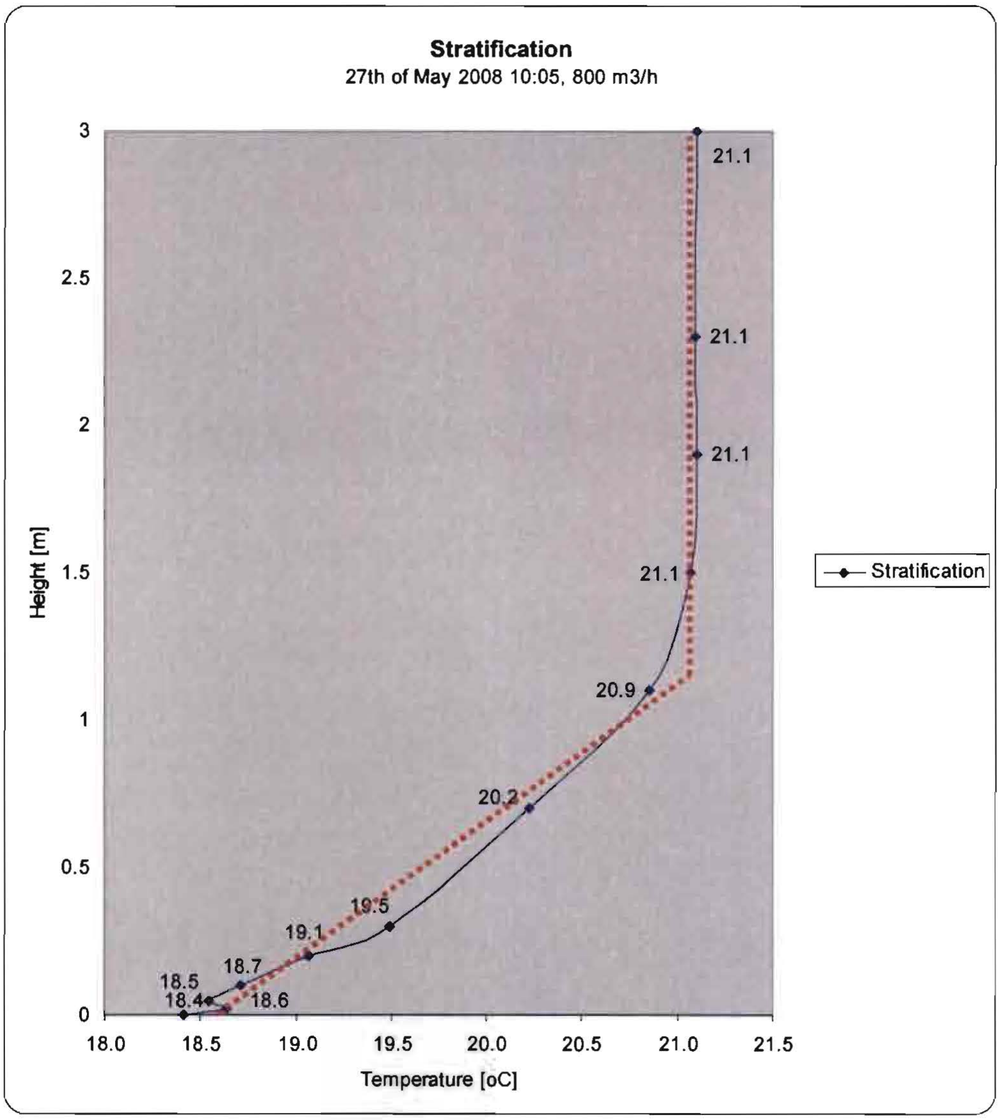
APPENDIX VII VERTICAL TEMPERATURE STRATIFICATION

The figure from below shows the plan of the classroom. The location of the PS is marked with a big circle. The location of the tripod is marked with a cross. The location of the vertical temperature gradient sensors is marked with a small circle.



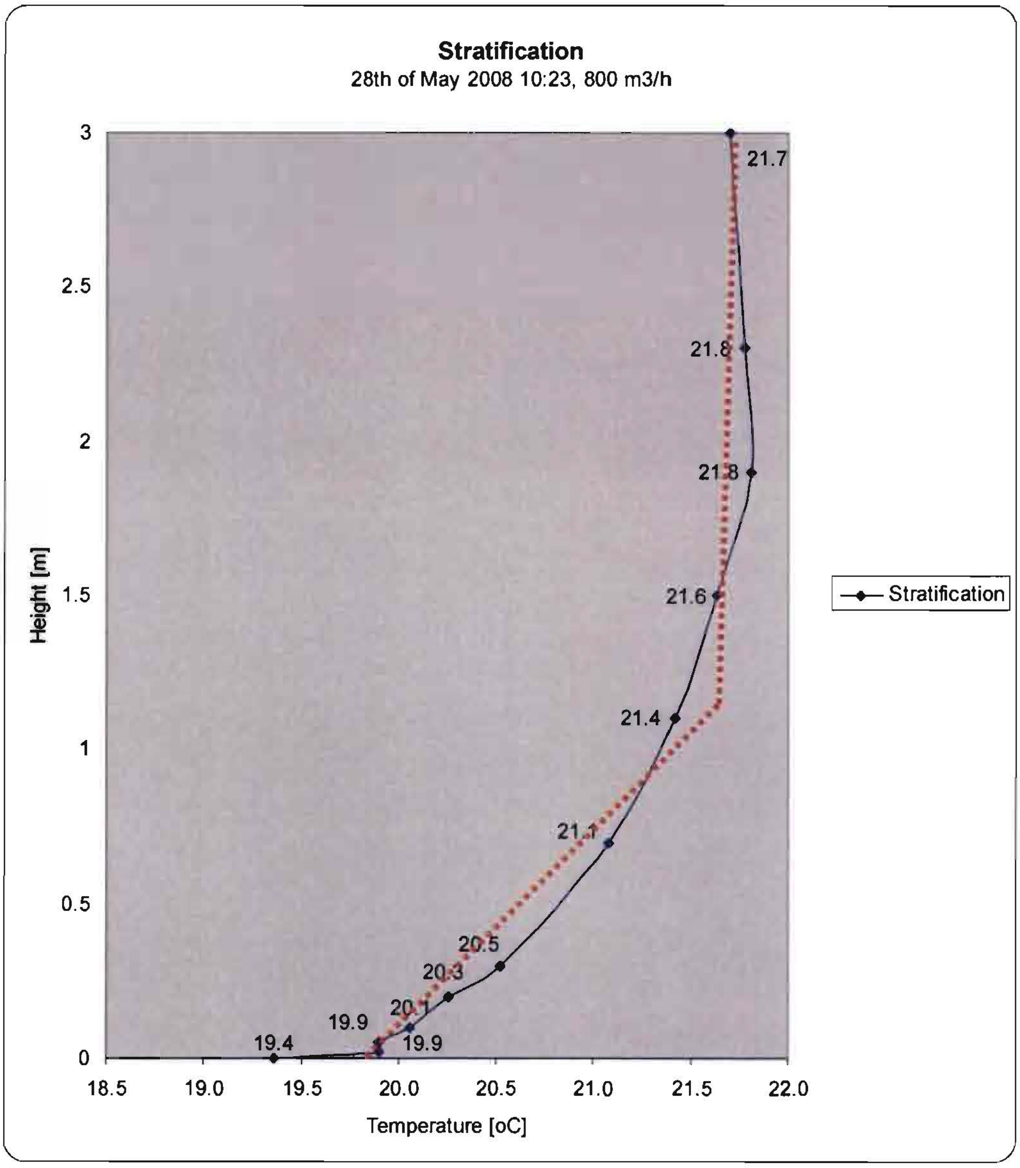
Ing. D.J.B.W.Schuiling
10 December 2008

The stratification graph of 27[th] May, the ventilation system is set on 80%.The stratification height is around 1 meter.



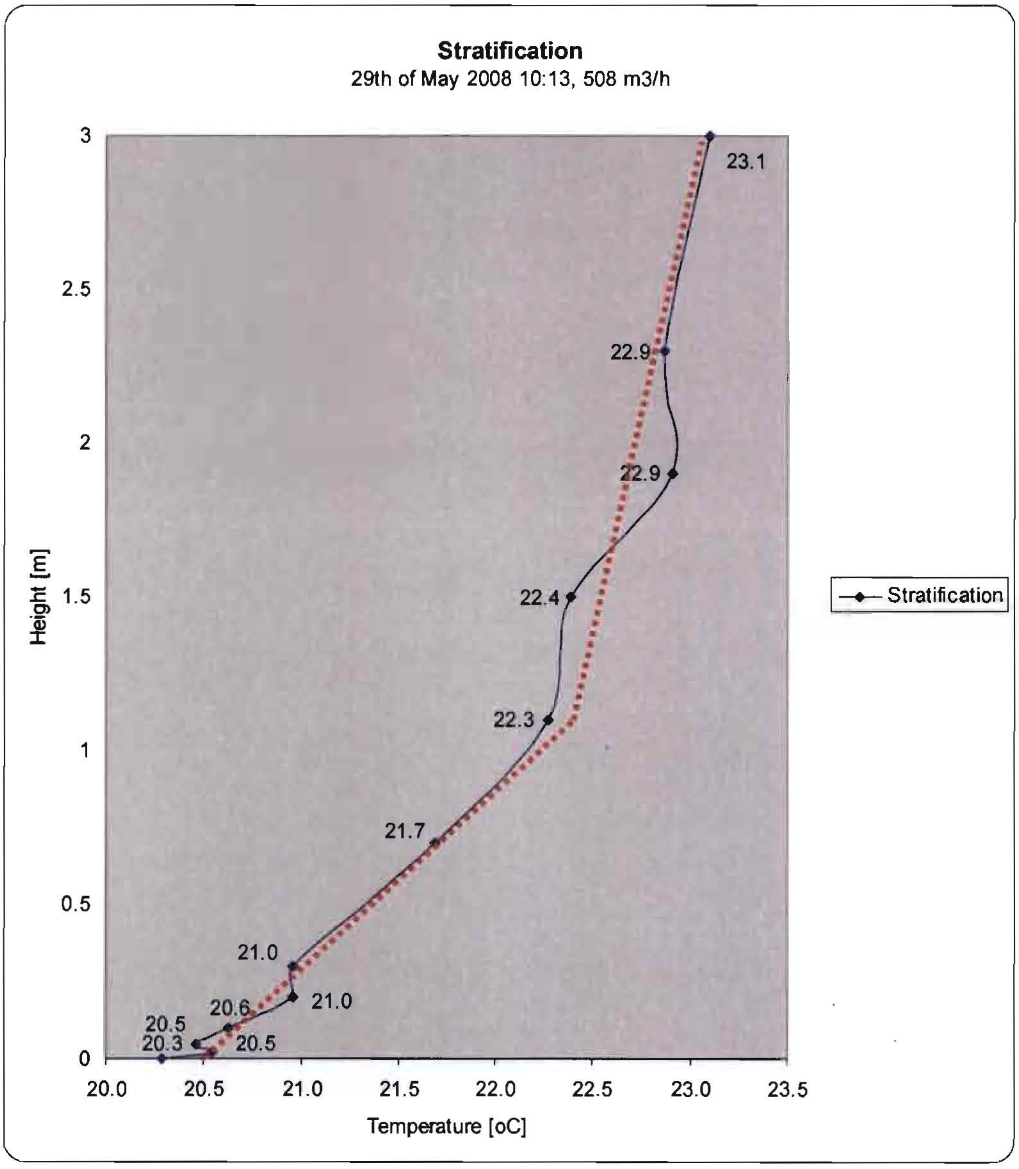
T_{supply} (T_s)	18,5	[°C]
$T_{outdoor}$	16,6	[°C]
$T_{extract}$ (T_e)	21,1	[°C]
$T_{occupied\ zone}$ (T_{oz})	20,9	[°C]
T_{floor}	18,4	[°C]
εT	1,08	[-]
ε	4	[%]

The stratification graph of 28th May, the ventilation system is set on 80%.The stratification height is around 1 meter.



