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Synopsis:

The main purpose of this report is investigations on ventilated windows. The article primarily dealing with analysis of window energy efficient design and its performance in cold and warm period of year. Analysis on seven different cases has been carried out to identify the important contributors to the total energy gains and losses. These are then optimised with best solutions to get as good results as possible in energy balance calculations. Energy balance calculations are second part of investigations. By implementation of this method and simulation programs, results obtained later can be compared. Problems, concerning panes configuration, location of low-E coating and position and type of shading device, can be solved afterwards. The last part of the project includes Simple calculation method applied to a real building in order to find most suitable option in aspect of energy balance during year.

Chapter 1

Preface

This report is an all year master thesis created by Giedrius Domarkas and Jonas Taminskas at Aalborg University. This is thesis of the master of science in Indoor Environmental Engineering. The subject of this project is *Ventilated window with solar shading/night blind.* This project is based on the theme: advanced modeling of ventilated window and integration into building, and is solved in accordance with knowledge gained trough years of studying.

The project work group would like to give thanks to the main supervisors Per Heiselberg and Olena K.Larsen. The supervisors are thanked for good guidance, criticism and knowledge sharing in all project period. Finally the building owner Henrik Fibiger is thanked for answering questions and guidance in his own renovated building in Herredsfoged.

The literature sources are given in numbers. The source is then found in the section *Bibliography.* Where the list of sources is given. The bibliography is placed in the back of the report. Also appendix is placed in the back of this report. The specific information is given in appendix and is named with letters. The additional information used in this project suchlike excel files, WIS simulation results is given in Appendix-CD.

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Chapter 2

Introduction

Many times per day you can hear about the problems also many conferences are being held regarding topic of global warming. Solutions to this problem is being tried to find on a world scale. But almost all biggest countries of the world agree on one aspect, that the only and the main solution to reduce CO_2 level and warm-house effect is switching to alternative fuel sources and simple but not the easiest way to implement- the reduction of energy consumption. A good example could be to mention that many European countries emit more CO_2 than their Kyoto target, i.e. Denmark is 21,53% above than in 2012 target. As a result of this, low energy buildings are coming to fashion. The fashion inspired by understanding how these buildings can consume less energy, and do that in very efficient way. The aim of this project is to cover the part where it would be possible to reduce buildings energy consumption by implementing new type of windows.

In the phase of designing new buildings or renovating old ones it is required to supply fresh air from outside regarding strict building regulations. Taking air during cold periods directly from outside and providing it to the inside of the building may cause drafts and uncomfortable ventilation. So an air must be preheated before letting it in. For provision of fresh air it is possible to use artificial ventilation systems with heat recovery units, but nowadays the aim is to reach the best indoor environment with lowest power consumption. Another problem can be found is that strict rules do not allow changing any of facade or inside of state protected old buildings. So possible solution would be to use ventilated double windows.

In most cases windows are the weakest part of the buildings envelope keeping in mind the thermal insulation. Depending on the size of glazed envelope it is possible to lose 10-25% of the heat during cold periods and get an excess heat from the sun during warm periods.

Ventilated double windows are great solution in many aspects. First to mentioned could be a great sound barrier, thats why they are often are mounted in buildings with noisy surroundings. Another important feature- a part responsible for controlling the sun light i.e. blinds, mounted inside the cavity, is protected from the environmental conditions. Even if there are very high wind it is not necessary to worry about rolling up the shading device. There is a huge potential keeping in mind the preheating of cold inlet air and cooling the cavity of window during warm periods.

In order to get well functioning window the design phase is important. All issues concerning ventilation, preheating and sun shading must be solved in complex. In order to ensure optimal functioning of the window and taking into consideration the requirements it is necessary to identify potential problems and finding right solutions.

Ventilated window can be easily attributed to passive technology category. By implementing it into buildings envelope an energy reduction can be achieved without using any energy. Improvement of windows leads to reduction of gains also usage of natural light and heat source- sun, reduces the total energy consumption for heating. To ensure constant acceptable conditions, mechanical air exhaust systems can be implemented. The objective of this study is to assess the impact of different window glass types, the influence of solar control devices to energy balance in room. The layout of window is also considered. Types and appropriate position of shading device as well as air flow rate trough ventilated cavity must be tested. Simulations has been fulfilled using weather data from danish reference year. The performance of designed windows is tested using different methods for calculating energy balance for warm and cold day, day and night and eventually for all reference year. In all simulations and calculations the window frame would not be taken into consideration. The air resistance and pressure drop in real scale model using different boundary conditions are then tested. This was done in order to know weather the system is able to work using natural ventilation.

Chapter 3

Literature review

3.1 Intro

The aim of this paragraph is to describe the concept of ventilated windows based on different sources of literature. In order get a clear overview of how this conceptional construction works, several examples from previous years experiments with airflow and thermal simulations are included. The experiments with a concept of window with ventilated air cavity started in late eight decade [21], [20] in Finland and Canada. These results were not what was expected i.e. due to cold climate the window was unable to recover enough heat to air. The inlet air caused droughts. Now there is a huge potential in experimenting with this system. There is several reasons why the growth of interest in this study is so big. According to (J.S. Carlos 2010) *"...this window system, that is applicable to both new and old buildings, has proved to be able to provide preheated ventilation air in winter time, by recovering part of the heat losses from indoors and by transferring solar radiation heat gains. This kind of system helps to reduce the global heating energy needs of a building, in winter, since it can lead to a significant reduction of the heat loss through ventilation."*[14] Also it must be mentioned that window is easy to install and prise is low, compared with other design solutions which helps to reduce energy demands. Still the complexity of ventilated window and applicability to different climatic regions increases the need for careful design. The comparison of literature sources and results from experiments not always relevant due to different climatic conditions and locations. But still the results are encouraging for adoption of this kind of window.

