MÄLARDALENS HÖGSKOLA

School of Sustainable Development of Society and Technology
Energy Engineering

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Assessment of Energy Recovery Technology in China:

Mechanical ventilation system with energy recovery

Mälardalen University
– *School of Sustainable Development of Society and Technology* –
In cooperation with:
The Hong Kong Polytechnic University
– *Building Services Engineering Department* –
and
Systemair AB

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Abstract

In the wake of the economic growth of the Chinese market the past couple of decades, the energy consumption has surged. One of the biggest consequences of the increased energy consumption is a massive increase in CO_2 emission. In fact, China has overtaken the U.S. as the biggest emitter of CO_2. In light of this energy-saving technology gets more important to implement. District heating is one of the solutions used with success in parts of China where heating is required. In this paper, an energy recovery technology has been examined for two climate zones in China namely a mechanical ventilation system using a flat-plate counter-flow heat exchanger. Beijing is located in a cold zone while Hong Kong is located in a zone with hot summers and mild winters. Cooling load calculations were conducted manually using the RTS – method developed by ASHRAE and heating load calculations were conducted for Beijing using Swedish guidelines stated in BBR. Further, the energy recovery unit (VM1) that was provided by Systemair AB was tested using a rig where different outdoor conditions were simulated. This data was then used to evaluate the potential for energy recovery in a model apartment located in the two zones. As expected, significant differences were obtained when comparing the performance for the two locations.

Key Words: Energy recovery, cooling load, heating load, RTS-method, ventilation load, China, climate zones, Systemair AB, The Hong Kong Polytechnic University

Preface

This is a D-level degree project performed partly at the School of Sustainable Development of Society and Technology, Mälardalens University and partly at the Building Services Engineering Department at The Hong Kong Polytechnic University. I have learned a great deal in the course of this project. Firstly, how important the planning stage is and the development of a time schedule. Secondly, the value of taking the time to examine what has to be done and how it should be done.
The experiences that I have acquired during this project will be of great value to me in the future of my work – and academic life.

I would like to take this opportunity to thank all the people involved in this project for their support. My supervisor Ingemar Josefsson for his patience with all my questions, and Professor Yang, Hong-Xing at The Hong Kong Polytechnic University for all the help and for providing the location for testing the energy recovery equipment. A big thanks to Mats Sándor and Mikael Lönnberg at Systemair AB for providing the VM1-unit and their support.
Last but not least my beloved wife who has supported me and been there for me all the way.

Kaj Piippo

Hong Kong, November 2008

Nomenclature

Notation

GHG	Green House Gases	
AHU	Air Handling Unit	
LCC	Life Cycle Cost (calculation, analysis)	
NTU	Number of Transfer Units	[-]
ε-NTU	Efficiency – NTU (method)	[W]
LMTD	Log Mean Temperature Difference (method)	[W]
Q	Heat transfer	[W, kW]
ε	Effectiveness	[-]
C_h	Heat capacity rate (hot fluid)	[W/K]
C_c	Heat capacity rate (cold fluid)	[W/K]
$C_{\min}$	min (C_h, C_c)	[W/K]
$t_{h,in}$	Incoming hot temperature	[°C]
$t_{c,in}$	Incoming cold temperature	[°C]
$\dot{m}$	Mass flow	[kg/s]
$\dot{q}$	Volumetric flow	[m^3/s]
ρ_{air}	Density of air (warm and cold fluids)	[kg/m^3]
$c_{p,c}$	Specific heat capacity (cold fluid)	[Ws/kg*K]
$c_{p,h}$	Specific heat capacity (warm fluid)	[Ws/kg*K]
U	Overall heat transfer coefficient	[W/m^2*K]
A	Area	[m^2]
ΔT_{lm}	Logarithmical Mean Temperature Difference	[°C]
CAV	Constant Air Volume	
EC (motor)	electronically commutated	
ACH	Air Changes per Hour	
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers	
CIBSE	Chartered Institution of Building Services Engineers	
CHP	Combined Heat and Power (plant)	
RTS	Radiant Time Series (method)	
PRC	People's Republic of China	
LCCenergy	Life Cycle Cost – considering energy consumption	
LCCmain	Life Cycle Cost – considering the maintenance	
Main	Short used for Maintenance	
PV	Present Value	
SPV	Single Present Value Factor	
UPV	Uniform Present Value Factor	

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Summary

In the past decade, China has overtaken the U.S. as the biggest emitter of green house gases where CO_2 is the biggest part. In light of this fact measures has been taken to cut emissions. Many projects were implemented due to the reason that China hosted the Olympics this year 2008. In order to cut emissions the energy consumption has to be reduced and other energy sources has to replace fossil fuels. In this paper a solution for energy saving in residential buildings in China has been examined, namely the use of mechanical ventilation with energy recovery, using a heat exchanger.

To evaluate the potential energy saving two different climate zones were chosen, one with cold winters and hot summers, the other with mild winters and hot summers. Beijing was chosen as location for the colder zone while Hong Kong was chosen for the hot zone.

A model apartment was then used for both locations using the same materials and orientation of the building in order to compare the energy saving potential.

The energy recovery equipment a VM1-unit (Air handling unit with a flat-plate counter-flow heat exchanger) was provided by Systemair AB. A test rig was constructed and measurements were conducted to evaluate the performance. The temperatures and relative humilities were recorded using data loggers for each of the ducts so the efficiency could readily be calculated. Using these data and the knowledge of the climate in the chosen locations design conditions were chosen for each month.

The load calculations were conducted manually with the help of Excel spreadsheets. For the cooling load calculations, ASHRAE’s Radiant Time Series (RTS) method was used and for heating load calculations the Swedish guidelines stated in Boverkets Byggregler (BBR) was used.

In order to draw conclusions of the equipments performance the measured data had to be analyzed. It was found that:

- Efficiency increases when the indoor – outdoor temperature difference increases
- Effectiveness and Efficiency decreases if humid and hot outdoor air condensates on the heat exchanger
- When air flow is increased the UA-value increases as well as the heat transfer rate

The energy saving potential using this equipment in a multi-storey building in Hong Kong is not enough to invest in it. The major contributing factor to this is because the VM1-unit can only be operated 6 months per year. Otherwise, it actually contributes to the cooling load. Another reason why the equipment does not yield higher energy saving in Hong Kong is due to the high latent load, a larger heat exchanger would be better with larger heat transfer area.

However, the energy saving potential in Beijing using this equipment is far greater and is worth investing in. Not only will it save about 2600 HK$ per year, it reduces CO_2 emissions with about 1000 kg per year as well. This equipment is designed and used in northern climate more similar to Beijing with great success so the result is not very surprising.

1 Introduction

1.1 Background

In the last decade, Chinas middle class has grown in strength in line with the country's rapid economic development [1]. Because of this people consume products like never before and new commercial and residential buildings are built every day [2]. All this, which leads to higher demand for energy. Since the main fuel for all types of power and heat generation in China is coal, which is the biggest source of CO_2 emissions, an increase in demand for energy would constitute a major environmental problem. According to the International Herald Tribune [3] China has already caught up with the US and surpassed them as the biggest emitter of green house gases in the world. However, if one looks at the emission per person the US is still in the lead where people produce about 4 times as much green house gases compared to people in China. The Chinese government has realized the problem and has begun to implement solutions to counter the large emission of greenhouse gases. An example is the use of district heating in urban areas [4]. This effective solution reduces coal-fired boilers for individual residential buildings. Instead, heat is produced at a central power plant. This applies to regions in China that have hot summers and cold winters, and of course the northern regions where the average temperature is so low that heating is needed throughout the year.

In this paper, a solution has been assessed that can be used in residential buildings to reduce energy consumption. This is an air-handling device that uses mechanical ventilation with a heat exchanger recuperative recovering some of the energy that would normally be vented out.
After a meeting at Mälardalens University with Professor Yang, Hong-Xing who was visiting from Hong Kong Polytechnic University, a decision was made to implement this project. Professor Yang expressed an interest in evaluating a ventilation system with a heat exchanger to determine whether there is any potential to save energy in buildings in China. There was also a discussion about whether this system could be used in Hong Kong, where the climate is subtropical, to save energy for cooling mode.

1.2 Purpose

The purpose with this paper is to investigate if there is any energy saving potential in buildings that uses different type of heating and natural ventilation, this by using a mechanical ventilation system with heat recovery. It is also of interest to examine whether there is potential to save energy with the same system but in subtropical climate, by pre-cooling incoming air in summer.

1.3 Delimitation

In this paper, only one type of energy recovery systems is evaluated namely the VM1-unit, which is a residential air-handling unit for spaces up to 150 m^2. It contains a counter-flow heat exchanger for energy recovery and the unit was provided by Systemair AB in Sweden.
Since houses in China usually consist of high-rise buildings, the assessment is limited to only one apartment in a high-rise building. Further, the apartment has a surface area of approximately 100 m² and it is located on the 10th floor. There are 3 adults and 1 child living in the apartment.

1.4 Problem formulation

The problem formulation can be divided in several parts:
1. Is the potential energy saving worth the investment in such a system?
2. Is the VM1 - unit able to efficiently pre-cool the incoming air in Hong Kong?
3. How long is the payback time?
4. Is there any market in China/Hong Kong for such a system?

1.5 Location

Two locations in China will be investigated. The first is an imaginary apartment in a high-rise residential building located in Beijing. The second is a similar apartment but located in Hong Kong. The choice of using an imaginary apartment is due to the complications in finding data of real buildings in Mainland China.

1.6 Method and equipment

The work is carried out in several steps. First, a literature review is done to get a deeper knowledge in the research already conducted in this field. It is also important to get a better picture of the conditions in China and the potential of saving energy in the building sector. This knowledge is then used for theoretical assessment of the situation. Finally, experimental measurements are made with a test rig and the results are analyzed.
A Life Cycle Cost calculation is made in order to decide if this system is profitable in the chosen locations, as well as an overview of the potential market.

2 Theory

2.1 Heat Exchangers

There are several types of heat exchangers on the market and in this project; we consider one that is used in residential buildings. There are both horizontal and vertical systems depending on the location where it is supposed to be installed. The most common types of residential heat exchangers are cross-flow, counter-flow, and rotating. The last is a rotating wheel that can be made out of absorptive material for humidity control. The previous two are of plate type.
Most often, these types of systems are used in colder climates to recover heat from ventilated air in order to pre-heat the incoming cold air, but they can also be used to cool the incoming warm air during the summer.
Rotating heat exchangers, transfer moisture, this means that some of the indoor moisture is transferred back. However, there is no need of condensate drainage. A certain leakage can be expected between the airflows, but it usually does not exceed more than 5%. Airflows passing through the plate heat exchanger are not mixed. The incoming air passes through filters to ensure the air is clean and there is no moisture transfer between the flows.

2.2 ε-NTU and LMTD

In order to determine the performance of the chosen heat exchanger-unit theoretically, the effectiveness-NTU method can be used. This method is very useful when the outgoing temperatures are unknown and is used with advantage when considering compact heat exchangers, since the overall heat transfer coefficient is more likely to remain uniform. The equations are obtained from [5].
The heat transfer is calculated with equation (1):

$$Q = \varepsilon \cdot C_{\min}(t_{h,in} - t_{c,in}) \qquad (1)$$

Where	Q	Heat transfer	[W, kW]
	ε	Effectiveness	[-]
	$C_{\min}$	Min (C_h, C_c)	[W/K]
	$t_{h,in}$	Incoming hot temperature	[°C]
	$t_{c,in}$	Incoming cold temperature	[°C]

From the manufacturer the AHU's flow range is provided and is given in [m^3/h] so in order to calculate C_h and C_c we need the flow in [kg/s] (2).

$$\dot{m} = \dot{q} \cdot \rho_{air} \qquad (2)$$

Where	$\dot{m}$	Mass flow	[kg/s]
	$\dot{q}$	Volumetric flow	[m^3/s]
	ρ_{air}	Density of air (warm and cold)	[kg/m^3]

With tabulated data of air properties, the specific heat capacity is obtained for the chosen temperatures. Together with this and (2), C_h and C_c can be calculated.

$$C_c = \dot{m} \cdot c_{p,c} \;\; \& \;\; C_h = \dot{m} \cdot c_{p,h} \qquad (3), (4)$$

Where $c_{p,c}$ & $c_{p,h}$ Specific heat capacity (warm and cold) [Ws/kg K]

The manufacturer can provide information about the heat exchanger, for example the overall heat- transfer coefficient U and the area (A) of the heat exchanger. With these, it is possible to obtain the number of transfer units (NTU) which can be said to be the thermal length of the heat exchanger. Unfortunately, in this case the manufacturer would not provide these data so in order to do the calculations a few assumptions has to be made. The first one is obvious which is that the area of the heat exchanger is constant. The second is that the heat transfer coefficient varies with the flow. Since the VM1-unit is a constant air volume unit with three settings one can assume that the heat transfer coefficient will be constant relative to the flow rate. To calculate the UA-value following equations are used:

$$NTU = \frac{U \cdot A}{C_{\min}} \qquad \rightarrow \qquad U \cdot A = NTU \cdot C_{\min} \qquad (5) \& (6)$$

Where	NTU	Number of transfer units	[-]
	U	Overall heat transfer coefficient	[W/m^2*K]
	A	Area	[m^2]

The NTU-value can also be obtained by using the ΔT_{lm} by using equation 7.

$$NTU = \frac{\left(T_{h,i} - T_{c,i}\right) \cdot \varepsilon}{\Delta T_{lm}} \qquad (7)$$

Moreover, the effectiveness ε is obtained by the following equation:

$$\varepsilon = \frac{\left(T_{h,i} - T_{h,o}\right)}{\left(T_{h,i} - T_{c,i}\right)} \qquad \text{when } C_h = C_{min} \qquad (8)$$

$$\varepsilon = \frac{\left(T_{c,o} - T_{c,i}\right)}{\left(T_{h,i} - T_{c,i}\right)} \qquad \text{when } C_c = C_{min} \qquad (8)$$

There is another method for dimensioning heat exchangers commonly used, if all the ingoing and outgoing temperatures are known, namely the Logarithmical Mean Temperature Difference method (LMTD). Here the heat transfer is calculated by following equation:

$$Q = U \cdot A \cdot \Delta T_{lm} \qquad (9)$$

Where ΔT_{lm} is the Logarithmical Mean Temperature Difference

$$\Delta T_{lm} = \frac{\left[\left(T_{H,in} - T_{C,out}\right) - \left(T_{H,out} - T_{C,in}\right)\right]}{LN\left[\frac{\left(T_{H,in} - T_{C,out}\right)}{\left(T_{H,out} - T_{C,in}\right)}\right]} = \frac{\left(\Delta T_A - \Delta T_B\right)}{LN\left(\frac{\Delta T_A}{\Delta T_B}\right)} \qquad (10)$$

The heat transfer rate can also be calculated by using equation (11).
Where the Q is determined depending on what airflow undergoes the largest change in temperature. The mass airflow, specific heat coefficient, and temperatures will correspond to that airflow. If the cold air flow is chosen:

$$Q = \dot{m}_h \cdot c_{p,h} \cdot \left(T_{h,i} - T_{h,o}\right) \quad \text{(hot)} \qquad (11)$$

$$Q = \dot{m}_c \cdot c_{p,c} \cdot \left(T_{c,o} - T_{c,i}\right) \quad \text{(cold)} \qquad (11)$$

If the heat transfer rate is calculated with equation (12), the UA-value can be obtained by:

$$U \cdot A = \frac{Q}{\Delta T_{lm}} \qquad (12)$$

Since the heat exchanger manufacturer would not disclose the heat transfer area or the overall heat transfer coefficient of the unit, the UA-value is estimated. The calculations can be found in chapter 3.7, page 27.

2.3 Ventilation

The process by which fresh air is introduced, in this case to an enclosed space, and contaminated air is removed from that same space is termed ventilation. There are two common methods of ventilation used:

- When the process occurs by natural means of wind effect and difference between the inside and outside temperatures creating pressure differentials, through an open window or ventilation panel, it is called natural ventilation
- When is the process is driven by mechanical fans to provide controlled ventilation to a system, it is called mechanical ventilation or forced ventilation.

The reasons for providing ventilation are:

- Legal requirements
- Dilute contaminants and removing them from the space
- To remove products of respiration (odours, CO_2)
- To provide a continuous supply of oxygen
- To create an adequate air movement for human comfort

According to the Buildings Department in Hong Kong [7] there is a requirement of 1,5 ACH in residential buildings, if the process is by means of natural ventilation. However, for kitchens an additional 5 ACH by means of mechanical ventilation should be provided.
For PRC there is a recommendation of 0,5 ACH to 1 ACH depending on what source is used for obtaining the design conditions. The ASHRAE standard [4] is often referred to in Hong Kong and according to the standard, concerning mechanical ventilation 10 l/s/person of air should be provided. The VM1 unit has 3 settings, MIN, NORM and MAX that provides constant airflow depending on how many ACH is required. The MIN setting is used when there are no people present, NORM setting is used for normal operation, and the MAX is used for forced ventilation. The fans for supply and discharge can be set to different speeds and be used to fine-tune the system. In this paper, the system was set to be balanced. Another consideration is the placement of the fresh air intake and the discharge extract air. These must be placed with enough space between them so that the discharge extract air will not pollute the fresh air.

2.4 Heating

In the northern region of China, heating is required during the winter and in the northernmost parts, heating is required most of the year. Heating is provided in several ways in these parts. For example, in Beijing, residential buildings may have a coal-fired boiler to heat the water, which is then distributed in the building and providing heat through radiators.

Another common option is the use of heat pumps. These account for 80 percent of heating and cooling systems sold in China. However, the heat pump is not optimal for the coldest regions. These options are normally used when the public heating system is not available. The public heating is a service to the residents during winter and is known as district heating.

District heating was adopted in China in the 1980's and they had the benefit of being able to use modern technology from start. In two decades, the development covered 1,4 million m² living area and about 600 cities had connected to the district-heating scheme. Today that number has grown to over 700 cities where district heating is being used [8].

The main fuel source used in the district heating plants in China is coal and compared to using individual coal fired boilers in buildings this system greatly reduces the CO2 emissions. Another fuel that is widely used is natural gas.

A typical configuration of the system is that the water is heated in the heating plant and transported by pipeline to residential buildings that are equipped with radiators. CHP plants have been developed to increase energy efficiency further, where the bi-product (steam) that is normally wasted is used for electricity generation.

Until recently, the price of heating has been based on residential area, but meters are being installed at the heating plants as well as in the apartments in order to monitor the actual energy consumption. Another improvement is that temperature control units will be installed in each individual apartment [8].

2.5 Cooling – Split systems and window units

The need for cooling in a subtropical climate as in Hong Kong is obvious because of the high temperature and humidity during much of the year. The most common ways to provide cooling in residential buildings in Hong Kong is the use of window-mounted cooling equipment. This is often combined with a split air-conditioning systems for larger apartments. However, the use of only split-systems is also common in both small and large apartments.

According to studies [9], it is clear that the initial cost is greatly reduced if using the above-mentioned systems instead of a central unit.

If the apartment has many rooms, a multi-split system can be used. The same outdoor fan unit is used for several fan coil units inside the apartment.

Another study [10] has shown that the demand for cooling in Beijing has increased steadily and one of the reasons stated is the wish for a more comfortable indoor environment. It is also clear that the same cooling equipment used in Hong Kong is also used in Beijing. In the section about heating, it is also mentioned that a common means of heating as well as cooling is the use of heat pumps in Beijing.

2.6 VM1 Energy Recovery Unit

The VM1 is an air-handling unit that is equipped with a counter-flow plate heat exchanger.
The heat exchanger is manufactured from sea water resistant aluminium. There is no mixing of air since it has channelled airflow guides. It also has two single inlet centrifugal fans with forward-curved impellers and maintenance-free EC motors. These can be set individually to ensure balanced ventilation. In normal operation, the unit has a power consumption of 60W and the airflow can be adjusted to 120 - 180 m³/h. Normal operational flow is 150 m³/h.
The unit works as a constant air volume (CAV) unit with 3 possible setting, MIN, NORM and MAX.
According to the manufacturer Systemair AB, the airflow is about 65% at MIN setting compared to the normal operation flow. The maximum flow has been measured to be around 265 m³/h.
Tests performed by the manufacturer show that a performance up to 90% efficiency [6] could be achieved. But when using this equipment in hotter and more humid climate the efficiency is expected to be lower due to the much higher latent loads.
For this system to work as efficient as possible, it is required that the space where it will be used is as air tight as possible. In this case, the VM1-unit will provide mechanical ventilation instead of the usual means that is natural ventilation. The heat exchanger makes it possible to save energy that would have been wasted in the winter and reduce the cooling load due to ventilation in the summer.
The unit is compact and does not take up a lot of space. It is designed to be installed hanging on the wall. The dimensions can be seen in appendix A and the unit in figure 1.
When choosing the installation position consideration must be taken that, the unit requires regular maintenance, filters need changing etc. This particular unit is optimized to run efficiently for spaces up to 150 m² and if the area is greater, a higher airflow rate can be provided by the VM2-unit. This type of AHU is normally used in a freestanding house, but for the testing, the unit is considered to be used for one apartment in a multi-story building. The reason for this choice is that the multi-story buildings are the most common place where people live in the selected areas. Usually if there is mechanical ventilation in a multi-story building there is a central unit that provides ventilation to the whole building.

Figure 1: VM1 Energy Recovery Unit

2.7 VM1 Test rig

In order to evaluate the performance of the energy recovery unit a test rig was built. The manufacturer of the unit and the heat exchanger has performed tests under controlled conditions. These test conditions are related to the colder climate in northern Europe. However, the intention of this paper is to assess the unit's performance in conditions similar to the ones chosen in China. Therefore, it was necessary to perform tests under these conditions so empiric data could be collected, analyzed, and then used for load calculations.

Outdoor design conditions had to be simulated for each month so the potential energy savings could be determined. In order to simulate outdoor conditions a HVAC-unit was used, a P.A. Hilton Ltd, model A574. The HVAC-unit was equipped with a centrifugal fan that was set at minimum speed. This compensated for most of the pressure loss over the heat exchanger that would have occurred. Further, the unit was equipped with a small water tank with a heater that could be used for generating water vapour. Finally, the HVAC-unit was also equipped with an air cooler. This made it possible to simulate outdoor conditions ranging from temperatures of 0 °C to 40 °C (dry bulb) and relative humidity from 30% to 98%.

The location for the rig was in the solar laboratory FJ009 at The Hong Kong Polytechnic University. A contractor was hired to do the installation work. Insulated soft duct was used for the biggest part except for 1,5 m of the inlet duct going into the VM1-unit and 1,5 m of the extract duct going out from the unit. These were made of hard plastic in order to have a fixed cross section area so the air velocity could readily be measured and calculated.

2.7.1 Measurement equipment

When evaluating the VM1-units performance it is necessary to measure temperature, relative humidity and the air velocity. A number of equipment can manage this. However, the following equipment was used in this paper:

U12 – 011 HOBO® Temperature/RH Data Logger

The HOBO data logger is a device that measures temperature as well as relative humidity. It has a large memory that makes it possible to use for long term measurements. It can also be programmed so the starting time can be preset and the measurement interval.

This means that the logger measures temperature and RH continuously for 1 min and calculates the average temperature and RH for that time.

The data loggers were placed in each of the 4 ducts connected to the VM1 unit. A hole was cut in the soft duct and then resealed with duct tape during the measurements. After the testing, the data logger was connected to a notebook and the data could be downloaded and viewed with the software (Onset Greenline) that comes with the logger.

Supply Air Duct (same as outside air) – N7 (Sensor name)
Inlet Air Duct – N8
Extract Air Duct (same as indoor air) – N9
Discharge Air Duct – N10

Pitot - static tube

A pitot-static tube was used to measure the dynamic pressure (P_v) in order to calculate the airflow rate. The static pressure (P_s) was also measured to determine the pressure loss over the heat exchanger. These measurements were conducted at the three different settings, MIN, NORM, and MAX. The tube was connected to a manometer that indicated the pressure in kPa.

The velocity was calculated by using Bernoulli's equation:

$$P_v = \frac{\rho * v^2}{2} \quad \text{-->} \quad v = \sqrt{\frac{2 * P_v}{\rho}} \qquad (13)$$

Where P_v is the dynamic pressure

ρ is the air density

When using a manometer a correction for the inclination of the meter has to be done as well. The measured data was corrected as follows:

*Measured Data*1000*0,2 = corrected value*

Where 0,2 is the inclination correction and 1000 converts the output data to Pa.
The static pressure measurements were done at the same locations where the data loggers were placed. This was done due to the existing holes in the ducts and for convenience.
The dynamic pressure measurements were conducted after the fans at the inlet air duct and the discharge air duct about 1,2 m from the fans, this to ensure that the flow is steady without turbulence. The ducts were straight with constant cross section area. Since the VM1-unit is, a constant air volume unit the supply airflow should be corrected by the fans to maintain a flow of about 150 m³/h, at NORM setting. The measurements show a slightly lower airflow at said setting. A possible reason for this can be the inaccuracy involved in reading the manometer.

2.7.2 Sensor placement

In figure 2, there are two sensors at every location but in reality, there was only one, but it recorded both temperature and RH as is represented in the figure. The ambient outdoor temperature and RH was recorded in the fresh air intake duct as it was assumed the same.
This was also the case with the ambient indoor temperature, which was recorded in the extract air duct.
Since there are fans in the unit the location for the sensors in the discharge extract air and inlet air duct was placed at a safe distance. According to ASHRAE standard [4], a safe distance is defined to be at least 7,5 diameters downstream and 3 diameters upstream from a disturbance.

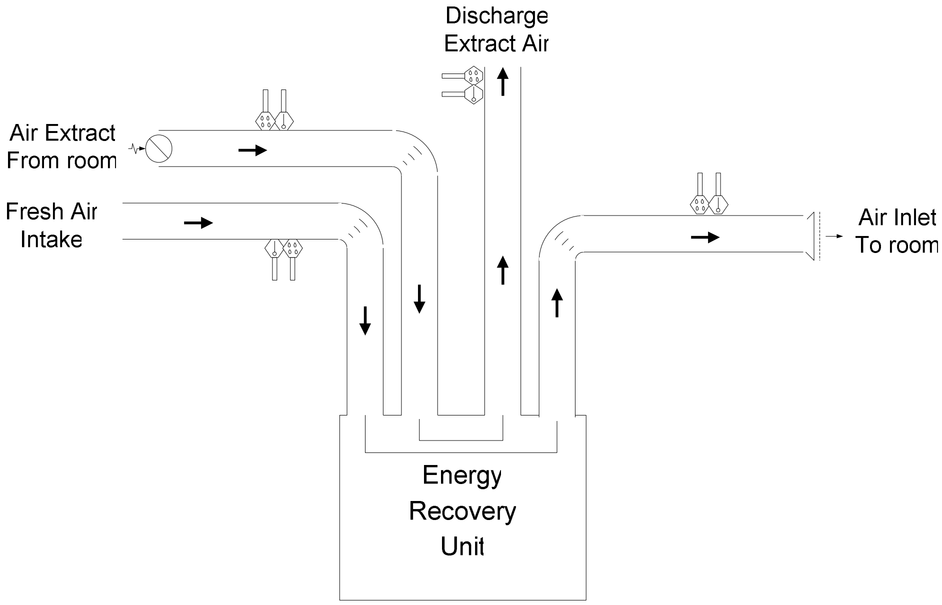

Figure 2: Schematic over test rig, sensor placement

2.7.3 Measurement Data

As explained earlier the measured temperature and relative humidity-data was downloaded to a notebook. The data was then viewed and analyzed with the Onset Greenline software. Figure 3 is extracted from the software showing data from a measurement. Each point (sample) is the average temperature, dew point temperature, and relative humidity for a 60-second period. The measurements made can be found in appendix B as well as the calculations of the temperature efficiency.

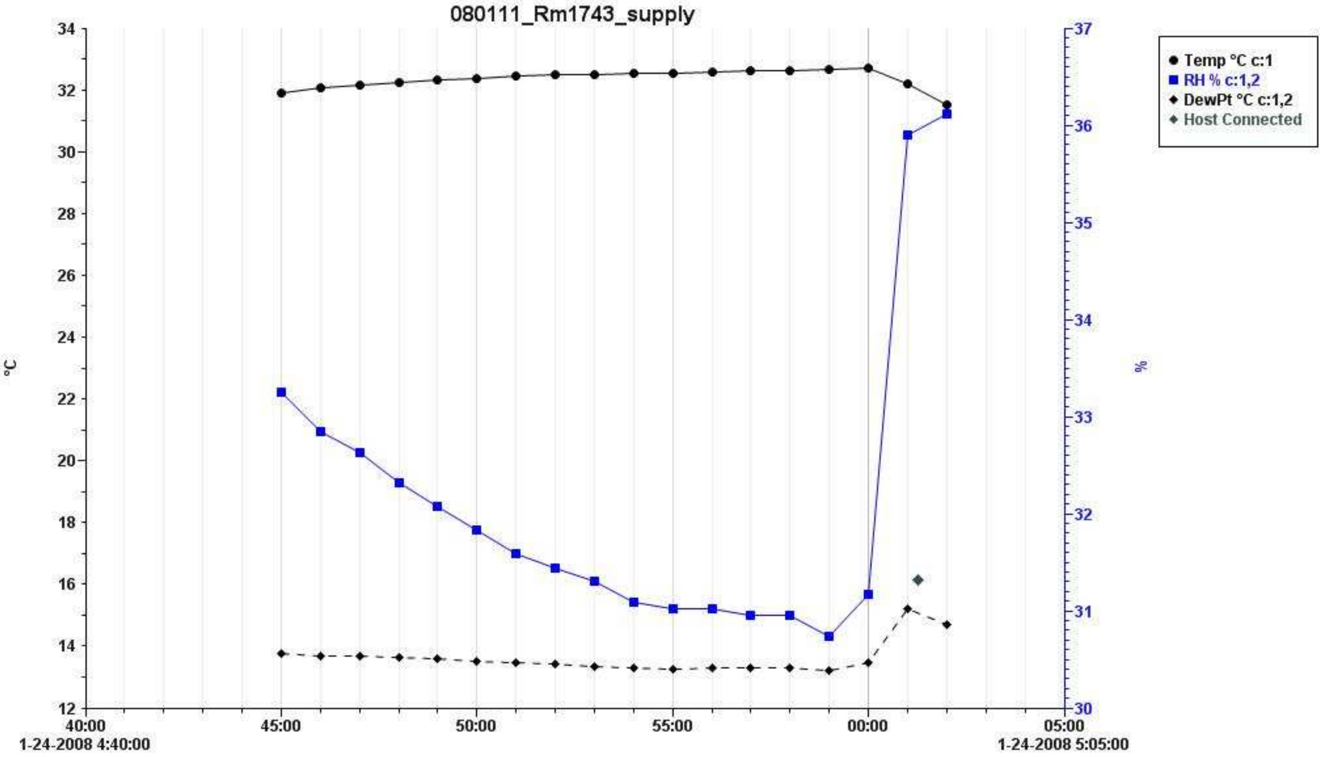

Figure 3: Sample of data set viewed with the Onset Greenline software

Where the left Y-axis is temperature (°C) and the right is relative humidity (%). The X-axis is the amount of measurement points (samples). The top curve is the temperature, the middle curve the relative humidity and the bottom curve is the dew point temperature.