T_{supply} (T_s)	20,2	[°C]
$T_{outdoor}$	18,0	[°C]
$T_{extract}$ (T_e)	21,7	[°C]
$T_{occupied\ zone}$ (T_{oz})	21,4	[°C]
T_{floor} (T_f)	19,4	[°C]
εT	1,25	[-]
ε	53	[%]

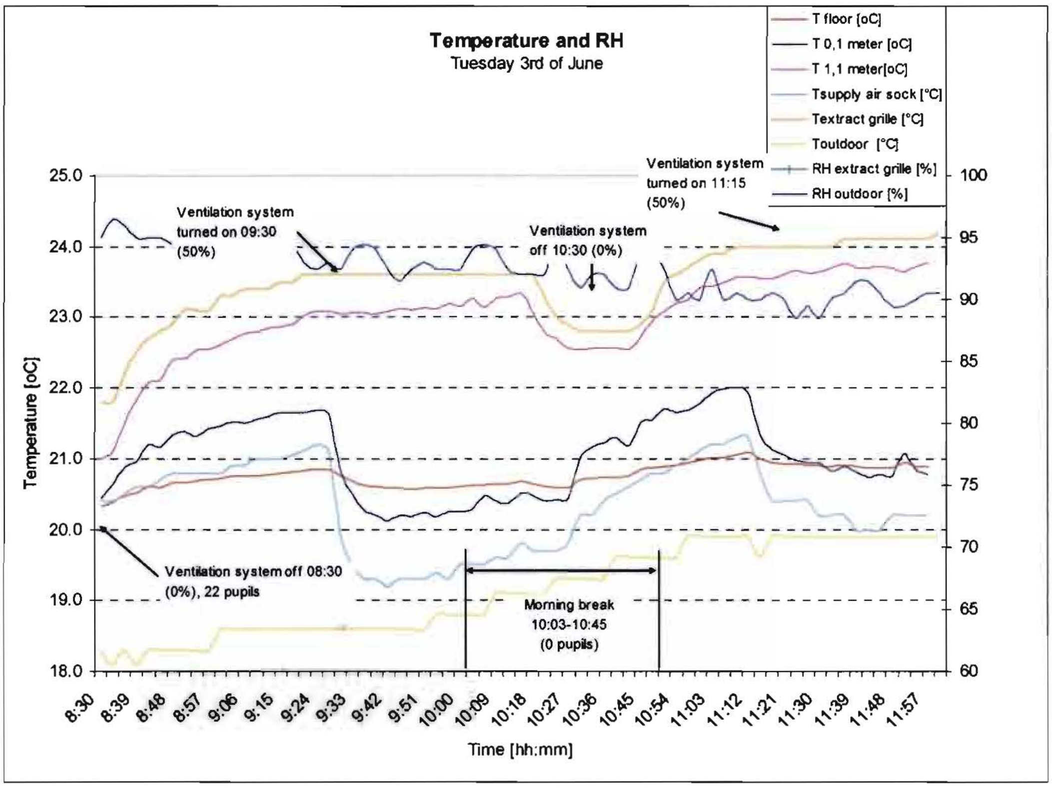
The stratification graph of 27th May, the ventilation system is set on 50%.The stratification height is around 1 meter.



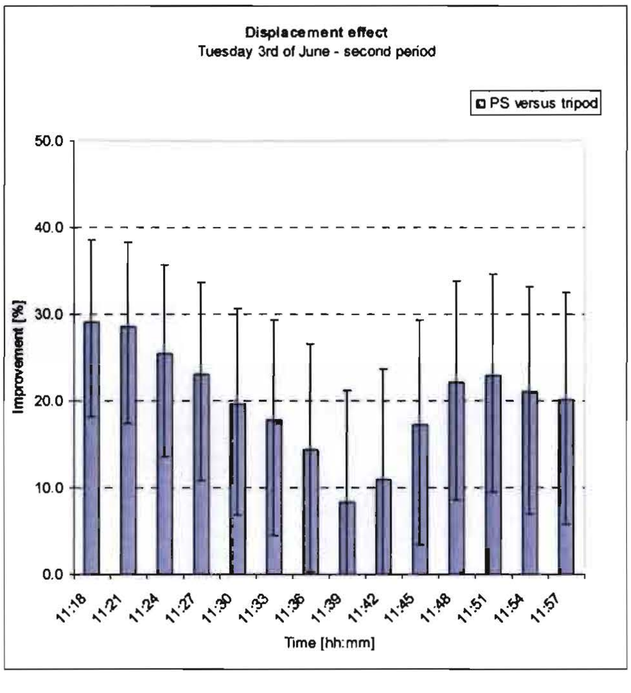
T_{supply} (T_s)	20,5	[°C]
$T_{outdoor}$	18,1	[°C]
$T_{extract}$ (T_e)	23,1	[°C]
$T_{occupied\ zone}$ (T_{oz})	22,3	[°C]
T_{floor} (T_f)	20,3	[°C]
εT	1,44	[-]
ε	8	[%]

APPENDIX VIII VENTILATION EFFICIENCY

Temperature curves of the efficiency measurements

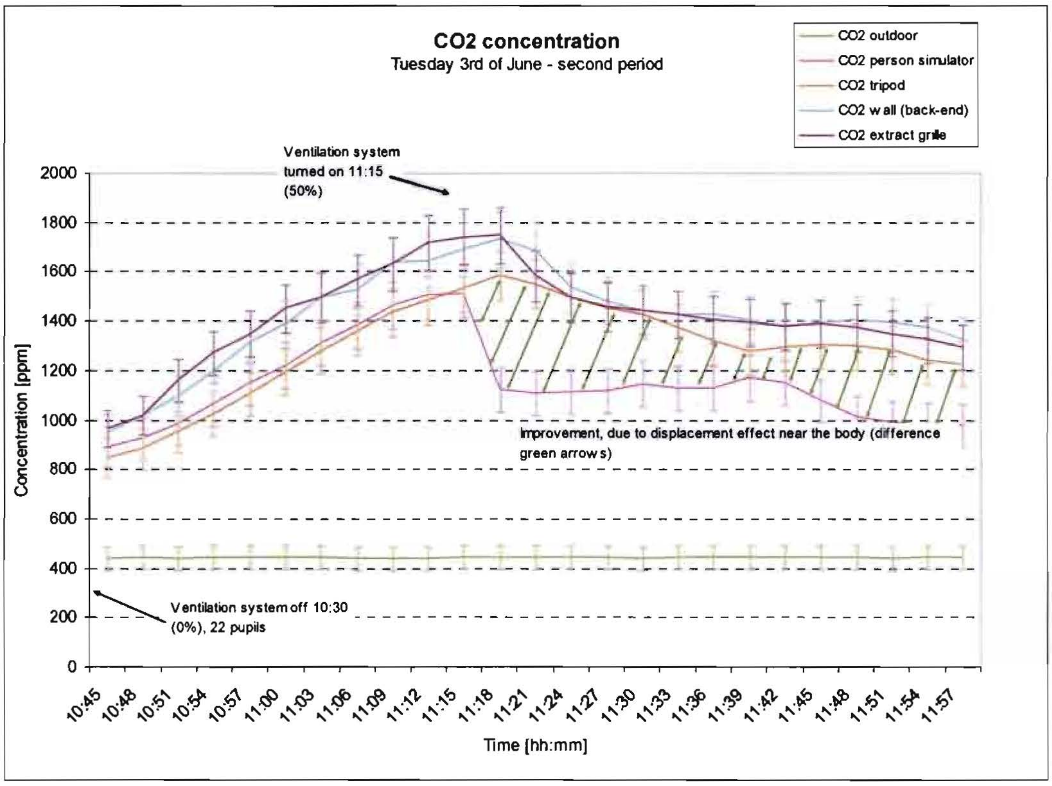


The graph below shows the benefit of the displacement effect near the PS

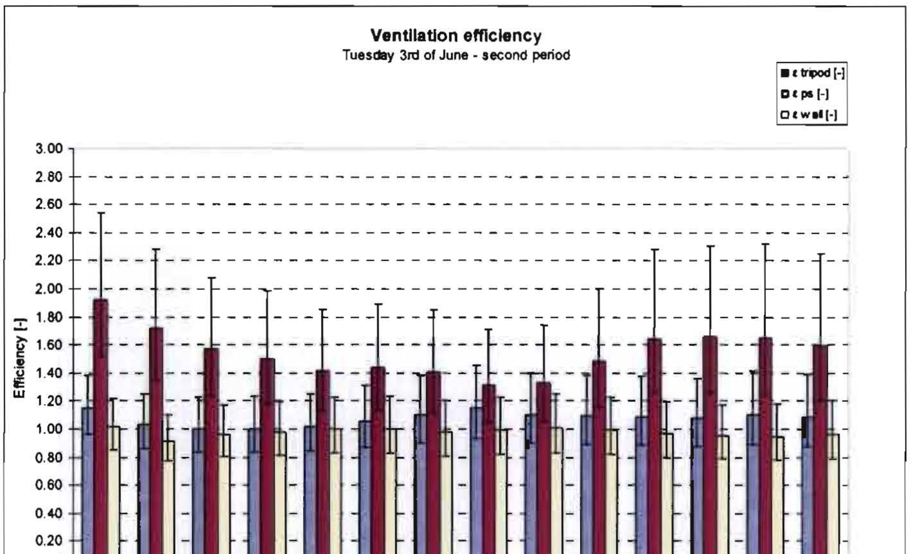


Ing. D.J.B.W.Schuiling

The next graph shows the CO_2 concentration at several locations. The benefit of the displacement effect near the PS is marked with green arrows.



The graph below shows the ventilation efficiency during the experiment



APPENDIX IX INSTRUMENTS & CALIBRATION

Monitoring

Serial-/ID-nr	Position (height)	Measurement	Sensor	Manufacturer and type	Range	Accuracy
Id1353 (transmitter)	Before heater	Temperature	NTC thermistor	Grant U-type (ultra precision) thermistor	-55 to 80°C	± 0,05 °C from 0-50°C
Id2580 (transmitter A)	AHU outdoor extract	Temperature	NTC thermistor	Grant U-type (ultra precision) thermistor	-55 to 80°C	± 0,05 °C from 0-50°C
Id2580 (transmitter B)	AHU outdoor supply	Temperature	NTC thermistor	Grant U-type (ultra precision) thermistor	-55 to 80°C	± 0,05 °C from 0-50°C
Id2580 (transmitter C)	AHU classroom extract	Temperature	NTC thermistor	Grant U-type (ultra precision) thermistor	-55 to 80°C	± 0,05 °C from 0-50°C
Id2580 (transmitter D)	AHU classroom supply	Temperature	NTC thermistor	Grant U-type (ultra precision) thermistor	-55 to 80°C	± 0,05 °C from 0-50°C
Id1361 (transmitter C)	Supply air sock	Temperature	NTC thermistor	Grant U-type (ultra precision) thermistor	-55 to 80°C	± 0,05 °C from 0-50°C
Id6942 (transmitter A)	Extract grille	Temperature	NTC thermistor	Grant U-type (ultra precision) thermistor	-55 to 80°C	± 0,05 °C from 0-50°C
Id6942 (transmitter D)	Extract grille	Relative humidity	RH	Escort, Ilog EI-HS-D-32-L	0 to 100%	accuracy ± 3% at 25 °C
Id6941 (transmitter A)	After heater	Temperature	NTC thermistor	Grant U-type (ultra precision) thermistor	-55 to 80°C	± 0,05 °C from 0-50°C
Id 1386		Squirrel data logger		Eltek	256 MB	-

Reference conditions

Serial/ID- nr	Measurement	Sensor	Manufacturer and type	Range	Accuracy
n/a	Carbon Dioxide (CO_2) concentration	CO_2	SenseAir, Asense standard	0 to 3000 ppm	± 1% of measurement range ± 5 % of measured value
n/a	Data logging	Analogue data logger	Escort, junior EJ-OE-U	0 to 10 Volt DC	40mV resolution, ± 80mV accuracy
n/a	Radiation temperature	Black bulb (Pt-100)		-100 to 300 °C	±0,1 °C
n/a	Air temperature		Escort, Ilog EI-HS-D-32-L	-40 to 70°C	±0,3 °C
n/a	Relative humidity	RH	Escort, Ilog EI-HS-D-32-L	0 to 100%	accuracy ± 3% at 25 °C
n/a	Air velocity	Omni-directional	Schmidt SS20.01	0 to 2,5 m/s	±2%
n/a		Hot-wire anemometer	Testo 425	0 to 10 m/s	±0,05 m/s and 5% of measured value
Id0320	Tracer gas	Photo acoustic infra-red spectroscopy	Brüel & Kjær type1302		
n/a	Data logging	Analogue data logger	Toshiba 320 CDT		
n/a	Tracer gas sampler				