3.2 Approaches for double ventilated window modeling

In order to start doing experiments with real scale models it is necessary to have derivations and verifications of theoretical models. Nowadays there are a wide range of programs which simulates building and mathematical models. Choosing appropriate software depends on how complex is the model and how accurate the result must be. There are two ways approaching the results of performance of proposed design- numerical and experimental.

Computational Fluid Dynamics is mathematical approach (CFD) usually used because its informativeness, time and money saving. CFD-simulations have the potential to achieve more accurate results compared with other simulation programs, but its implementation in practice is quite difficult. In order to make simulations for whole year the variety of input parameters and different configurations becomes very complex. Due to complexity of simulations the time of computational time would be enormous. So for this project it is chosen to use more user-friendly programs. For calculating temperatures in the cavity of the ventilated (non ventilated) window, also for finding g and U values of glazing unit. The temperature at the inlet is also taken into consideration. For those simulations one of suitable software is program called WIS 3.

According to Flamant G., Heijmans N., Guiot E. *"WIS is a uniform, multi-purpose, European-based software tool designed to assist in determining the thermal and solar characteristics of window systems (glazing, frames, solar shading devices, etc.) and window components. The tool contains databases with component properties and routines for calculation of the thermal/optical interactions of components in a window. One of the unique elements in the software tool is the combination of glazings and shading devices, with the option of free or forced air circulation between both. This makes the tool particularly suited to calculate the thermal and solar performance of complex windows and active facades. The WIS algorithms are based on international (CEN, ISO) standards, but WIS also contains advanced calculation routines for components or conditions where current standards do not apply. Control systems and building modeling are not considered in this tool."* [8]

3.3 Different window configurations

In order to start simulations with simulation programs it is necessary analyze available studies and publications in the field of ventilated window. The reports main focus is finding parameters such as inner and outdoor glazing types, depth of the air gap, appropriate position of shading device, if the presence of different solar control products makes any difference [1] and were used by authors in their modeling process. Harris Poirazis in 2008 presented an article concerning the analyses of energy use and indoor climate in double skin office buildings. Author claims that, the increase of air space between glazing increases thermal resistance. Also author recommends to use 15 mm width air space because after a little extra thermal benefit is obtained. In order to improve window system further it is possible to put third pane of glass and have second air space which provides further improvement.[19]

Other author M.E.McEvoy claims that *…"from the earlier work it was concluded that cavity widths at or below 30mm were of interest and consequently the design of the test window allowed variation of the cavity width to 10, 20, or 30 mm."*[15] Also author in his other report [16] point out that *…"preheat decreases with increasing cavity width, thermal comfort actually improves due to the reduced airflow speeds from the window"* The studies with 10 mm to 50 mm cavity widths was done.

Other important parameter of ventilated window is inner and outdoor glazing types such as presence and absence of a low emissivity glass. The author Harris Poirazis in his article claims that *…"drastic changes can be obtained by applying a coating on the glass. Coatings can influence the range of transmitted radiation and its absolute level. Efficient solar shading can be obtained by reflective coatings. Increased reflection results in reduced total transmission. Lower U values can be obtained with coatings of low emissivity."*

Author concludes in his article that, (2008) ...*"when the inner clear pane is replaced with a low E hard coated pane, the performance improves dramatically. As to thermal comfort the airflow windows perform better than the rest of the cases due to the increased PMV values during winter months. In cases with low E inner pane the quality of the thermal environment can improve drastically, reaching the comfort levels of a* 30% *glazed building with improved window thermal and optical properties."*

According to author M.E McEvoy ...*"in the case of the a two-pane window, the difference between the presence and absence of a low-E coating was negligible, whereas a triple glazed window having a low-E coating facing into the ventilated layer, supplied the maximum pre-heating of the ventilation air."*

3.4 Shading device

It is known that in well insulated buildings the biggest part of heat is gained or lost through windows. During warm period of the year due to internal and external heat gains through glazing units there is always a risk of overheating. In winter time the situation can be different- due to high glazing unit area the thermal looses can be too high. In regard with modeling double ventilated window it is important to take into consideration the shading device.

In the paper of Elisabeth Gratia and Andreť De Herde there are in details revealed the results concerning the colors and positions of the shading device. The simulations are applied to office building with double skin facade, but most of the results can be used in double ventilated/ non ventilated window due to physical similarity. According to authors *"One of the most efficient natural cooling strategies is the use of solar blinds. The temperature of the air layer in the double-skin is influenced by many factors (solar radiation, outside temperature, wind speed, windows openings, type of glazing, etc.) but also by the presence of shading systems"..."The position of the blind within the air cavity affects the rate of the heat transfer to the interior and amount of thermal stress on the glazing layers. Placed too close to the interior facade, inadequate air flow around the blind may occur and conductive and radiative heat transfer to the interior are increased. The blind should be placed toward the exterior pane with adequate room for air circulation on both sides. With wind-induced ventilation or high velocity thermal-driven ventilation, the bottom edge of the blind should be secured to prevent fluttering and noise.*[7]

3.5 Summary

According to the reviewed literature, the ventilated window system helps to save energy both in summer and winter time. On the other hand hand the design of this system is complex. Furthermore analyzed literature gives an idea about depth of ventilated cavity, position of low E coated glass and shading device. It is chosen to make ventilated window modeling with 30 mm depth ventilated cavity and use triple glazed window having a low-E coating in different positions. Also the appropriate position and type of shading device will be attempt to discover.

Chapter 4

Simulation of ventilated window

In order to predict the energy performance of the ventilated window and model different design possibilities the program WIS is chosen. This software tool allows analyze multi-glazing unit with ventilated gap. Also it is possible to place the blind within the air cavity and test different positions. The calculations is made to find the optimal window configuration, preheating ability, U and g values. The configurations of different multi-glazing units are shown in tables 4.1 and 4.2.