Design Temperatures:

From the test-data, supply temperatures were chosen that match outdoor design conditions as closely as possible. The data is summarized in tables for each measurement with the temperature efficiency calculated as well in appendix B.
The temperature efficiency was calculated using equation 14.

$$\eta = \frac{t_{TL} - t_{OUT}}{t_{FL} - t_{OUT}} \qquad (14)$$

Where	t_{TL}	Air Inlet [N8]	[°C]
	t_{FL}	Air Extract [N9]	[°C]
	t_{OUT}	Fresh Air Intake [N7]	[°C]

2.8 Analyzes of Test Data

In order to evaluate the performance of the VM1-unit the data has to be analyzed to see what variables affect the result. For instance how the relative humidity (RH) or the temperature difference of the indoor and outdoor conditions affect the efficiency of the unit.
For normal setting, a summary in table 1 can be seen. In addition, the data is presented in diagram 1 as well. The left Y-axis show temperature and relative humidity, the right Y-axis show temperature efficiency. The X-axis is the number of measurements (samples).

Oudoor Air [℃]	Indoor Air [℃]	Outdoor RH [%]	Efficiency [%]
31,9	20,0	33,3	87,7
32,0	20,3	32,1	90,2
32,0	20,3	32,6	89,6
32,3	20,2	32,3	89,1
32,0	20,1	32,1	88,0
32,4	20,1	31,1	87,6
32,5	20,1	31,6	92,3
32,5	20,0	31,4	85,8
32,1	20,0	31,3	84,2
32,5	20,0	31,1	83,9
32,5	20,0	31,0	83,1
32,6	19,1	31,0	77,0
32,6	19,1	31,0	76,1
32,6	20,0	31,0	80,8
32,7	20,0	30,7	80,2
32,7	20,1	31,2	79,6
30,3	25,4	36,3	63,4
30,7	25,4	35,4	67,1
31,1	25,4	34,8	70,3
31,4	25,4	34,2	71,7
31,6	25,5	33,8	72,9
31,8	25,5	33,5	73,3
31,9	25,5	33,2	73,9
32,0	25,5	33,0	74,3
32,1	25,5	32,7	74,2

Table 1: NORM setting test data

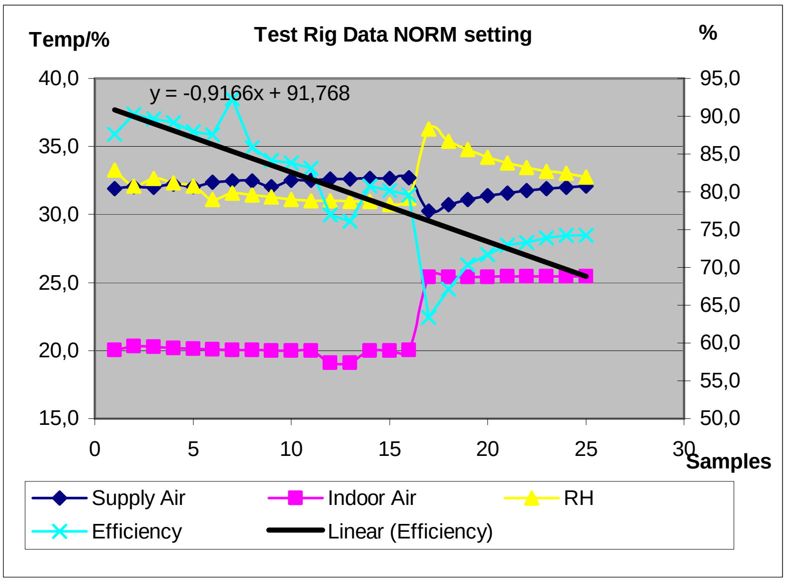

Diagram 1: Test Data NORM setting

As can be seen the general trend is that when the temperature difference between indoor and outdoor air decreases the efficiency also decreases. The relative humidity is between 31 – 34%, and does not affect the efficiency in this case. The sharp drop in efficiency at sample 17 is due to the significant decrease in temperature difference.

More data was analyzed with other temperatures but with the same setting. A summary can be seen in table 2 - 4. The data is shown graphically in diagram 2 - 4 as well. Temperatures of supply air and indoor air are read on the left Y-axis while efficiency and RH is read on the right. The X-axis represents the number of samples. Supply air is the same as outdoor air in these examples.

Oudoor Air [℃]	Indoor Air [℃]	Outdoor RH [%]	Efficiency [%]
2,1	21,3	80,6	79,9
2,1	21,0	81,1	80,7
2,8	21,2	81,5	78,7
2,9	21,2	81,3	78,3
3,1	21,1	81,3	77,8
3,3	21,0	81,4	77,3
3,5	20,9	80,1	76,8
3,8	20,8	80,9	76,0
4,1	20,7	81,2	75,0
4,5	20,5	81,4	74,3

Table 2: Test Rig Data – NORM

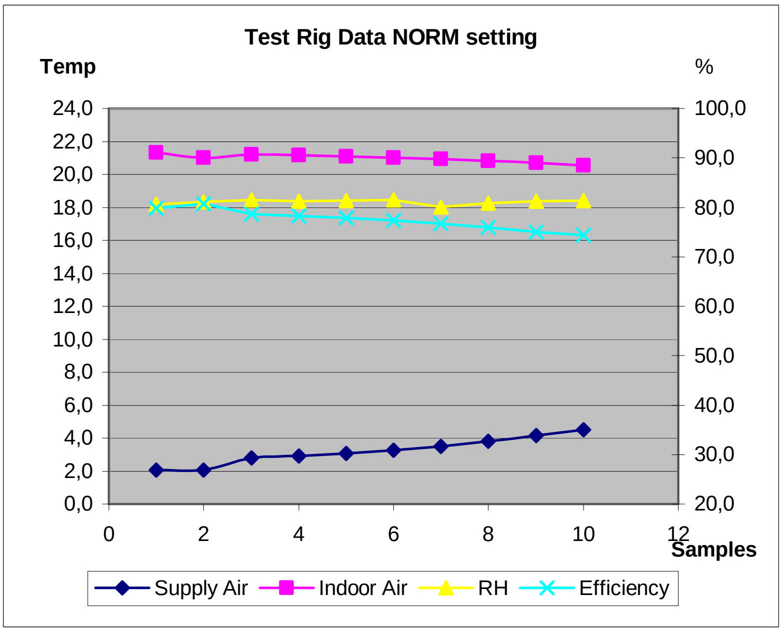

Diagram 2: Test Rig Data – NORM setting

Oudoor Air [℃]	Indoor Air [℃]	Outdoor RH [%]	Efficiency [%]
11,1	21,0	91,9	98,1
11,6	21,6	92,0	91,4
11,6	21,5	92,1	91,8
11,6	21,4	92,1	91,7
11,6	21,3	92,2	91,9
12,8	21,2	92,8	90,4
13,2	20,4	92,6	77,1
13,2	20,5	92,5	78,1
13,3	20,6	92,5	79,2
13,3	20,4	92,6	75,7
13,3	20,7	92,5	80,7
13,3	20,1	92,5	84,7
13,4	20,9	92,5	84,2
13,4	21,1	92,5	88,0
13,4	21,0	92,0	74,8

Table 3: Test Rig Data – NORM

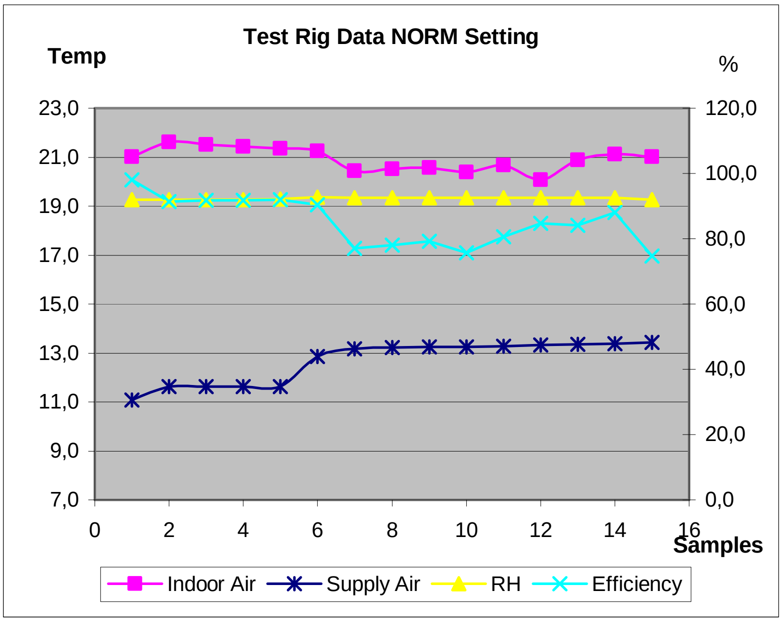

Diagram 3: Test Rig Data – NORM setting

Oudoor Air [℃]	Indoor Air [℃]	Outdoor RH [%]	Efficiency [%]
16,6	21,7	91,6	73,4
16,6	21,6	91,5	73,1
16,6	21,6	91,3	72,3
16,7	21,5	90,9	71,6
16,9	21,5	90,7	68,4
17,0	21,0	90,2	74,7
17,2	21,3	89,3	68,4
17,5	21,2	88,3	71,8
18,0	21,2	87,0	71,0
18,7	21,1	84,8	70,3

Table 4: Test Rig Data - NORM

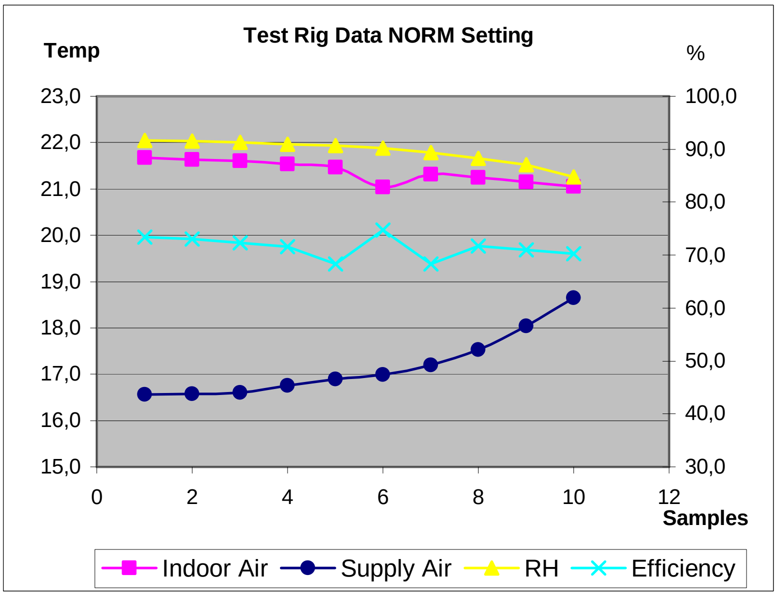

Diagram 4: Test Rig Data – NORM setting

As can be seen yet again the efficiency decreases as the temperature difference decreases. Another observation is that the efficiency increases slightly with higher humidity (RH).

3 Load Calculations

There are a large number of methods developed for calculating cooling/heating loads. In Hong Kong, the CIBSE and ASHRAE standards are widely used when dimensioning a cooling system. In this paper the Radiant Time Series (RTS) method developed by ASHRAE [4] was chosen for cooling load calculations, while the guidelines in BBR was used for heating load calculation. The transmission loss is calculated using the BBR guidelines and the ventilation loss and free heating is calculated using a spreadsheet, which can be seen in appendix F.

Design cooling loads are based on the assumption of steady-periodic conditions. This means it is assumed that the design day's weather, occupancy, and heat gains conditions are identical to those for preceding days and repeat on an identical 24h cyclical basis.

The calculations are best done by using a spreadsheet since they involve a large number of parameters. For each month, a design day was chosen and design temperatures were taken from tests carried out in this paper. Temperatures were chosen to as closely as possible resemble those of climate data retrieved from the Hong Kong Observatory website [11] and a NASA-sponsored site [12]. Cooling Load calculations were made for each month that was then put together for the total annual cooling load.

When determining the heating and cooling loads on residential buildings there are a few unique features that must be considered, such as:

- Most residential buildings are occupied 24 hours per day
- Internal loads are small if compared with industrial and commercial buildings
- Dehumidification occurs only during cooling operation
- Most residences are conditioned as a single zone.

These parameters will give a different load characteristic compared to commercial buildings, but there is one aspect that is the same for both cases, which is the need for accurate weather data. This will contribute to a more accurate estimation of the cooling and heating loads. For in reality we deal in estimations due to the complexity of these calculations. One of the risks with inaccurate data is that the system can be under-or oversized. Common practice is to oversize the system slightly so it will be able to cope with extreme conditions.

3.1 Climate Data

The two locations chosen in this paper are Beijing and Hong Kong since they have different climatic characteristics in China. Beijing is situated in a cold region according to The Thermal Design Code for Civil Buildings (China GB50176-93), while Hong Kong is located in a mild region with hot summers and mild winters. Beijing on the other hand has relatively cold and dry weather. Due to these factors, a more comprehensive evaluation of the VM1-unit can be conducted. The amount of energy that potentially can be recovered in both regions will be investigated.

There are many sources for obtaining temperature data and in this chapter; the method for how design temperatures were chosen will be explained.

The first set of data was taken from The Hong Kong Observatory website. In table 5 the mean maximum temperature for the two locations are presented for each of the months. Since it is a mean temperature, it is necessary to consider that the temperature will be higher then the mean for about 50% of the time. The design temperature used in July in Hong Kong for critical processes is 32,8 °C [4] which is about 4,8 % larger then the mean max temperature stated on The Hong Kong Observatory website. Just as a comparison, in order to get an approximation of temperatures at 1% occurrence every month, the temperatures were increased 4,8% for each month.

	Data Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Max Temp (℃) Hong Kong	1971-2000	18,6	18,6	21,5	25,1	28,4	30,4	31,3	31,1	30,2	27,7	24	20,3
Mean Max Temp (℃) Beijing	1961-1990	1,6	4	11,3	19,9	26,4	30,3	30,8	29,5	25,8	19	10,1	3,3

Table 5: Mean maximum temperatures in Hong Kong and Beijing

For Beijing, the design temperature is 33 °C, [4] in July, which is about 7% larger than the mean maximum temperature stated on The Hong Kong Observatory website. The same approach is used for these temperatures as for the Hong Kong case. A summary of these can be seen in table 6.

	Data Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Max Temp (℃) Hong Kong	1971-2000	19,5	19,5	22,5	26,3	29,8	31,9	32,8	32,6	31,6	29,0	25,2	21,3
Mean Max Temp (℃) Beijing	1961-1990	1,7	4,3	12,1	21,3	28,2	32,4	33,0	31,6	27,6	20,3	10,8	3,5

Table 6: Corrected maximum temperatures for design conditions in Hong Kong and Beijing

The design temperatures used as reference [4] are based on annual percentiles and cumulative frequency of occurrence, in this case 1%.

If the mean temperatures were used as design temperatures, the system would be undersized and would not be able to handle peak load cases. During the summer period, the daily temperature range is less then in the winter. However, as estimation the same range has been used throughout the year, which is a result of the added percentage. Extreme temperatures will occur that are larger then the design temperatures and the system will not be able to handle the loads, but this is likely to occur only a short period in the hottest month(s).

A more complete summary of the temperatures can be found in appendix C

In Hong Kong, cooling might be required the whole year depending on the internal loads, which the calculations will show. However, since the mean temperature drops to 21 °C in December and even below that in January and February the indoor set point temperature will be 22 °C. Meanwhile in Beijing, there is a heating period, normally 15th November to 15th March, which is the winter period. Then there are transition periods in spring and fall and finally a cooling period in summer.

3.1.1 Chosen Climate Data for Load Calculations

From the measurements done with the test rig, temperatures were chosen so they as closely as possible resemble previous mentioned design conditions. A summary of the chosen temperatures can be seen in table 7. Temperatures are in °C and RH in %. All measurement data are presented in appendix B.

Hong Kong												
Month	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
T outside	16,6	17	18,7	25	29	30,4	32,6	32,4	30,4	29	25	21
RH	90	90	85	80	70	70	78	79	70	70	80	80
T supply	20,2	20	20,3	25	27,1	28,2	29,4	29,3	28,2	27,1	25	21
RH	80	80	78	80	75	77	90	90	77	75	80	80
T room	21,6	21	21,1	25	25	25,5	24,7	24,3	25,5	25	25	21
RH	60	60	60	50	51	55	65	64	55	51	50	50
η [%]	72,3	79,5	70,3	0	49,0	45,3	40,5	38,3	45,3	49,0	0	0
Beijing												
Month	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
T outside	1	2,3	12	15,2	29	32,1	33,2	30,1	26	15,6	11,1	1,8
RH	71	73	63	65	69	76	73	69	71	63	92	71
T supply	17,7	17,6	18,8	20,2	27,8	29,4	29,4	28,2	26	20	20,8	17,7
RH	38	41	48	53	72	91	91	77	71	53	62	38
T room	21,2	21	21,6	22	25,4	24,8	24,8	25,5	26	22	21	21,3
RH	52	51	47	49	50	64	64	55	50	49	56	52
η [%]	82,4	81,6	70,8	73,5	32,4	36,5	44,8	39,7	0	69,1	98	81,5
🟩	Higher load using VM1 unit due to higher latent load											

Table 7: Temperature and humidity data from tests

Unfortunately, the relative humidity is a bit higher for some of the months compared to the real life conditions. However, these humilities were assumed as design conditions in order to evaluate the performance of the equipment. The reason for the difference in the measured data compared to real life conditions were due to the difficulties in maintaining steady conditions and controlling the temperature and relative humidity with accuracy. The HVAC-unit used for the simulations was equipped with four heaters of varying power, 2 x ½ kW and 2 x 1 kW.
There were also two water heaters, 1 x 1 kW and 1 x 2 kW. In order to regulate the temperature and relative humidity different heater configurations were used. As a last option the cooling coil could be used, which had a power of 2 kW. The only settings for the cooling were on or off.
No possibilities to fine tune the system was available so as many measurements as possible with different configurations were conducted.
When the outdoor temperature is the same as the room temperature the bypass function is used, which is the reason for the 0% efficiency for some of the months.

3.2 Model apartment used for the calculations

The model apartment is assumed located at an intermediate level between adjacent apartments. There are 2 external walls to the north and south. A layout of the apartment is shown in appendix D. It is also assumed that there are 4 people living in the apartment, 3 adults, and one child. The additional adult is assumed a caretaker who takes care of the child. Detailed information of the apartment is given in table 8.

Items	Description
General information	
Floor area and height	102 m^2; floor-to-floor height = 2,6 m
Window features	Clear glass single glazing; Window height = 1,2 m Window width = 0,9 m; Aluminium frame
Occupancy density	25,5 m^2/person
Lighting density	2,9 W/m^2 [300W]
Equipment load	10 W/m^2 [1050W]
Space design temperatures	Winter: 22 ℃ in HK and 21 ℃ in Beijing Summer: 25 ℃ in HK and 26℃ in Beijing Spring and Fall 23 ℃ in Beijing
Infiltration	0,1 ACH
Ventilation	150 m^3/h
Building envelope structure	
Exterior walls (outer to inner)	Ceramic tiles (12mm) + cement mortar (10mm) + concrete (300mm) + plaster (10mm)
Interior walls	plaster (10mm) + concrete (150mm) + plaster (10mm)
Ceiling/Floor	Tiles (12mm) + concrete (150mm) + plasterboard (10mm)

Table 8: Model apartment information

In each of the rooms there is a 40W light bulb to provide light and also 4 smaller 25W light bulbs are spread out in the apartment, which makes the total lighting 300 W.
The equipment load is made up by the common household appliances for instance, TV, DVD, computer(s) and the usual kitchen appliances, rice cooker, microwave oven, oven etc.

Since the VM1-unit functions as a CAV-system with 3 settings where NORM is the intended setting that provides about 150 m^3/h of air, all of the rooms will get the same airflow. Considering this the load calculations will be conducted regarding the apartment as a single zone.

Due to the ductwork and heat exchanger there will be pressure losses in the system, but the fans will compensate for this to maintain a constant flow, which may lead to higher energy consumption. The possible increase in energy consumption is not considered in this paper.

Even though the climate is colder in Beijing compared to Hong Kong studies show [17] that the choice of materials in the buildings does not differ significantly. It is still common to build residential buildings without insulation and with single glazing windows in such a cold climate.

Input Data for Walls and Windows:

In Hong Kong due to the climate insulation is seldom used, usually the wall is made of concrete with plaster in the interior surface and mosaic tiles on the exterior surface. Surprisingly the same materials are used in Beijing and only about 20% of the buildings have insulation [10].
In the following tables, 9 and 10 the window and wall areas are shown as well as their respective (total) U-values, stated in the ASHRAE guidelines [4]. Information about the wall configuration is found in table 8.

Wall Data: Cast-In-Place concrete wall, 300 mm	
U_w (W/m^2 K)	**3,1**
Wall area (m^2)	**13,56**
Window Data:	
U_w (W/m^2 K)	**5**
Window area (m^2)	**4,32**

Table 9: Northern orientation

Wall Data: Cast-In-Place concrete wall, 300 mm	
U_w (W/m^2 K)	**3,1**
Wall area (m^2)	**14,6**
Window Data:	
U_w (W/m^2 K)	**5**
Window area (m^2)	**5,76**

Table 10: Southern orientation

The windows are single glazing clear glass and have a thickness of 6 mm. Windows that are low-e or tinted are more common in residential areas with more expensive buildings, but in an average residential area, the chosen window type is dominant [17].

3.3 Schedules – Occupancy, Appliances and Lighting

There are major differences in the way residential and commercial buildings are used considering the time when it is being occupied. In a commercial building with offices, the building is usually more or less empty after office hours, while a residential building can be occupied throughout the whole day. The weekends differ as well in terms of occupancy. In order to do cooling load calculations an occupancy schedule has to be determined. In table 11, the assumed schedule for the model apartment can be seen and it is expressed in percent where 100 % means that everyone is at home etc.

Time	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Mon - Sun	100	100	100	100	100	100	100	100	25	25	25	25	25	25	25	25	50	50	100	100	100	100	100	100

Table 11: Occupancy schedule where occupants are expressed in percent

The parents work from 9 AM to 6.30 PM and the child goes to kindergarten from 9 AM to 4.30 PM. Meanwhile the caretaker (nanny) is assumed to be at home the whole day in the calculations but in reality some daily chores requires going out but is not considered in this case.
A schedule for when appliances are used is also necessary to decide. As can be seen in table 12 some appliances are used in the morning at breakfast time and later in the evening.

Time	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Mon - Sun	0	0	0	0	0	0	**50**	**50**	**50**	0	0	0	0	0	0	0	**75**	**100**	**100**	**75**	**75**	**50**	0	0

Table 12: Appliances schedule expressed in percent

Finally, a schedule for the usage of lighting is decided and can be seen in table 13.

Time	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Mon - Sun	0	0	0	0	0	0	**50**	**25**	0	0	0	0	0	0	0	0	**50**	**100**	**100**	**100**	**50**	**25**	0	0

Table 13: Lighting schedule expressed in percent

The ventilation is assumed to run at normal setting throughout the whole day.

3.4 Cooling Load Calculation – Hong Kong

The calculations have been made using a spreadsheet in Microsoft Excel. In table 14, the data used for calculating the cooling load in July is presented as an example. The solar constant data vary for every month due to earth's position in relation to the sun. In appendix E, the solar constant data is summarized.

Table 14: Input Data for cooling load calculation in Hong Kong

General Input:		**Solar Constants, July:**		**Sol-Air Temp. Input:**	
Month	**7**	For Month	**7**	Absorptance, α	**0,45**
Longitude	**-114,11**	Equation of Time [ET], min	**-6,2**	h (outside), h_o	**17,3**
Latitude	**22,2**	δ	**20,6**	Emittance	**0,85**
CN	**1**	A (W/m²)	**1085**	ΔR	**0**
ρ_g	**0,2**	B	**0,207**		
T_o, Design Temp (AST = LST 14:00) [℃]	**32,6**	C	**0,136**		
Daily Temp. Range [K]	**4,5**	Local Std Time Meridian	**-120**		
T_r = Presumed constant room temp. [℃]	**25,5**				
Azimuth, Ψ (Orientation of Wall, N)	**180**				
Tilt, Σ (Wall type: Vertical light-coloured)	**90**				

CN = Clearness number
δ = Solar Declination, degree
LST = Local Standard Time, hour
AST = Apparent Solar Time, hours
ρ_g = Ground reflectivity
h_o = Outdoor Air Film Heat transfer coefficient
ΔR is assumed to be 0 for vertical walls

The building has vertical walls that are light-coloured. Since vertical surfaces receive long-wave radiation from the ground and surrounding buildings as well as from the sky, accurate ΔR values are difficult to determine. ΔR is the difference between long-wave radiation incident on surface from sky and surroundings and radiation emitted by blackbody at outdoor air temperature [W/m²]. The constants B and C are dimensionless numbers that varies depending on what month is chosen.

These parameters are necessary for calculating the solar position and further the diffuse and direct solar heat gains, the equations can be seen in appendix E. Values for clearness number, emittance, absorptance, and outdoor air-film heat- transfer coefficient are obtained from the ASHRAE fundamentals handbook [4].

Result

The peak cooling load results from the spreadsheets are summarized in table 15. Peak load occurs at 2 pm for each month. As can be seen the peek cooling load can be larger when using the VM1-unit for some months (marked in green in the table).

	Coil's Cooling Load			Coil's Cooling Load - VM1		
Month	**Sensible**	**Latent**	**Total [W]**	**Sensible**	**Latent**	**Total [W]**
Jan	1097,7	170,5	**1268,1**	1273,9	318,4	**1592,3**
Feb	987,9	246,2	**1234,1**	1134,8	343,0	**1477,8**
Mar	834,4	307,3	**1141,7**	912,7	326,4	**1239,1**
Apr	916,5	783,9	**1700,4**	916,5	783,9	**1700,4**
Maj	1598,1	969,7	**2567,7**	1505,0	880,6	**2385,7**
Jun	1819,9	1016,7	**2836,5**	1712,2	942,7	**2654,9**
Jul	2339,0	1471,9	**3810,8**	2182,3	1354,8	**3537,1**
Aug	2432,1	1536,3	**3968,4**	2280,4	1397,8	**3678,2**
Sep	2196,0	1016,7	**3212,7**	2088,3	942,7	**3031,0**
Oct	2450,0	969,7	**3419,6**	2356,9	880,6	**3237,6**
Nov	2007,3	539,4	**2546,7**	2007,3	539,4	**2546,7**
Dec	2112,5	622,1	**2734,7**	2112,5	622,1	**2734,7**
🟩	Cooling Load is larger when using the VM1-unit					

Table 15: Monthly Peek Cooling Load in Hong Kong

The peek cooling load occurs in August and is about 4 kW.
The cooling load is then calculated for each month and then added up for the yearly load. A summary can be seen in table 16.

	Coil's Cooling Load				Coil's Cooling Load - VM1				
Month	**Sensible**	**Latent**	**Total [Wh] per day**	**Total [kWh] per month**	**Sensible**	**Latent**	**Total [Wh] per day**	**Total [kWh] per month**	**Optimal Load**
Jan	2727,9	1873,0	4600,9	**142,6**	6958,0	5013,2	11971,3	**371,1**	**142,6**
Feb	4059,3	3864,1	7923,4	**221,9**	7584,5	5956,3	13540,7	**392,7**	**221,9**
Mar	4686,9	4765,3	9452,2	**293,0**	6566,9	5208,8	11775,8	**365,0**	**293,0**
Apr	11656,1	14656,9	26313,0	**789,4**	11656,1	14656,9	26313,0	**789,4**	**789,4**
Maj	29877,1	18582,6	48459,7	**1502,3**	27644,5	16659,0	44303,4	**1373,4**	**1373,4**
Jun	35457,8	19469,1	54926,9	**1647,8**	32872,7	17826,2	50698,9	**1521,0**	**1521,0**
Jul	47373,9	27915,1	75289,0	**2334,0**	43613,7	25300,7	68914,4	**2136,3**	**2136,3**
Aug	47705,2	29240,2	76945,4	**2385,3**	44062,5	26200,5	70263,0	**2178,2**	**2178,2**
Sep	37369,3	19010,5	56379,8	**1691,4**	34784,2	17376,6	52160,8	**1564,8**	**1564,8**
Oct	39302,1	18866,6	58168,7	**1803,2**	37069,5	16934,0	54003,5	**1674,1**	**1674,1**
Nov	24539,0	9516,1	34055,0	**1021,7**	24539,0	9516,1	34055,0	**1021,7**	**1021,7**
Dec	25847,8	11970,4	37818,1	**1172,4**	25847,8	11970,4	37818,1	**1172,4**	**1172,4**
				15004,9				**14560,0**	**14088,7**

Table 16: Summary of the yearly cooling load in Hong Kong

As can be seen in the table cooling is required the whole year. A summary of the equations used for calculating sensible and latent loads is found in appendix F.
An observation is that the cooling load is larger in January, February, and March when using the VM1-unit compared to when it is not used. A solution to this is to use the bypass function in the VM1-unit for these months to take advantage of the free cooling. Without the energy recovery equipment the annual cooling load would be 15000 kWh compared to 14000 kWh if it were to be

used properly. A total saving of 1000 kWh per year could be achieved. The largest energy saving is in August, which is about 200 kWh less when using the VM1-unit.
The results for the ventilation loads are necessary for calculating the potential amount of energy that can be saved using the energy recovery unit. In table 17, the peek ventilation load for Hong Kong can be seen which occurs at 2 pm each month.

	Ventilation Load			Ventilation Load - VM1			
Month	**Sensible**	**Latent**	**Total [W]**	**Sensible**	**Latent**	**Total [W]**	**Optimal Load**
Jan	-244,8	115,5	**-129,3**	-68,5	263,4	**194,8**	**-129,3**
Feb	-195,8	191,2	**-4,6**	-49,0	288,0	**239,0**	**-4,6**
Mar	-117,5	252,3	**134,8**	-39,2	271,4	**232,2**	**134,8**
Apr	0,0	728,9	**728,9**	0,0	728,9	**728,9**	**728,9**
Maj	195,8	914,7	**1110,5**	102,8	825,6	**928,5**	**928,5**
Jun	239,9	961,7	**1201,6**	132,2	887,7	**1019,9**	**1019,9**
Jul	386,8	1416,9	**1803,7**	230,1	1299,8	**1529,9**	**1529,9**
Aug	396,6	1481,3	**1877,9**	244,8	1342,8	**1587,6**	**1587,6**
Sep	239,9	961,7	**1201,6**	132,2	887,7	**1019,9**	**1019,9**
Oct	195,8	914,7	**1110,5**	102,8	825,6	**928,5**	**928,5**
Nov	0,0	484,4	**484,4**	0,0	484,4	**484,4**	**484,4**
Dec	0,0	567,1	**567,1**	0,0	567,1	**567,1**	**567,1**
🟩	Cooling Load is larger using the VM1-unit						

Table 17: Ventilation peek load in Hong Kong

The peek ventilation load occurs in August and is about 1900 W. In table 18, the total yearly ventilation load can be seen.