Primary zone

Serial-/ID-nr	Position (height)	Measurement	Sensor	Manufacturer and type	Range	Accuracy
Id0708	Several distances and heights	Air velocity	Thermo anemometer Transducer with probe	Sensor Electronic HT-428-05 and HT-412-2	0,05-5 m/s (0-5V)	From 0,05-1 m/s ± 0,02 m/s and ±1% of measured value From 1-5 m/s ± 3% of measured value
Id0840	Several distances and heights	Air velocity	Thermo anemometer Transducer with probe	Sensor Electronic HT-428-05 and HT-412-2	0,05-5 m/s (0-5V)	From 0,05-1 m/s ± 0,02 m/s and ±1% of measured value From 1-5 m/s ± 3% of measured value
Id0837	Several distances and heights	Air velocity	Thermo anemometer Transducer with probe	Sensor Electronic HT-428-05 and HT-412-2	0,05-5 m/s (0-5V)	From 0,05-1 m/s ± 0,02 m/s and ±1% of measured value From 1-5 m/s ± 3% of measured value
Id1386		Squirrel data logger		Grant 2020 series (2F8)	156 MB	

Temperature stratification

Serial-/ID-nr	Position (height)	Measurement	Sensor	Manufacturer and type	Range	Accuracy
Id1735	0,02 m	Temperature	NTC thermistor	Grant U-type (ultra precision) thermistor	-55 to 80°C	± 0,05 °C from 0-50°C
Id1736	0,05 m	Temperature	NTC thermistor	Grant U-type (ultra precision) thermistor	-55 to 80°C	± 0,05 °C from 0-50°C
Id1737	0,1 m	Temperature	NTC thermistor	Grant U-type (ultra precision) thermistor	-55 to 80°C	± 0,05 °C from 0-50°C
Id1738	0,2 m	Temperature	NTC thermistor	Grant U-type (ultra precision) thermistor	-55 to 80°C	± 0,05 °C from 0-50°C
Id1739	0,3 m	Temperature	NTC thermistor	Grant U-type (ultra precision) thermistor	-55 to 80°C	± 0,05 °C from 0-50°C
Id1740	0,7 m	Temperature	NTC thermistor	Grant U-type (ultra precision) thermistor	-55 to 80°C	± 0,05 °C from 0-50°C
Id1741	1,1 m	Temperature	NTC thermistor	Grant U-type (ultra precision) thermistor	-55 to 80°C	± 0,05 °C from 0-50°C
Id1742	1,5 m	Temperature	NTC thermistor	Grant U-type (ultra precision) thermistor	-55 to 80°C	± 0,05 °C from 0-50°C
Id1743	1,9 m	Temperature	NTC thermistor	Grant U-type (ultra precision) thermistor	-55 to 80°C	± 0,05 °C from 0-50°C
Id1744	2,3 m	Temperature	NTC thermistor	Grant U-type (ultra precision) thermistor	-55 to 80°C	± 0,05 °C from 0-50°C
Id1384		Squirrel data logger		Grant 2020 series (2F8), firmware 4.3	156 MB	

Ventilation efficiency

Serial-/ID-nr	Position (height)	Measurement	Sensor	Manufacturer and type	Range	Accuracy
Id1716	Person simulator 1,1 m	CO_2 concentration	Non-dispersive Infrared Technology (NDIR)	E+E Elektronik EE80 series	0-2000 ppm	± 50 ppm +2% of measured value
Id 1714	Tripod 1,1 m	CO_2 concentration	Non-dispersive Infrared Technology (NDIR)	E+E Elektronik EE80 series	0-2000 ppm	± 50 ppm +2% of measured value
Id1731	Person simulator 0,1 m	Temperature	NTC thermistor	Grant U-type (ultra precision) thermistor	-55 to 80°C	± 0,05 °C from 0-50°C
Id1732	Person simulator 1,1 m	Temperature	NTC thermistor	Grant U-type (ultra precision) thermistor	-55 to 80°C	± 0,05 °C from 0-50°C
Id0887		Squirrel data logger		Grant 2020 series (1F8)	156 MB	

APPENDIX X JUDGEMENT OF THE DV SYSTEMS

Only a comparison between the mentioned two systems is performed, other systems like exhaust only and natural ventilation aren't included

Judgement scale:

Poor	Neutral	Good
-	o	+

.

Judgement of two DV systems based on several aspects

Aspects	**DV-system 1**	**DV-system 2**
Noise level [1)]	o	+
Room flexibility [2)]	-	o
Implementation (existing buildings and new buildings) [3)]	+ and o	- and +
Costs (initial costs and exploitation costs) [4)]	+ and -	- and +
Energy use [5)]	+	+
Robustness [6)]	o	+
Maintenance [7)]	o	+
Individual adaptation [8)]	+	+

Possible supplements to expand or improve the two DV systems

Supplements (x is optimal, - is no option)		
Regulation of ventilation system [A)]		
Light Switch	x	x
Time table regulation	x	x
Demand controlled ventilation	x	x
Energy efficiency [B)]		
Heat recovery system	x	x
Regulating bypass 0-100%	x	x
Comfort [C)]		
Integrated cooling system	-	x
Regulating bypass 0-100%	x	x
Flexibility [D)]		
Double wall	-	x
Textile air diffuser at wall (above breathing height)	x	x
Textile air diffuser at the ceiling	-	x

1) A higher risk of exceeding specified noise level produced by ventilation system 1. There's minimal space to add silencers. System 2 has the opportunity to implement silencers in the central system
2) The flexibility of the room decreases when a plug & play unit is placed in the room. The AHU takes some room space and the air in- and outlet are fixed in the outer wall or roof so it can't be replaced. System 2 takes less room space, but it isn't optimal because the position of the supply and extraction opening is fixed
3) Implementation of system 1 is relatively easy in existing and new school buildings. On the other hand a more intelligent integral design could be made with a new school building when system 2 is applied. Depending on the building structure, but generally system 2 is more difficult to implement in a existing school building
4) System 1 could be a modular investment (e.g. each year) but is more expensive because of the system components like AHU' s. System 2 needs a basic investment with a central AHU and ductwork to the classroom but is less expensive in exploitation costs (maintenance costs)
5) Both systems have a heat recovery system and can be provided with demand controlled ventilation (VAV-system) which reduces energy use. Note: a ventilation system needs energy, extra (electrical) energy use is inevitable to obtain a good indoor climate
6) When the supply and extract ducts and diffusers of system 2 are placed between two walls the robustness of the system increases. The textile supply diffuser will be placed behind a perforated panel. Pupils can't demolish the ductwork and textile supply diffuser like they can with system 1
7) System 2 needs less maintenance like replacing fewer filters on a yearly basis and cleaning ventilators. On the other hand system 2 needs more ductwork cleaning, but this is cheaper than yearly replacement of filters
8) Both systems are provided with an overrule function to accept human interference. Both systems are depending on the internal heat loads and the local heating system to obtain a minimal air supply temperature at low outdoor temperature <0°C

A) The ventilation system can be switched with lighting system as a basic regulation. A timer can be added the ventilation system must reset the CO_2 concentration to outdoor values during the breaks without spoiling lighting energy. Also when free cooling at night is desired during summer a timer becomes necessary. A demand controlled ventilation system reduces or increases the amount of fresh air based on the CO_2 concentration in the classroom. This system saves valuable ventilation energy when the classroom isn't occupied or when the windows are opened. Also a temperature sensor can be placed to reduce the supplied air flow when outdoor temperature become extremely low

B) Above a certain outdoor air temperature the full recovery of heat from the extracted air is unwanted because of overheating. In this case a regulating bypass can be applied to avoid extra heat when the bypass is fully opened to obtain an air supply temperature of minimal 18°C. Most of the time a heat recovery system is able to regulate supply air temperature within specified range. Because of the excess of heat in a classroom (especially new schools with good insulation) most of the time no heating coil is needed. The supply air temperature is indirectly regulated by the additional heating system (e.g. radiators) in the classroom at low outdoor air temperature. The additional heating system needs to be regulated by a thermostatic control valve. In most young, good isolated school buildings a low efficiency (50-70%) heat recovery system is more than enough to preheat the supply air. In addition the supply air can also be regulated by increasing the amount of extracted air or temporarily reducing the amount of supplied air. The choice of the efficiency of a heat recovery system needs to be calculated for each situation.

C) An extra cooling coil can be added in the central AHU combined with a refrigeration machine. Because of the available space a air conditioning system for system 2 is difficult to implement

A regulating bypass provides an accurate supply air temperature for outdoor temperatures between e.g. 14 (the temperature of which a non regulating bypass recovers unwanted heat) to 18-19°C (the desires minimal air supply temperature).

D) Although the primary zone stays the same, the duct system is aesthetically removed

Although this research doesn't include the influence of a textile air diffuser above breathing height, this option could gives more flexibility to position closets beneath the diffuser (maybe with a small distance from the wall to allow a part of the air to pass behind the closet to the wall).

A textile air diffuser at ceiling height (when ceiling height is sufficient >3 meter) reduces the efficiency of the ventilation system. The eventually efficiency becomes somewhere between displacement ventilation and mixing ventilation. As a result more air is needed to obtain the same CO_2 concentration

APPENDIX XI ENERGY COSTS CALCULATION

In this appendix a rough estimation of the energy costs is made based on the year 2007. Average day temperatures are used to calculate the energy needs. Only the costs for ventilation are calculated, no heat loss through building envelopes is taken into account. The calculations are based on 180 school days per year wit an average teaching program of 6 hours per day. For the estimation and comparison of the thermal energy consumption the following options are evaluated:

- Option 1: DV with 80% heat recovery, air flow of 550 m^3/h, good IAQ, good thermal comfort, moderate energy consumption;
- Option 2: DV with 80% heat recovery, air flow of 550 m^3/h, good IAQ, good thermal comfort, low energy consumption;
- Option 3: Natural ventilation with limited air flow of 300 m^3/h (based on measurements), poor IAQ, good thermal comfort, low energy consumption;
- Option 3: Natural ventilation with the same IAQ as the DV system, needed air flow of 750 m^3/h, good IAQ, poor thermal comfort, high energy consumption.

Assumptions

Electrical energy costs		
Capacity ventilators	200	[W]
Electrical energy costs per unit	0,17	[€, kWh]
Thermal energy costs		
Energy capacity of Gas	35,2	[MJ/m^3]
Themal energy costs per unit	0,51	[€/m^3]

Outcome calculations

Comparison options	**Option 1**	**Option 2**	**Option 3**	**Option 4**
Thermal energy loss [MJ]	1758	79	2643	6606
Accompanying costs [€/yr]	25	1	38	96
Electrical energy consumption [kWh]	216	216	0	0
Accompanying costs [€/yr]	37	37	0	0
Total energy costs per year [€]	**62**	**38**	**38**	**96**

A DV system with a 50% heat recovery system uses more energy than a natural ventilated classroom (option 3). On the other hand it provides a good indoor air quality and uses less energy than option 4. A DV with a 80% heat recovery system uses the same energy as a typical ventilated Dutch school (option 3). The DV system provides a good IAQ and thermal comfort.

7Y400 DESIGN METHODOLOGY

Assignment 3: Methodical Design for primary school ventilation

D.J.B.W. Schuiling
Building Services
0556949

17th December 2007

TABLE OF CONTENTS

1. INTRODUCTION METHODICAL DESIGN APPROACH

In this study, a methodical design approach (from Kroonenberg) is used to evaluate the ventilation concept for primary schools. This design approach is used to create structure in the design process. Several design aspects can be ordered to create an overall view of the design problem. The methodical design method can be distinguished into four main segments:

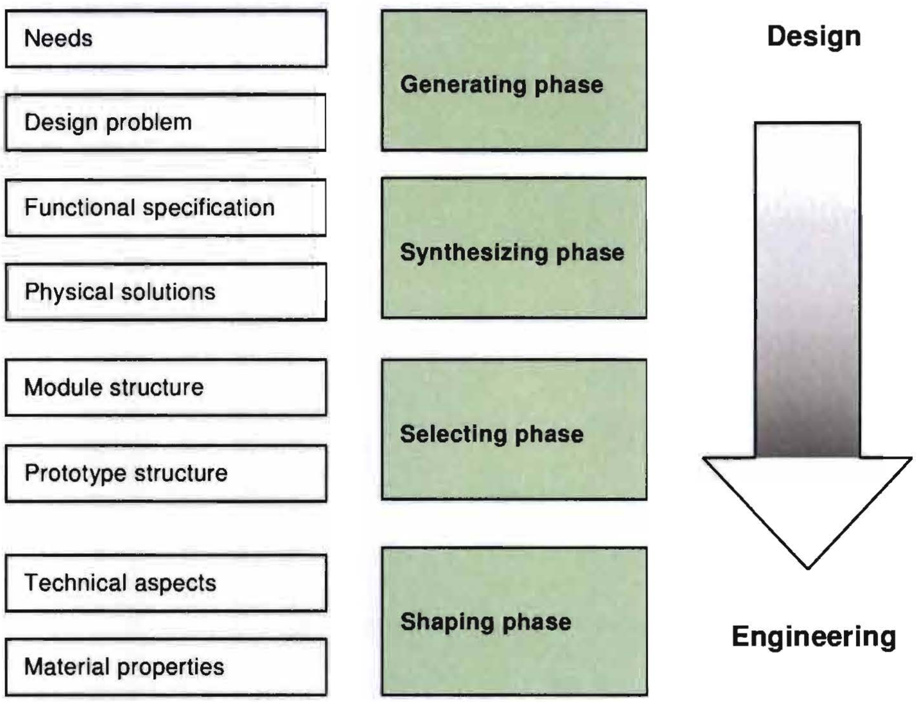


Figure 1.1 The methodical design procedure

The methodical design process starts with an abstract problem definition and it will end with a definite solution to the design problem. Each phase has a different level of abstraction hierarchy which starts with the primary needs and ends with a suitable concept to fulfil these needs.