4.1 Environment

For each simulation it is necessary specify simulation environment parameters. The following information has to be given:

- outdoor and indoor air temperatures
- outdoor and indoor radiant temperatures
- direct solar radiation
- convective surface coefficient outdoor
- convective surface coefficient indoor

Using WIS program it is not possible to make dynamic simulations for all year or day time. So it is chosen to make many static simulations in order to get better overview about window performance. All simulation files are given in appendix CD. Both typical summer and winter days are selected from DRY (Danish reference year). Summer and winter days are split in 24 hours and simulations for 24 hours are done. The outdoor air, radiant temperatures and direct solar radiation are taken. The direct solar radiation for horizontal surface is given in DRY. So direct solar radiation for vertical surface facing to south is recalculated. Ventilated windows to south direction is analyzed. The intensity of direct solar radiation on a vertical surface is calculated [9]:

$$\begin{aligned} &I_{s\varphi} = I_n \cdot cos\beta, if cos\beta > 0 \\ &I_{s\varphi} = 0, if cos\beta \leq 0 \end{aligned} \tag{4.1}$$

where

$$cos\beta = cos\alpha_s \cdot cos(\gamma_s - \gamma_f) sin\varphi_f + sin\alpha_s \cdot cos\varphi_f \tag{4.2}$$

- I_n is the intensity of direct radiation normal to the solar beam (W/m^2);
- β is the angle between the solar beam and a line normal to the surface;
- γ_s is the solar azimuth angle (south 0^o);
- γ_f is the wall azimuth angle (south 0^o);
- φ_f is the angle of the sloping surface (vertical 90^o);
- α_s is solar altitude angle (^{o}).

WIS program does not take into consideration diffuse radiation. But diffuse radiation is used afterwards in energy balance calculation. The intensity of diffuse solar radiation for vertical surface is also recalculated:

$$\begin{aligned} I_{dv} &= I_d(0,55 + 0,437cos\beta + 0,313(cos\beta)^2), if cos\beta > -0,2 \\ I_{dv} &= I_d \cdot 0,45, if cos\beta \leq -0,2 \end{aligned} \tag{4.3}$$

where

- I_d is the intensity of diffuse sky radiation(W/m^2).

The convective surface coefficient outdoor and indoor data is taken from [2]. According standard convective surface coefficient outdoor is $23W/m^2K$ and convective surface coefficient indoor is $8W/m^2K$. It is assumed that indoor air and radiant temperatures are 20^oC and do not change for summer and winter time. The outdoor air and radiant temperatures also recalculated direct, diffuse solar radiation both for summer and winter days for 24 hours are shown in figures 4.1 and 4.2. The table with exact values is in appendix A.

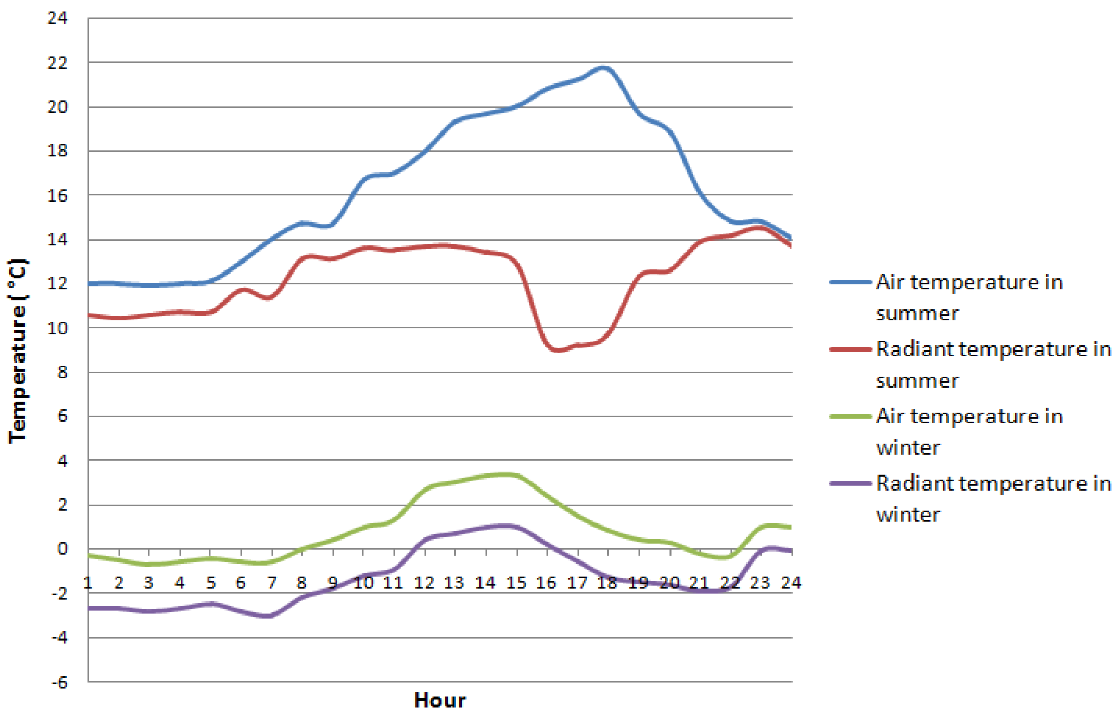

Figure 4.1: The outdoor air and radiant temperatures both for summer and winter days