	Ventilation Load				Ventilation Load - VM1				
Month	**Sensible**	**Latent**	**Total [Wh] per day**	**Total [kWh] per month**	**Sensible**	**Latent**	**Total [Wh] per day**	**Total [kWh] per month**	**Optimal Load**
Jan	-8851,7	-1757,0	-10608,7	**-328,9**	-4621,6	1383,2	-3238,4	**-100,4**	**-328,9**
Feb	-7478,2	234,1	-7244,2	**-210,1**	-3953,1	2326,3	-1626,8	**-47,2**	**-210,1**
Mar	-5862,8	1135,3	-4727,5	**-146,6**	-3982,7	1578,8	-2403,9	**-74,5**	**-146,6**
Apr	-2976,5	11026,9	8050,4	**241,5**	-2976,5	11026,9	8050,4	**241,5**	**241,5**
Maj	1723,6	14952,6	16676,3	**517,0**	-508,9	13029,0	12520,0	**388,1**	**388,1**
Jun	2913,5	15839,1	18752,6	**562,6**	328,4	14196,2	14524,6	**435,7**	**435,7**
Jul	6240,1	24285,1	30525,3	**946,3**	2480,0	21670,7	24150,7	**748,7**	**748,7**
Aug	6409,0	25610,2	32019,2	**992,6**	2766,4	22570,5	25336,9	**785,4**	**785,4**
Sep	2715,0	15380,5	18095,5	**542,9**	129,9	13746,6	13876,6	**416,3**	**416,3**
Oct	1855,9	15236,6	17092,5	**529,9**	-376,6	13304,0	12927,3	**400,7**	**400,7**
Nov	-3042,7	5886,1	2843,4	**85,3**	-3042,7	5886,1	2843,4	**85,3**	**85,3**
Dec	-3042,7	8340,4	5297,7	**164,2**	-3042,7	8340,4	5297,7	**164,2**	**164,2**
				3896,7				**3444,0**	**2980,6**

Table 18: Summary of yearly ventilation cooling load in Hong Kong

As can be confirmed from the summary of the yearly ventilation load, it yields the same amount of saving using the VM1-unit as in the yearly cooling load summary, which is about 1000 kWh per year. The total ventilation load is about 3900 kWh without the unit and the optimal load is about 2900 kWh.

3.5 Cooling Load Calculation – Beijing

The same approach has been adopted for the calculations concerning Beijing. Since Beijing is in another climate zone the daily mean temperature will be lower compared to Hong Kong and the daily temperature range will be larger. Finally, the period of cooling is shorter. The significant change in data for calculating the solar constants is the longitude and latitude, which will affect all of the calculation results. In table 19 similar data is presented as for the previous case but now for conditions in Beijing. Again, the month July has been chosen as an example. The heating period in Beijing is from 15th of November to 15th of March [3], so it is assumed that cooling is needed in various degrees the rest of the year, though the cooling load is not very high in April and October.

General Input:		**Solar Constants, July:**		**Sol-Air Temp. Input:**	
Month	7	For Month	7	Absorptance, α	0,45
Longitude	-116,25	Equation of Time [ET], min	-6,2	h (outside), h_o	17,3
Latitude	39,55	δ	20,6	Emittance	1
CN	1	A (W/m²)	1085	ΔR	0
ρ_g	0,2	B	0,207		
T_o, Design Temp (AST = LST 14:00) [℃]	33	C	0,136		
Daily Temp. Range [K]	9,2	Local Std Time Meridian	-120		
T_r = Presumed constant room temp. [℃]	25				
Azimuth, Ψ (Orientation of Wall, N)	180				
Tilt, Σ (Wall type: Vertical light-coloured)	90				

Table 19: Input Data for cooling load calculation in Beijing

The building in Beijing is assumed to be the same as in Hong Kong, same orientation etc.

Result

The peek cooling load is summarized in table 20.

	Coil's Cooling Load			Coil's Cooling Load - VM1		
Month	**Sensible**	**Latent**	**Total [W]**	**Sensible**	**Latent**	**Total [W]**
Maj	1477,3	933,6	2410,8	1418,5	876,0	2294,5
Jun	2097,4	1326,0	3423,4	1965,2	1402,0	3367,2
Jul	2523,0	1389,0	3911,9	2336,9	1402,0	3738,9
Aug	1992,1	942,8	2935,0	1899,1	942,7	2841,8
Sep	1421,4	570,2	1991,6	1421,4	570,2	1991,6

Table 20: Summary of the peek cooling load in Beijing

The peek cooling load occurs in July and the highest dimensioning load is about 3,9 kW. A summary of the yearly cooling load is seen in table 21.

	Coil's Cooling Load				Coil's Cooling Load - VM1			
Month	**Sensible**	**Latent**	**Total [Wh] per day**	**Total [kWh] per month**	**Sensible**	**Latent**	**Total [Wh] per day**	**Total [kWh] per month**
Maj	12728,7	8751,1	21479,8	665,9	11318,7	7709,8	19028,4	589,9
Jun	29163,1	13214,7	42377,8	1271,3	25990,5	14123,7	40114,2	1203,4
Jul	41661,9	18554,6	60216,6	1866,7	37196,8	18388,3	55585,1	1723,1
Aug	23951,9	10235,0	34186,9	1059,8	21719,3	10066,3	31785,6	985,4
Sep	3616,8	2702,1	6318,9	189,6	3616,8	2702,1	6318,9	189,6
				5053,3				**4691,4**

Table 21: Summary of the yearly cooling load in Beijing

If the VM1-unit is used the potential energy saving will be about 350 kWh per year for free cooling during the summer period. The total cooling load without energy recovery is about 5050 kWh per year while using the VM1-unit the total cooling load is about 4700 kWh.

Similarly as for the previous case, the peek ventilation load is summarized for the Beijing location in order to estimate the energy saving potential. The summary can be seen in table 22.

	Coil's Cooling Load			Coil's Cooling Load - VM1		
Month	**Sensible**	**Latent**	**Total [W]**	**Sensible**	**Latent**	**Total [W]**
Maj	176,3	878,6	**1054,8**	117,5	821,0	**938,5**
Jun	357,4	1271,0	**1628,4**	225,2	1347,0	**1572,2**
Jul	411,3	1334,0	**1745,2**	225,2	1347,0	**1572,2**
Aug	225,2	887,8	**1113,0**	132,2	887,7	**1019,9**
Sep	0,0	515,2	**515,2**	0,0	515,2	**515,2**

Table 22: Summary of ventilation peek load in Beijing

The ventilation peek load occur in July and is about 1,7 kW. Further, the yearly ventilation load is summarized in table 23.

	Ventilation Load				Ventilation Load - VM1			
Month	**Sensible**	**Latent**	**Total [Wh] per day**	**Total [kWh] per month**	**Sensible**	**Latent**	**Total [Wh] per day**	**Total [kWh] per month**
May	-3773,4	5121,1	1347,7	**41,8**	-5183,4	4079,8	-1103,7	**-34,2**
Jun	574,3	9584,7	10158,9	**304,8**	-2598,4	10493,7	7895,4	**236,9**
Jul	3785,0	14924,6	18709,6	**580,0**	-680,2	14758,3	14078,2	**436,4**
Aug	-1275,5	6605,0	5329,6	**165,2**	-3508,0	6436,3	2928,3	**90,8**
Sep	-7672,8	-927,9	-8600,7	**-258,0**	-7672,8	-927,9	-8600,7	**-258,0**
				833,7				**471,8**

Table 23: Summary of yearly ventilation cooling Load in Beijing

Though there is a cooling load in May and September, the total ventilation load is actually a heating load. In this case, it contributes to a lessening of the total yearly cooling load with about 350 kWh.

3.6 Heating Load Calculation

The heating load calculations have been done according to The National Board of Housing, Building and Planning guidelines (Building regulations – BBR).
In Hong Kong, some heating is required during the winter months but not a significant amount, which is why no heating load calculations are done. However, in Beijing, the winters can be quite cold and the public district heating period usually starts in middle of November and ends in the middle of March.

To calculate the transmission losses one first have to determine the monthly heating degree hours Q [K*h/month]. This is done using equation 15:

$$Q=\left(t_{in}-t_{out}\right)*T \qquad (15)$$

Where	t_{in}	Indoor temperature	[°C]
	t_{out}	Mean monthly outdoor temperature	[°C]
	T	Time per month	[Hours]

The next step is to summarize the transmission losses for the relevant surfaces in the apartment.

$$\sum (U * A) \qquad (16)$$

Where	U	Overall heat transfer coefficient	[W/m^2*K]
	A	Surface Area	[m^2]

Finally, the transmission losses W_T [Wh/month] per month based on the heating degree hours is calculated:

$$W_T = \sum (U * A) * Q \qquad (17)$$

Further, the ventilation losses can be calculated using equation 18:

$$W_V = 0,33 * n * V * Q \qquad (18)$$

Where	0,33 is the amount of energy it takes to heat 1 m^3 of air 1 °C [0,33 Wh/m^3 K]	[Wh]
	n is the air changes per hour	[ACH]
	V volume	[m^3]
	Q degree hours per month	[K*h/month]

The value 0,33 is derived by the following equations/calculations:

$$q = m \cdot c_p \cdot \Delta t$$

Where $m = \rho \cdot V$ $\left[kg = \frac{kg}{m^3} \cdot m^3 \right]$

So the equation can be written as

$$q = \rho \cdot V \cdot c_p \cdot \Delta t$$

Where the volume, (V), is known as well as Δt, cp and the density.

$$q = 1,2 \cdot 1 \cdot 1 \cdot 1 = 1,2 \qquad [kWs]$$

$$q = \frac{1200}{3600} = 0,33 \qquad [Wh]$$

However, there is another way to obtain the ventilation heat loss, which is to use the spreadsheet that was used to calculate the cooling load, but only the part that concerns the ventilation. This is also the method chosen in this paper.

During the winter, there are not only losses but also sources of free heating. The sources considered stated in the BBR are people, appliances and from the sun. A summary of the figures used in the guidelines can be seen in table 24.

Free Heating:	
	[kWh/pers/day]
From People =	1,2
From spplience =	8
From sun =	7,2
People =	4

Table 24: Data stated in the BBR for free heating

In addition, here another option is available which is to use the spreadsheet used for the load calculations where free heating comes from internal loads.

3.6.1 Heating Load – Beijing

The outdoor temperatures chosen for the heating load calculations are a bit higher then than they might be in reality. The reason for this is that it was not possible to simulate outdoor conditions with a lower temperature than 1 °C. Unfortunately, the data logger recording the supply temperature shut down when the temperature sank below 1 °C.
The total yearly heating load without using the VM1-unit can be seen in table 25 and visualized in diagram 5.

Heating Load/Month	
OCT	927,2
NOV	1404,8
DEC	3006,3
JAN	3059,0
FEB	2632,1
MAR	1426,8
APR	949,3
Σ	**13405,5**

Table 25: Yearly heating load

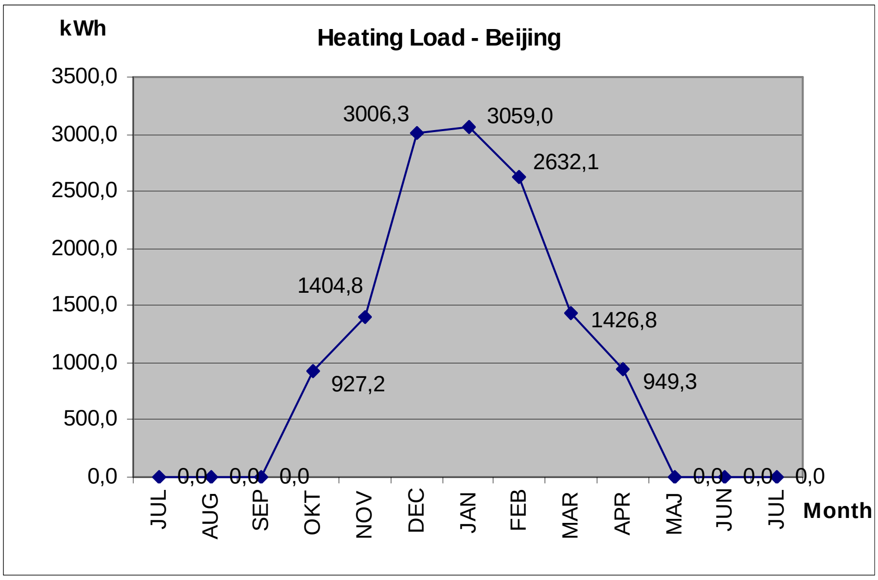

Diagram 5: Yearly heating load without VM1-unit

The total heating load for the Beijing apartment is about 13400 kWh and the peek load occurs in January with 3059 kWh when the outdoor temperature is the lowest.

In table 26, the yearly heating load is summarized when the VM1-unit is used for energy recovery. The result is also shown in diagram 6 graphically.

Heating Load/Month	
OCT	610,7
NOV	940,0
DEC	2318,1
JAN	2325,4
FEB	2046,1
MAR	1114,6
APR	719,5
Σ	10074,4

Table 26: Yearly heating load with VM1-unit

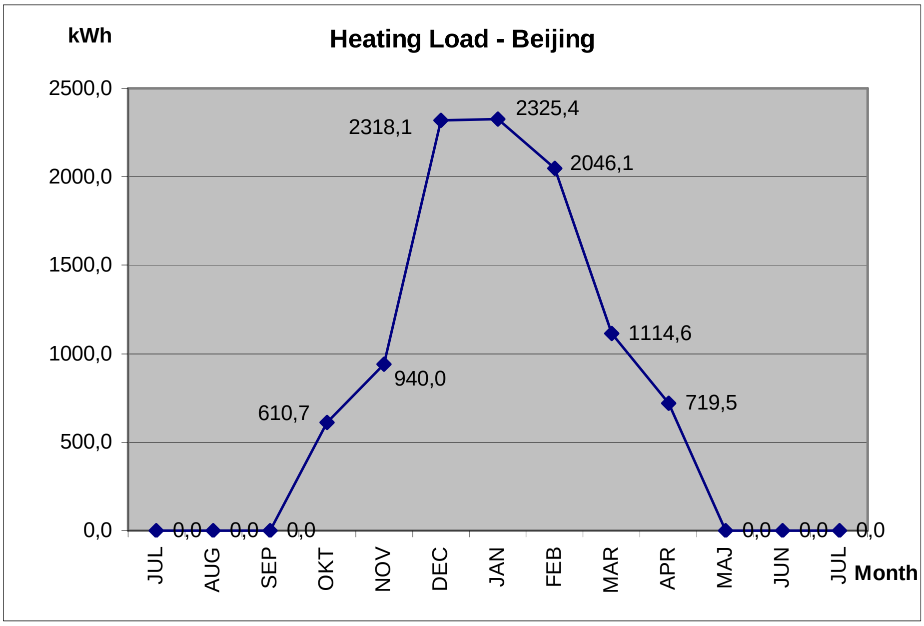

Diagram 6: Yearly heating load with VM1-unit

When using the energy recovery unit the yearly heating load is lowered with about 3300 kWh to 10100 kWh. The calculations can be found in appendix G.

3.7 Calculation of UA-values

In this part, the data recorded when testing the VM1-equipment is analyzed and conclusions drawn from the results. Some of the data used for the load calculations are when the unit is at MAX and MIN setting instead of the intended NORM setting. The reason for this is that insufficient data was recorded during testing unfortunately. Theoretical calculations of the efficiency and UA-value will show an approximate fault that could have occurred from using these other settings.

The UA-value is variable and is dependent on the airflow. Since the VM1-unit has three settings, there will also be three different UA-values. The temperature range goes from about 1 °C to 35 °C, which means that the density and the specific heat capacity will be variable. However, the specific heat capacity does not vary as much as the density. In light of this, three temperature ranges were chosen, cold, medium, and warm.

Cold is 1 – 14 °C, medium is 15 – 25 °C and warm is 26 – 35 °C. A summary of the physical data can be seen in table 27.

Setting	qv	Temperature	Density	Cp
MIN	0,025	Cold	1,3	1005
NORM	0,042	Medium	1,2	
MAX	0,074	Warm	1,16	

Table 27: Property of Air at different settings and temperatures

Using the equations in chapter 2.2, the UA-value could then be calculated as can be seen in table 28. In appendix H, the full table can be seen which show all data included in the calculations.

Supply	Inlet	Extract	Discharge											
N7	N8	N9	N10	Setting	m, c	m, h	Cmin	Q	UA	UA-ave	ε	ε ave	η	η ave
2,5	17,5	21,0	11,2	MIN	0,033	0,030	30,2	298,1	52,3		53,3%		81,1%	
16,6	20,4	21,7	18,6	MIN	0,030	0,030	30,2	94,1	57,4	60,2	60,4%	63,8%	75,1%	77,9%
32,4	26,5	24,9	29,1	MIN	0,030	0,029	29,1	170,0	70,8		77,7%		77,7%	
2,1	17,4	21,0	11,3	NORM	0,055	0,050	50,7	491,6	81,5		51,2%		80,7%	
16,9	20,0	21,5	17,9	NORM	0,050	0,050	50,7	179,6	146,9	127,0	77,6%	66,4%	68,4%	73,1%
31,9	23,9	20,5	30,0	NORM	0,050	0,049	49,0	393,6	152,6		70,3%		70,3%	
4,9	16,3	20,4	12,1	MAX	0,096	0,089	89,2	742,0	135,4		53,8%		73,5%	
16,6	19,3	21,3	17,6	MAX	0,089	0,089	89,2	333,4	227,2	206,3	78,5%	71,5%	57,5%	71,1%
34,2	26,8	25,2	30,5	MAX	0,089	0,086	86,3	639,2	256,4		82,2%		82,2%	
35,0	30,3	25,5	31,1	NORM	0,050	0,049	49,0	230,2	53,1		49,4%		49,4%	

Table 28: Summary of the UA-value calculations

The effectiveness (ε) is defined as the ratio of the actual heat transfer to the maximal heat transfer. The actual heat transfer is determined by the air stream that has the lowest heat capacity. The temperature efficiency has also been calculated denoted η, with the use of equation 14. An observation when examining the calculations is that when the airflow is increased the UA-value increases as well as the heat exchangers effectiveness (ε). However, with the increased airflow the temperature efficiency (η) decreases, but is still mostly dependent on the temperature difference. A larger temperature difference will produce better temperature efficiency. The UA-value is dependent on the mean temperature difference as well as the heat transfer rate. So if the heat transfer rate increases the UA-value increases. Some of the relations are shown in diagram 7. The last row in table 28 is chosen just to show how the result would be when the outdoor air is so humid that it condensation occur on the heat exchanger. As can be seen the UA-value decreases by a factor 3 compared to similar conditions. Effectiveness and efficiency decrease as well.

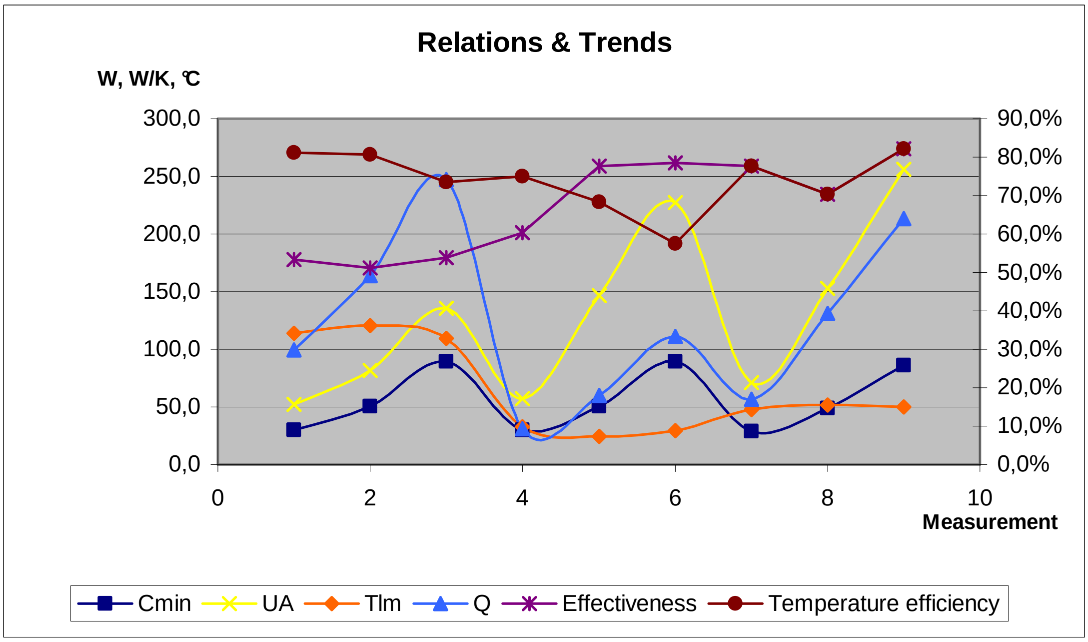

Diagram 7: Relations and trends

In diagram 7, the relations between parameters are shown. The value of ΔT_{lm} (Tlm in diagram) has been multiplied by a factor 20 so it would be easier to see what is affected by it or what it affects. The heat transfer rate has been divided by 3 for the same reason. As can be seen, Cmin, UA, and Q are related which is also a fact when considering the equations in chapter 2.2.

3.8 Summary of calculations

In this chapter, the load calculations are summarized in order to get a better overview of the results. These results will be used for investigating the feasibility of investing in the evaluated system. This will be done by Life Cycle Cost analysis presented in chapter 5. Table 29 shows the results for Hong Kong while table 30 shows results for Beijing.

Hong Kong:

A	**Natural Ventilation**	**[kWh]**
	Cooling Load	15000
B	**VM1**	
	Cooling Load	14000
	Sum of savings	**1000**

Table 29: Summary of Results – Load calculations

As can be seen 1000 kWh can be saved using the VM1-unit in Hong Kong.

Beijing:

A	**Natural Ventilation**	**[kWh]**
	Cooling Load	5050
	Heating Load	13400
	SUM	18450
B	**VM1**	
	Cooling Load	4700
	Heating Load	10100
	SUM	14800
	Sum of savings	**3650**

Table 30: Summary of Results – Load Calculations

In the summer there is very little energy saving while the winter period yields a decent saving. The total annual energy recovery is about 3650 kWh.

4 Life Cycle Cost - and Present Value Calculations

This chapter will describe how investments profitability is assessed using Life Cycle Cost – and Present Value calculations. The LCC calculation show an investments total costs during its economic lifetime. In the LCC the investment cost is included as well as the operating and maintenance costs. With this method, it becomes clear that better value does not always mean lowest capital cost alone. Instead, it is important to examine all the costs involved in the assets life cycle, like operating and maintenance costs. It can be well worth investing a larger initial sum for a lower operations cost when regarding the increasing energy prices.
Fundamentally, LCC is a tool to support decision-making, where the decision requires assessment of current and future costs.

4.1 LCC – Equations

Two alternatives will be investigated in this paper. The first is with natural ventilation when there is no initial capital cost and only the operating cost. The other is with the investment of the VM1-unit. To begin with, the options are examined without regard to energy price increase and then again with respect to the price increase to compare the difference.
With a LCC analysis, there is always some degree of uncertainty, because it is difficult to predict future costs. Assumptions must be made on the interest rate and energy price increase. Interest rates are affected primarily by inflation and by the current economic situation. Would a major economic crisis occur it could also affect interest rates. For example, if there would be a crisis in a foreign oil-producing country, that in turn would cause the price of oil to increase. This would not affect the long-term interest rates at the beginning, but eventually the effects would be noticed. Energy prices are affected by taxes, which governments add on fuel.
Another reason for energy price to increase is the availability of fossil fuels. This increase is not necessarily constant and can behave more erratically depending on costs for extracting the fuels. However, the assumptions made in this chapter are the following:

Interest rate (*i*):	5%
Energy price increase (*e*):	3,5%

In order to calculate the increase of the energy price by time, equation (19) is used:

$$E = E_0 \cdot (1+e)^n \qquad (19)$$

where

where	E	is the total energy cost
	E_0	is the annual energy cost
	e	is the energy price increase
	n	is the year(s)

On the other hand costs has to be discounted to present value, which means the interest has to be taken away from future returns or payments. It is done with equation (20).

$$PV = E_0 \cdot (1+i)^{-n} \qquad (20)$$

where	PV	is the Present Value
	i	is the interest rate

Equations (19) and (20) can be combined so the present energy cost raised by the energy price increase (*e*), to the year (*k)* and after discounted again with the interest rate (*i*) to present value. The total investment cost *I* is expressed by summarized annual values added by the investment cost.

$$I = y + \sum_{n=0}^{k} \left(E_0 \cdot \frac{(1+e)^n}{(1+i)^n} \right) \qquad (21)$$

where *y* is the initial investment cost

The compounds of the LCC calculation can be expressed as:

LCC = I + LCCenergy + LCCmain – Residual Value

Where the initial investment, *I*, is the price for the asset as well as the installation cost.
The total investment can also be connected with operating costs, which are costs for running the system. This includes reoccurring payments like energy costs (*LCCenergy*) and other more sporadic payments as maintenance costs (*LCCmain*).
The operating costs may well be the largest part of the total costs, especially if the increase of energy price is considered, as was mentioned earlier.
When the asset is not needed anymore or its expected lifetime has been reached, it might still have a residual value. Depending on the product, this can vary greatly. For some products, parts can be sold and recycled, whereas for other projects or constructions it is an additional cost for handling the disposal.
The alternatives that will be investigated in this paper have the same calculation period of 20 years. This even though there is no investment in alternative 1 and 3. Every annual operation cost will be discounted to present value. The further the operation costs the lower present value as will be seen. The annual values are added up and the alternatives compared to see which the lowest total investment cost have. In the first two alternatives the annual energy price increase is not considered, however this is investigated in alternative 3 and 4.

4.2 LCC - Beijing

Alternative 1:

The first alternative does not have an investment cost. Instead, the current operating costs are calculated. Tariff's can be found on the HSE website [13]. The energy consumption is taken from the summary in chapter 3.8. However, in this calculation the energy price is not included. A summary of costs can be seen in table 31.

Investment cost	0	$HK
Interest rate	5	%
Calculation time	20	yrs
Energy Costs		
Tariff electricity	0,959	$HK/kWh
Energy consumption	18450	kWh/yr
Energy price	17693,6	$HK/yr

Table 31: Summary of costs

The LCC calculation is summarized in table 32, where the Uniform Present Value is used for reoccurring costs and Single Present Value for one-time costs.

Cost items (1)	Base Date Cost (2)	Year of Occurence (3)	Discount Factor (4)	Present Value (5)=(2)*(4)
Investment cost	0	Base Date	Already PV	**0,0**
			SPV20	
Residual Value	0		1,00	**0,0**
			UPV20	
LCCenergy	17693,6	Annual	12,46	**238194,3**
			UPV20	
LCCmain	0	Annual	12,46	**0,0**
Total LCC				**238194,3**

Table32: LCC calculation summary

UPV is calculated with:

$$UPV = \frac{\left(1-\left(1+r\right)^{-n}\right)}{r} \quad (22)$$

n is the amount of years
r is the interest rate

The total life cycle cost for Alternative 1 is about 238200 HK$.

Alternative 2:

Investing in an air-handling unit requires a substantial instalment, although, since it is an energy recovery unit operating costs are expected to decrease. A summary of the costs is seen in table 33.

Investment cost	30000	$HK
Interest rate	5	%
Calculation time	20	yrs
Energy Costs		
Energy price increase	3,5	%
Tariff electicity	0,959	$HK/kWh
Energy consumption	14800	kWh/yr
Energy Cost	14193,2	$HK/yr
VM1 Energy cons	60	W
Annual usage	8760	h
Energy consumption	525,6	kWh/yr
Energy Cost	504,1	$HK/yr

Table 33: Summary of costs

As in previous case, a LCC calculation is conducted and can be seen in table 34.

Cost items (1)	Base Date Cost (2)	Year of Occurence (3)	Discount Factor (4)	Present Value (5)=(2)*(4)
Investment cost	30000	Base Date	Already PV	**30000,0**
			SPV20	
Residual Value	0		1,00	**0,0**
			UPV20	
LCCenergy (1)	14193,2	Annual	12,46	**176847,3**
			UPV20	
LCCenergy (2)	504,1	Annual	12,46	**6280,5**
			UPV20	
LCCmain	330	Annual	12,46	**4112,5**
Total LCC VM1				**217240,3**

Table 34: LCC calculation summary

The total life cycle cost for Alternative 2 is about 217200 HK$.
LCCenergy (1) is the annual energy consumption. The electricity tariff for heating and cooling is assumed the same. LCCenergy (2) is the cost of running the air-handling unit and LCCmain is the maintenance cost. The maintenance in this case is changing the filter once a year.
Considering these alternatives the second one with the VM1-unit is the most favourable choice, which is about 21000 HK$ cheaper.
The alternatives will be investigated when considering the energy price increase. This will give an indication of the sensitive nature of this type of calculations.

Alternative 3:

This case corresponds to Alternative 1 with the difference of the consideration of energy price increase. In table 35, the costs are seen.

Investment cost	0	$HK
Interest rate	5	%
Calculation time	20	yrs
Energy Costs		
Energy price increase	3,5	%
Tariff electicity	0,959	$HK/kWh
Energy consumption	18450	kWh/yr
Energy price	17693,6	$HK/yr

Table 35: Summary of Costs

Alternative 3 is where no investment is done and the only cost is the amount of energy consumed that is needed for cooling. The total LCC when considering the rise in energy price is 323000HK$. There is no equipment with an economic lifetime to base the calculation. However, to be able to compare with the investment of the air-handling unit, the same lifespan has been chosen in this alternative. Equation (21) was used for the calculation. The annual energy cost can be seen in table 36.