2. FUNCTIONAL LEVEL

2.1. GENERATING PHASE

The first phase describes the primary needs of the users and the specific design problem(s). Afterwards, a list of requirements can be generated. The requirements can be divided into two groups. One group contains all the requirements regarding the functionality of the design. The other group contains all the requirements that are important for the realization of the design. These functional requirements are for example: room temperature, indoor air quality, noise level (generated by the building services). The realization aspects are for example: flexibility, number of components, costs.

Problem description

Pupils and teachers have some primary needs according to the indoor climate of a classroom. The indoor climate must provide:

- A good Indoor Air Quality
- A good thermal comfort level

Indirectly the building services can contribute to:

- A pleasant environment
- An environment that stimulates learning performance and concentration
- A climate that prevents decrease of human health (reduce sick symptoms like coughing, sneezing, red eyes, etc.)

There are more aspects that describe the total indoor climate of a classroom like for example: the mental aspect, the individual preferences (like colours, materials), the view in- and outside of the classroom. Only the physical aspects, which can be directly influenced by the building services, are evaluated in this research. The figure below shows the main physical aspects that are important for the welfare of the pupils and teachers.

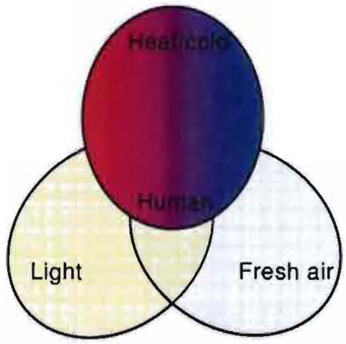


Figure 2.1 Primary needs of pupils and teachers in a classroom in terms of physical aspects

Most primary schools in the Netherlands contain similar characteristics which enable to describe a "standard" classroom (see picture 1.4 as an example of a standard classroom).

Figure 2.2 Primary school "De Pijler" at Maasdam

Characteristics

- Floor surface around 52 m^2 (7,2x7,2 metres) and room height around 3 metres;
- Situated near a façade with (large) window surface;
- Ventilation through windows in the façade;
- Cold (draught) in winter and hot in summer, depending on outdoor climate;
- A lot of people in a small area. Occupation around 1 person per 2 m^2 (around 25 pupils and a teacher);
- Heat (required to compensate transmission, infiltration and ventilation) is generated by radiators beneath windows;
- Some computers in the classroom;
- A lot of disturbances like air flow through windows and doors, human activity, many objects;
- High risk of transferring pollution like bacteria, fungi, fibres, odours, etc.
- Little free space available;
- Outdoor awnings
- TL lightings

Functional (user) and realization requirements

After the main problem definition is formulated, a list of requirements is made. These requirements can be separated into function requirements and realization requirements. The table below gives the specified requirements for the highest hierarchic level: the functional level:

Function	
1	Winter climate (chance of draught)
2	Summer climate (room temperature and efficient heat extraction)
3	Indoor Air Quality (effective removal of contaminants)
4	Individual adaptation (air volume/temperature)
5	Noise (environmental and produced by ventilation system)
6	User dependency (human intervene)
Realization	
1	Implementation
2	Flexibility
3	Costs
4	Energy use (thermal and electric energy)
5	Reliability
6	Maintenance

Table 2.1 list of requirements on the functional level

Task

Create a ventilation/heating concept for primary schools with respect to the mentioned needs and characteristic problems

2.2. SYNTHESIZING PHASE

This phase describes the functions that need to be fulfilled. These functions can be represented by function blocks. Next several physical solutions for each function are collected in a morphological overview. At the end of this phase the best solutions for each function are connected and the total design concept is achieved. Sometimes the total design concept is better if a less optimal solution is chosen for an individual function. To see if a solution is feasible it can be checked with all the functions and the requirements. If not, another solution must be examined or the functions need to be adjusted. Often multiple variants of design concepts appear to be suitable. Therefore these variants are compared with each other in detail in the next phase.

Problem approach from different abstraction levels

The main problem can be approached from three different abstraction levels (see figure 2.3): the human orientated level (e.g. accumulation of fresh air), the work space orientated level and the classroom orientated level. Each level is limited by the system boundary. The human level is the most important level and is thereby evaluated with the energy, matter and information method (see appendix I).

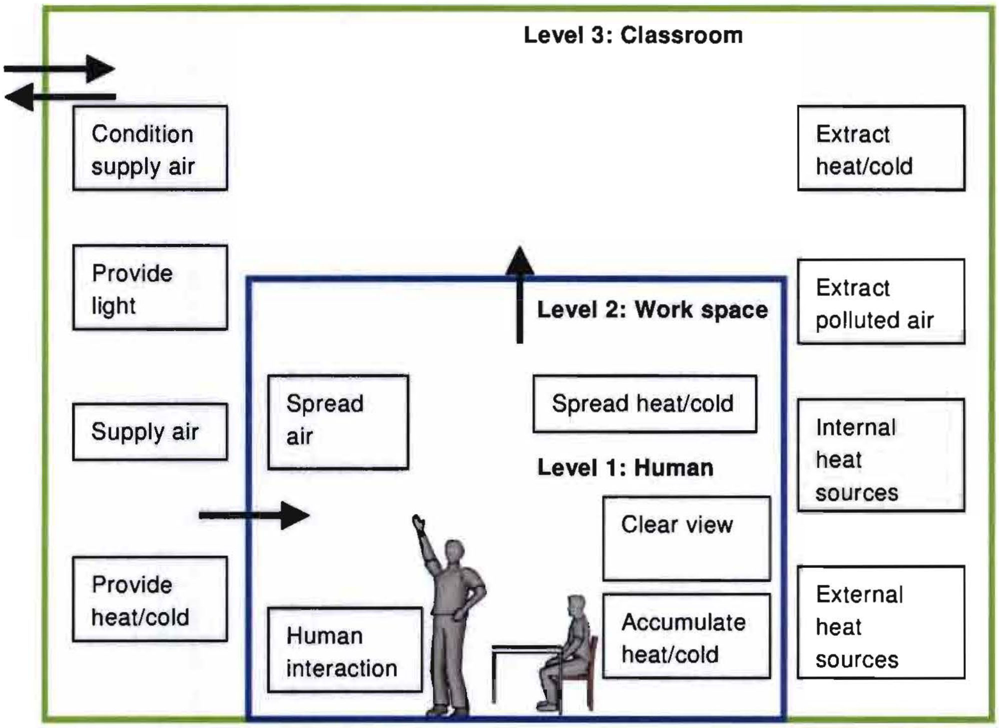


Figure 2.3 System boundaries and within a classroom

Level 1: Human orientated (pupils and teacher)

- Heat production (determined by age and activity level)
- Exchange heat trough skin surface
- Inhaling fresh air and exhaling used air
- Emit contamination like CO_2, hair, skin particles, body odours, dust, bacteria, pathogens, etc.
- Produce moisture through skin and respiratory tract

Note: pupils and teachers have other metabolism levels and thereby need different climate conditions.

Level 2: Work space (interaction with surrounding)

- Refreshment of used air by fresh air
- Heat exchange body and surroundings
- Exchange of moisture and contaminants

Level 3: Classroom orientated

- Production of internal and external heat (Sun, lighting, computers)
- Supply and extraction of air
- Removal of contaminants from people, furniture, plants, chalk of blackboard
- Extraction of heat

The function blocks are categorized into four main segments of supply, spread, use and extract. All functions can be placed within this format (see figure 2.4).

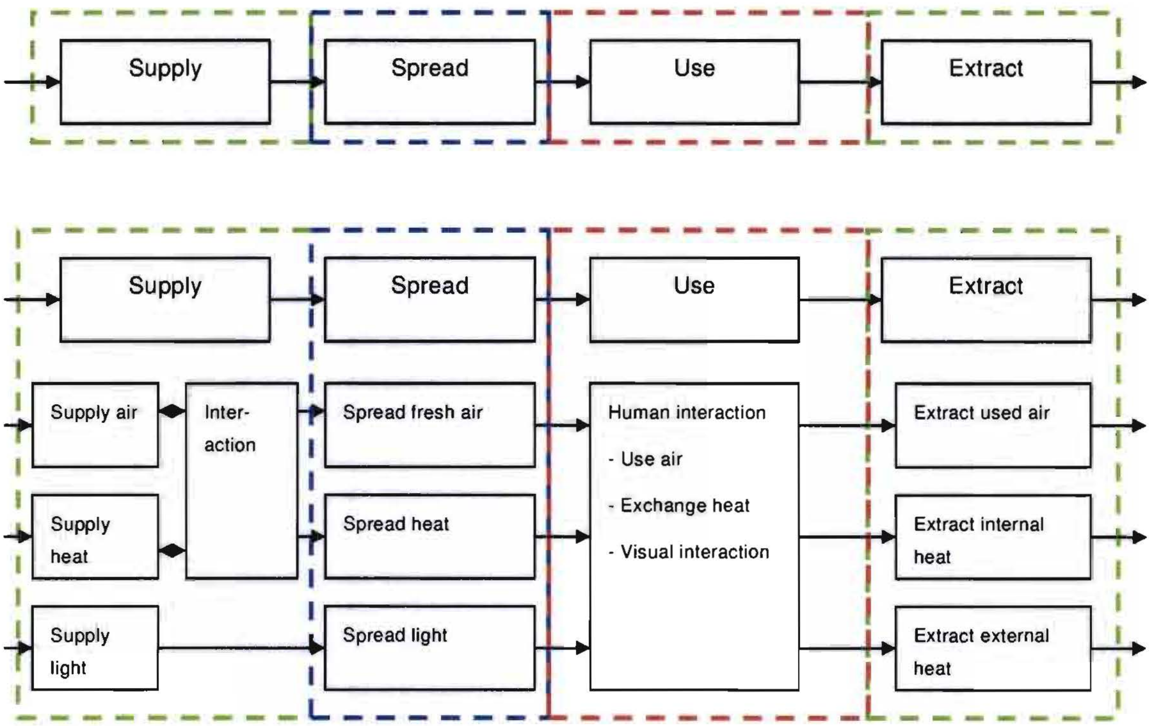
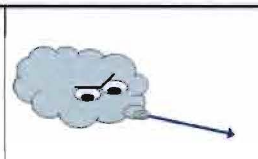
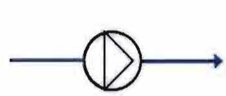
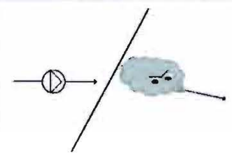
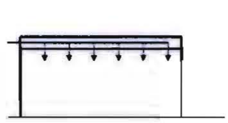
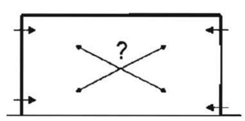
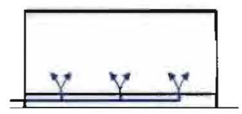
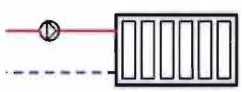
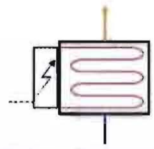
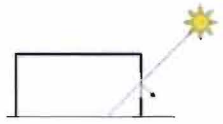
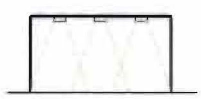
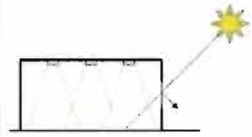
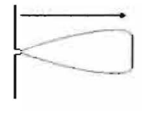
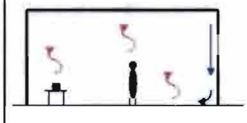
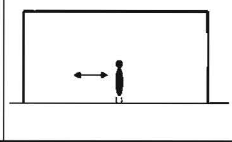
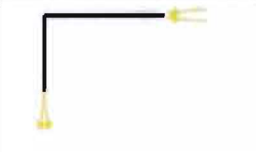
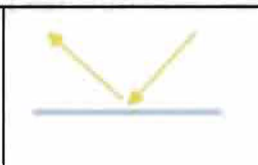
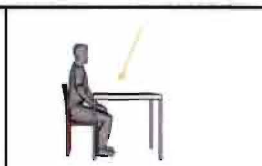
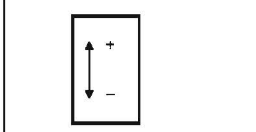
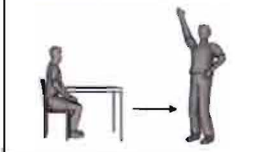
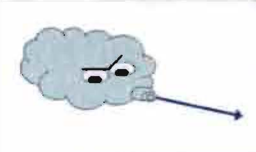
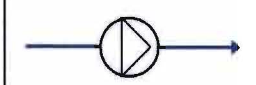
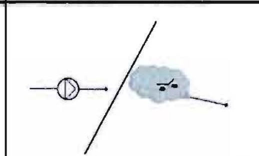
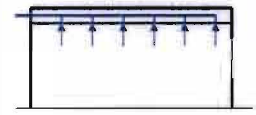
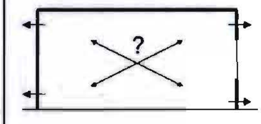
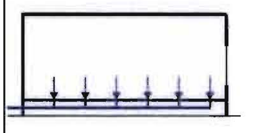
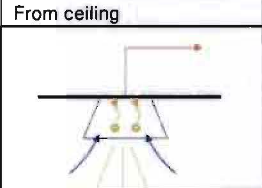
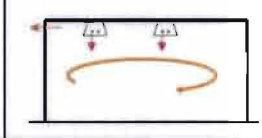
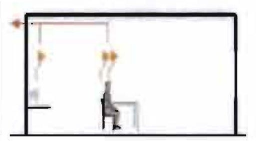
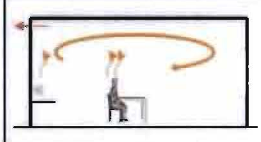
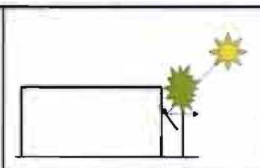
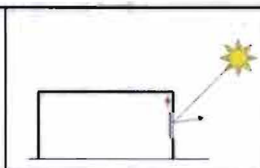
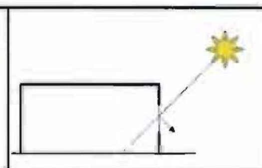