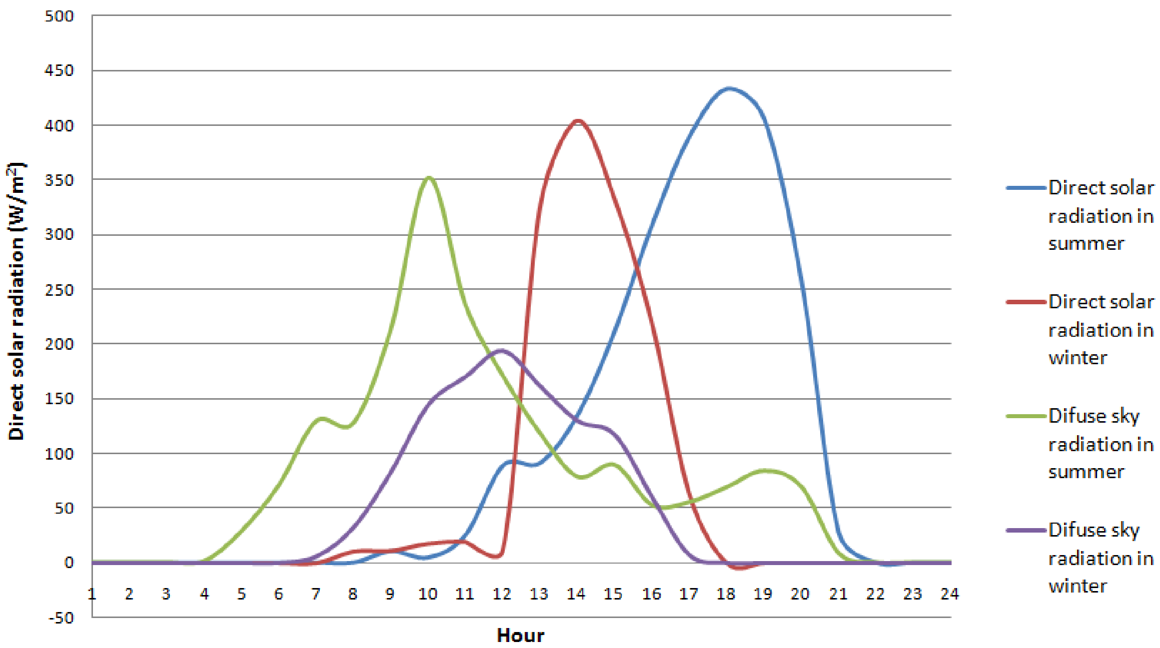

Figure 4.2: Direct solar radiation facing south both for summer and winter days

4.2 Different window configurations

In order to find optimal window configuration it is chosen to simulate seven different glazing alternatives without shading(it is called A, B, C...). Different ventilated window configurations are shown in 4.1 and 4.2.

Case	**External pane**	**Ventilated gap (30mm)**	**Intermediate pane**	**Gap (12mm)**	**Internal pane**	**U-value CEN**
A	Clear glass (6mm)	Air	Clear glass (4mm)	Air	Clear glass (4mm)	1.81
B	Clear glass (6mm)	Air	Clear glass (4mm)	Argon	Low E coated CU (4mm)	1.02
C	Clear glass (6mm)	Air	Low E coated CU (4mm)	Argon	Clear glass (4mm)	1.09
D	Low E coated CU (6mm)	Air	Clear glass (4mm)	Argon	Clear glass (4mm)	1.75

Table 4.1: Table with different window configurations

Window Case	**External pane**	**Gap (12mm)**	**Intermediate pane**	**Ventilated gap (30mm)**	**Internal pane**	**U-value CEN**
E	Clear glass (6mm)	Argon	Clear glass (4mm)	Air	Clear glass (4mm)	1.74
F	Low E coated CU (6mm)	Argon	Clear glass (4mm)	Air	Low E coated (4mm) CU	1.07
G	Clear glass (6mm)	Argon	Low E coated UC (4mm)	Air	Low E coated CU (4mm)	1.03

Table 4.2: Table with different window configurations

4.3 Different configurations and layouts

For general overview there are 7 different cases, which are tested in the project, presented below. In figures there are windows with closed cavity shown. Cases A and E are only with clear glass panes. Cases B, C, D, F and G are combined clear glass panes and panes covered with low-E coating. Low-E coated CU means that coating is from outside so far Low-E coated UC is from inside.