Year, n	Energy cost
0	17693,6
1	17440,8
2	17191,6
3	16946,0
4	16703,9
5	16465,3
6	16230,1
7	15998,2
8	15769,7
9	15544,4
10	15322,4
11	15103,5
12	14887,7
13	14675,0
14	14465,4
15	14258,7
16	14055,0
17	13854,2
18	13656,3
19	13461,2
20	13268,9
Σ	**322992,1**

Table 36: Annual energy cost

Alternative 4:

Year, n	LCCenergy (1)	LCCenergy (2)
0	14193,2	504,1
1	13990,4	496,8
2	13790,6	489,8
3	13593,6	482,8
4	13399,4	475,9
5	13208,0	469,1
6	13019,3	462,4
7	12833,3	455,8
8	12649,9	449,2
9	12469,2	442,8
10	12291,1	436,5
11	12115,5	430,3
12	11942,4	424,1
13	11771,8	418,1
14	11603,7	412,1
15	11437,9	406,2
16	11274,5	400,4
17	11113,4	394,7
18	10954,7	389,0
19	10798,2	383,5
20	10643,9	378,0
Σ	**259094,0**	**9201,3**

Table 37: Summary of annual energy costs

Cost items (1)	Base Date Cost (2)	Year of Occurence (3)	Discount Factor (4)	Present Value (5)=(2)*(4)
Investment cost	0	Base Date	Already PV	**30000,0**
Residual Value	0			**0,0**
LCCenergy (1)	0	Annual		**259094,0**
LCCenergy (2)	0,0	Annual		**9201,3**
			UPV20	
LCCmain	330	Annual	12,46	**4112,5**
Total LCC VM1				**302407,8**

Table 38: LCC calculation summary

Instead of using the discount factor as in Alternative 1 & 2 the values are calculated annually with equation (21) and then added together in order to account for the energy price increase. The annual energy costs are presented in table 37. The total LCC for alternative 4 is about 302400HK$ which is 20600HK$ cheaper than alternative 3. The LCC can be seen in table 38.
It was mentioned earlier that these kind of calculations are of sensitive nature and as can be seen when comparing Alternative 1 with 3 and 2 with 4 the LCC is about 85000HK$ more expensive. The reason is due to the consideration of the energy price increase. Other assumptions can affect the outcome as well, so careful considerations have to be made when estimating investments, and their life cycle costs.

4.2.1 Pay-Off Time and Present Value Calculation Beijing

With the Pay-Off method no regard for energy price increase is taken, instead it is a straightforward method where investment cost is divided by the annual total savings. In this case, the Total Cost Saving is subtracted by the Total Operating Cost and Maintenance to obtain the Sum of Savings. The Pay-Off time is 12 years when rounded up, and a summary can be seen in table 39.

Beijing		
Investment	30000	HK$
Calculation Time	20	Yrs
Energy Tariff	0,959	HK$/kWh
Annual Saving	3650	kWh/yr
Total Cost Saving	3500,4	HK$/yr
Power Consumption	60	W
Usage	8760	h
Total Operating Cost	504,1	HK$/yr
Maintenance	330	HK$/yr
Sum of savings	**2666,3**	HK$/yr
Pay-off Beijing	**11,3**	**Yrs**

Table 39: Pay-Off calculation

The idea with conducting a Present Value calculation is to calculate the future value of the investment into present value. If the calculated present value is larger then the initial investment the investment is considered profitable. A summary of the costs and savings is seen in table 40.

Beijing		
Investment	30000	HK$
Calculation Time	20	Yrs
Energy Tariff	0,959	HK$/kWh
Annual Saving	3650	kWh/yr
Total Cost Saving	3500,4	HK$/yr
Power Consumption	60	W
Usage	8760	h
Total Operating Cost	504,1	HK$/yr
Maintenance	330	HK$/yr
Sum of Savings	**2666,3**	HK$/yr

Table 40: Summary of costs and savings

The PV calculation is done in two ways. The first will not consider the energy price increase. The UPV factor is calculated with (22) and multiplied with the Sum of Savings:

2666,3 * 12,46 = 33222 HK$

The present value is larger than the investment cost, which means the investment is profitable. A larger PV would mean a more profitable investment.

Year, n	Energy saved	Energy consumed	Main
0	3500,4	504,1	330,0
1	3450,3	496,8	314,3
2	3401,1	489,8	299,3
3	3352,5	482,8	285,1
4	3304,6	475,9	271,5
5	3257,4	469,1	258,6
6	3210,8	462,4	246,3
7	3165,0	455,8	234,5
8	3119,8	449,2	223,4
9	3075,2	442,8	212,7
10	3031,3	436,5	202,6
11	2987,9	430,3	192,9
12	2945,3	424,1	183,8
13	2903,2	418,1	175,0
14	2861,7	412,1	166,7
15	2820,8	406,2	158,7
16	2780,5	400,4	151,2
17	2740,8	394,7	144,0
18	2701,7	389,0	137,1
19	2663,1	383,5	130,6
20	2625,0	378,0	124,4
Σ	**63898,2**	**9201,3**	**4442,5**

Table 41: Summary of annual costs and savings

The second way is to consider the annual increase of energy price. Energy prices are calculated annually with equation (21) and added up. The feasibility of the investment is determined by:

PV = Energy Saved – Energy Consumed – Main

PV = 63898,2 – 9201,3 – 4442,5 = 52254,3 HK$

The result is about 52000 HK$ which is well above the investment cost of 30000 HK$. As can be seen when the energy price increase is considered the result become more profitable. This shows how the assumptions that are made affect the result. Different interest rates and assumed energy increase rates must be considered carefully when conducting this kind of calculations. A summary of the annual costs and savings can be seen in table 41.

4.3 LCC – Hong Kong

The same calculations will be done for the Hong Kong location as was done for Beijing. Four LCC calculations, Alternative 1 & 2 without regarding energy price increase and Alternative 3 & 4 with this factor considered.

Alternative 1:

This alternative is with natural ventilation and only the calculated energy consumption required offsetting the cooling load. In table 42, a summary of the costs involved can be seen.

Investment cost	0	$HK
Interest rate	5	%
Calculation time	20	yrs
Energy Costs		
Energy price increase	3,5	%
Tariff electicity	0,959	$HK/kWh
Energy consumption	15000	kWh/yr
Energy price	14385,0	$HK/yr

Table 42: Summary of costs

As was mentioned earlier, the same strategy is used for these calculations as for the Beijing case. A summary of the LCC can be seen in table 43.

Cost items (1)	**Base Date Cost (2)**	**Year of Occurence (3)**	**Discount Factor (4)**	**Present Value (5)=(2)*(4)**
Investment cost	0	Base Date	Already PV	**0,0**
			SPV20	
Residual Value	0		1,00	**0,0**
			UPV20	
LCCenergy	14385,0	Annual	12,46	**193653,9**
			UPV20	
LCCmain	0	Annual	12,46	**0,0**
Total LCC				**193653,9**

Table 43: Summary of LCC calculation

The total LCC for Hong Kong without the VM1 – unit is about 194000 HK$.

Alternative 2:

In this alternative, the investment of the VM1-unit is considered and the related operation costs. A summary of the costs is found in table 44.

Investment cost	30000	$HK
Interest rate	5	%
Calculation time	20	yrs
Energy Costs		
Energy price increase	3,5	%
Tariff electicity	0,959	$HK/kWh
Energy consumption	14000	kWh/yr
Energy Cost	13426	$HK/yr
VM1 Energy consump	60	W
Annual usage	8760	h
Energy consumption	525,6	kWh/yr
Energy Cost	504,1	$HK/yr

Table 44: Summary of costs related to the investment of the VM1-unit

The LCC calculation is summarized in table 45

Cost items (1)	**Base Date Cost (2)**	**Year of Occurence (3)**	**Discount Factor (4)**	**Present Value (5)=(2)*(4)**
Investment cost	30000	Base Date	Already PV	**30000,0**
			SPV20	
Residual Value	0		1,00	**0,0**
			UPV20	
LCCenergy (1)	13426	Annual	12,46	**167288,0**
			UPV20	
LCCenergy (2)	504,1	Annual	12,46	**6280,5**
			UPV20	
LCCmain	330	Annual	12,46	**4112,5**
Total LCC VM1				**207681,0**

Table 45: Summary of LCC calculation

The total LCC for the alternative with VM1 is about 207700 HK$. Comparing alternative 1 and 2, it is clear that it would be about 13700 HK$ more expensive to invest in the VM1 – unit.

Alternative 3:

To investigate the alternatives again but considering the energy price increase will show if there is any point in investing in the energy recovery equipment in Hong Kong. The related costs are summarized in table 46.

Investment cost	0	$HK
Interest rate	5	%
Calculation time	20	yrs
Energy Costs		
Energy price increase	3,5	%
Tariff electicity	0,959	$HK/kWh
Energy consumption	15000	kWh/yr
Energy price	14385,0	$HK/yr

Table 46: Summary of costs

Year , n	Energy cost
0	14385,0
1	14179,5
2	13976,9
3	13777,3
4	13580,4
5	13386,4
6	13195,2
7	13006,7
8	12820,9
9	12637,7
10	12457,2
11	12279,2
12	12103,8
13	11930,9
14	11760,5
15	11592,5
16	11426,9
17	11263,6
18	11102,7
19	10944,1
20	10787,8
Σ	**262595,2**

Table 47: Annual energy costs

When considering the energy price increase the total LCC without any investment is 262600 HK$. The summary of annual energy costs can be seen in table 47.

Alternative 4:

In table 48, the annual energy costs are summarized and the LCC calculation presented in table 49.

Year, n	LCCenergy (1)	LCCenergy (2)
0	13426,0	504,1
1	13234,2	496,8
2	13045,1	489,8
3	12858,8	482,8
4	12675,1	475,9
5	12494,0	469,1
6	12315,5	462,4
7	12139,6	455,8
8	11966,2	449,2
9	11795,2	442,8
10	11626,7	436,5
11	11460,6	430,3
12	11296,9	424,1
13	11135,5	418,1
14	10976,4	412,1
15	10819,6	406,2
16	10665,1	400,4
17	10512,7	394,7
18	10362,5	389,0
19	10214,5	383,5
20	10068,6	378,0
Σ	**245088,9**	**9201,3**

Table 48: Annual energy costs

Cost items (1)	Base Date Cost (2)	Year of Occurence (3)	Discount Factor (4)	Present Value (5)=(2)*(4)
Investment cost	0	Base Date	Already PV	**30000,0**
Residual Value	0			**0,0**
LCCenergy (1)	0	Annual		**245088,9**
LCCenergy (2)	0,0	Annual		**9201,3**
			UPV20	
LCCmain	330	Annual	12,46	**4112,5**
Total LCC VM1				**288402,8**

Table 49: Summary of LCC calculation

When considering the energy increase for the VM1 alternative it is about 25800 HK$ more expensive than without the equipment. The total LCC is about 288400 HK$.
For both cases (energy increase or not) the total Life Cycle Cost is more expensive when investing in the VM1 – unit.

A simple way of showing that the investment is not profitable can be seen in the following summary, table 50.

Hong Kong		
Investment	30000	HK$
Interest Rate	5	%
Calculation Time	20	Yrs
Energy Tariff	0,959	HK$/kWh
Annual Saving	1000	kWh/yr
Total Cost Saving	959	kr/år
Power Consumption	60	W
Usage	8760	h
Total Operating Cost	504,1	HK$
Maintenance	330	HK$
Sum of Savings	**124,9**	HK$
Pay-off Hong Kong	**240,1**	yrs

Table 50: Pay-off calculation

The annual sum of saving is so small it will take an unreasonably long time to get the invested money back.
Considering this, a present value calculation will not be conducted for this alternative since it is clear the investment is not profitable.

5 Discussion

The world is facing a potential environmental disaster, where CO_2 emission is predicted to continue increasing for the next couple of decades. The largest emitter of CO_2 today is China, who overtook the U.S. first position in 2006 with 8% higher emission. In 2005, China had emissions that were 2% lower than the U.S. and the supposed reason for the massive increase in emission was a soaring demand for coal to generate electricity [16]. As was mentioned in the introduction of this paper, most of the power stations in China use fossil fuels, where coal is the main fuel. However, ever since the announcement that China was going to host the 2008 Olympics major reforms were implemented in order to reduce emissions.

In light of this, all measures that can reduce energy consumption, which would ultimately lead to a reduction in emissions, should be considered.

In this paper one such measure has been investigated, which is the use of energy recovery technology. This type of technology is used in residential buildings for heat recovery in Sweden and northern parts of Europe, as well as in North America. However, the use of mechanical ventilation with energy recovery is not commonly used in China, thus the investigation done in this paper.

5.1 Hong Kong

The performance of these types of systems is well documented considering heat recovery, but one of the purposes of this paper is to investigate the potential energy savings when used in sub-tropical climates.

Summer condition measurements show that a high efficiency can be achieved when the temperature difference is enough and the air is dry. However, when the humidity reaches 70% and higher, so reduces the efficiency significantly, in particular when the temperature difference is not sufficient.. As conditions in southern China are relatively humid all year around, it poses a problem.

Load calculations conducted with natural ventilation and mechanical ventilation with energy recovery show that the savings are quite small. Further, the LCC and Pay-back time calculations show that investing in this technology will not be profitable.

Possible reasons for the poor result could be:

- For 3 out of 12 months, the heat exchanger is not even in use due to design temperatures being the same as assumed indoor temperatures.
- For another 3 months, the heat exchanger is actually too efficient, and raises the supply temperature so it increases cooling load. The only option is to use the bypass function in order to keep cooling loads down.
- For the remaining 6 months when the VM1-unit actually is used to pre-cool the incoming air the efficiency is quite low ($\eta < 50\%$).
- The VM1-unit is designed for a market with a different climate, and tests show it would not perform adequately in its current design in sub-tropical climates.
- The heat exchanger cannot perform efficiently when the outdoor air is too humid due to condensation. The consequence of intake air condensating on the heat exchanger is that the inlet air temperature is increased which in turn decreases the temperature difference. A lower temperature difference means a lower efficiency.

Possible reasons for using mechanical ventilation in Hong Kong would be to obtain a better indoor air quality, since the systems have filters that clean incoming air.

5.2 Beijing

The same evaluation of the VM1-system was applied to conditions similar to those that can be found in northern parts of China or Beijing. The area is classified as a cold area and conditions are similar to those of northern U.S. So intuitively, one would expect the performance to be better. The calculations show that the VM1-unit works more effectively in a climate similar to Beijing's. In chapter 3.1.1, table 7, on can see that the efficiency is much higher most of the year, with an exception of the summer months.
Reasons for the VM1-units better performance in Beijing could be:

- It is possible to use the unit for a longer period for energy recovery. It is operational 11 out of 12 months.
- The outdoor air is less humid which allows the unit to function as designed..
- During winter the mean temperature difference is much larger compared to summer, which results in a higher heat transfer and efficiency.

The profitability calculations show that it would be worth investing in this system. Since it lowers energy consumption, it also contributes to reducing CO_2 emission.

The cost of heating is based on the size of the apartment rather than the actual energy consumption, which makes it more difficult to estimate the savings in money. However in this paper the price for heating is assumed the same as for cooling, which is based on consumption. A point of interest could be to estimate the reduction of CO_2 emission when using the VM1-unit. The most common fuel used for district heating (in China) is coal, which has a carbon intensity factor of 0,32 kg CO_2/kWh [15]. Therefore, the total amount of saved CO_2 emission per year in Beijing would be:

$$\text{Total saved emission} = (3650-525{,}6) * 0{,}32 = 1000 \text{ kg } CO_2 \text{ per year}$$

Where 3650 (kWh) is the total saving using the VM1-unit and 525,6 (kWh) is the energy consumption when using the unit. The net saving would be about 3125 kWh per year.
For Hong Kong, it would be about 150 kg CO_2 per year, which probably would not be enough to use as an argument for investing in the equipment.

5.3 General points

The choice of using a manual way of calculating cooling and heating loads was mainly done in order to gain experience. Many assumptions were made, but most of them are in accordance with ASHRAE standard guidelines. There are also many manual methods one can use for the calculations. Several uses tabulated values for simplicity while others require that all parameters be calculated. The Radiant Time Series (RTS) method is sort of a middle way that uses some tabulated values while most parameters has to be calculated by hand (or using spreadsheets).

The energy consumption for tap water heating was not considered in this paper.

6 Conclusion

This master thesis has examined the potential for energy saving in two regions of China using mechanical ventilation with energy recovery. In order to accomplish this empirical tests of the equipment was performed using a test rig and theoretical calculations determining the potential energy savings.

When considering Hong Kong, the load calculations show that cooling is needed throughout the whole year. The energy savings are severely diminished since the equipment is of use only 6 months per year and even then the maximum energy saving is only 200 kWh. Calculations show that the operating costs are barely covered by the energy savings. It is evident that the VM1-units design is not suitable for the subtropical climate in Hong Kong.

However, the climate in Beijing is more similar to the conditions that the equipment is designed to use. Calculations also show that the potential for energy recovery is much higher compared to in Hong Kong, especially during wintertime. The yearly saving in Beijing when using the VM1-unit is about 3100 kWh or 2600 HK$, which is enough for it to be a profitable investment.

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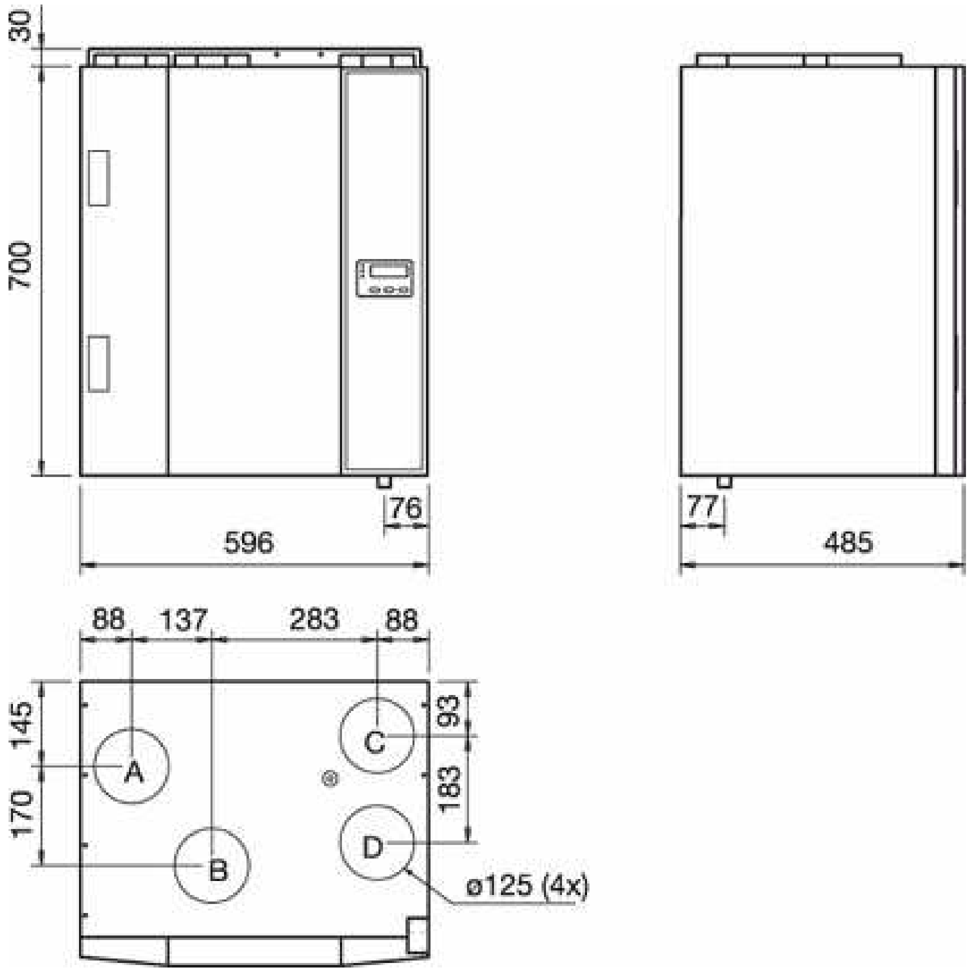
Appendix A: VM1 – unit dimensions

Dimensions of the VM1 Heat Recovery Unit:

Measurements are in [mm].



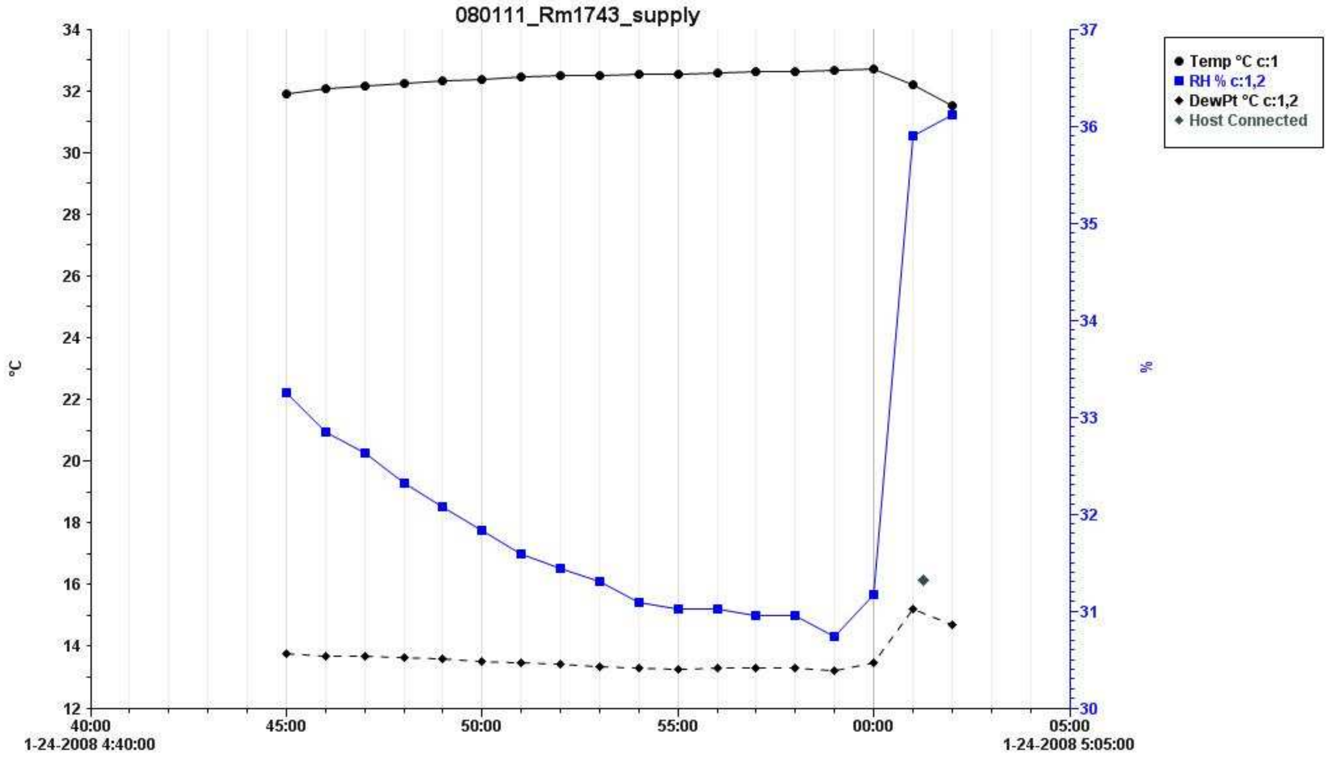
A Outside air
B Extract air
C Exhaust air
D Supply air

Appendix B: Measurement Data from Test rig

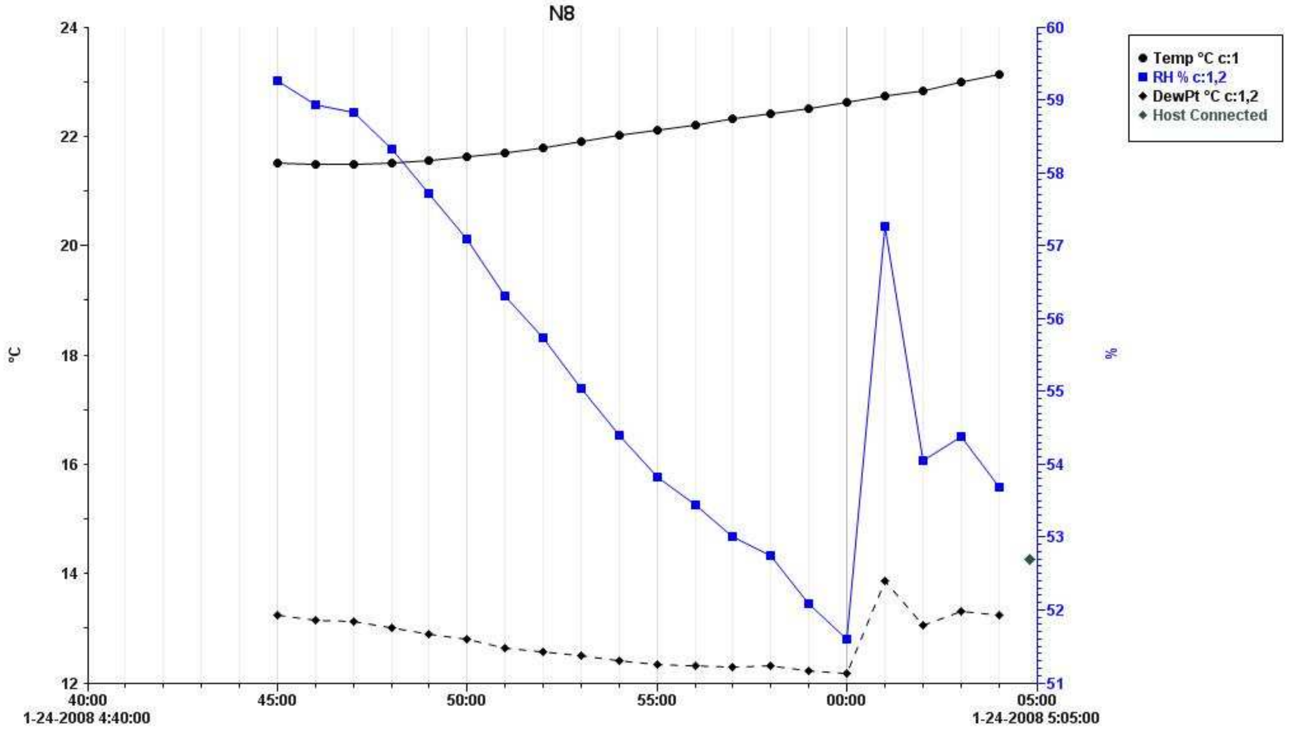
For the measurements, 4 data loggers were used and in total, there were 6 measurements of varying length. The data can be seen as graphs that were extracted from the software used together with the loggers. In addition, the data is summarized in a table showing the temperature, relative humidity and the temperature efficiency.