Figure 2.4 Segment of different orientation levels

Morphological overview on the highest hierarchic level: the functional level

Supply air				
	Natural supply	Mechanical supply	Hybrid supply	
				
	From ceiling	From wall/façade	From floor	
Supply heat				
	Water system	Electric heating	Mass to air	
Supply light				
	Natural daylight	Artificial light	Combination	
Spread air				
	High impulse (inducing/mixing)	Density differences (buoyancy)	Coanda effect	Human activity (mixing)
Spread heat				
	By convection (e.g. air heating battery, convector)	By conduction (e.g. contact with heated surfaces (seat, table))	By radiation (e.g. radiator, floor heating, TABS, radiant panel)	

Spread light				
	Conduction	Reflection (e.g. blinds, surfaces)	Direct light, no indirect transport	Individual lighting
Human interaction				
	Opening window/door	Adjusting HVAC settings (heating, fresh air)	Person adaptation (e.g. Adjusting activity level)	
Extract used air				
	Natural extract	Mechanical extract	Hybrid extract	
				
	From ceiling	From wall/façade	From floor	
Extract/reduce internal heat (Light)				
	Direct heat extract from light	Indirect heat extraction		
Extract/reduce internal heat (Persons and/or PCs)				
	Direct heat extraction	Indirect heat extraction		

Extract/reduce external heat				
	External sun block	Internal sun block	No sun block	

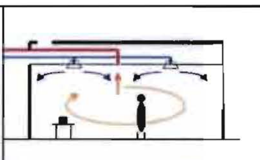
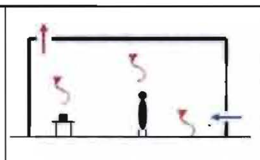
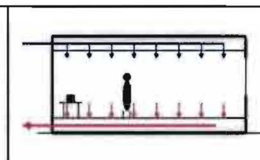
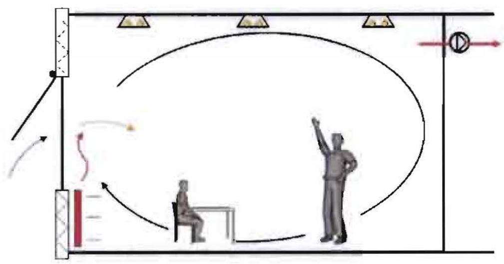
Result ventilation type				
	Mixing ventilation	Passive displacement ventilation	Active displacement ventilation (piston flow)	

Figure 2.5 Morphological overview on the functional level

The morphological overview gives a lot of possibilities, is this case there are at least **1.259.712 possibilities!!**

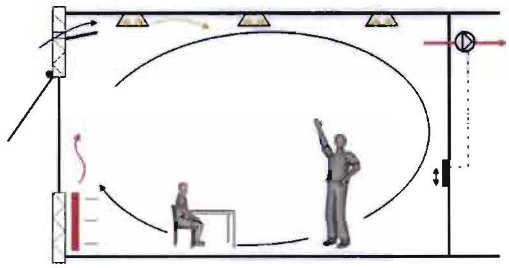
At the end of the morphological overview a selection of the most promising combinations of sub functions is made. Several variants are selected within the morphological overview, the most promising structure schemes are added in appendix II and are also visualized in the figures below.

Variant 1 (red): Standard school in the Netherlands



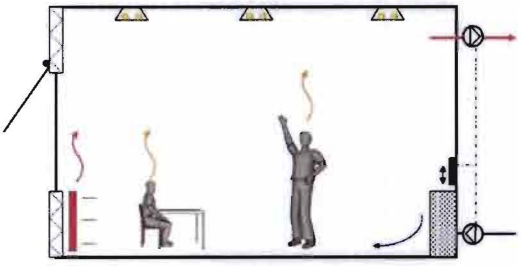
This variant is a very common situation in the Netherlands. A natural ventilation supply through windows/grilles in the façade combined with a central (toilet) ventilation system. The heating system of the classroom isn't modified (radiators beneath each window).

Variant 2 (light blue): Natural supply guidance



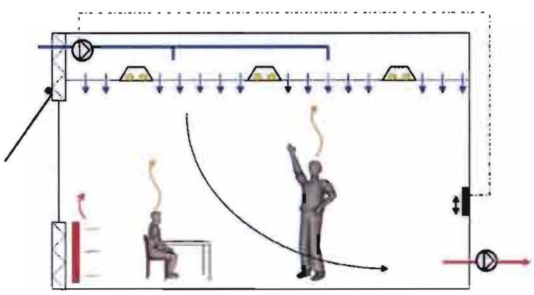
This variant is based on a natural ventilation supply grille combined with a board/panel to aim the airflow. The hybrid exhaust system supports to obtain the needed ventilation rate. The heating system of the classroom isn't modified (radiators beneath each window).

Variant 3 (dark blue): Displacement ventilation



This variant is based on the displacement ventilation concept. The mechanically balanced ventilation system guarantees the needed ventilation rate. The heating system of the classroom isn't modified (radiators beneath each window).

Variant 4 (green): Piston flow ventilation



This variant is based on the piston flow ventilation technique. A full piston flow system in a typical classroom is not possible because of the room height. Therefore this technique is combined with a central exhaust system. By this way the air flow path is bending to the exhaust opening. The heating system of the classroom isn't modified (radiators beneath each window).

2.3. SELECTING PHASE

The next phase is to judge which variant fits best. The variants are judged on basis of the desired values in the list of requirements. This is difficult because al lot of requirements quantitative and part qualitative. Each requirement is evaluated and judged in an overview for a clear and objective discussion. These results are visualized by an S-graph with a realize and a function axis. With the S-graph it is easy to see if improvements must take place on the functional or the realization side. The best variants lie near the diagonal line and have high scores in both aspects. The table below (table 2.2) shows the outcome of the assessment of the 4 variants. The motivation for the assessment can be found in appendix III.

nr.	Function	Credits	Standard school Netherlands (red)	Air flow guidance board (light blue)	Displacement ventilation (bleu)	Piston flow system (green)
1	Winter climate (chance of draught)	**4**	1	2	4	4
2	Summer climate (room temperature and efficient heat extraction)	**4**	1	3	4	3
3	Indoor Air Quality (effective removal of contaminants)	**4**	1	2	4	4
4	Individual adaptation (air volume/temperature)	**4**	3	3	4	4
5	Noise	**4**	2	3	3	2
6	User dependency	**4**	2	3	3	4
	Total	**100%**	**42**	**67**	**92**	**88**
	Realization					
1	Implementation	**4**	4	4	3	3
2	Flexibility	**4**	4	4	2	4
3	Costs	**4**	4	3	2	2
4	Energy use (thermal and electric energy)	**4**	1	2	3	3
5	Reliability	**4**	4	3	3	3
6	Maintenance	**4**	4	3	2	1
	Total	**100%**	**88**	**79**	**63**	**67**

Table 2.2 The appreciation of the most promising variants

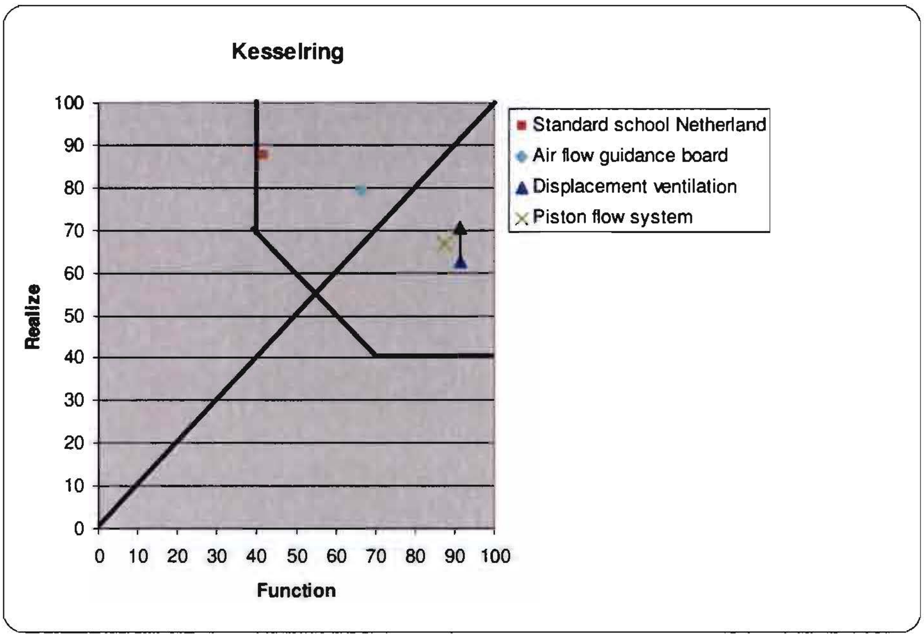


Figure 2.6 The Kesselring diagram

The figure above shows the outcome of the variant assessment. It shows that the standard school is appreciated worst. The air flow guidance board has a high score on the realize aspect and a relatively low score at the function aspect. The piston flow system and the displacement system have almost the same score on both aspects. The piston flow system is more flexible than the displacement system while the piston flow system isn't very easy reachable for maintenance. Although the displacement ventilation system scores low at the realize aspect is has a high potential to overtake the air flow guidance board system and the piston flow system. The displacement ventilation system can't get cheaper or easier to maintain but there is some potential in the flexibility at the realize side. The maximum score the displacement ventilation system can achieve at this side is 71% (see arrow in figure 2.6).