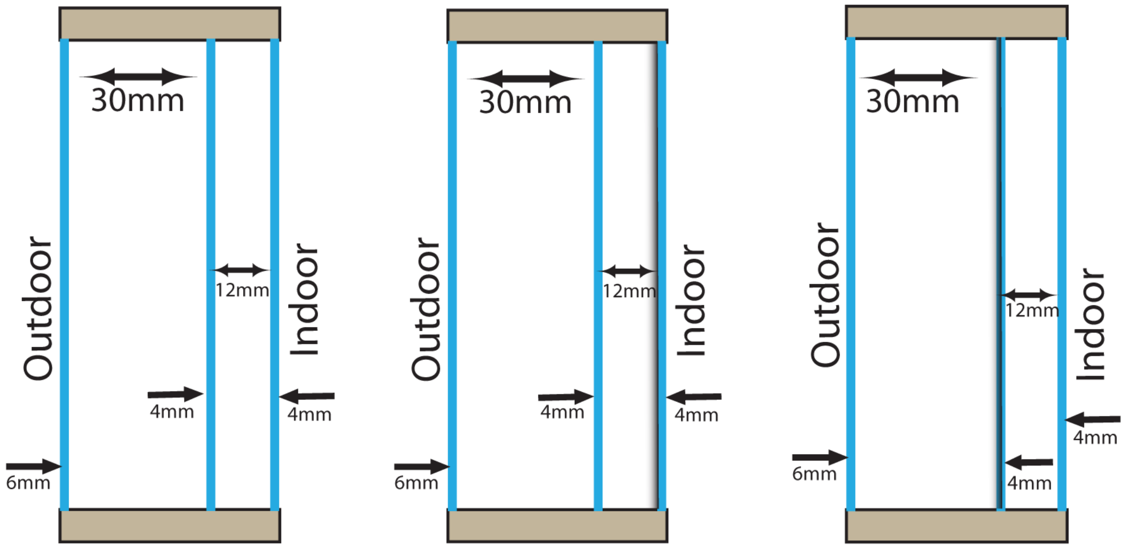

Figure 4.3: Cases A, B and C

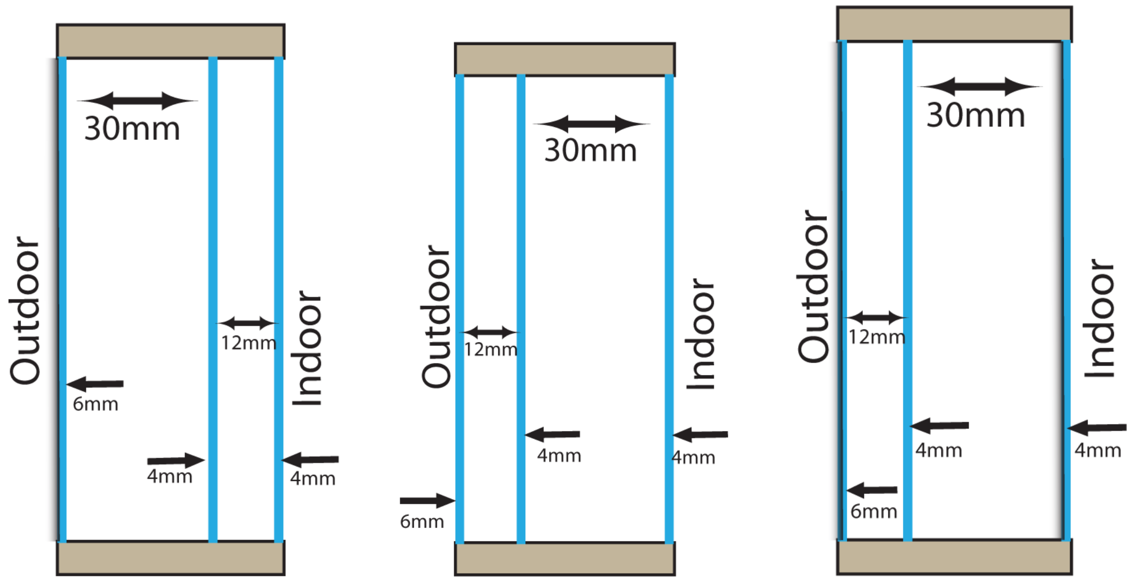

Figure 4.4: Cases D, E and F

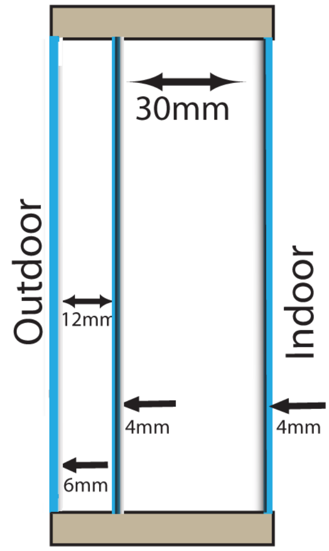

Figure 4.5: Case G

In the figure 4.6 the composition of window is presented. This composition is applied to cases B, C, D, F. The low-e coating in simulations is facing outdoor side of the glass pane. In case G both coatings are facing into cavity.

Figure 4.6: Composition of window pane

For windows with ventilated cavity, the same layouts are applied as it is done with windows without ventilation. Example of window with ventilated cavity and window with ventilated cavity and shading device is shown below.

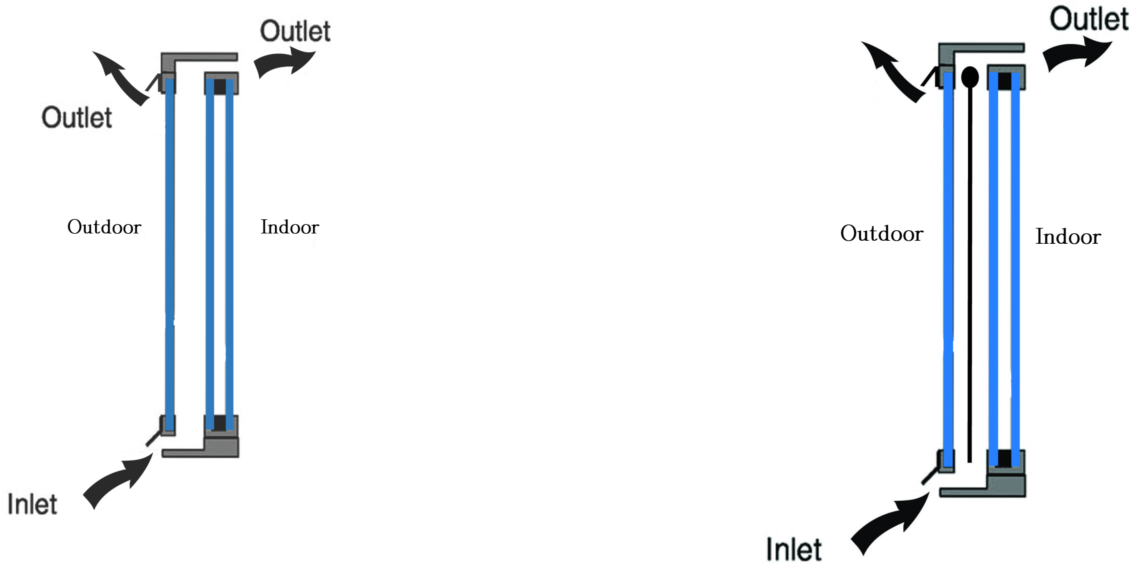

Figure 4.7: Composition of window with ventilated cavity in left figure, and window with ventilated cavity and shading device in right figure

The case above presents window layout A, with ventilated cavity. There are only clear glass panes.