Measurement 1:

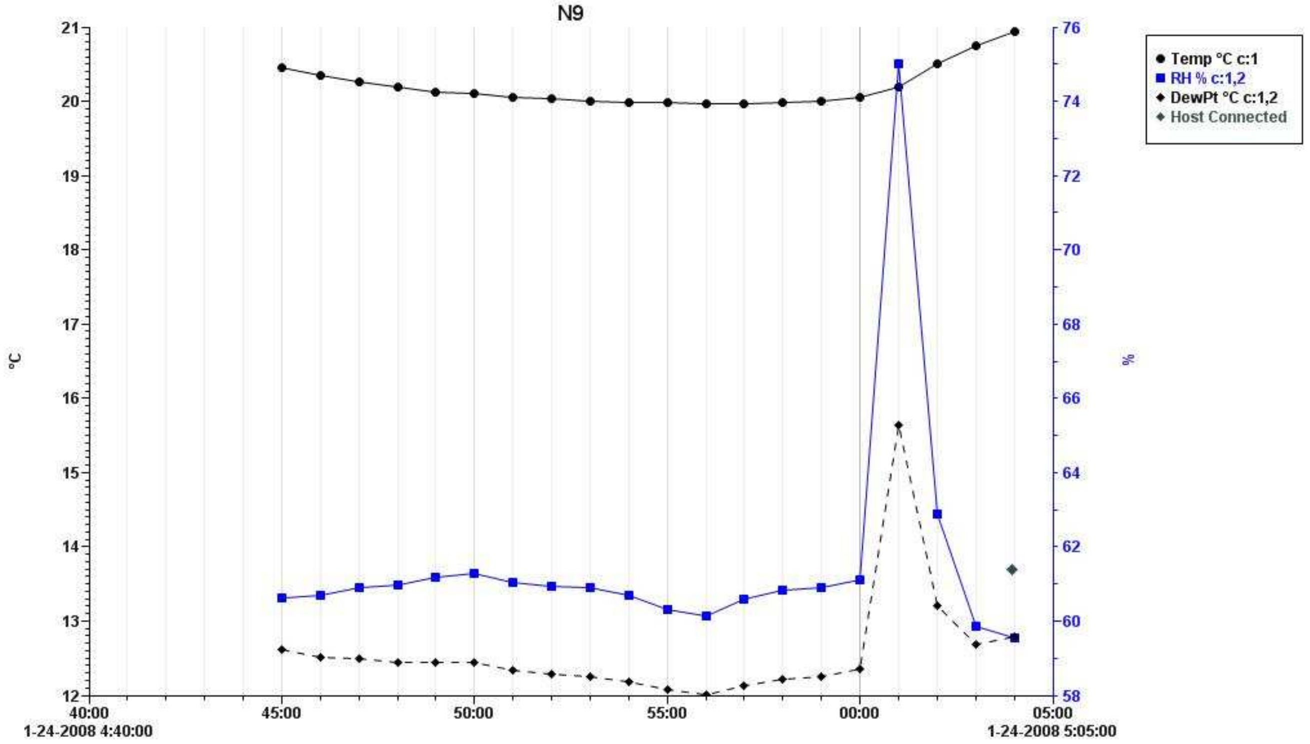
Sensor N7 – Supply Air Duct



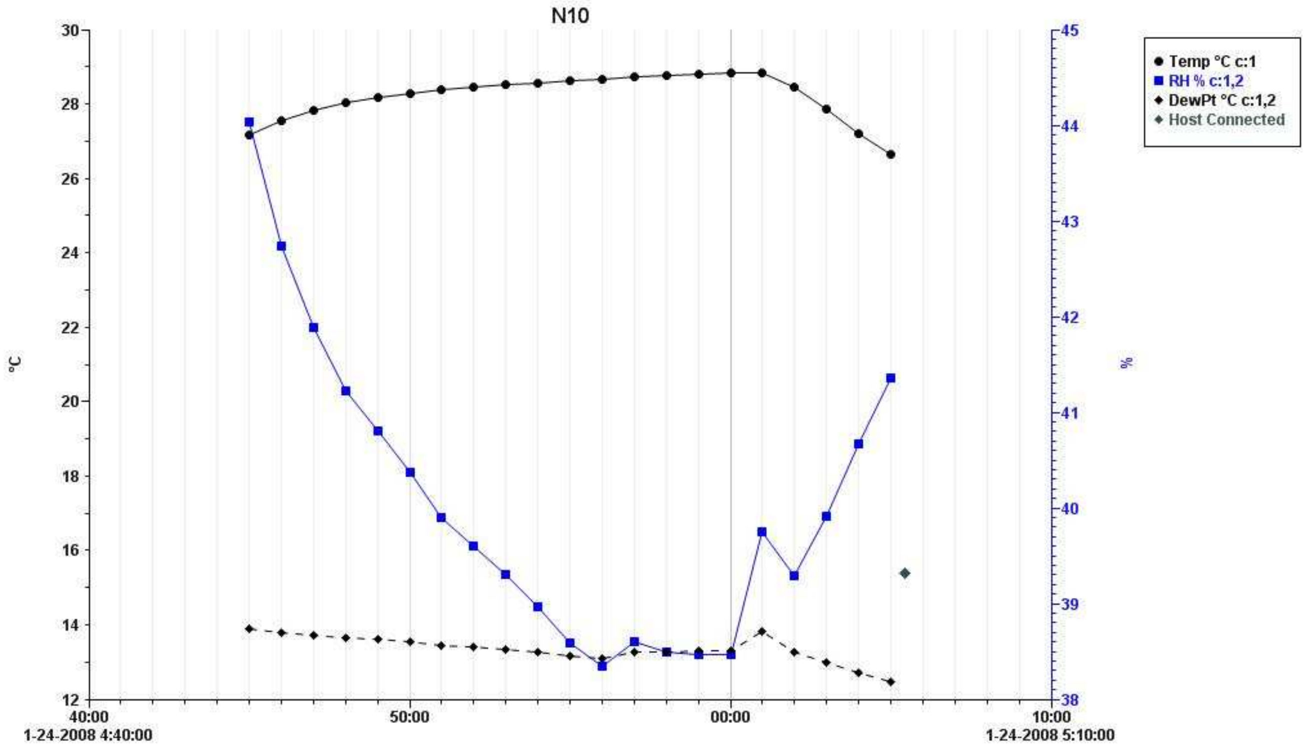
Sensor N8 – Inlet Air Duct



Sensor N9 – Extract Air Duct



Sensor N10 – Discharge Air Duct

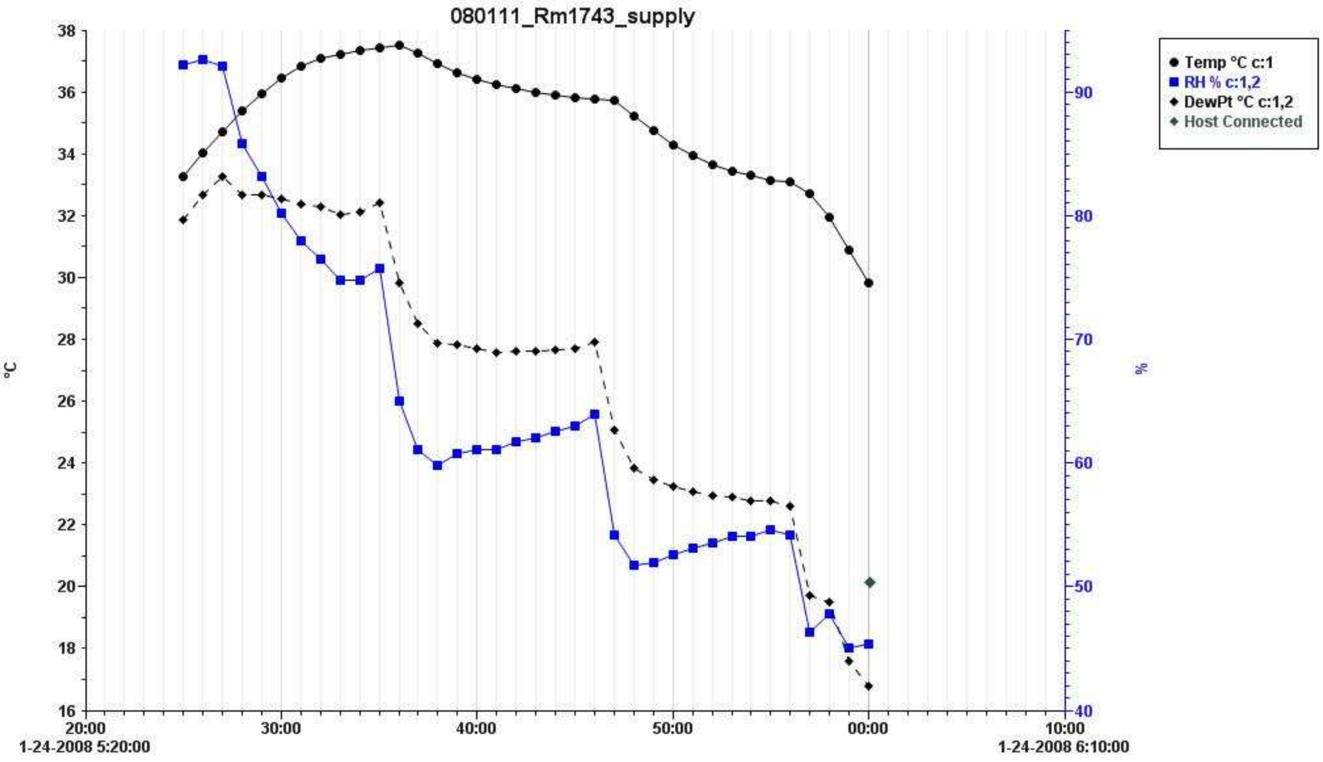


Measurement 1: Data table

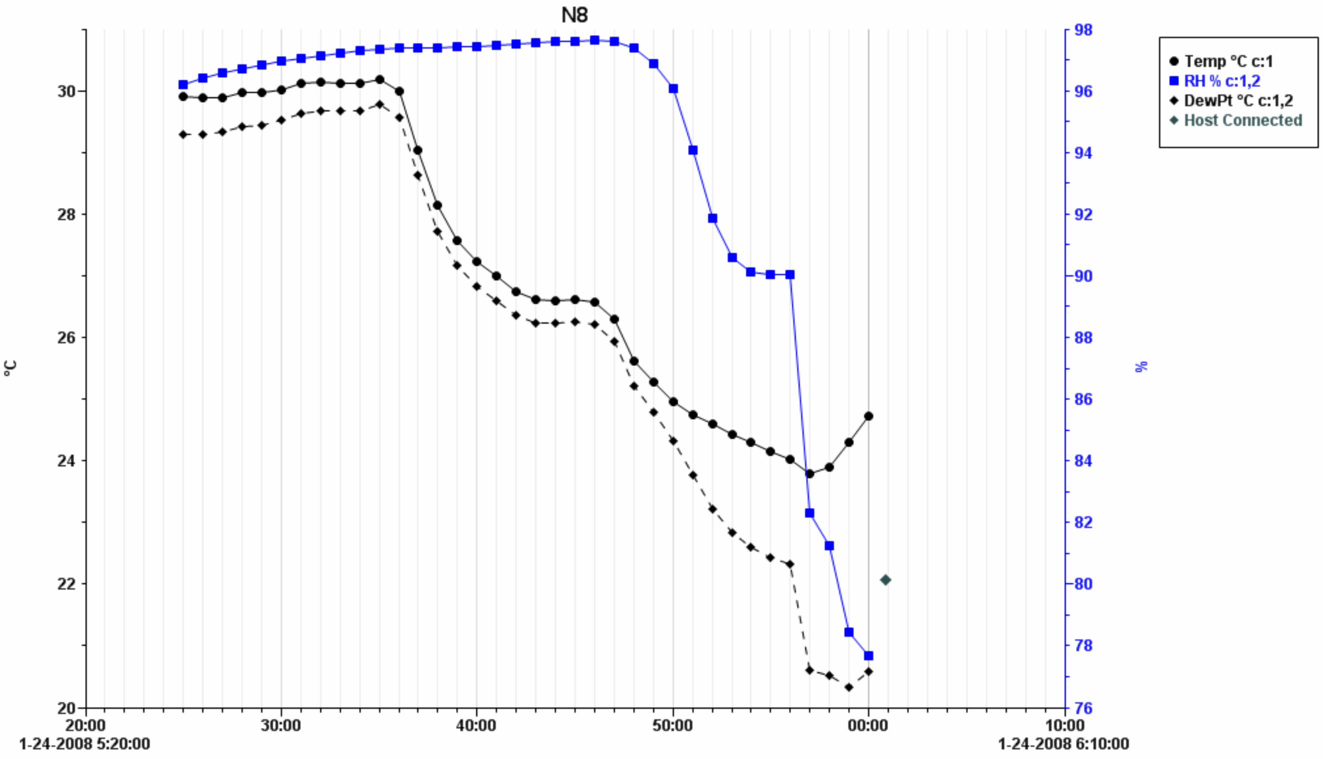
	Temperature [℃]					Relative Humidity [%]				
	Fresh Air Intake	Air Inlet	Extract Air	Discharge Extract Air	Temp. Efficiency	Fresh Air Intake	Air Inlet	Extract Air	Discharge Extract Air	
Sample	**N7**	**N8**	**N9**	**N10**	**η**	**N7**	**N8**	**N9**	**N10**	**Setting**
1	31,9	21,5	20,0	27,2	87,7%	33,3	59,0	60,6	44,0	NORM
2	32,0	21,5	20,3	27,6	90,2%	32,1	58,9	60,7	42,7	NORM
3	32,0	21,5	20,3	27,8	89,6%	32,6	58,8	60,9	41,9	NORM
4	32,3	21,5	20,2	28,0	89,1%	32,3	58,3	60,1	41,2	NORM
5	32,0	21,6	20,1	28,2	88,0%	32,1	57,7	61,2	40,8	NORM
6	32,4	21,6	20,1	28,0	87,6%	31,1	57,1	61,3	40,4	NORM
7	32,5	21,0	20,1	28,4	92,3%	31,6	56,3	61,0	39,9	NORM
8	32,5	21,8	20,0	28,4	85,8%	31,4	55,7	60,9	39,6	NORM
9	32,1	21,9	20,0	28,5	84,2%	31,3	55,0	60,1	39,0	NORM
10	32,5	22,0	20,0	28,6	83,9%	31,1	54,4	60,7	39,0	NORM
11	32,5	22,1	20,0	28,6	83,1%	31,0	53,8	60,3	38,6	NORM
12	32,6	22,2	19,1	28,7	77,0%	31,0	53,4	60,1	38,4	NORM
13	32,6	22,3	19,1	28,7	76,1%	31,0	53,0	60,6	38,6	NORM
14	32,6	22,4	20,0	28,8	80,8%	31,0	52,7	60,8	38,5	NORM
15	32,7	22,5	20,0	28,8	80,2%	30,7	52,1	60,1	38,5	NORM
16	32,7	22,6	20,1	28,8	79,6%	31,2	51,6	61,1	38,5	NORM

Measurement 2:

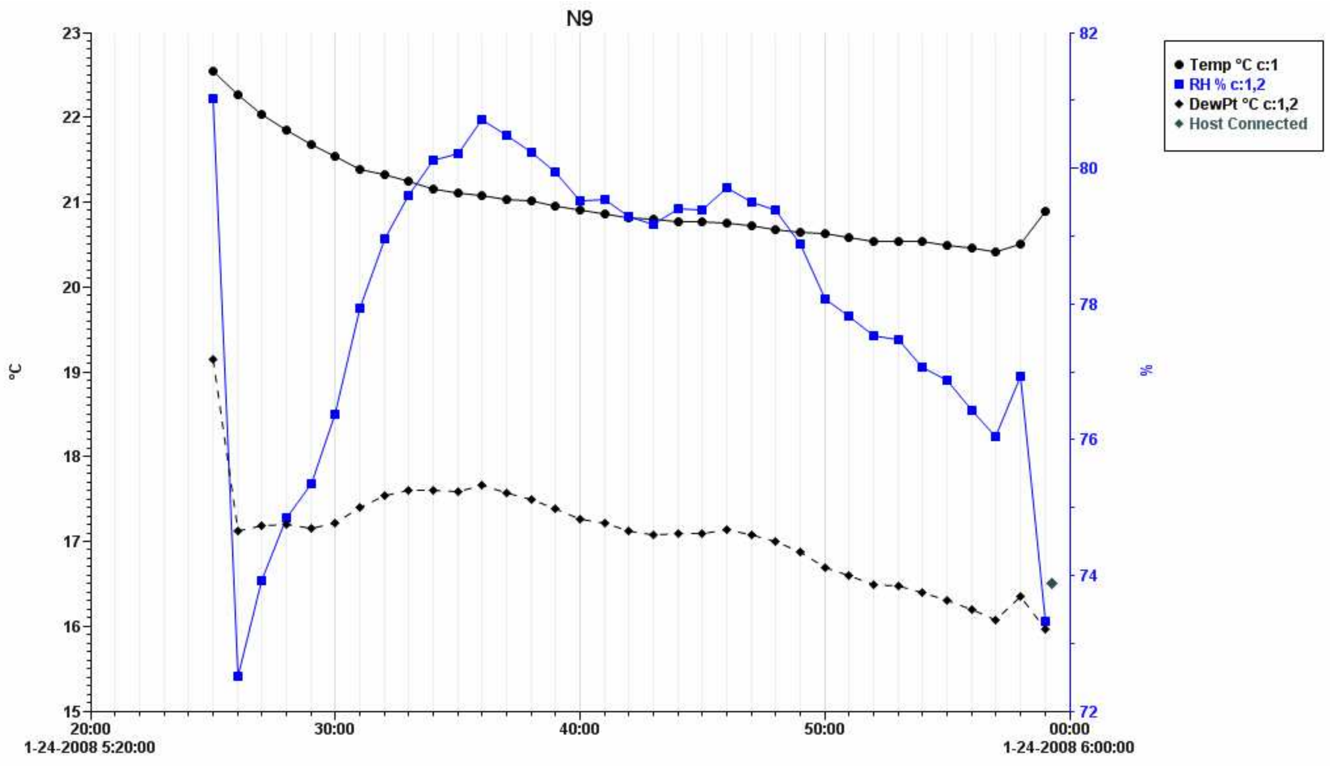
Sensor N7 – Supply Air Duct



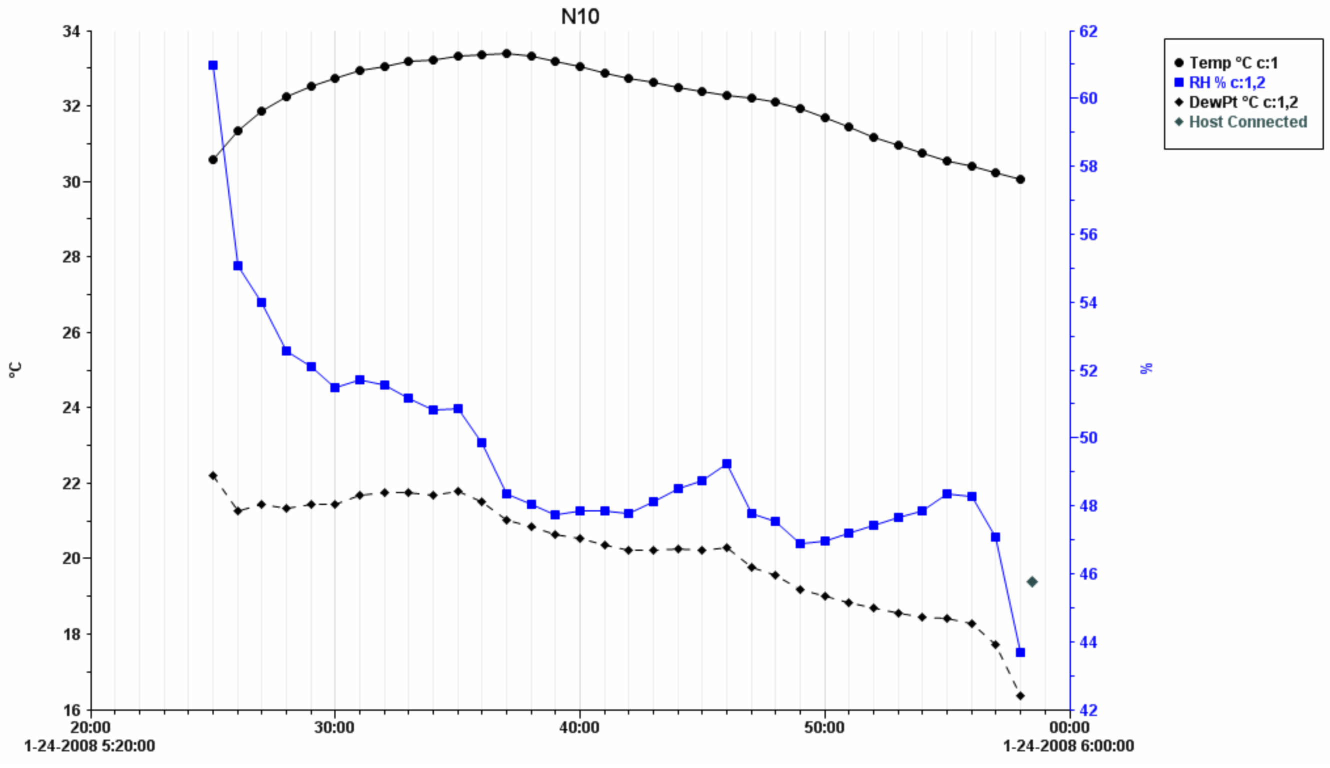
Sensor N8 – Inlet Air Duct



Sensor N9 – Extract Air Duct



Sensor N10 – Discharge Air Duct

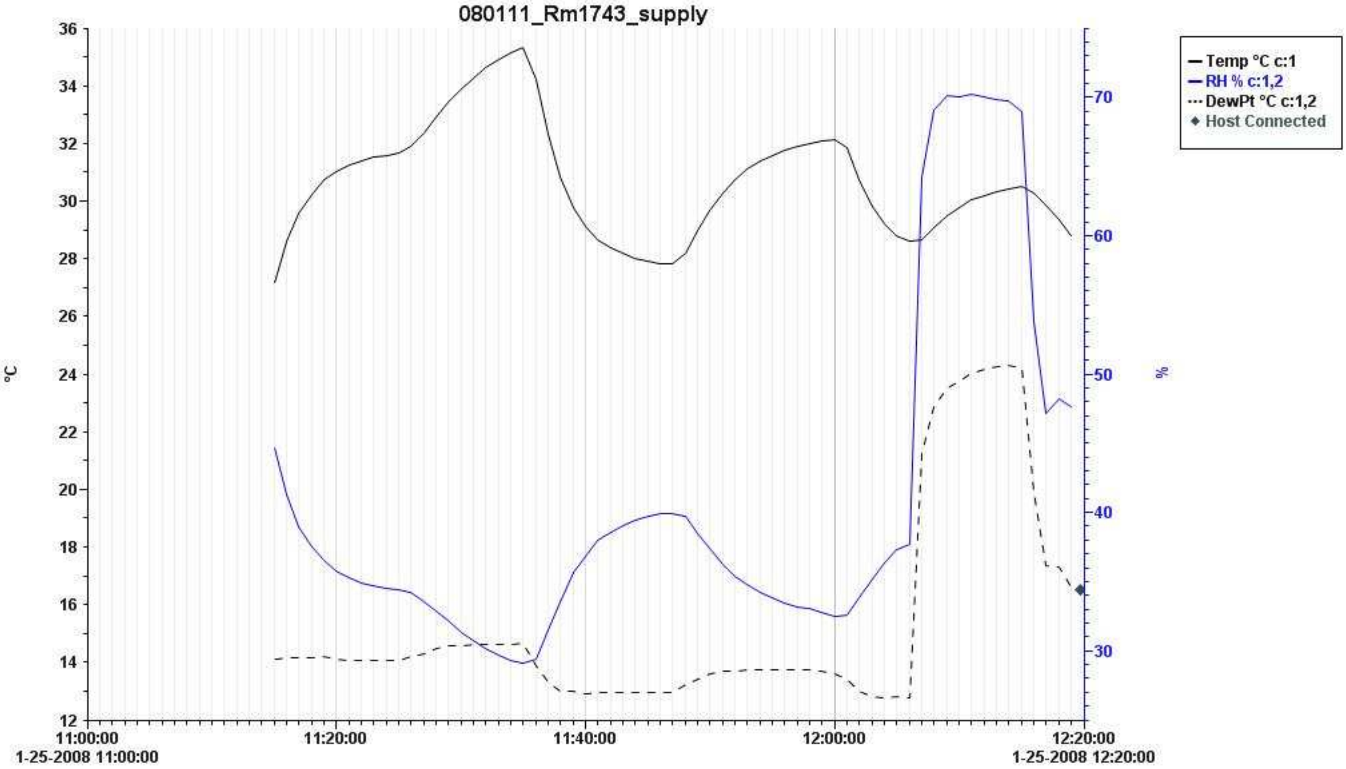


Measurement 2: Data table

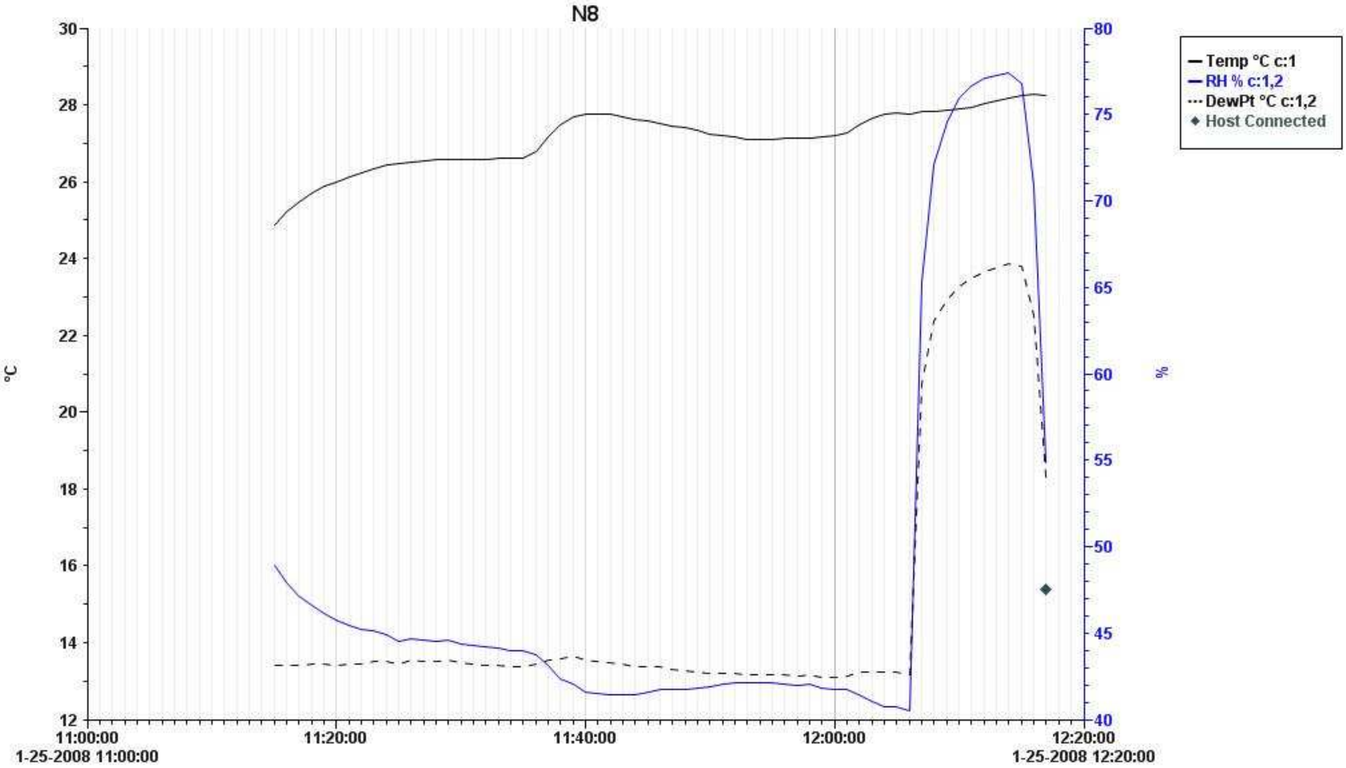
	Temperature [℃]					Relative Humidity [%]				
	Fresh Air Intake	Air Inlet	Extract Air	Discharge Extract Air	Temp. Efficiency	Fresh Air Intake	Air Inlet	Extract Air	Discharge Extract Air	
Sample	**N7**	**N8**	**N9**	**N10**	**η**	**N7**	**N8**	**N9**	**N10**	**Setting**
1	33,3	29,9	22,5	30,6	31,2%	92,2	96,2	81,0	61,0	NORM
2	34,0	29,1	22,3	31,3	42,0%	92,6	96,4	72,5	55,1	NORM
3	34,7	29,1	22,0	31,9	44,3%	92,1	96,1	73,9	54,0	NORM
4	35,4	30,0	21,8	32,3	39,9%	85,8	96,7	74,8	52,6	NORM
5	36,0	30,0	21,7	32,5	42,0%	83,1	96,8	75,4	52,1	NORM
6	36,5	30,0	21,5	32,7	43,2%	80,1	96,9	76,4	51,5	NORM
7	36,8	30,1	21,0	32,9	42,5%	78,0	97,0	77,9	51,7	NORM
8	37,1	30,1	21,3	33,1	44,0%	76,5	97,1	79,0	51,6	NORM
9	37,2	30,1	21,2	33,2	44,4%	74,8	97,2	79,6	51,2	NORM
10	37,3	30,1	21,2	33,2	44,6%	74,7	97,3	80,1	50,8	NORM
11	37,4	30,2	21,1	33,3	44,3%	75,7	97,4	80,2	50,9	NORM
12	37,5	30,0	21,1	33,4	45,8%	65,0	97,4	80,1	49,9	NORM
13	37,3	29,0	21,0	33,4	50,9%	61,1	97,4	80,5	48,4	NORM
14	36,9	28,1	21,0	33,3	55,2%	59,8	97,4	80,0	48,1	NORM
15	36,6	27,6	20,1	33,2	54,7%	60,7	97,4	79,9	47,7	NORM
16	36,4	27,2	20,9	33,1	59,1%	61,0	97,4	79,5	47,9	NORM
17	36,3	27,0	20,9	32,9	60,2%	61,1	97,0	79,5	47,8	NORM
18	36,1	26,7	20,8	32,7	61,2%	61,7	97,5	79,0	47,8	NORM
19	36,0	26,6	20,8	32,6	61,6%	62,1	97,5	79,0	48,1	NORM
20	35,9	26,6	20,1	32,5	58,8%	62,6	97,6	79,0	48,5	NORM
21	35,8	26,6	20,1	32,4	58,4%	63,0	97,6	79,4	48,7	NORM
22	35,1	26,6	20,7	32,3	59,3%	63,9	97,6	79,7	49,2	NORM
23	35,7	26,3	20,7	32,2	62,8%	54,2	97,6	79,5	47,8	NORM
24	35,2	25,6	20,7	32,1	66,0%	51,8	97,4	79,0	47,5	NORM
25	34,1	25,3	20,1	31,9	62,7%	52,0	96,1	78,9	46,1	NORM
26	34,3	25,0	20,6	31,7	68,2%	52,6	96,1	78,1	47,0	NORM
27	33,1	24,1	20,6	31,4	72,1%	53,1	94,1	77,8	47,2	NORM
28	33,7	24,6	20,5	31,2	69,0%	53,0	91,8	77,5	47,4	NORM
29	33,4	24,4	20,5	30,1	69,8%	54,0	90,1	77,5	47,7	NORM
30	33,3	24,3	20,5	30,7	70,5%	54,1	90,1	77,1	47,8	NORM
31	33,2	24,1	20,5	30,5	71,1%	54,6	90,0	76,9	48,4	NORM
32	33,1	24,0	20,0	30,4	69,5%	54,2	90,0	76,4	48,3	NORM
33	32,7	23,8	20,4	30,2	72,6%	46,3	82,3	76,0	47,1	NORM
34	31,9	23,9	20,5	30,0	70,3%	47,8	81,3	76,9	43,7	NORM

Measurement 3:

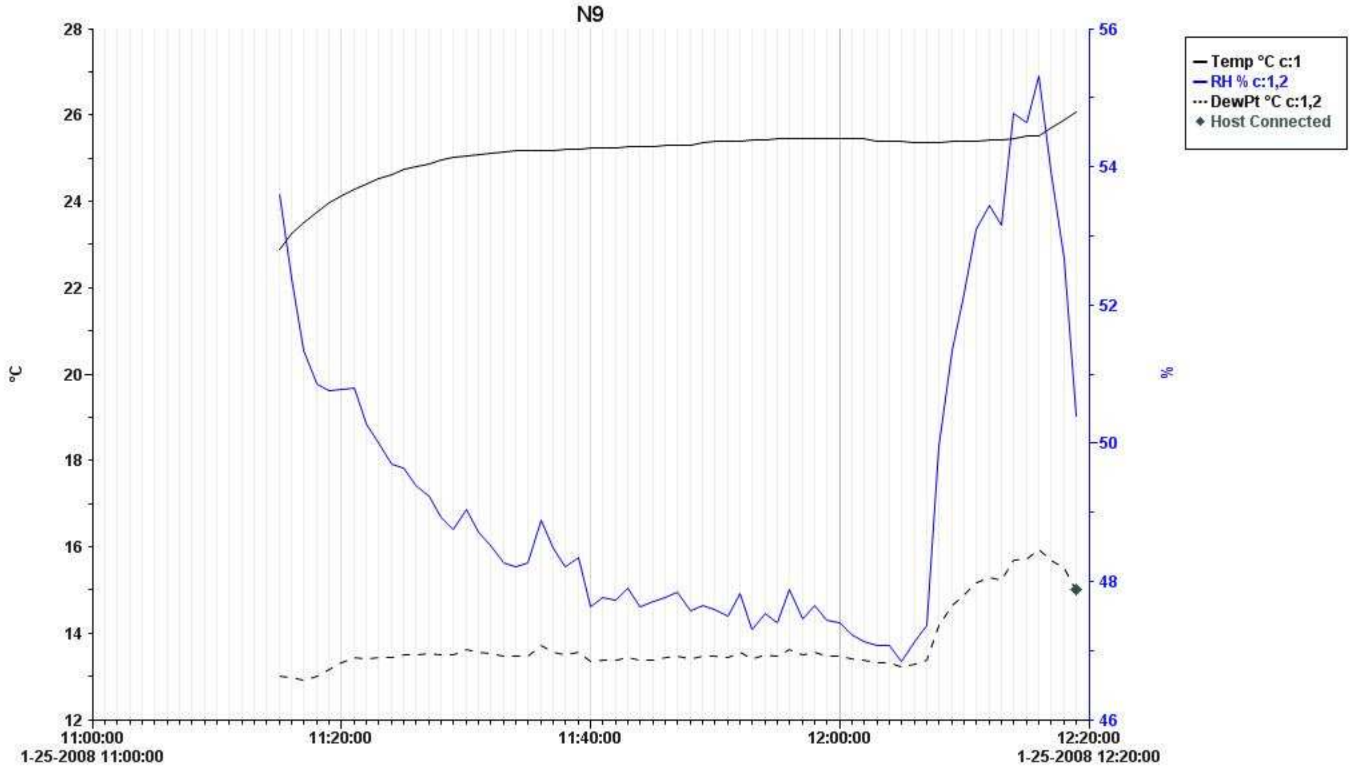
Sensor N7 – Supply Air Duct



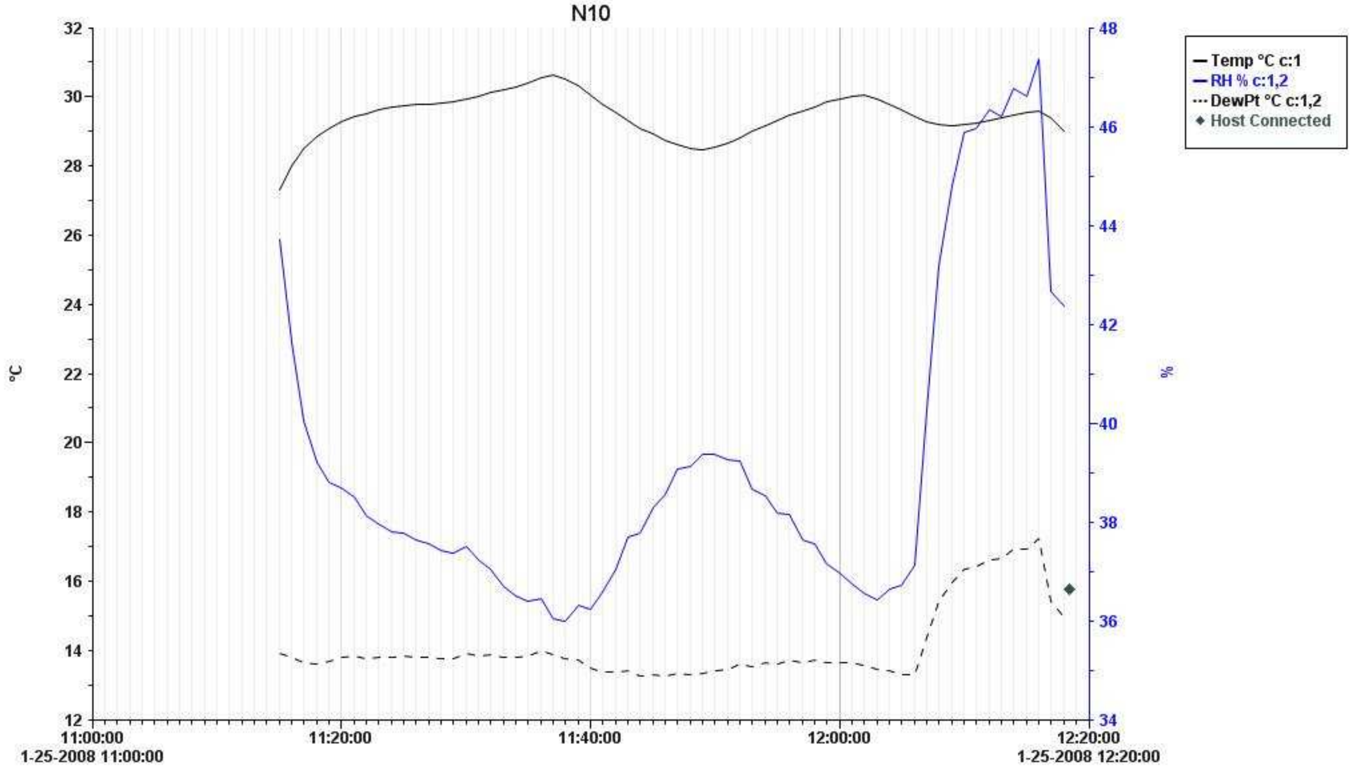
Sensor N8 – Inlet Air Duct



Sensor N9 – Extract Air Duct



Sensor N10 – Discharge Air Duct



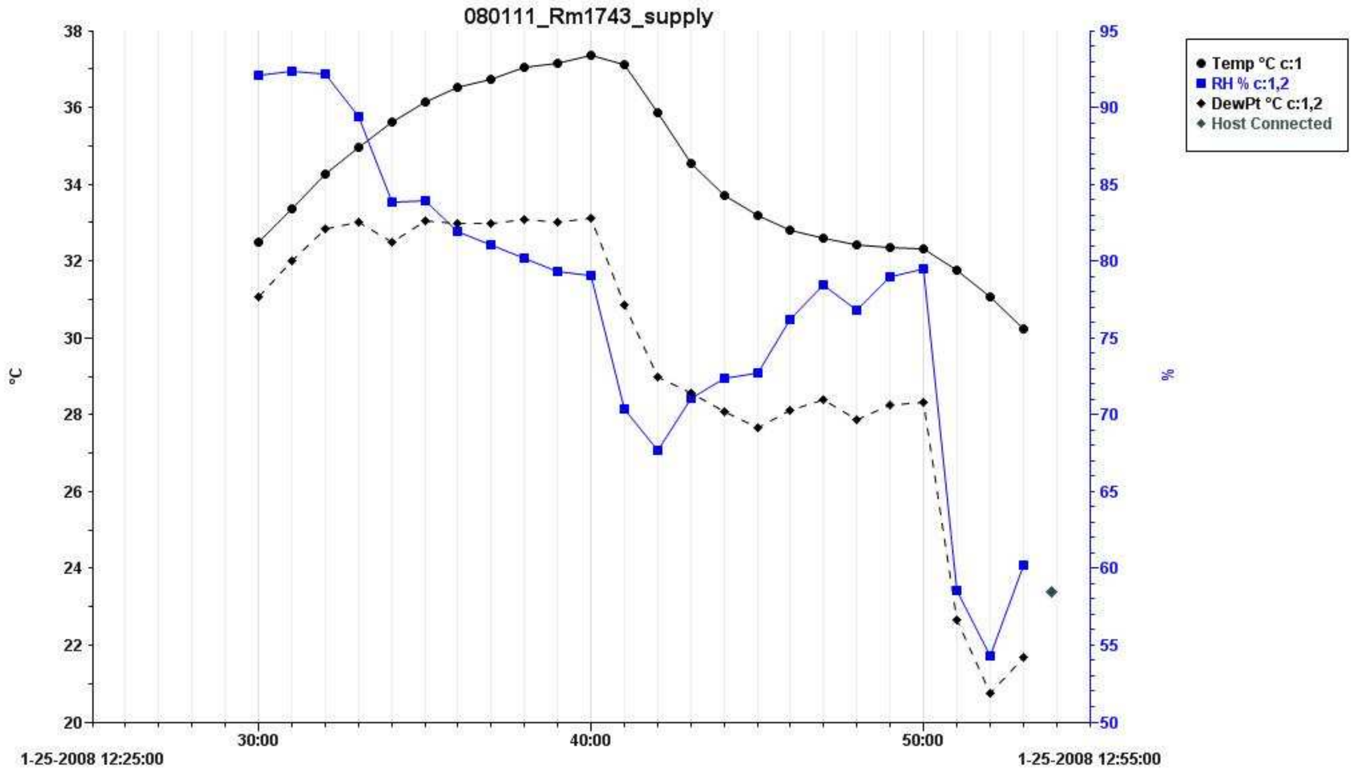
Measurement 3: Data table

	Temperature [℃]					**Relative Humidity [%]**				
	Fresh Air Intake	**Air Inlet**	**Extract Air**	**Discharge Extract Air**	**Temp. Efficiency**	**Fresh Air Intake**	**Air Inlet**	**Extract Air**	**Discharge Extract Air**	
Sample	**N7**	**N8**	**N9**	**N10**	**η**	**N7**	**N8**	**N9**	**N10**	**Setting**
1	27,2	24,9	22,9	27,3	54,0%	44,6	48,9	53,6	43,7	NORM
2	28,6	25,0	23,3	28,0	67,1%	41,2	47,9	52,4	41,6	NORM
3	29,1	25,5	23,5	28,5	64,7%	39,0	47,1	51,3	40,1	NORM
4	30,2	25,7	23,8	28,8	70,2%	37,5	46,6	50,9	39,2	NORM
5	30,7	25,9	24,0	29,0	71,7%	36,5	46,2	50,8	38,8	NORM
6	31,0	26,0	24,1	29,0	73,0%	35,7	45,8	50,8	38,7	NORM
7	31,0	26,1	24,3	29,4	72,4%	35,0	45,4	50,8	38,5	NORM
8	31,4	26,2	24,4	29,5	73,7%	34,9	45,2	50,3	38,1	NORM
9	31,1	26,3	24,5	29,6	72,4%	34,7	45,0	50,0	38,0	NORM
10	31,6	26,4	24,6	29,1	74,2%	34,0	44,9	49,7	37,8	NORM
11	31,7	26,5	24,7	29,1	74,8%	34,4	44,6	49,6	37,8	MIN
12	31,9	26,5	24,8	29,8	75,7%	34,2	44,7	49,4	37,6	MIN
13	32,4	26,5	24,9	29,1	77,7%	33,5	44,6	49,2	37,6	MIN
14	32,9	26,6	24,9	29,8	79,6%	32,8	44,1	48,9	37,4	MIN
15	33,4	26,6	25,0	29,9	81,5%	32,2	44,6	48,7	37,4	MIN
16	33,9	26,6	25,0	29,9	82,4%	31,3	44,4	49,0	37,5	MIN
17	34,3	26,6	25,1	30,0	83,9%	30,7	44,3	48,1	37,2	MIN
18	34,7	26,6	25,1	30,1	84,7%	30,2	44,2	48,5	37,0	MIN
19	34,9	26,6	25,1	30,2	85,1%	29,7	44,0	48,3	36,7	MIN
20	35,2	26,6	25,2	30,3	85,6%	29,3	44,0	48,2	36,5	MIN
21	35,3	26,6	25,2	30,4	85,7%	29,1	44,0	48,3	36,0	MAX
22	34,2	26,8	25,2	30,5	82,2%	29,4	43,7	48,9	36,0	MAX
23	32,0	27,2	25,2	30,6	71,2%	31,5	43,1	48,5	36,0	MAX
24	30,8	27,5	25,0	30,1	57,8%	33,6	42,4	48,2	36,0	MAX
25	29,1	27,7	25,0	30,3	34,5%	35,7	42,1	48,3	36,3	MAX
26	29,1	27,8	25,2	30,1	35,1%	36,9	41,6	47,6	36,2	MAX
27	28,7	27,8	25,2	29,1	26,0%	37,9	41,5	47,8	36,6	MAX
28	28,4	27,8	25,2	29,1	19,7%	38,6	41,4	47,1	37,1	MAX
29	28,2	27,7	25,3	29,3	16,1%	39,1	41,5	47,9	37,7	MAX
30	28,0	27,6	25,3	29,0	14,3%	39,4	41,5	47,6	37,8	MAX
31	27,9	27,6	25,3	28,9	12,1%	39,7	41,6	47,7	38,3	NORM
32	27,8	27,5	25,3	28,7	12,6%	39,9	41,7	47,8	38,6	NORM
33	27,8	27,5	25,3	28,6	13,8%	39,9	41,1	47,8	39,1	NORM
34	28,2	27,4	25,3	28,5	27,3%	39,7	41,7	47,6	39,1	NORM
35	29,0	27,3	25,4	28,5	45,2%	38,5	41,8	47,6	39,4	NORM
36	29,1	27,2	25,0	28,5	45,5%	37,4	41,9	47,6	39,4	NORM
37	30,3	27,2	25,4	28,7	63,4%	36,3	42,1	47,0	39,2	NORM
38	30,7	27,2	25,4	28,8	67,1%	35,4	42,1	47,8	39,2	NORM
39	31,1	27,1	25,4	28,1	70,3%	34,8	42,1	47,3	38,7	NORM
40	31,4	27,1	25,4	29,2	71,7%	34,2	42,1	47,5	38,5	NORM
41	31,6	27,1	25,5	29,3	72,9%	33,8	42,1	47,4	38,2	NORM
42	31,8	27,1	25,5	29,5	73,3%	33,5	42,1	47,9	38,2	NORM
43	31,9	27,1	25,5	29,1	73,9%	33,2	42,0	47,5	37,6	NORM
44	32,0	27,1	25,5	29,7	74,3%	33,0	42,0	47,7	37,6	NORM
45	32,1	27,2	25,5	29,1	74,2%	32,7	41,8	47,4	37,0	NORM
46	32,1	27,2	25,5	29,9	74,0%	32,5	41,7	47,4	36,9	MAX
47	31,8	27,3	25,5	30,0	71,7%	32,6	41,7	47,2	36,7	MAX
48	30,7	27,5	25,5	30,0	61,5%	33,1	41,4	47,1	36,5	MAX
49	29,8	27,7	25,4	29,9	49,0%	35,2	41,0	47,1	36,4	MAX

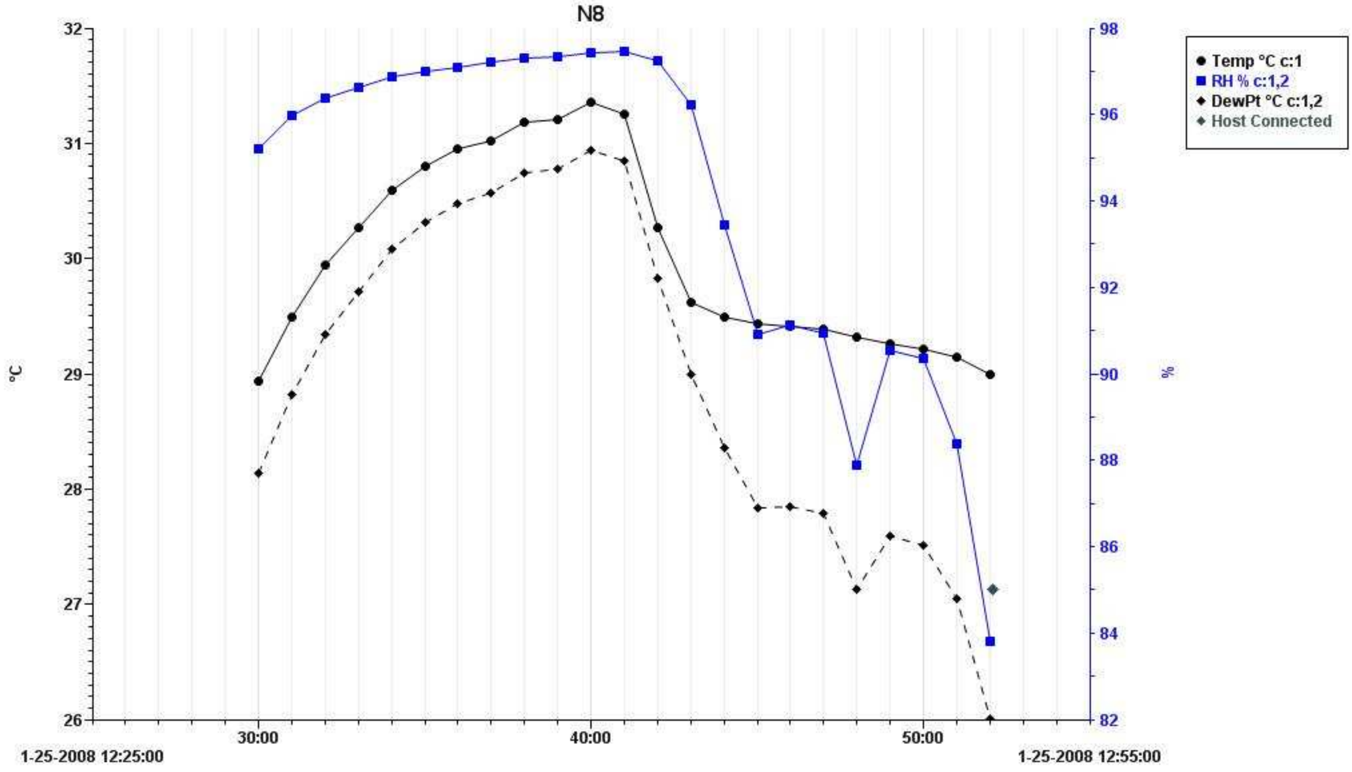
50	29,0	27,8	25,4	29,1	35,1%	36,4	40,8	47,1	36,6	MAX
51	28,8	27,8	25,0	29,6	26,9%	37,3	40,7	46,8	36,1	MAX
52	28,6	27,8	25,4	29,4	25,2%	37,7	40,5	47,1	37,1	MAX
53	28,6	27,8	25,4	29,3	24,9%	64,3	65,3	47,4	40,3	MAX
54	29,0	27,8	25,4	29,0	32,4%	69,1	72,1	49,9	43,2	MAX
55	29,0	27,1	25,0	29,2	49,0%	70,1	74,6	51,3	44,8	MAX
56	29,1	27,9	25,0	29,0	29,2%	70,0	75,9	52,2	45,9	MAX
57	30,0	27,9	25,4	29,0	45,1%	70,0	76,6	53,1	46,0	MAX
58	30,2	28,0	25,4	29,3	45,5%	70,0	77,1	53,4	46,3	MAX
59	30,3	28,1	25,4	29,4	45,7%	69,8	77,2	53,2	46,0	MAX
60	30,4	28,2	25,5	29,5	45,3%	69,7	77,4	54,8	46,8	MAX
61	30,1	28,2	25,5	29,1	39,7%	68,9	76,8	54,6	46,6	MAX
62	30,3	28,3	25,5	29,1	41,6%	53,8	70,8	55,3	47,4	MAX

Measurement 4:

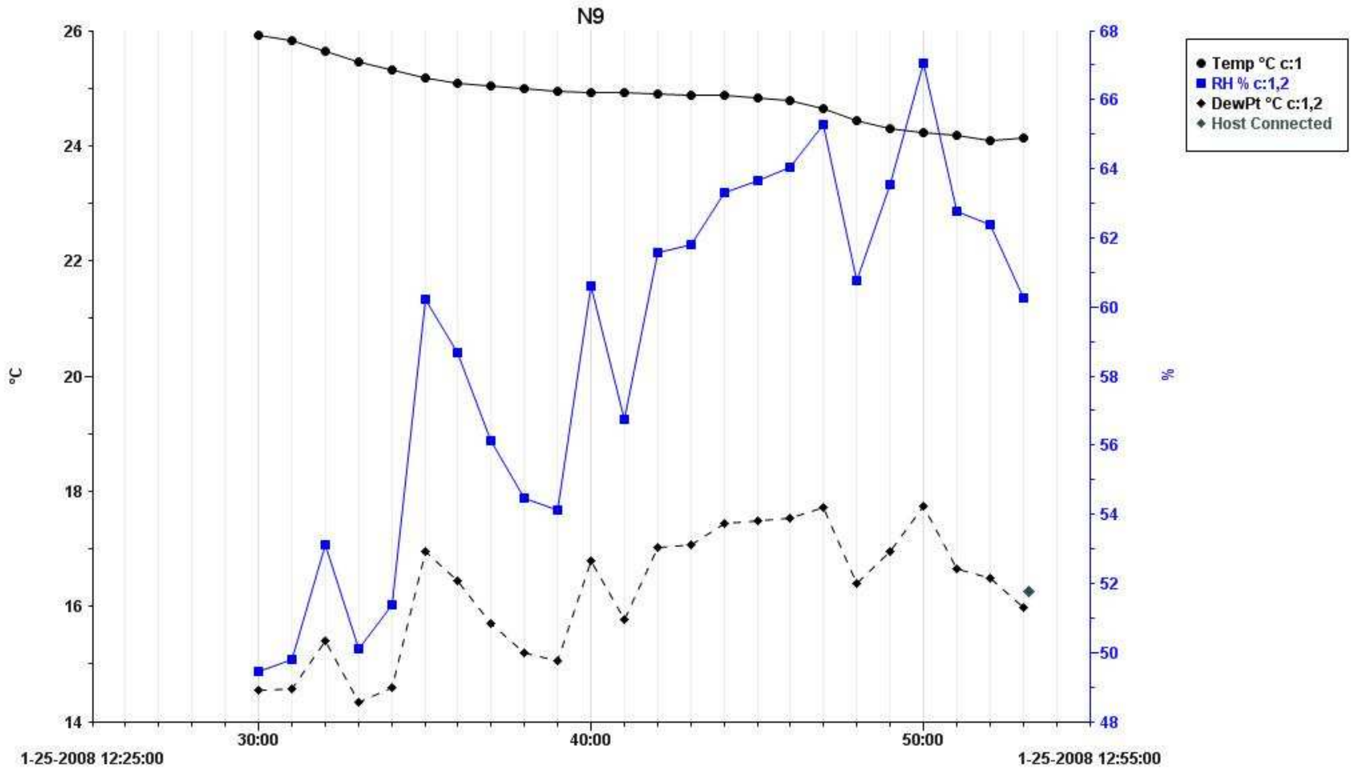
Sensor N7 – Supply Air Duct



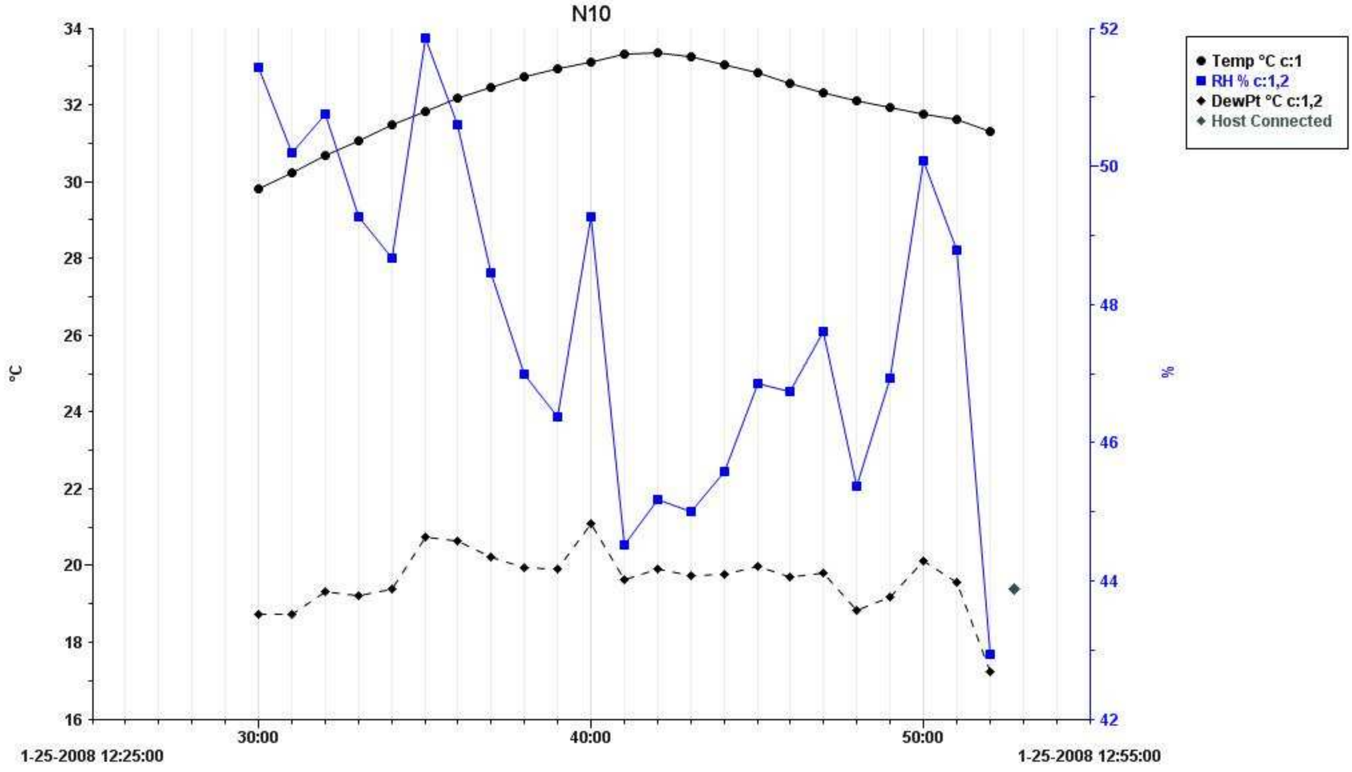
Sensor N8 – Inlet Air Duct



Sensor N9 – Extract Air Duct



Sensor N10 – Discharge Air Duct

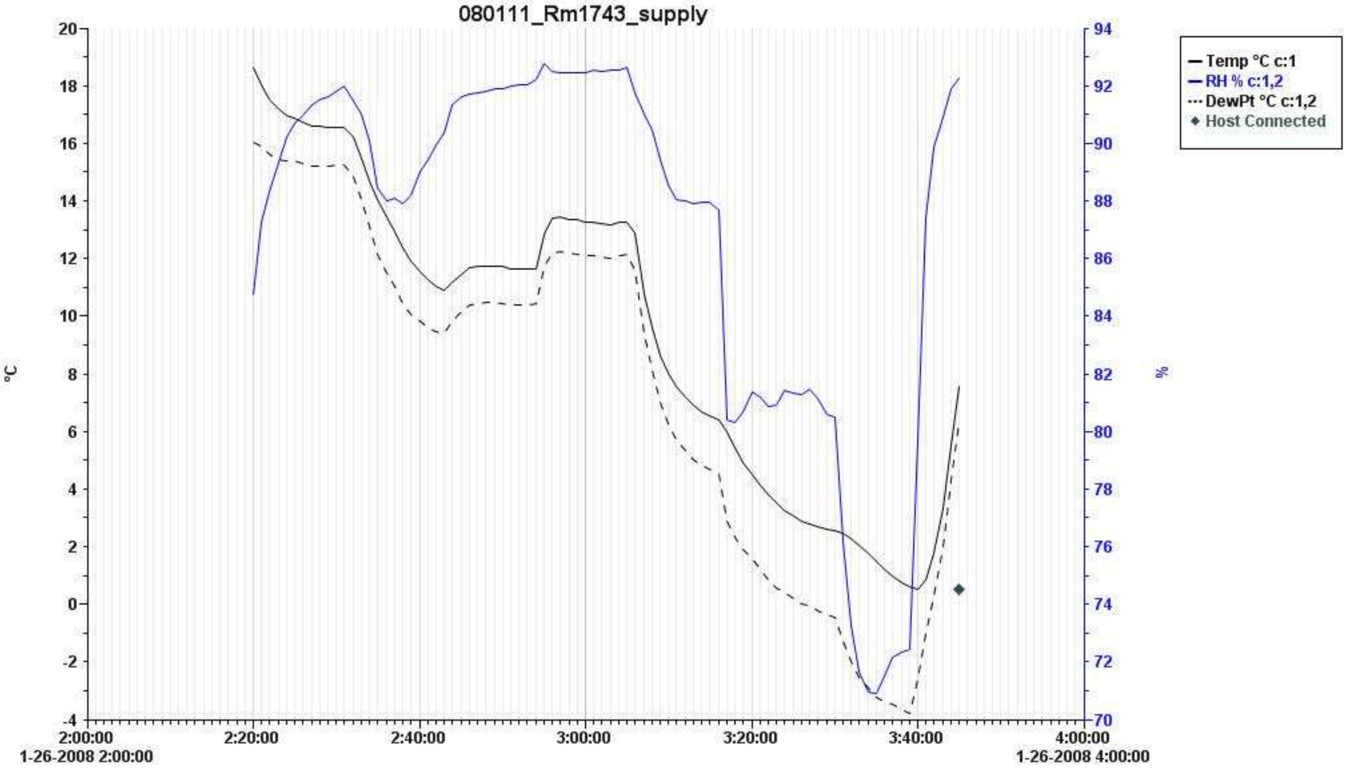


Measurement 4: Data table

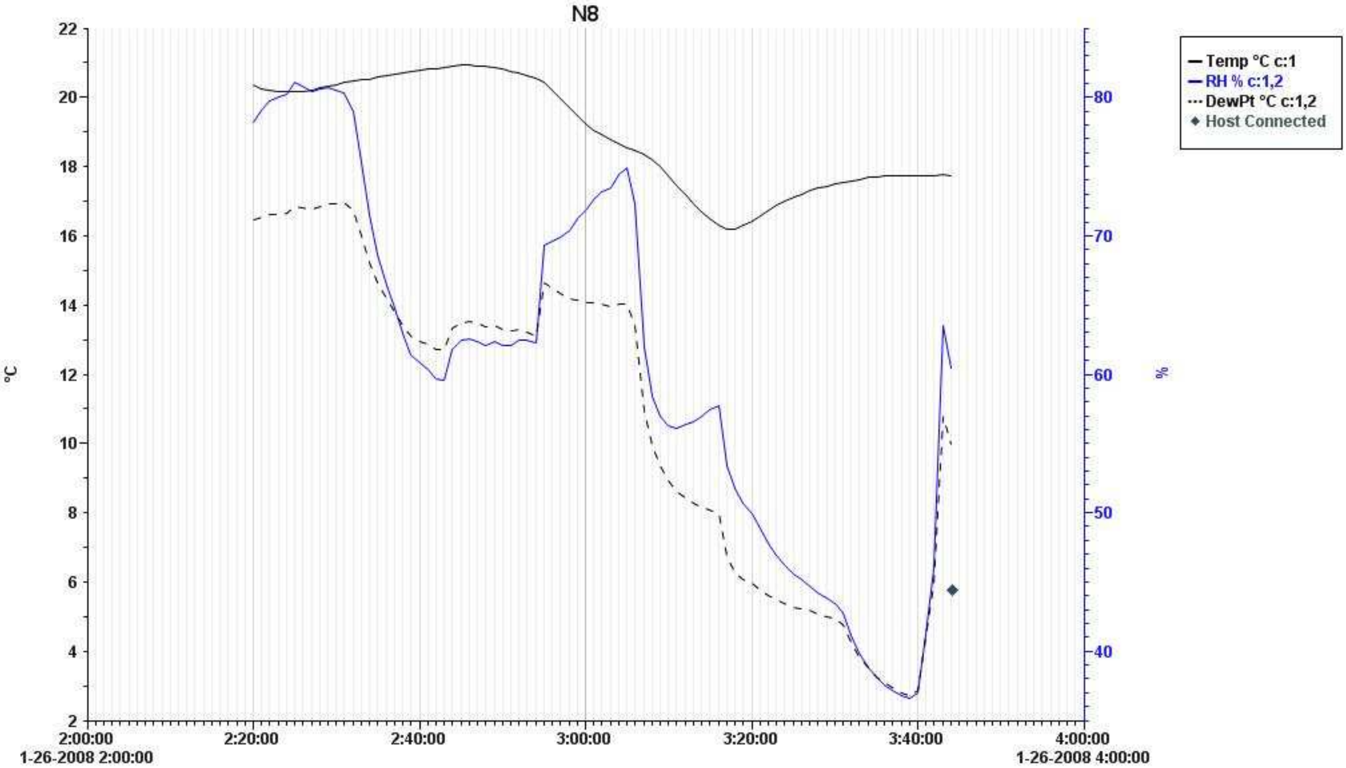
	Temperature [℃]					Relative Humidity [%]				
	Fresh Air Intake	Air Inlet	Extract Air	Discharge Extract Air	Temp. Efficiency	Fresh Air Intake	Air Inlet	Extract Air	Discharge Extract Air	
Sample	**N7**	**N8**	**N9**	**N10**	**η**	**N7**	**N8**	**N9**	**N10**	**Setting**
1	32,5	28,9	25,9	29,8	53,9%	92,1	95,2	49,4	51,4	NORM
2	33,4	29,0	25,8	30,2	57,2%	92,3	96,0	49,8	50,2	NORM
3	34,3	29,9	25,6	30,7	50,1%	92,2	96,4	53,0	50,8	NORM
4	35,0	30,3	25,5	31,1	49,4%	89,4	96,6	50,1	49,3	NORM
5	35,6	30,6	25,3	31,5	48,8%	83,8	96,9	51,4	48,7	NORM
6	36,1	30,8	25,2	31,8	48,8%	83,9	97,0	60,2	51,9	NORM
7	36,5	30,1	25,1	32,2	56,2%	81,9	97,1	58,7	50,6	NORM
8	36,7	31,0	25,0	32,5	48,7%	81,1	97,2	56,1	48,5	NORM
9	37,0	31,2	25,0	32,7	48,7%	80,2	97,3	54,4	47,0	NORM
10	37,2	31,2	24,9	32,9	48,7%	79,0	97,3	54,1	46,4	NORM
11	37,3	31,4	24,9	33,1	48,2%	79,0	97,4	60,6	49,3	MAX
12	37,1	31,3	24,9	33,3	48,1%	70,4	97,5	56,7	44,5	MAX
13	35,9	30,3	24,9	33,4	51,1%	67,7	97,2	61,6	45,2	MAX
14	34,5	29,6	24,9	33,3	51,0%	71,1	96,2	61,8	45,0	MAX
15	33,7	29,0	24,9	33,1	52,7%	72,4	93,4	63,3	45,1	MAX
16	33,2	29,4	24,8	32,1	44,8%	72,8	90,9	63,6	46,9	MAX
17	32,1	29,4	24,8	32,6	36,5%	76,2	91,1	64,0	46,7	MAX
18	32,6	29,4	24,7	32,0	40,5%	78,4	90,1	65,3	47,6	MAX
19	32,4	29,3	24,4	32,1	39,0%	76,1	87,9	60,8	45,4	MAX
20	32,4	29,3	24,3	31,9	38,3%	78,9	90,1	63,6	46,9	MAX
21	32,3	29,2	24,2	31,8	38,2%	79,5	90,4	67,1	50,1	MAX
22	31,8	29,0	24,2	31,6	36,2%	58,6	88,4	62,8	48,8	MAX
23	31,1	28,1	24,1	31,3	42,5%	54,3	83,8	62,4	42,9	MAX