2.4. SHAPING PHASE

In the last phase the details and materials of the best variant are determined. The finally used material depends on several aspects (e.g. safety, easy to use/clean). Also the several components of the design concept are figured out.

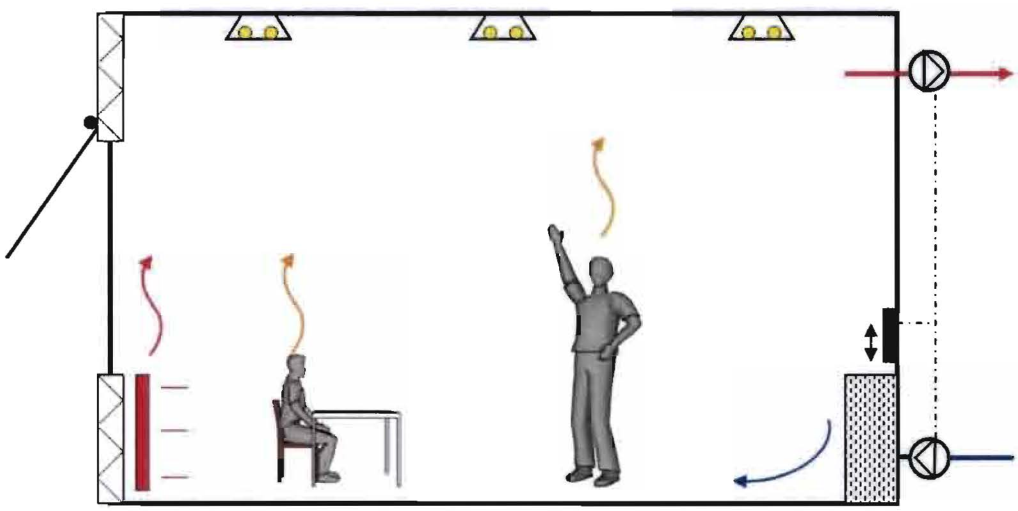


Figure 2.7 The displacement ventilation concept

To create an affordable concept the available resources for heating and lighting stay preserved. The ventilation concept must be suitable to apply in an existing primary school. The mechanical balanced system consists of a supply facility at floor surface and an exhaust facility at ceiling surface to preserve the displacement effect. Displacement ventilation is more efficient than mixing ventilation and thereby needs 30% less air than mixing ventilation. The amount of air needed to obtain an acceptable indoor air quality is adjustable. Also the supply air temperature must be kept above a certain value to prevent temperature stratification in the classroom. The air supply temperature and air volume can be regulated by hand or automatically. The exact components that are used for the implementation of the displacement ventilation concept are described in chapter 3.

3. COMPONENT LEVEL

3.1. GENERATING PHASE

Design problem

In this phase, the design problem is concentrated on the ventilation process. Fresh air from outside must be conditioned and supplied into the breathing area (and improve the indoor air quality) in an effective way. The air needs to be transported without any draught.

Functional (user) and realization requirements

The requirements of the component level are based on a lower hierarchic level and are more concrete. The requirements are strongly related to the quality, the size, and the capacity of several components which are a part of the design concept. The table below gives the specified requirements for the lower hierarchic level: the component level:

Function	
1	Temperature winter 20-22°C (thermal comfort)
2	Temperature summer 23-28°C when $T_{outdoor}$>28°C (thermal comfort)
3	Temperature stratification < 3K/m (thermal comfort)
4	Air speed <0,2 m/s (summer) and <0,16 m/s (winter), prevention draught
5	Relative humidity 40-65% (indoor air quality)
6	Average CO_2 concentration ~1000 ppm (indoor air quality)
7	Effective removal of contaminated air and/or heated air (efficiency)
8	Noise level below 35 dB(A) (general aspect)
9	Easy to use (general aspect)
10	Individual adaptation (general aspect)
Realization	
1	Realization
2	Safety/child friendly
3	Flexibility
4	Maintenance
5	Number of components
6	Costs (investment and exploitation)
7	Necessary instalment space
8	Energy use
9	Reliability (independent from outdoor climate)
10	Robustness

Table 3.1 list of requirements on the component level

3.2. SYNTHESIZING PHASE

The design problem is translated in a new function blocks which together represent the ventilation function (see figure 3.1).

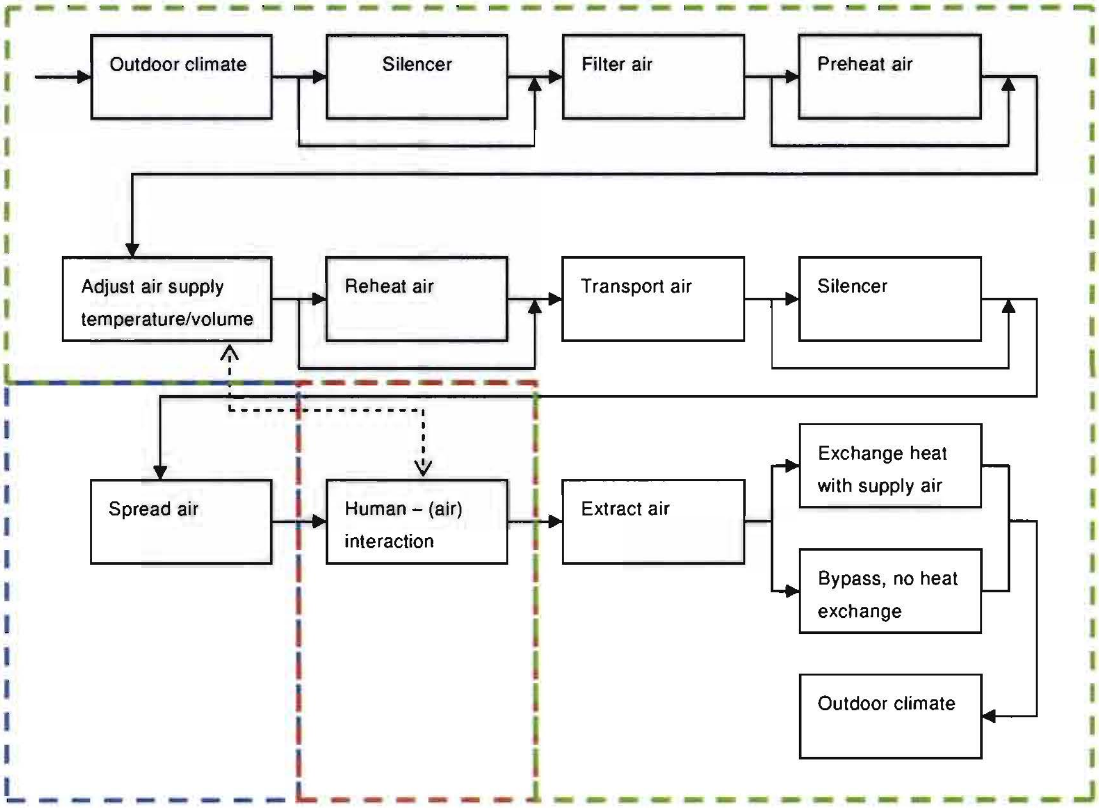
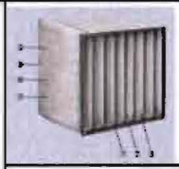
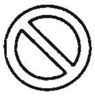
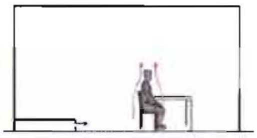


Figure 3.1 ventilation function blocks

Morphological overview on the component level

Based on the detailed ventilation function block a second morphological overview is given:

Sound reduction				
	Silencer	Reduced sound level ventilator	No sound reduction	
Filter air				
	Air filter	Air filter with signal	No filter	
Preheat				
	Cross-flow plate heat exchanger	Counter-flow plate heat exchanger	Ground exchange (mass accumulation)	No preheat
Reheat air				
	Reheat battery (water)	Reheat battery (electric)	No reheat	
Transport air				
	Duct system	Double wall	Raised floor	
Spread air				
	Low velocity terminal	Textile duct system	Inducing floor grille	Personalized

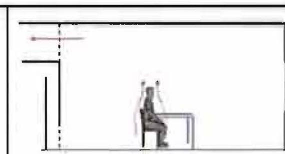
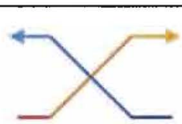
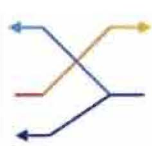
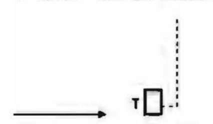
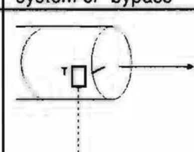
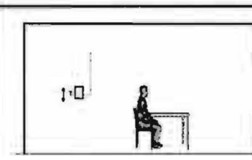
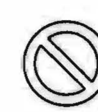
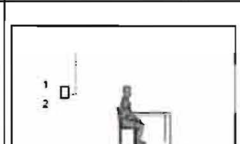
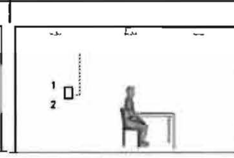
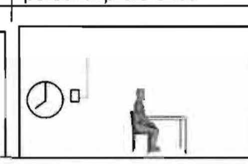
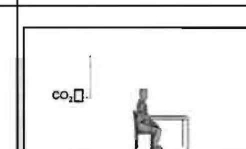
Extract air				
	Grille in wall	Grille in ceiling (above users)	From opening in double wall	
Extract heat from used air				
	Only through exchange system	Through exchange system or bypass	No exchange	
Regulate air supply temperature				
	By temperature sensor in room at floor height	By temperature sensor in duct	By temperature sensor and personal preference	No temperature control
Regulate air volume				
	High/ low by teacher	Switched with lighting system	Time dependant	By CO_2 sensor freq. ventilators

Figure 3.2 Morphological overview on the component level

3.3. SELECTING PHASE

Based on the list of demands and the following option is chosen:

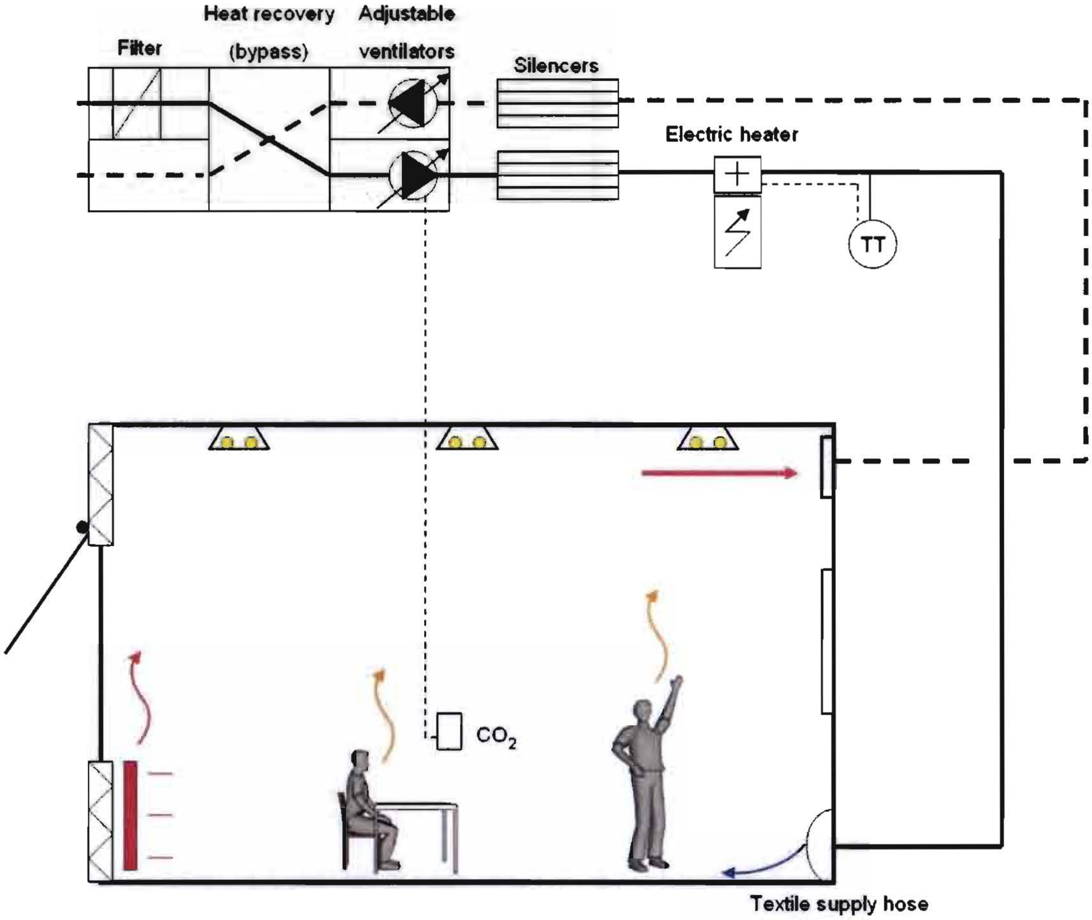


Figure 3.3 The optimized ventilation concept for existing primary schools

3.4. SHAPING PHASE

Additive information for the chosen concept:

- Silencers are added because it's difficult to obtain a sound level around 35 dB (A) in the classroom without any silencers;
- Filters can have a surplus value for a child who has asthma and is thus desired. Filters need to be replaced once a year, the maintenance intensity increases;
- Occupied classrooms have an excess amount of heat, thereby a cross flow heat exchange system (efficiency of 50-70%) is with a low pressure drop is sufficient to heat up the supply air for a large period of a year. In winter a extra electric heater is available to heat up the supply air to the desired air supply temperature;
- Normal ductwork is capable of transporting the air into and out of the classroom in standard situations. When individual adjustability is desired a raised floor could applied to create an extra space for individual adjustment equipment (see appendix IV);
- The air is spread into the breathing area with a textile duct system. This hose is safe, easy to clean and relatively cheap compared with low velocity diffusers;
- The air supply temperature, which is kept constant by the electrical heater, is set by the limited value at what draught problems do not occur (in winter);
- The amount of air supplied by the ventilation system is measured by the CO_2 sensor which is located at 1, 1 meter above the floor surface.