4.4 Simulations of window with shading device

During modeling of ventilated window it is important to take into consideration the shading device. The different shading positions with 4 l/s forced ventilation and closed gap is tested. Roller blind is tested in three different positions in the center of the gap, closer to inside pane or closer to outside pane. Also comparison of window performance with shading device and without shading device is done both for summer and winter case. Furthermore the venetian blind with 90^o and 45^o slat angles are tested. Different ventilated window configurations with shading are shown in 4.3 and 4.6.

Case	A sh
External pane	Clear glass (6mm)
Ventilated gap (14mm)	Air
Shading	Roller blind (0.23mm)
Ventilated gap (14mm)	Air
Intermediate pane	Clear glass (4mm)
Gap (12mm)	Air
Internal pane	Clear glass (4mm)

Table 4.3: Table with window configuration

For simulations later in the project the shading device is used. The properties of roller blind and venetian blind is presented below.

Shading system	
VSL 816 roller blind, transparent	
thickness	0.23 mm
material conductivity	0.2 W/m^2K
material IR emissivity outdoor	0.506
material IR emissivity indoor	0.802
material IR transmissivity	0.079

Table 4.4: Properties of shading device

Shading system	
Venetian Blind 4 Perforation 8083	
thickness	0.22 mm
slat chord width	25 mm
crown height	2 mm
slat pitch	20 mm
slat angle	-90^o - 90^o
material conductivity	100 W/m^2K
material IR emissivity outdoor	0.75
material IR emissivity indoor	0.75
material IR transmissivity	0.01

Table 4.5: Properties of shading device

Case	External pane	Gap (12mm)	Intermediate pane	Ventilated gap	Shading	Ventilated gap	Internal pane
G	Clear glass (6mm)	Argon	Low E coated UC (4mm)	Air (14mm)	Roller blind (0.23mm)	Air (14mm)	Low E coat-ed CU (4mm)
G (21/7)	Clear glass (6mm)	Argon	Low E coated UC (4mm)	Air (21mm)	Roller blind (0.23mm)	Air (7mm)	Low E coat-ed CU (4mm)
G (7/21)	Clear glass (6mm)	Argon	Low E coated UC (4mm)	Air (7mm)	Roller blind (0.23mm)	Air (21mm)	Low E coat-ed CU (4mm)
G (45^o)	Clear glass (6mm)	Argon	Low E coated UC (4mm)	Air (14mm)	Venetian blind (0.22mm)	Air (14mm)	Low E coat-ed CU (4mm)
G (90^o)	Clear glass (6mm)	Argon	Low E coated UC (4mm)	Air (14mm)	Venetian blind (0.22mm)	Air (14mm)	Low E coat-ed CU (4mm)

Table 4.6: Table with different window configurations

4.5 Window glass types

In order to make WIS simulations it is necessary to select glass types in different layers. It is chosen to analyze transparent systems in combination of two different glass types, clear glass and low E coated glass with two different thicknesses. Low E coated glass helps to reflect radiant infrared solar energy and keeps radiant heat on the same side of the glass from which is originated. Furthermore Low E coated glass allows to pass visible light, while clear glass transmit almost all radiant infrared solar energy and visible light. Low E coated glass has a thin metal coating on the glass, within an air gap. This layer reflects thermal radiation in this case reducing heat transfer through the glass. Low-E coating allows solar radiation to pass through the glass panes into a room while it also helps to reduce heat loss and allows the room to be preheated by direct sunshine. By changing the location of the coating, the insulating properties of the window are not affected, only the percentage of solar heat gain. All pane types and pane properties used in simulations are shown in 4.7.

Glazing Unit	**Thickness (mm)**	**Emissivity indoor**	**Emissivity outdoor**	**Reflectance indoor**	**Reflectance outdoor**	**Direct solar transmittance**
Clear glass (clear04.gvb)	4	0.837	0.837	0.075 (s) 0.080 (v)	0.075 (s) 0.080 (v)	0.844 (s) 0.898 (v)
Clear glass (clear04.gvb)	6	0.837	0.837	0.073 (s) 0.079 (v)	0.073 (s) 0.079 (v)	0.810 (s) 0.888 (v)
Low E coated CU (Planibel Top N4.gvb)	4	0.837	0.050	0.231 (s) 0.080 (v)	0.249 (s) 0.060 (v)	0.640 (s) 0.872 (v)
Low E coated CU (Planibel Top N6.gvb)	6	0.837	0.050	0.218 (s) 0.080 (v)	0.248 (s) 0.060 (v)	0.628 (s) 0.867 (v)
Low E coated UC (Planibel top4.gvb)	4	0.052	0.837	0.308 (s) 0.088 (v)	0.285 (s) 0.116 (v)	0.576 (s) 0.827 (v)

Table 4.7: Pane properties for the glazing used for ventilated window alternatives

(s)=solar (v)=visual

Chapter 5

WIS model description

The aim of this section is to explain WIS model and how program WIS finds U values and temperatures in the ventilated and (non ventilated) window cavity of glazing unit. The general software information is given in chapter 3. This section is done in order to be able to evaluate results after simulations and make conclusion. WIS model description is written according [12], [5], [6], [18], [2] and [3].

5.1 WIS model with closed cavity

The heat transfer though the central part of glazing for the non-ventilated cavity calculation is based on EN 673 standard. The U value is calculated:

$$\frac{1}{U} = \frac{1}{h_e} + \frac{1}{h_t} + \frac{1}{h_i} \tag{5.1}$$

where

- h_e and h_i are the external and internal heat transfer coefficients $[W/m^2K]$;
- h_t is the total thermal conductance of glazing $[W/m^2K]$.