Measurement 5:

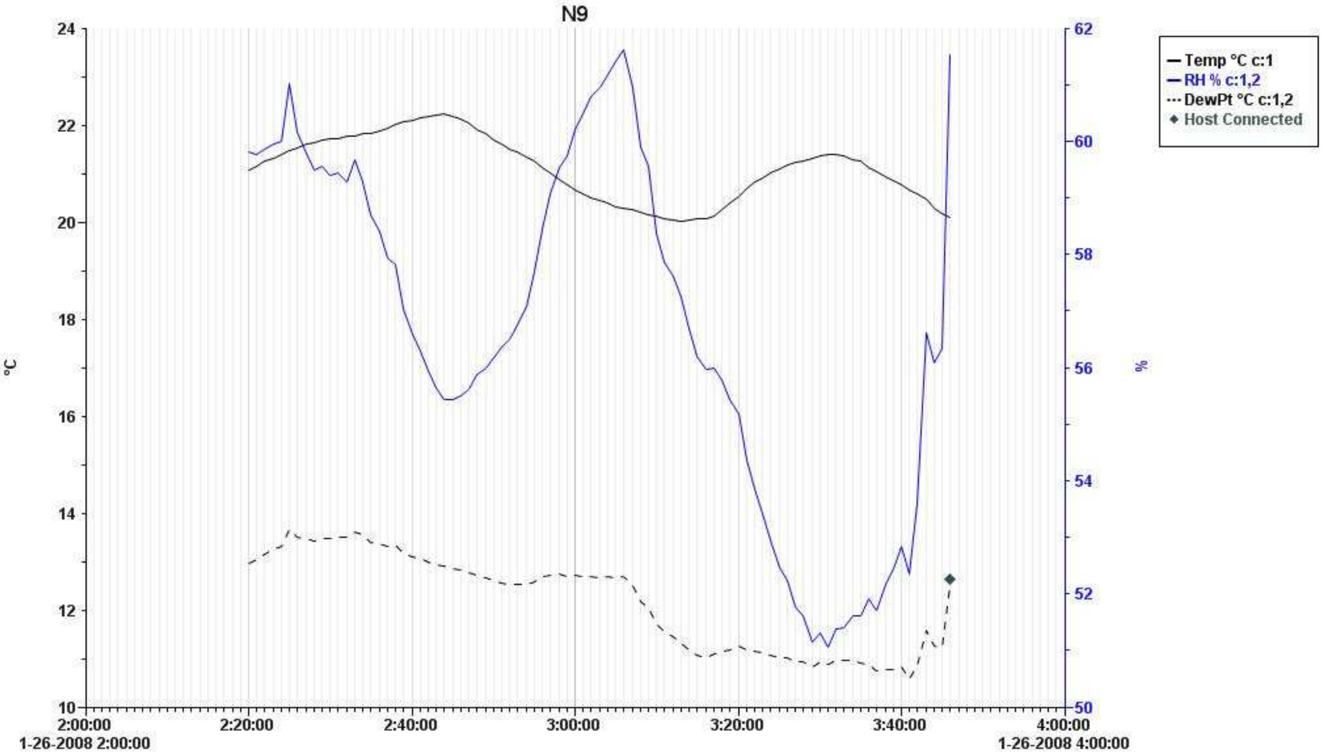
Sensor N7 – Supply Air Duct



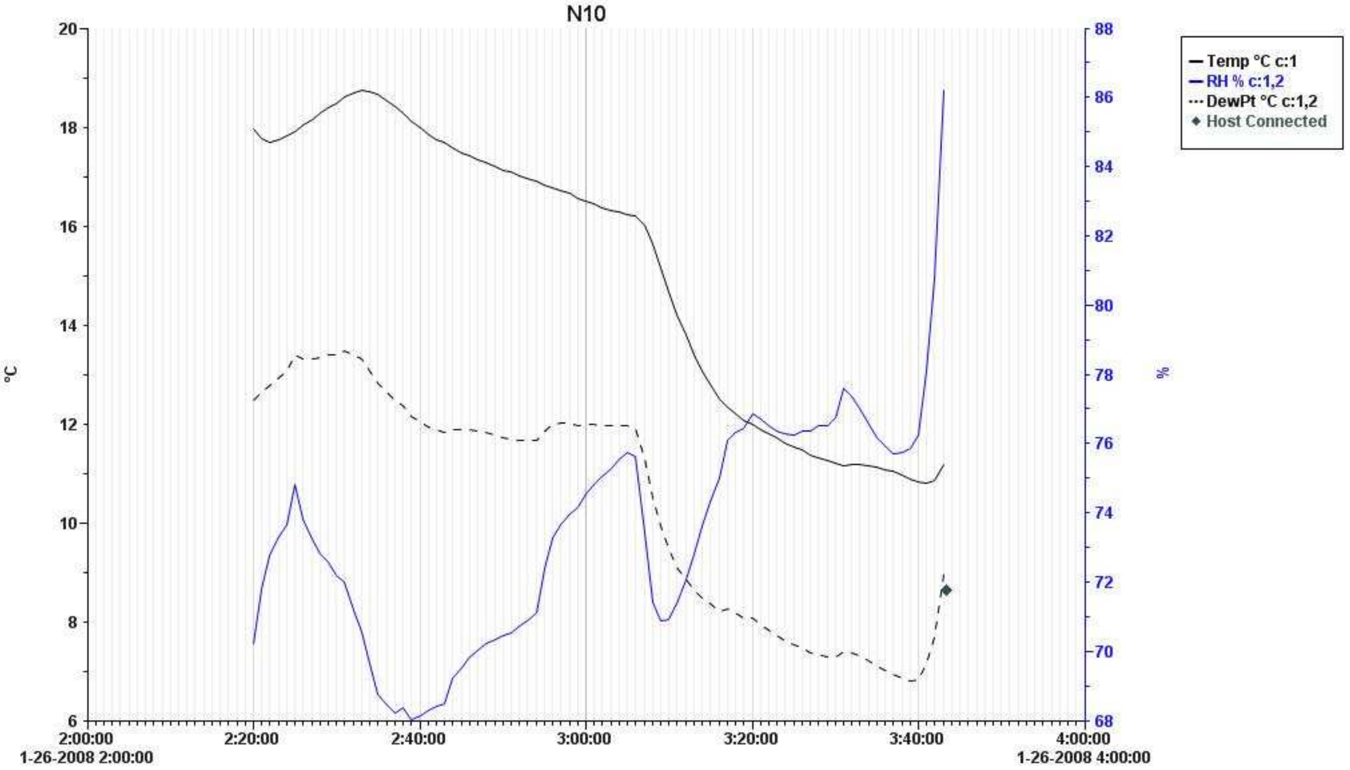
Sensor N8 – Inlet Air Duct



Sensor N9 – Extract Air Duct



Sensor N10 – Discharge Air Duct



Measurement 5: Data table

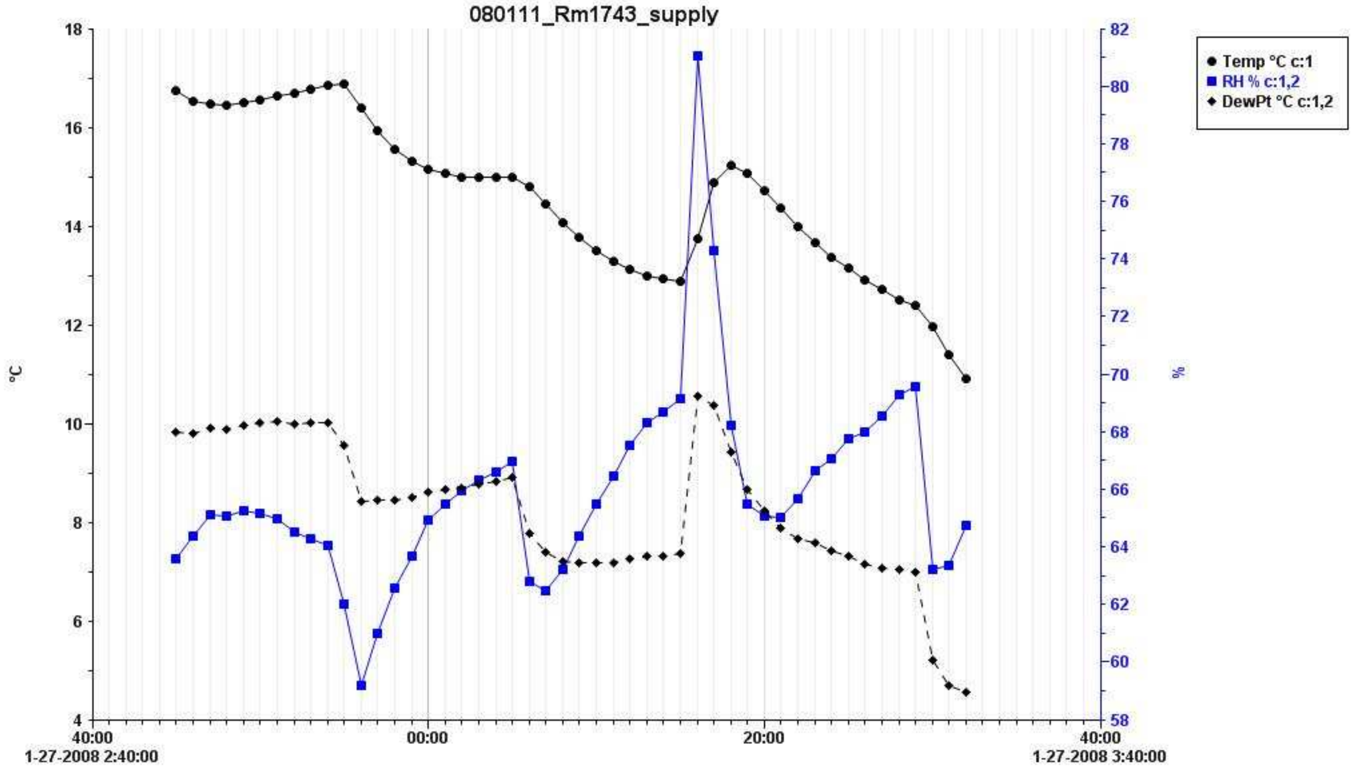
	Temperature [℃]					Relative Humidity [%]				
	Fresh Air Intake	Air Inlet	Extract Air	Discharge Extract Air	Temp. Efficiency	Fresh Air Intake	Air Inlet	Extract Air	Discharge Extract Air	
Sample	**N7**	**N8**	**N9**	**N10**	**η**	**N7**	**N8**	**N9**	**N10**	**Setting**
1	18,7	20,3	21,1	18,0	70,3%	84,8	78,2	59,8	70,2	NORM
2	18,0	20,2	21,2	17,8	71,0%	87,0	79,1	59,8	71,8	NORM
3	17,5	20,2	21,2	17,7	71,8%	88,3	79,8	59,9	72,1	NORM
4	17,2	20,0	21,3	17,7	68,4%	89,3	80,0	60,0	73,3	NORM
5	17,0	20,0	21,0	17,8	74,7%	90,2	80,3	60,0	73,6	NORM
6	16,9	20,0	21,5	17,9	68,4%	90,7	81,1	61,0	74,8	NORM
7	16,7	20,2	21,5	18,0	71,6%	90,9	80,8	60,2	73,8	NORM
8	16,6	20,2	21,6	18,2	72,3%	91,3	80,4	59,8	73,2	NORM
9	16,6	20,3	21,6	18,3	73,1%	91,5	80,6	59,0	72,8	NORM
10	16,6	20,3	21,7	18,0	73,4%	91,6	80,7	59,6	72,6	NORM
11	16,6	20,4	21,7	18,5	73,7%	91,1	80,5	59,4	72,2	MIN
12	16,6	20,4	21,7	18,6	75,1%	92,0	80,0	59,4	72,0	MIN
13	16,2	20,5	21,8	18,7	76,8%	91,5	79,0	59,0	71,2	MIN
14	15,5	20,5	21,8	18,7	79,9%	91,0	75,0	59,7	70,6	MIN
15	14,7	20,5	21,8	18,7	81,9%	90,1	71,5	59,3	69,6	MIN
16	14,0	20,6	21,8	18,7	84,1%	88,5	68,7	58,7	68,8	MIN
17	13,4	20,6	21,9	18,5	85,3%	88,0	66,0	58,4	68,5	MIN
18	12,1	20,1	21,9	18,4	81,0%	88,1	64,8	57,9	68,2	MIN
19	12,4	20,7	22,0	18,3	86,4%	87,9	63,0	57,8	68,3	MIN
20	11,9	20,7	22,1	18,1	87,0%	88,0	61,4	57,0	68,0	MIN
21	11,6	20,1	22,1	18,0	80,8%	89,0	60,9	56,6	68,1	MAX
22	11,3	20,8	22,2	17,8	87,7%	89,5	60,3	56,3	68,3	MAX
23	11,1	20,8	22,2	17,7	88,0%	89,9	59,7	55,9	68,4	MAX
24	10,9	20,9	22,2	17,7	88,2%	90,4	59,6	55,6	68,5	MAX
25	11,2	20,9	22,2	17,6	88,1%	91,4	61,8	55,4	69,2	MAX
26	11,5	20,9	22,2	17,5	88,4%	91,6	62,0	55,4	69,5	MAX
27	11,7	20,9	22,0	17,4	89,6%	91,7	62,5	55,5	69,8	MAX
28	11,7	20,9	22,0	17,3	89,1%	91,7	62,4	55,6	70,0	MAX
29	11,7	20,9	21,9	17,3	89,9%	91,8	62,1	55,9	70,2	MAX
30	11,7	20,9	21,8	17,2	90,5%	91,9	62,3	56,0	70,3	MAX
31	11,1	20,8	21,0	17,0	98,1%	91,9	62,0	56,2	70,4	NORM
32	11,6	20,7	21,6	17,1	91,4%	92,0	62,1	56,4	70,5	NORM
33	11,6	20,7	21,5	17,0	91,8%	92,1	62,0	56,5	70,7	NORM
34	11,6	20,6	21,4	17,0	91,7%	92,1	62,5	56,8	70,9	NORM
35	11,6	20,6	21,3	16,9	91,9%	92,2	62,0	57,1	71,1	NORM
36	12,8	20,4	21,2	16,1	90,4%	92,8	69,3	57,7	72,0	NORM
37	13,4	20,2	21,1	16,8	88,0%	92,5	69,7	58,4	73,0	NORM
38	13,4	19,1	21,0	16,7	74,8%	92,0	69,9	59,1	73,7	NORM
39	13,4	19,7	20,9	16,7	84,2%	92,5	70,4	59,5	74,0	NORM
40	13,3	19,0	20,1	16,6	84,7%	92,5	71,2	59,7	74,2	NORM
41	13,3	19,2	20,7	16,5	80,7%	92,5	71,9	60,2	74,6	NORM
42	13,3	19,1	20,6	16,4	79,2%	92,5	72,6	60,5	74,8	NORM
43	13,2	18,9	20,5	16,4	78,1%	92,5	73,2	60,8	75,0	NORM
44	13,2	18,8	20,4	16,0	77,1%	92,6	73,5	60,9	75,3	NORM
45	13,3	18,7	20,4	16,3	75,7%	92,6	74,4	61,2	75,5	NORM
46	13,3	18,6	20,3	16,2	75,0%	92,6	74,9	61,4	75,7	MAX
47	12,9	18,5	20,3	16,2	75,3%	91,8	72,3	61,6	75,6	MAX
48	10,8	18,3	20,2	16,0	79,9%	90,1	62,0	60,9	73,4	MAX
49	9,6	18,0	20,2	15,6	79,3%	90,5	58,4	59,9	71,4	MAX

50	8,6	18,0	20,0	15,2	82,2%	89,4	56,9	59,6	70,9	MAX
51	8,0	17,7	20,1	14,7	80,2%	88,5	56,3	58,4	70,9	MAX
52	7,5	17,5	20,1	14,2	79,1%	88,0	56,1	57,9	71,4	MAX
53	7,2	17,2	20,0	13,8	77,8%	88,0	56,4	57,6	72,1	MAX
54	6,9	16,9	20,0	13,4	76,6%	87,9	56,6	57,2	72,8	MAX
55	6,7	16,7	20,0	13,1	75,0%	87,9	57,0	56,7	73,6	MAX
56	6,5	16,5	20,1	12,8	73,6%	87,1	57,4	56,2	74,0	MAX
57	6,4	16,3	20,1	12,5	72,5%	87,7	57,8	56,0	75,0	MAX
58	6,1	16,2	20,1	12,0	72,1%	381,0	53,0	56,0	76,1	MAX
59	5,4	16,2	20,2	12,2	72,7%	80,3	51,7	55,8	76,0	MAX
60	4,9	16,3	20,4	12,1	73,5%	80,7	50,7	55,4	76,4	MAX
61	4,5	16,4	20,5	12,0	74,3%	81,4	49,9	55,2	76,9	NORM
62	4,1	16,6	20,7	11,1	75,0%	81,2	48,8	54,4	76,7	NORM
63	3,8	16,7	20,8	11,8	76,0%	80,9	47,8	53,9	76,5	NORM
64	3,5	16,9	20,9	11,1	76,8%	80,1	46,9	53,4	76,4	NORM
65	3,3	17,0	21,0	11,6	77,3%	81,4	46,2	53,0	76,3	NORM
66	3,1	17,1	21,1	11,1	77,8%	81,3	45,5	52,5	76,3	NORM
67	2,9	17,2	21,2	11,5	78,3%	81,3	45,1	52,2	76,3	NORM
68	2,8	17,3	21,2	11,0	78,7%	81,5	44,7	51,8	76,4	NORM
69	2,1	17,4	21,0	11,3	80,7%	81,1	44,2	51,6	76,5	NORM
70	2,1	17,4	21,3	11,2	79,9%	80,6	43,8	51,1	76,5	NORM
71	2,6	17,1	21,4	11,0	77,1%	80,5	43,5	51,3	76,1	MIN
72	2,5	17,5	21,0	11,2	81,1%	76,2	42,8	51,1	77,6	MIN
73	2,3	17,6	21,0	11,2	81,6%	73,3	41,1	51,4	77,4	MIN
74	2,0	17,6	21,4	11,2	80,7%	71,6	39,9	51,4	77,0	MIN
75	1,8	17,7	21,3	11,2	81,5%	70,9	38,1	51,6	76,6	MIN
76	1,0	17,7	21,2	11,1	82,4%	70,9	38,1	51,6	76,2	MIN
77	1,2	17,7	21,1	11,1	82,9%	71,5	37,6	51,9	75,9	MIN
78	1,0	17,7	21,0	11,0	83,6%	72,1	37,2	51,7	75,7	MIN
79	0,1	17,7	20,9	11,0	84,7%	72,3	36,8	52,2	75,1	MIN
80	0,6	17,7	20,8	10,9	84,7%	72,4	36,6	52,4	75,8	MIN
81	0,5	17,7	20,1	10,8	88,0%	79,1	37,0	52,1	76,2	MIN
82	0,9	17,7	20,7	10,1	85,1%	87,4	41,3	52,3	78,1	MIN
83	1,8	17,7	20,6	10,9	84,8%	89,9	46,0	53,6	80,7	MIN
84	3,4	17,8	20,5	11,2	84,2%	90,9	63,5	56,6	86,2	MIN

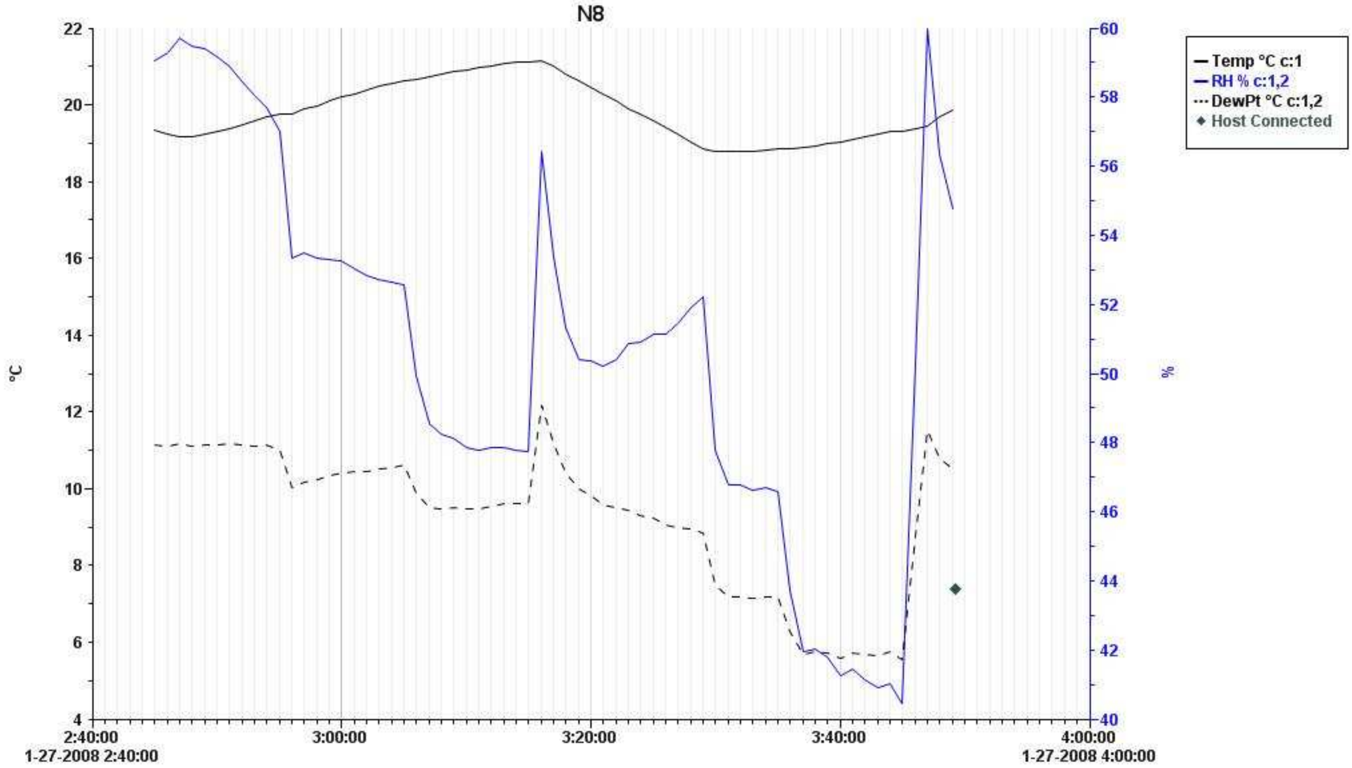
Measurement 6:

During this measurement, the data logger N7 stops recording after 48 samples while the other continue to record 66 samples. The reason for this can be that the data logger battery ran out too fast due to the cold temperature.