Additional durable energy possibilities which can be added to the ventilation concept are described in appendix V.

4. CONCLUSION

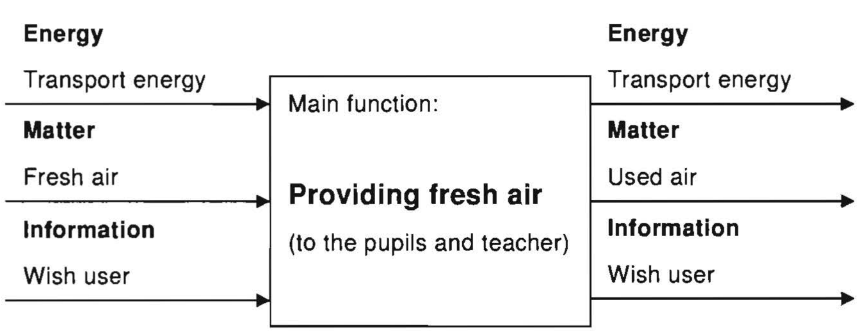
AT the end of the subject Design Methodology 7Y400 the following conclusions can be drawn:

- Methodical design approach is an open way to create a design concept. The designer is forced perform close research of the design problem in a structural way. Complex design problems can be divided into sub problems of manageable size;
- The decisions that are made during the design phases can be evaluated and reproduced. Other designer can go back into the design concept and improve it wherever they want;
- The morphological overview is a way to express and structure thoughts during the design process;
- The requirements for the assessment of the design need to be set up by a design team and not only by an individual. By this way the requirements are more objective and complete;
- The Kesselring graph is a fast and effective way to visualize shortcoming or superiority of design variants;
- The methodical design process is an open process which leaves space for individual interpretation of the design problem or approach strategy.

APPENDIX I

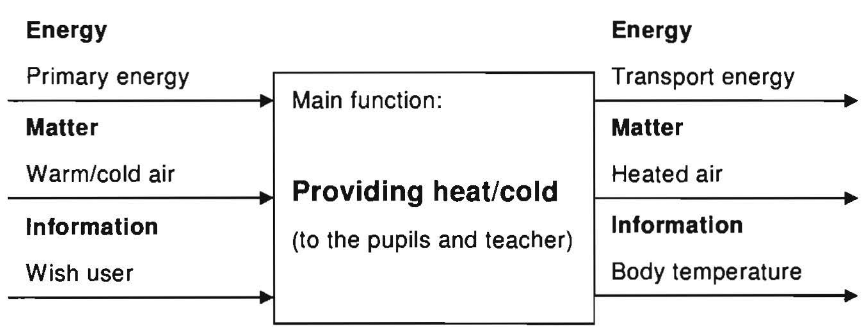
Ventilation

	Accumulate	Transform	Transport
Energy	Release body heat	Movement into heat	
Matter	Emit/absorb contamination, moisture and body odour	Oxygen accumulated and CO_2 is returned	Air is inhaled and exhaled
Information	Quality of air, wish user	O_2/CO_2 level	



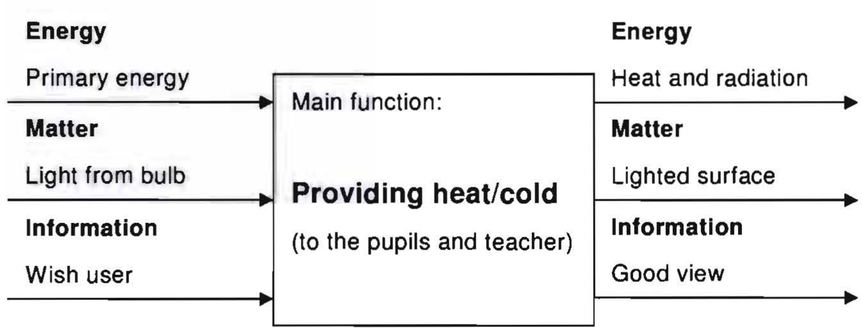
Heating/cooling

	Accumulate	Transform	Transport
Energy	Storage of energy in body	Heating energy into warm body/Body into warm air	Primary energy (gas, electricity) for transport
Matter	Heat from air and radiation	Heat/cooling medium	Warm/cold air
Information	Air temperature	Body temperature	Air temperature