The total conductance of glazing is found:

$$\frac{1}{h_t} = \sum_1^N \frac{1}{h_s} + \sum_1^M d_j \cdot r_j \tag{5.2}$$

where

- h_s is the heat transfer coefficient of the closed air cavity $[W/m^2K]$;
- N is the number of spaces;
- d_j is the thickness of each material layer $[m]$;
- r_j is the thermal resistivity of each material $[mK/W]$;
- M is the number of material layers.

$$h_s = h_r + h_g \tag{5.3}$$

where

- h_r is the radiation conductance $[W/m^2K]$;
- h_g is the gas conductance $[W/m^2K]$.

The radiation conductance is given by:

$$h_r = 4\sigma(\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1)^{-1} \cdot {T_m}^3 \tag{5.4}$$

where

- σ is Stefan-Boltzmann's constant, $5,67 \times 10^{-8}$ $[W/m^2K^4]$;
- T_m is the mean absolute temperature of the gas space$[K]$;
- ε_1 and ε_2 are the corrected emissivities at T_m;

The gas conductance h_g is calculated:

$$h_g = Nu\frac{\lambda}{s} \tag{5.5}$$

where

- s is the width of the space $[m]$;
- λ is the thermal conductivity $[W/(mK)]$;
- Nu is the Nusselt number.

$$Nu = A(GrPr)^n \tag{5.6}$$

where

- A is a constant for vertical window is $0,035$;
- Gr is the Grashof number;
- Pr is the Prandtl number;
- n is an exponent for vertical window is $0,38$.

$$Gr = \frac{9,81 s^3 \Delta T \rho^2}{T_m \mu^2} \tag{5.7}$$

$$Pr = \frac{\mu c}{\lambda} \tag{5.8}$$

where

- ΔT is the temperature difference between glass surfaces bounding the gas space $[K]$;
- ρ is the density $[kg/m^3]$;
- μ is the dynamic viscosity $[kg/(m \cdot s)]$;
- c is the specific heat capacity $[J/(kg \cdot K)]$;
- T_m is the mean temperature$[K]$.

For the glazing units with more than one gas space h_s the heat transfer coefficient is calculated using iteration procedure. The gas space conductance h_s of each gas space is determined at a mean temperature of $283K$. For the first step of the iteration procedure a temperature difference of $\Delta T = 15/N\ (K)$ for each space is used in equation 5.7. With gas space conductances h_s obtained, new ΔT_s values for each space shall be calculated form the equation:

$$\Delta T_s = 15(\frac{\frac{1}{h_s}}{\Sigma_1^N \frac{1}{h_s}}) \tag{5.9}$$

These ΔT_s values are used for the second iteration, and so on. This converged resistance shall be used in 6.5 and 5.2 to calculate U value.

5.2 WIS model with ventilation

The U value calculation when window cavity is ventilated is calculated according ISO 15099:2003 standard. The U value consists of three different components:

$$U = U_{conv} + U_{ir} + U_{vent} \tag{5.10}$$

where

- U_{conv} is convective and thermal radiative heat transfer coefficient from the room to window$[W/m^2K]$;
- U_{ir} is heat transfer coefficient due to direct solar radiation $[W/m^2K]$;
- U_{vent} is ventilative heat transfer coefficient from the room to the window by air entering the room from the cavity $[W/m^2K]$.

$$U_{conv} = \frac{Q_{conv}}{A_{gl}(T_i - T_e)} \tag{5.11}$$

$$U_{vent} = \frac{Q_{vent}}{A_{gl}(T_i - T_e)} \tag{5.12}$$

where

- Q_{conv} is the net transmission heat flow from the room to window induced by convective and thermal radiative heat exchange$[W/m^2K]$;
- Q_{vent} is the net ventilative heat flow from room to window induced by air entering the room from the cavity, which is heated or cooled under influence of indoor-outdoor temperature difference (can be positive or negative value)$[W/m^2K]$;
- Q_{ir} is the energy gain to the room by direct solar radiation, transmitted into the room via the window $[W/m^2K]$;
- A_{gl} is the area of the transparent part of the window $[m^2]$;
- T_i is the indoor environment temperature $[^oC]$;
- T_e is the outdoor environment temperature $[^oC]$.

where Q_{conv}, Q_{vent} and Q_{ir} is calculated:

$$Q_{conv} = (h_{ci} + h_ri) \cdot A_{gl} \cdot (T_i - T_{gl,si}) \tag{5.13}$$

where

- h_{ci} is the indoor convective heat transfer coefficient$[W/m^2K]$;
- h_{ri} is the indoor radiative heat transfer coefficient$[W/m^2K]$;
- $T_{gl,si}$ is the indoor surface temperature of the window $[^oC]$.

$$Q_{vent} = \rho \cdot c_p \cdot \varphi_v \cdot W(T_i - T_{gap,out}) \tag{5.14}$$

where

- ρ is the volumetric density of air$[kg/m^3K]$;
- c_p is the thermal capacity of air $[J/kgK]$;
- φ_v is the cavity air flow ($[m^3/s]$ per one meter window width);
- W is the window width $[m]$;

- $T_{gap,out}$ is the temperature of the air at the exit of the cavity $[^oC]$;

$$Q_{ri} = \tau_{sol} \cdot A_{gl} \cdot I_{sol} \tag{5.15}$$

where

- τ_{sol} is the direct solar transmittance of the window;
- I_{sol} is the amount of incident solar radiation $[W/m^2]$.

5.3 Temperatures in ventilated cavity

The temperature profile is calculated using simple model when the mean velocity of the air in the ventilated gap is known. The air temperature in cavity varies with height, because of the air flow 5.1. The temperature profile depends on the air velocity in the ventilated gap and the heat transfer coefficient to both layers.