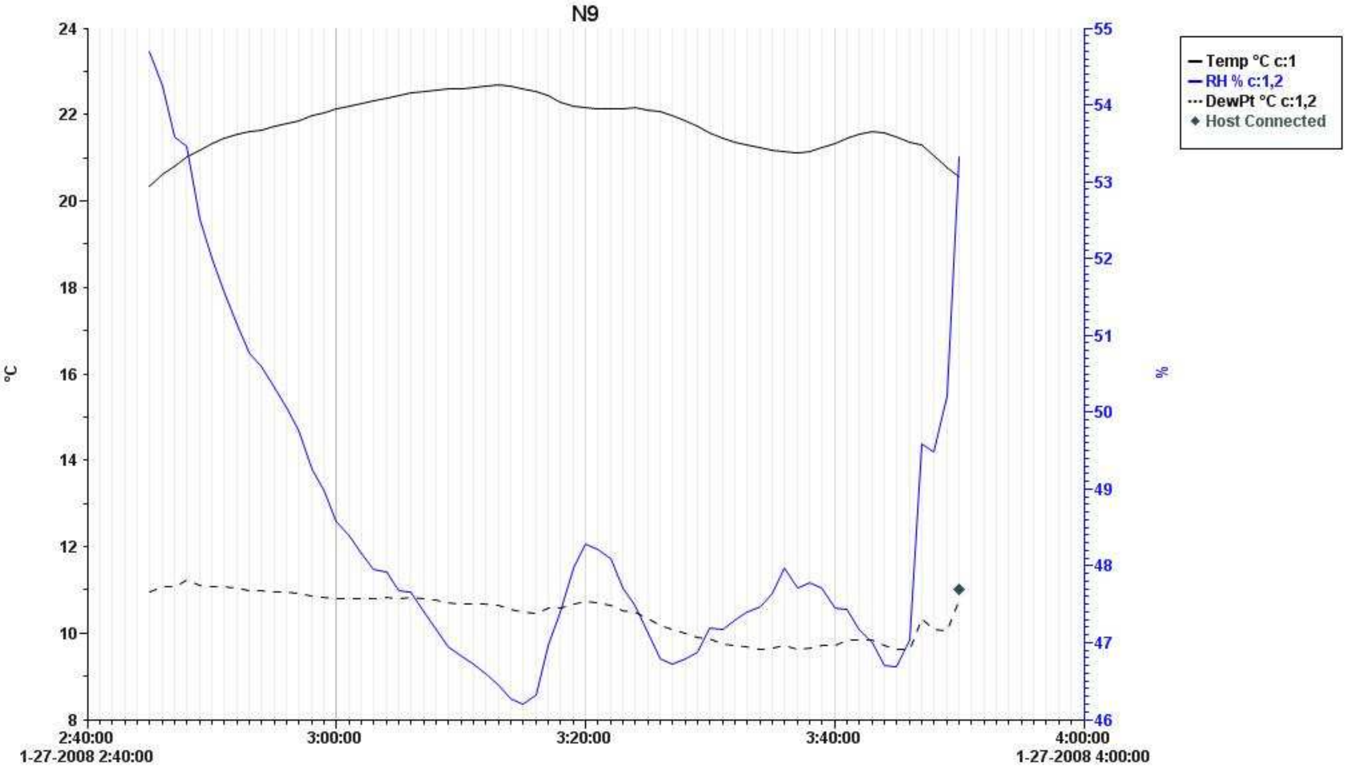
Sensor N7 – Supply Air Duct



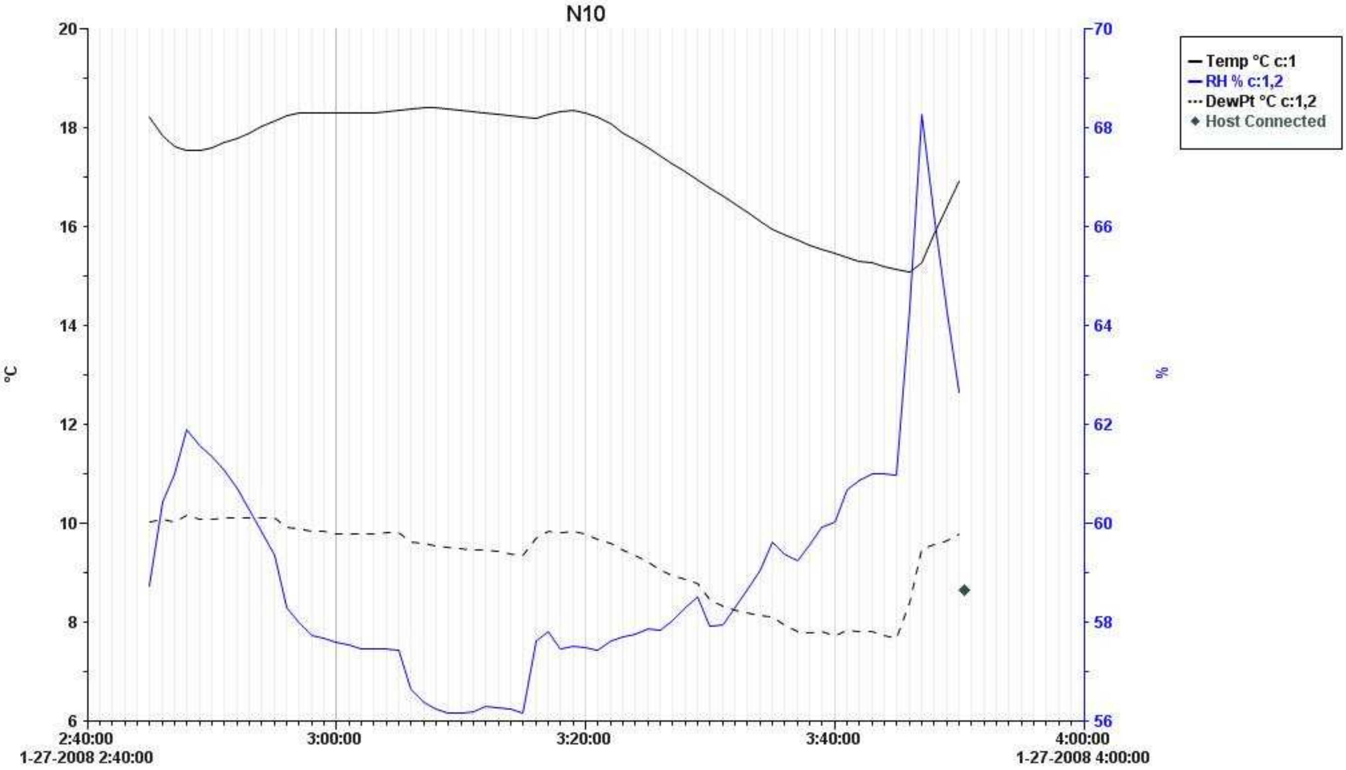
Sensor N8 – Inlet Air Duct



Sensor N9 – Extract Air Duct



Sensor N10 – Discharge Air Duct



Measurement 6: Data table

	Temperature [℃]					Relative Humidity [%]				
	Fresh Air Intake	Air Inlet	Extract Air	Discharge Extract Air	Temp. Efficiency	Fresh Air Intake	Air Inlet	Extract Air	Discharge Extract Air	
Sample	**N7**	**N8**	**N9**	**N10**	**η**	**N7**	**N8**	**N9**	**N10**	**Setting**
1	16,7	19,3	20,3	18,0	72,2%	63,6	59,0	54,7	58,7	MAX
2	16,5	19,2	20,6	17,8	65,7%	64,4	59,3	54,2	60,4	MAX
3	16,5	19,2	20,8	17,6	62,3%	65,1	59,7	53,6	61,0	MAX
4	16,4	19,2	21,0	17,5	59,6%	65,1	59,5	53,5	61,9	MAX
5	16,5	19,2	21,2	17,5	58,3%	65,2	59,4	52,1	61,5	MAX
6	16,6	19,3	21,3	17,6	57,5%	65,2	59,2	52,0	61,3	MAX
7	16,1	19,4	21,4	17,7	61,9%	65,0	58,9	51,6	61,1	MAX
8	16,7	19,5	21,5	17,8	57,6%	64,5	58,4	51,1	60,7	MAX
9	16,8	19,6	21,6	17,9	58,1%	64,3	58,0	50,8	60,2	MAX
10	16,8	19,7	21,7	18,0	58,9%	64,1	57,7	50,6	59,8	MAX
11	16,9	19,7	21,7	18,1	59,3%	62,0	57,0	50,0	59,3	NORM
12	16,4	19,1	21,8	18,2	49,7%	59,2	53,3	50,1	58,3	NORM
13	15,9	19,9	21,9	18,3	66,6%	61,0	53,5	49,8	58,0	NORM
14	15,6	20,0	22,0	18,3	69,1%	62,6	53,3	49,3	57,7	NORM
15	15,3	20,1	22,0	18,3	71,2%	63,7	53,3	49,0	57,7	NORM
16	15,2	20,2	22,0	18,3	73,5%	64,9	53,3	48,6	57,6	NORM
17	15,1	20,3	22,2	18,3	73,3%	65,5	53,0	48,4	57,5	NORM
18	15,0	20,4	22,0	18,3	76,8%	65,9	52,1	48,0	57,4	NORM
19	15,0	20,5	22,3	18,3	75,0%	66,3	52,7	48,0	57,4	NORM
20	15,0	20,6	22,4	18,3	75,4%	66,6	52,6	47,9	57,4	NORM
21	15,0	20,6	22,4	18,3	75,7%	66,9	52,1	47,7	57,4	MIN
22	14,8	20,7	22,5	18,4	76,4%	62,8	50,0	47,7	56,1	MIN
23	14,5	20,7	22,5	18,0	77,5%	62,5	48,6	47,4	56,4	MIN
24	14,1	20,8	22,6	18,0	79,2%	63,0	48,2	47,2	56,2	MIN
25	13,8	20,9	22,6	18,4	80,5%	64,4	48,1	46,1	56,2	MIN
26	13,5	20,9	22,6	18,3	81,4%	65,5	47,9	46,8	56,2	MIN
27	13,3	20,1	22,6	18,3	72,9%	66,5	47,8	46,7	56,2	MIN
28	13,1	21,0	22,7	18,3	82,7%	67,0	47,9	46,6	56,3	MIN
29	13,0	21,1	22,7	18,2	83,5%	68,3	47,9	46,4	56,3	MIN
30	12,1	21,1	22,7	18,2	85,3%	68,7	47,8	46,3	56,2	MIN
31	12,9	21,1	22,6	18,0	84,8%	69,2	47,1	46,2	56,0	MAX
32	13,7	21,2	22,5	18,2	84,2%	81,0	56,4	46,3	57,6	MAX
33	14,9	21,0	22,4	18,2	81,0%	74,3	53,4	47,0	57,8	MAX
34	15,2	20,8	22,3	18,3	79,1%	68,2	51,0	47,4	57,4	MAX
35	15,1	20,6	22,2	18,3	78,0%	65,5	50,0	47,1	57,5	MAX
36	14,7	20,0	22,2	18,3	71,6%	65,1	50,4	48,3	57,5	MAX
37	14,4	20,3	22,0	18,0	77,2%	65,0	50,2	48,2	57,4	MAX
38	14,0	20,1	22,0	18,1	76,2%	65,6	50,4	48,0	57,1	MAX
39	13,7	19,9	22,0	17,9	74,8%	66,7	50,9	47,7	57,7	MAX
40	13,4	19,7	22,2	17,7	72,6%	67,1	50,9	47,0	57,8	MAX
41	13,1	19,6	22,1	17,6	71,8%	67,8	51,1	47,1	57,8	MAX
42	12,9	19,4	22,1	17,4	71,1%	68,0	51,1	46,8	57,8	NORM
43	12,7	19,2	22,0	17,2	70,2%	68,6	51,4	46,7	58,0	NORM
44	12,5	19,0	21,8	17,1	69,9%	69,3	51,9	46,8	58,3	NORM
45	12,4	18,8	21,7	16,9	69,1%	69,6	52,2	46,9	58,5	NORM
46	12,0	18,8	21,6	16,8	70,8%	63,2	47,8	47,2	57,9	NORM

Appendix C: Climate Data

Climate data for Hong Kong and Beijing.

Climatological Information for Hong Kong, China
Location of weather station: 22.3 N, 114.2 E, altitude: 62m

	Data Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Maximum Temperature (℃)	1971-2000	18,6	18,6	21,5	25,1	28,4	30,4	31,3	31,1	30,2	27,7	24	20,3
Mean Temperature (℃)	1971-2001	16,1	16,3	18,9	22,5	25,8	27,9	28,7	28,4	27,6	25,3	21,4	17,8
Mean Minimum Temperature (℃)	1971-2002	14,1	14,4	16,9	20,6	23,9	26,1	26,7	26,4	25,6	23,4	19,4	15,7

Climatological Information for Beijing, China
Location of weather station: 39.8 N, 116.5 E, altitude: 54m

	Data Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Maximum Temperature (℃)	1961-1990	1,6	4	11,3	19,9	26,4	30,3	30,8	29,5	25,8	19	10,1	3,3
Mean Temperature (℃)	1961-1991	-4,3	-1,9	5,1	13,6	20	24,2	25,9	24,6	19,6	12,7	4,3	-2,2
Mean Minimum Temperature (℃)	1961-1992	-9,4	-6,9	-0,6	7,2	13,2	18,2	21,6	20,4	14,2	7,3	-0,4	-6,9

As can be seen these data has been collected during a period of 30 years and the mean temperatures has been calculated. For design purposes for cooling load calculations the Mean Maximum Temperature was chosen. There is one consideration for this choice, which is that the temperature is a mean. This means that roughly, 50% of the temperatures should be higher then the mean temperature and 50% is lower. The effect of this is that sizing the system and the equipment based on the Mean Maximum Temperatures can in fact lead to an undersized system.

Appendix D: Model apartment layout

Appendix E: Solar Constants – Equations

This is a summary of all the equations used in the Excel spreadsheet for the load calculations. They can be found in the ASHRAE Fundamentals Handbook [4].

Solar Radiation:

Equation (1) Relates Apparent Solar Time (AST) to local standard time (LST) as follows:

$$AST = LST + ET/60 + (LSM - LON)/15 \qquad (1)$$

where

AST = apparent solar time, decimal hours
LST = local solar time, decimal hours
ET = equation of time, decimal minutes
LSM = local standard time meridian, decimal ° of arc
LON = local longitude, decimal ° of arc

In table A, data is summarized for each month and can be found in the Handbook [4].

Solar Constants

			A	B	C
Month	**ET, min.**	**δ**	**W/m²**	**(Dimensionless Ratios)**	
1	-11,2	-20	1230	0,142	0,058
2	-13,9	-10,8	1215	0,144	0,06
3	-7,5	0	1186	0,156	0,071
4	1,1	11,6	1136	0,18	0,097
5	3,3	20	1104	0,196	0,121
6	-1,4	23,45	1088	0,205	0,134
7	-6,2	20,6	1085	0,207	0,136
8	-2,4	12,3	1107	0,201	0,122
9	7,5	0	1151	0,177	0,092
10	15,4	-10,5	1192	0,16	0,073
11	13,8	-19,8	1221	0,149	0,063
12	1,6	-23,45	1233	0,142	0,057

Table A: Extraterrestrial Solar Irradiance and Related Data

Equation 2 is used to calculate the total short-wavelength irradiance E_t reaching a terrestrial surface.

$$E_t = E_{DN} * cos\theta + E_d + E_r \qquad (2)$$

where

E_{DN} = Direct solar radiation
E_d = Sky Diffuse Irradiance on surface
E_r = Ground-reflected Diffuse Irradiance
$cos\theta$ = cosine of the angle of incidence θ between the incoming solar rays and a line normal (perpendicular) to the surface

Determining Solar Angle:

Equation 3 is used to calculate the hour angle (degrees).

$$H = 15(\mathrm{AST} - 12) \tag{3}$$

Equations 4 and 5 relate β and Φ to the three angles previously mentioned:

$$\sin\beta = \cos L \cos\delta \cos H + \sin L \sin\delta \tag{4}$$

$$\cos\phi = \frac{\sin\beta \sin L - \sin\delta}{\cos\beta \cos L} \tag{5}$$

where

β = solar altitude above the horizontal
ϕ = solar azimuth measured from the south
L = local latitude
δ = solar declination (degrees)

Equation 6 for surface solar azimuth:

$$\gamma = \phi - \psi \tag{6}$$

where

ϕ = solar azimuth
ψ = surface azimuth

For any surface, the incident angle θ is related to β, γ, and the tilt angle of the surface Σ by:

$$\cos\theta = \cos\beta \cos\gamma \sin\Sigma + \sin\beta \cos\Sigma \tag{7}$$

where Σ = tilt of surface from horizontal. When the surface is horizontal, Σ = 0° and

$$\cos\theta_H = \sin\beta \tag{8}$$

For a vertical surface, Σ = 90° and

$$\cos\theta_V = \cos\beta \cos\gamma$$

Direct Normal Irradiance:

$$E_{DN} = \frac{A}{\exp(B/\sin\beta)} \tag{9}$$

where

A = apparent solar irradiation at air mass $m = 0$ (Table A)
B = atmospheric extinction coefficient (Table A)

Diffuse and Ground-Reflected Radiation:

The ratio Y of sky diffuse radiation on a vertical surface to sky diffuse radiation on a horizontal surface is given by:

$Y = 0.55 + 0.437\cos\theta + 0.313\cos^2\theta$ for $\cos\theta > -0.2$ (10)

$Y = 0.45$ for $\cos\theta \leq -0.2$

Diffuse irradiance Ed is given by:

$E_d = CYE_{DN}$ for vertical surfaces (11)

$E_d = CE_{DN}\dfrac{1+\cos\Sigma}{2}$ for surfaces other than vertical (12)

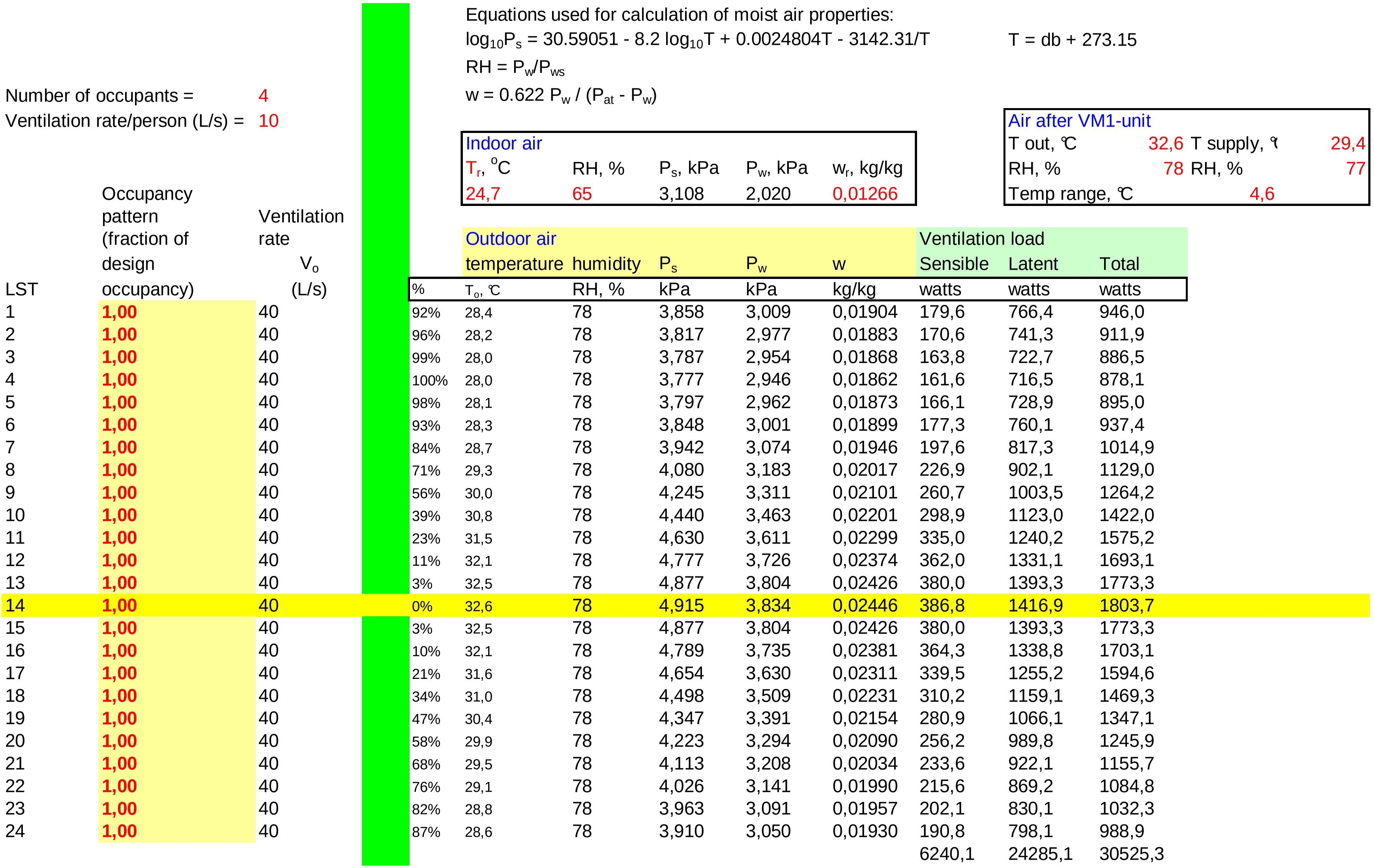
Ground-reflected irradiance Er is given by:

$E_r = E_{DN}\left(C+\sin\beta\right)\rho_g\dfrac{1-\cos\Sigma}{2}$ for surfaces at all orientations (13)

where ρ_g is ground reflectivity, often taken to be 0,2 for typical mixture of ground surfaces.

Appendix F: Ventilation Load - Equations

Unfortunately the spreadsheets used to calculate the cooling load are too big to display, but can be found attached as Excel-files. However, a sample from the spreadsheet showing the ventilation load calculation can be seen below.



Number of occupants = 4
Ventilation rate/person (L/s) = 10

Equations used for calculation of moist air properties:

$\log_{10}P_s = 30.59051 - 8.2 \log_{10}T + 0.0024804T - 3142.31/T$ T = db + 273.15

$RH = P_w/P_{ws}$

$w = 0.622\ P_w / (P_{at} - P_w)$

Indoor air				
T_r, °C	RH, %	P_s, kPa	P_w, kPa	w_r, kg/kg
24,7	65	3,108	2,020	0,01266

Air after VM1-unit			
T out, °C	32,6	T supply, °C	29,4
RH, %	78	RH, %	77
Temp range, °C	4,6		

LST	Occupancy pattern (fraction of design occupancy)	Ventilation rate V_o (L/s)		Outdoor air temperature	humidity	P_s	P_w	w	Ventilation load Sensible	Latent	Total
			%	T_o, °C	RH, %	kPa	kPa	kg/kg	watts	watts	watts
1	1,00	40	92%	28,4	78	3,858	3,009	0,01904	179,6	766,4	946,0
2	1,00	40	96%	28,2	78	3,817	2,977	0,01883	170,6	741,3	911,9
3	1,00	40	99%	28,0	78	3,787	2,954	0,01868	163,8	722,7	886,5
4	1,00	40	100%	28,0	78	3,777	2,946	0,01862	161,6	716,5	878,1
5	1,00	40	98%	28,1	78	3,797	2,962	0,01873	166,1	728,9	895,0
6	1,00	40	93%	28,3	78	3,848	3,001	0,01899	177,3	760,1	937,4
7	1,00	40	84%	28,7	78	3,942	3,074	0,01946	197,6	817,3	1014,9
8	1,00	40	71%	29,3	78	4,080	3,183	0,02017	226,9	902,1	1129,0
9	1,00	40	56%	30,0	78	4,245	3,311	0,02101	260,7	1003,5	1264,2
10	1,00	40	39%	30,8	78	4,440	3,463	0,02201	298,9	1123,0	1422,0
11	1,00	40	23%	31,5	78	4,630	3,611	0,02299	335,0	1240,2	1575,2
12	1,00	40	11%	32,1	78	4,777	3,726	0,02374	362,0	1331,1	1693,1
13	1,00	40	3%	32,5	78	4,877	3,804	0,02426	380,0	1393,3	1773,3
14	1,00	40	0%	32,6	78	4,915	3,834	0,02446	386,8	1416,9	1803,7
15	1,00	40	3%	32,5	78	4,877	3,804	0,02426	380,0	1393,3	1773,3
16	1,00	40	10%	32,1	78	4,789	3,735	0,02381	364,3	1338,8	1703,1
17	1,00	40	21%	31,6	78	4,654	3,630	0,02311	339,5	1255,2	1594,6
18	1,00	40	34%	31,0	78	4,498	3,509	0,02231	310,2	1159,1	1469,3
19	1,00	40	47%	30,4	78	4,347	3,391	0,02154	280,9	1066,1	1347,1
20	1,00	40	58%	29,9	78	4,223	3,294	0,02090	256,2	989,8	1245,9
21	1,00	40	68%	29,5	78	4,113	3,208	0,02034	233,6	922,1	1155,7
22	1,00	40	76%	29,1	78	4,026	3,141	0,01990	215,6	869,2	1084,8
23	1,00	40	82%	28,8	78	3,963	3,091	0,01957	202,1	830,1	1032,3
24	1,00	40	87%	28,6	78	3,910	3,050	0,01930	190,8	798,1	988,9
									6240,1	24285,1	30525,3

The cooling load is split into sensible and latent load and is calculated separately. The sources that provides latent load in this case come from people and ventilation air. Sources that are not considered are appliances that produces water vapour such as rice cookers, kettles etc. On the other hand, sources for sensible heat gain are appliances that give off heat, lighting, and of course the sun.

Equations used for calculating moist air properties:

The relative humidity can be calculated by equation A.

$\varphi = RH = \frac{P_w}{P_s}$ usually expressed as a percentage (A)

$P_w = P_s \cdot RH$

Where	P_w	is the actual water vapour pressure	[Pa]
	P_s	is the saturation water vapour pressure	[Pa]

Using Dalton's law for dry air and water vapour and applying the ideal gas law, following equation for humidity ratio is obtained.

$$w = 0,622 \cdot \frac{P_w}{P_{at} - P_w} \qquad \text{(B)}$$

Where	P_{at}	is the atmospheric pressure	[Pa]

The equation used for calculating the saturated vapour pressure over water was obtained from CIBSE Guide C: Reference Data.

$$\log_{10} P_s = 30,59051 - 8,2 \cdot \log_{10} T + 0,0024804 \cdot T - \frac{3142,31}{T} \quad \text{[Pa]} \qquad \text{(C)}$$

$T = db + 273{,}15$ [K]

Where	T	is temperature in Kelvin and *db* is temperature, greater than or equal to 0 °C
	P_s	is saturated vapour pressure [Pa] over water at temperature *t* [°C]

When the moist air conditions have been calculated the heat gain can be determined. This is done by calculating the sensible and latent heat gains separately. Equation D is used for sensible heat gain and equation E for latent heat gain.

$$q_S = \rho \cdot V_o \cdot C_{pa} \cdot \Delta t \qquad [\mathrm{W}] \qquad (\mathrm{D})$$

$$q_L = \rho \cdot V_o \cdot \left(w - w_r \right) \cdot h_{fg} \qquad [\mathrm{W}] \qquad (\mathrm{E})$$

Where	ρ	is the density	[kg/m³]
	V_o	is the airflow rate	[m³/s]

$C_{pa} = C_{pd} + w \cdot C_{ps}$ since C_{pd} and C_{ps} are functions of temperature, C_{pa} is also a function of temperature, in addition, a function of the humidity ratio.
An estimated mean value based on temperature range and humidity ratio Cpa is usually set to 1020 [J/kg K].

Δt	is the temperature difference between indoors and outdoors	[K]
h_{fg}	is the latent heat	[kJ/kg dry]
$(w - wr)$	is the difference between outdoor and indoor humidity ratio	[kg/kg]

Finally, to obtain the total heat gain sensible and latent heat gains are added together.

Appendix G: Heating Load Calculations

Using the equations 13 to 15 the heat transmission losses are calculated and the ventilation heat losses are calculated using the excel spreadsheets used to for obtaining the cooling ventilation loads. The U-values are found in ASHRAE Fundamentals Handbook [4]. Area N is the area of the north wall and S for the south wall. Same notation goes for the windows.

Wall Data:	
U - value [W/m² K] =	**3,1**
Area N [m²] =	**13,6**
Area S [m²] =	**14,6**
Window Data:	
U - value [W/m² K] =	**5**
Area N [m²] =	**4,32**
Area S [m²] =	**5,76**
Σ(U*A) =	**137,82**

Yearly Heating Load without VM1-unit:

Month	**Days**	**T_r**	**T_o**	**Hours**	**Q**	**W_T/month**	**Wv/month**	**Free Heating**	**Heating Load**
JAN	31	21,2	1	744	15028,8	2071,3	1508,7	521	3059,0
FEB	29	21	2,3	696	13015,2	1793,8	1308,8	470,5	2632,1
MAR	31	21,6	12	744	7142,4	984,4	963,5	521	1426,8
APR	30	22	15,2	720	4896	674,8	778,8	504,2	949,3
OCT	31	22	15,6	744	4761,6	656,2	791,9	521	927,2
NOV	30	21	11,1	720	7128	982,4	926,6	504,2	1404,8
DEC	31	21,3	1,8	744	14508	1999,5	1527,8	521	3006,3
Total [kWh]						**9162,3**	**7806,2**	**3562,9**	**13405,5**

Heating Load Calculation for Beijing without VM1-unit

The ventilation-heating load W_V is calculated with the Excel spreadsheet shown in appendix F.

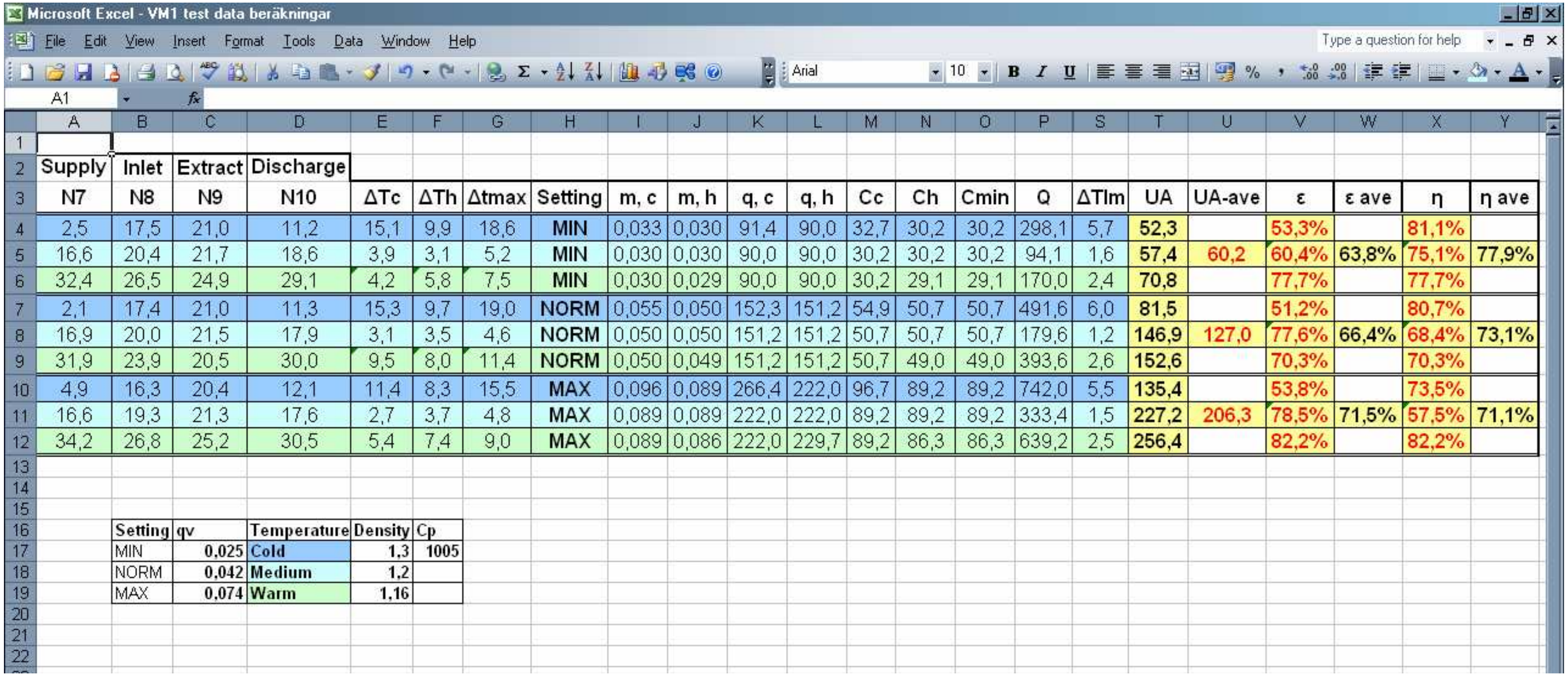
Yearly Heating Load using the VM1-unit:

Month	**Days**	**T_r**	**T_o**	**Hours**	**Q**	**W_T/month**	**Wv/month**	**Free Heating**	**Heating Load**
JAN	31	21,2	1	744	15028,8	2071,3	775,2	521	2325,4
FEB	29	21	2,3	696	13015,2	1793,8	722,9	470,5	2046,1
MAR	31	21,6	12	744	7142,4	984,4	651,2	521	1114,6
APR	30	22	15,2	720	4896	674,8	548,9	504,2	719,5
OCT	31	22	15,6	744	4761,6	656,2	475,5	521	610,7
NOV	30	21	11,1	720	7128	982,4	461,8	504,2	940,0
DEC	31	21,3	1,8	744	14508	1999,5	839,6	521	2318,1
Total [kWh]						**9162,3**	**4475,0**	**3562,9**	**10074,4**

Heating Load Calculations for Beijing using the VM1-unit

Appendix H: UA calculations

The Excel calculations of the UA-value for different states are presented below. The effectiveness and temperature efficiency has also been calculated.



Supply	Inlet	Extract	Discharge																				
N7	N8	N9	N10	ΔTc	ΔTh	Δtmax	Setting	m, c	m, h	q, c	q, h	Cc	Ch	Cmin	Q	ΔTlm	UA	UA-ave	ε	ε ave	η	η ave
2,5	17,5	21,0	11,2	15,1	9,9	18,6	MIN	0,033	0,030	91,4	90,0	32,7	30,2	30,2	298,1	5,7	52,3		53,3%		81,1%	
16,6	20,4	21,7	18,6	3,9	3,1	5,2	MIN	0,030	0,030	90,0	90,0	30,2	30,2	30,2	94,1	1,6	57,4	60,2	60,4%	63,8%	75,1%	77,9%
32,4	26,5	24,9	29,1	4,2	5,8	7,5	MIN	0,030	0,029	90,0	90,0	30,2	29,1	29,1	170,0	2,4	70,8		77,7%		77,7%	
2,1	17,4	21,0	11,3	15,3	9,7	19,0	NORM	0,055	0,050	152,3	151,2	54,9	50,7	50,7	491,6	6,0	81,5		51,2%		80,7%	
16,9	20,0	21,5	17,9	3,1	3,5	4,6	NORM	0,050	0,050	151,2	151,2	50,7	50,7	50,7	179,6	1,2	146,9	127,0	77,6%	66,4%	68,4%	73,1%
31,9	23,9	20,5	30,0	9,5	8,0	11,4	NORM	0,050	0,049	151,2	151,2	50,7	49,0	49,0	393,6	2,6	152,6		70,3%		70,3%	
4,9	16,3	20,4	12,1	11,4	8,3	15,5	MAX	0,096	0,089	266,4	222,0	96,7	89,2	89,2	742,0	5,5	135,4		53,8%		73,5%	
16,6	19,3	21,3	17,6	2,7	3,7	4,8	MAX	0,089	0,089	222,0	222,0	89,2	89,2	89,2	333,4	1,5	227,2	206,3	78,5%	71,5%	57,5%	71,1%
34,2	26,8	25,2	30,5	5,4	7,4	9,0	MAX	0,089	0,086	222,0	229,7	89,2	86,3	86,3	639,2	2,5	256,4		82,2%		82,2%	

Setting	qv	Temperature	Density	Cp
MIN	0,025	Cold	1,3	1005
NORM	0,042	Medium	1,2	
MAX	0,074	Warm	1,16	