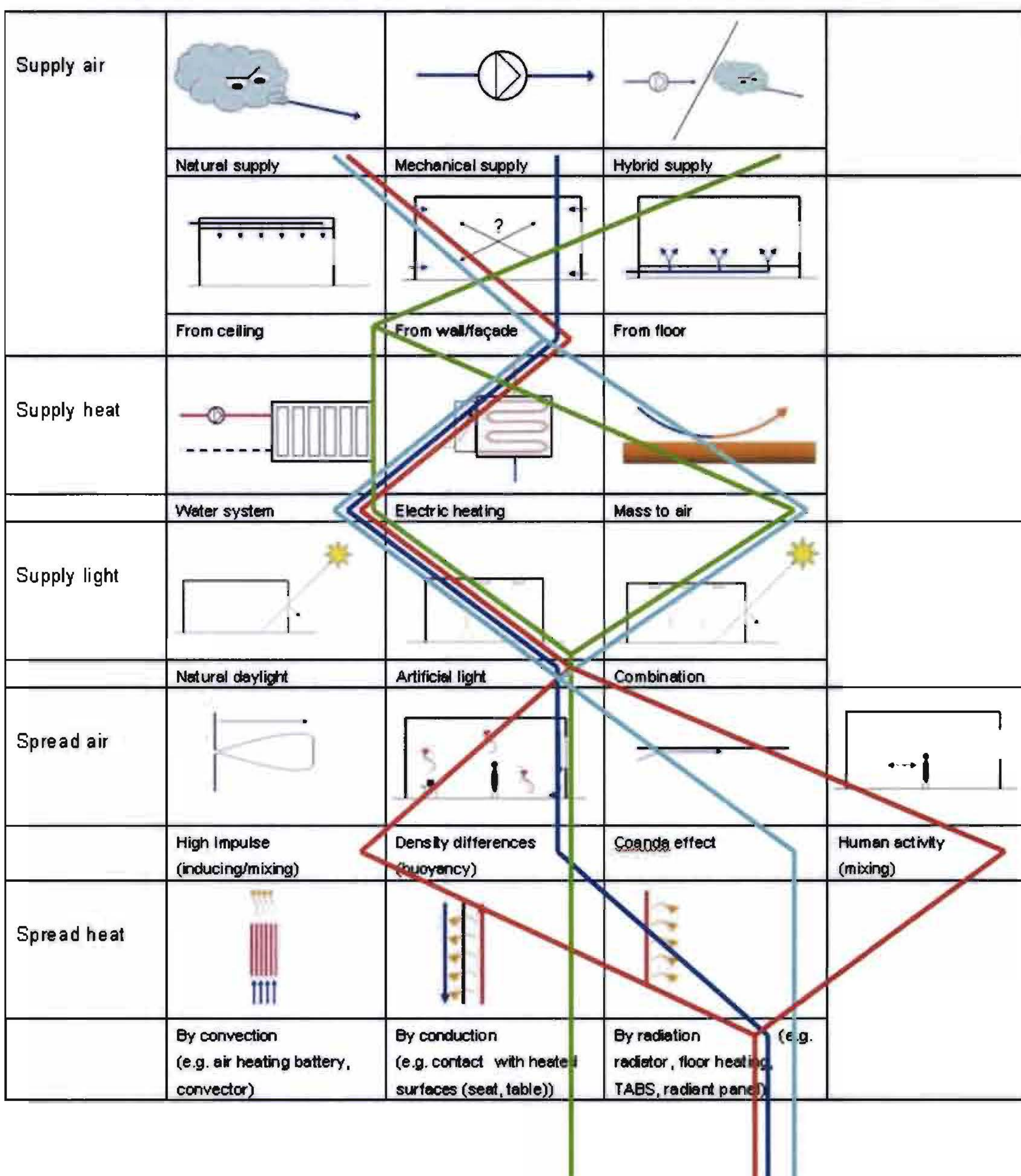


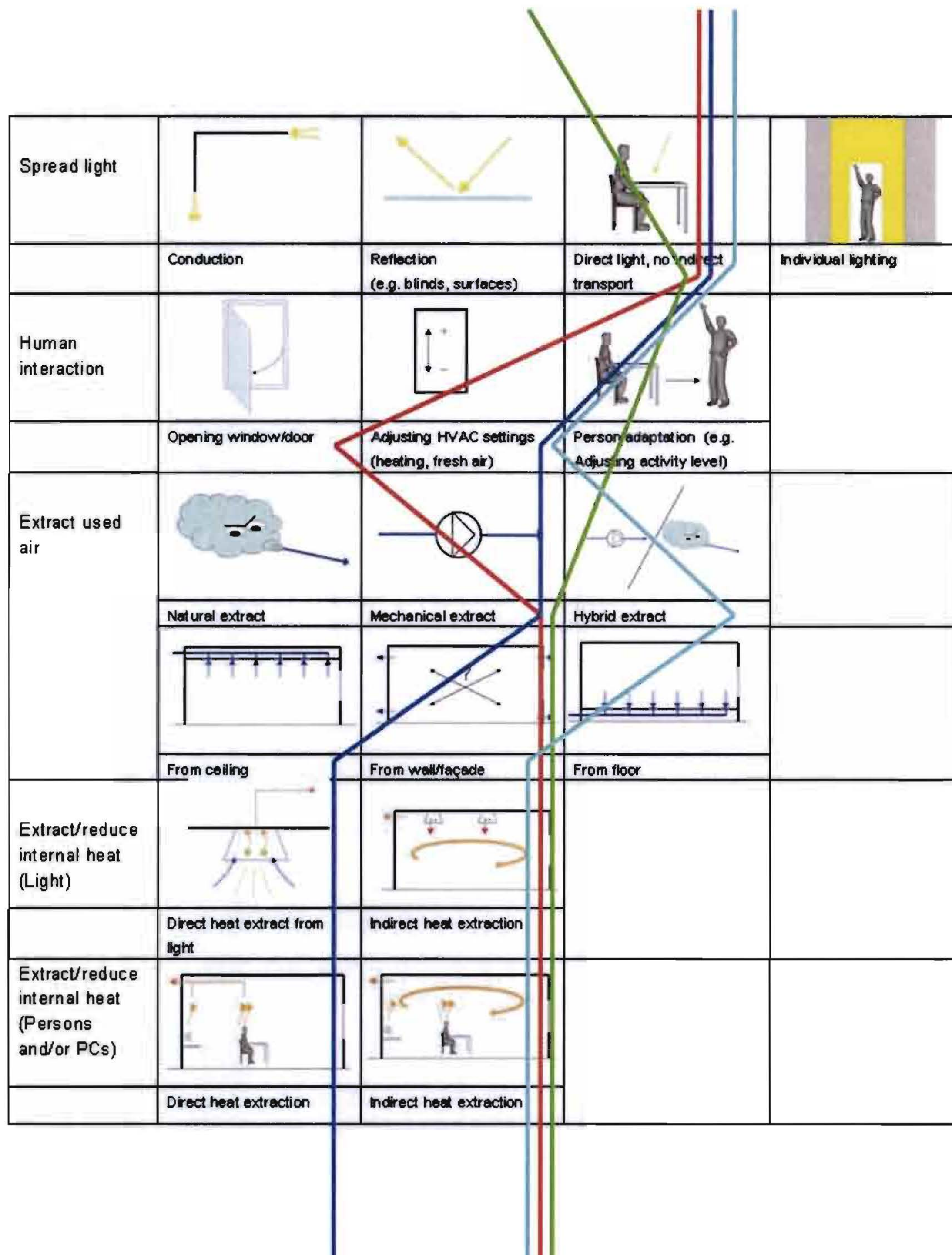
Lighting

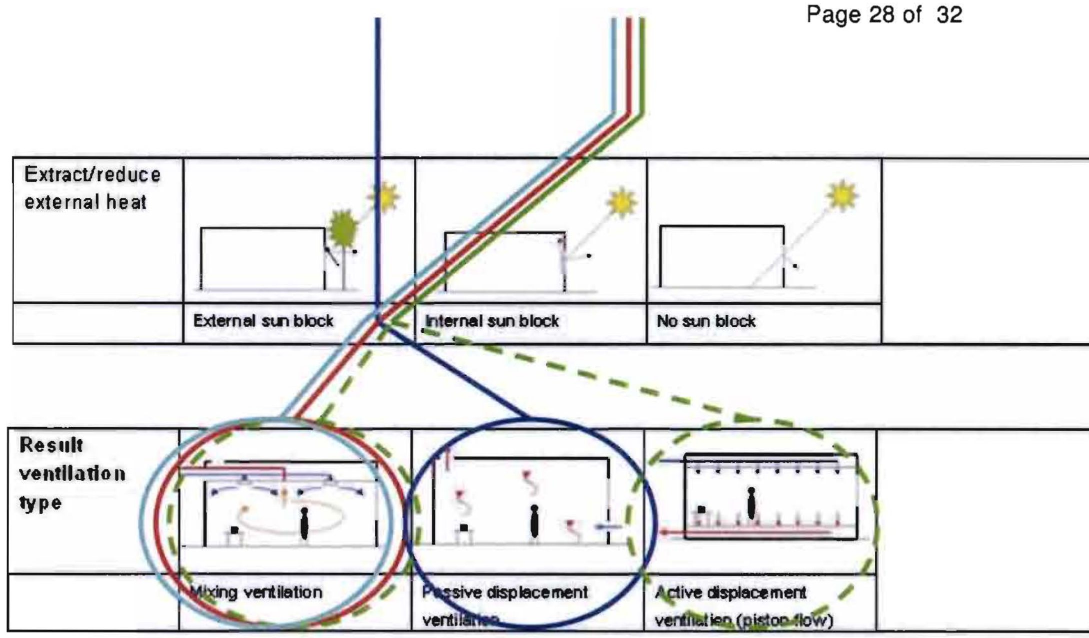
	Accumulate	Transform	Transport
Energy	Electrical energy	Electricity into light	Electricity cable
Matter	Lighted environment	Light into good sight	Radiation
Information	Good view	Observation of the eye	Good view



APPENDIX II


Supply air
Natural supply
Mechanical supply
Hybrid supply
From ceiling
From wall/façade
From floor
Supply heat
Water system
Electric heating
Mass to air
Supply light
Natural daylight
Artificial light
Combination
Spread air
High impulse (inducing/mixing)
Density differences (buoyancy)
Coanda effect
Human activity (mixing)
Spread heat
By convection (e.g. air heating battery, convector)
By conduction (e.g. contact with heated surfaces (seat, table))
By radiation (e.g. radiator, floor heating, TABS, radiant panel)


Spread light
Conduction
Reflection (e.g. blinds, surfaces)
Direct light, no indirect transport
Individual lighting
Human interaction
Opening window/door
Adjusting HVAC settings (heating, fresh air)
Person adaptation (e.g. Adjusting activity level)
Extract used air
Natural extract
Mechanical extract
Hybrid extract
From ceiling
From wall/façade
From floor
Extract/reduce internal heat (Light)
Direct heat extract from light
Indirect heat extraction
Extract/reduce internal heat (Persons and/or PCs)
Direct heat extraction
Indirect heat extraction


Extract/reduce external heat
External sun block
Internal sun block
No sun block
Result ventilation type
Mixing ventilation
Passive displacement ventilation
Active displacement ventilation (piston flow)

APPENDIX III

Variant 1		**Comment**
Function	1	When the windows are opened draught is inevitable
	2	No air circulation and heat extraction is guaranteed, temperature could rise up high
	3	No air circulation is guaranteed and the ventilation efficiency is limited (max. 1)
	4	The air volume isn't adaptable exactly and the minimum supply air isn't guaranteed
	5	High, the user must open windows. These windows are closed at night.
	6	Noise from outside
Realize	1	Easy implementation
	2	The windows in the facade aren't influencing the flexibility of the classroom
	3	Cost are low, classrooms already contain windows
	4	The heat loss due to opened windows is very high in winter
	5	High, a windows isn't blocked by pollution
	6	Very little maintenance is needed
Variant 2		**Comment**
Function	1	The air enters the room with high velocities, chance of draught is depending on the air flow path
	2	The supply air doesn't always reach the users , there could form a shortcut between supply and extract air
	3	No air circulation is guaranteed and the ventilation efficiency is limited (max. 1)
	4	The air volume could be adapted but the supply air isn't controllable
	5	Noise from outside is reduced, mechanical extract system produced noise
	6	Natural supply grilles must be closable because of draught problem might occur. Therefore the air supply rate isn't always guaranteed.
Realize	1	Easy to implement
	2	The natural supply grilles aren't influencing the flexibility of the classroom
	3	The hybrid ventilation system needs a detection system combined with a extraction fan
	4	No heat recovery system could be applied to heat the supply air. A high heat loss due to ventilation
	5	The air supply grilles could get polluted and the hybrid system could error
	6	The air supply grilles must be cleaned once a year. The mechanical extraction system needs maintenance
Variant 3		**Comment**
Function	1	Low air velocities, the air supply temperature can be controlled by an air handling unit
	2	Heat is directly "displaced" to the extract grilles. The room temperature could get significantly low.
	3	Good fresh air supply, the ventilation efficiency could become more than 1. Minimum air volume is guaranteed.
	4	The air volume and air supply temperature could be regulated by the users
	5	The mechanical ventilation system produces noise
	6	The air supply grilles could be blocked by obstacles
Realize	1	The ventilation system needs some space of the classroom (e.g. a corner).
	2	The supply grille are replaceable very easy, the duct systems must be adapted. The classroom flexibility isn't influenced very much
	3	The mechanical ventilation system is expensive
	4	A heat recovery system could be applied but the ventilators need electric energy
	5	The air supply grilles could get polluted and the mechanical ventilation system could error
	6	The air supply grilles must be cleaned once a year. The mechanical ventilation system needs maintenance

Variant 4		**Comment**
Function	1	Low air velocities, the air supply temperature can be controlled by an air handling unit above the ceiling
	2	Heat is extracted at floor surface, little mixing of air with heat sources occur
	3	Good fresh air supply, the ventilation efficiency could become more than 1. Minimum air volume is guaranteed.
	4	The air volume and air supply temperature could be regulated by the users
	5	The mechanical ventilation system produces noise, extra attention is needed because the supply system is in the classroom
	6	Little influence by user is possible
Realize	1	The classroom needs a lowered ceiling, the supply system needs to be assembled above this ceiling
	2	The mechanical ventilation system in the lowered ceiling doesn't influence the flexibility of the classroom
	3	The mechanical ventilation system is expensive
	4	A heat recovery system could be applied but the ventilators need electric energy
	5	The air supply in the ceiling could get polluted and the mechanical ventilation system could error
	6	The air supply in the ceiling must be cleaned once a year. Maintenance of the ceiling is difficult/expensive. The mechanical ventilation system needs maintenance

APPENDIX IV

The ventilation concept for existing primary schools with advanced individual adjustability. This variant is chosen to take into account the different levels of metabolism between pupils and teachers. With this variant the teacher is capable of creating his own air temperature (with an extra electric heater and inducing floor diffusers) on his platform.

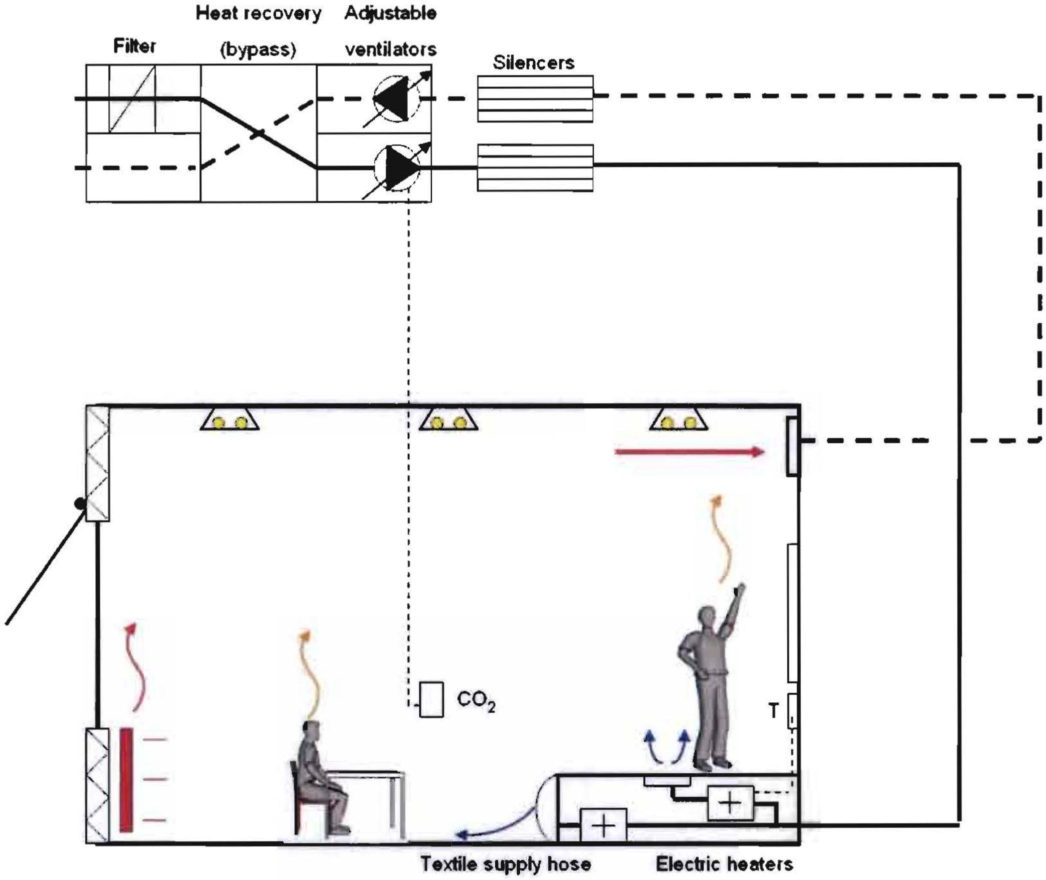
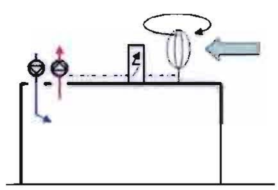
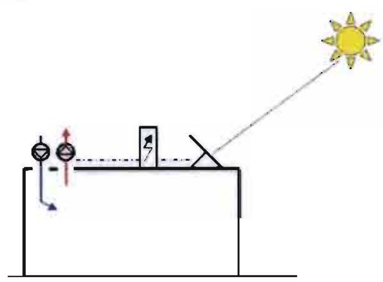
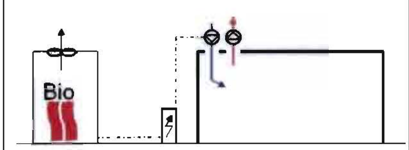


Figure 3.3 The optimized ventilation concept for existing primary schools

APPENDIX V

Some examples of durable energy sources which could be added to the ventilation concept.

Durable electrical energy	 Electricity by a windmill	 Electricity by solar panels	 Electricity by a biogas plant