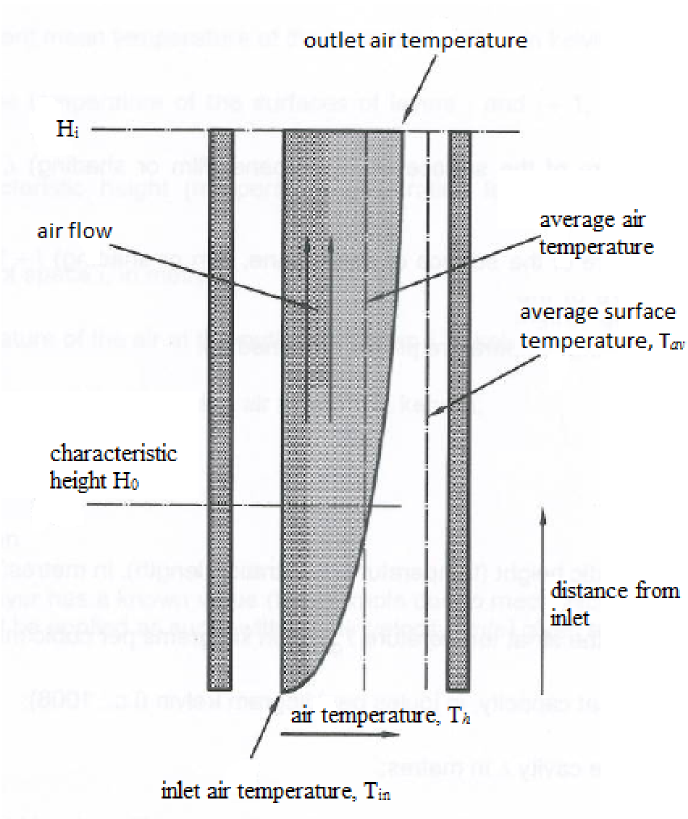

Figure 5.1: Air flow in the gap of a window system

The temperature in the certain height is found:

$$T_h = T_{av} - (T_{av} - T_{in})e^{\frac{-x}{H_0}} \tag{5.16}$$

where

- T_h is the temperature of the air in gap in certain height from the inlet in $[K]$;
- T_{in} is the temperature of the incoming air in ventilated gap in $[K]$;
- H_0 is the characteristic height (temperature penetration length) in $[m]$;
- T_{av} is the average temperature of the surfaces of layers given by equation in $[K]$:

$$T_{av} = \frac{(T_i + T_{i+1})}{2} \tag{5.17}$$

where

- T_i and T_{i+1} are the temperatures of the surfaces of layer (pane, film or shading) facing cavity in $[K]$.

The characteristic height of the temperature profile is defined by:

$$H_0 = \frac{\rho_i \cdot c_p \cdot b_i}{2 \cdot h_c} \cdot V_i \tag{5.18}$$

where

- ρ_{air} is density of air at temperature T_h $[kg/m^3]$;
- c_p is the specific heat capacity $[J/(kg \cdot K)$
- b_i is the width of the cavity $[m]$
- V_i is the mean velocity of the air flow in the cavity $[m/s]$

The average temperature given in 5.17 in cases then shading is applied is found different. The two cavities with different T_{av} and no air exchange between is assumed. All temperatures in order to find average temperatures are taken facing into cavities.

Chapter 6

Results

6.1 Windows with closed cavity

In order to get an overview of window performance, and reduce number of glazing alternatives it is chosen to make energy balance calculations with 7 different window layout cases. The main aim of those calculations is to see which windows performs best during winter and summer i.e. during winter day the total energy balance must be as high as possible and during summer day vice versa. The calculations are made for 24 hours during both winter and summer periods only considering the type of different layers at the horizontal panes and different setup. Before results are discussed it must be mentioned that in WIS simulations window frame is not taken into consideration. For windows with non ventilated cavity it is chosen to use equation 6.1. The results are shown below.

$$Q = ((I_{s\varphi} + I_{dv}) \cdot g \cdot A) - (T_{in} - T_{out}) \cdot U \cdot A \tag{6.1}$$

where

- Q is heat load (Wh);
- U is heat transfer coefficient (W/m^2K), program WIS gives combined U value- U_{conv} and U_{ir};
- $I_{s\varphi}$ is intensity of direct solar radiation on the vertical window (W/m^2);
- U_{conv} convective and thermal radiative heat transfer coefficient from room to window (W/m^2K);
- U_{ir} heat transfer coefficient due direct solar radiation (W/m^2K);
- I_{dv} is intensity of diffuse sky radiation (W/m^2);
- g is the value of the pane;
- A surface area (m^2);
- T_{in} indoor air temperature (^oC);
- T_{out} outdoor air temperature (^oC).

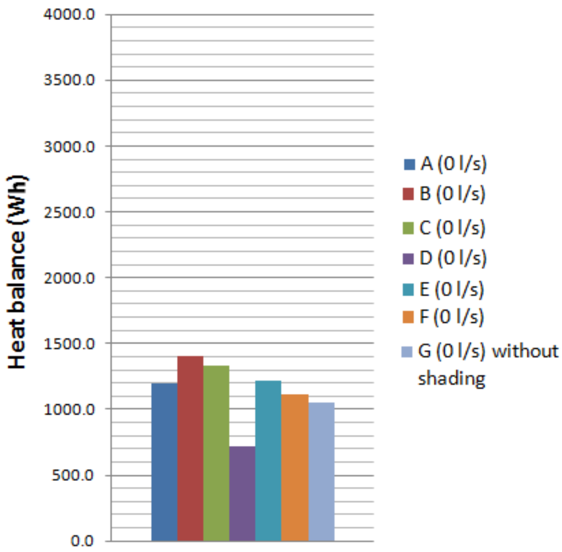

Figure 6.1: Closed cavity winter

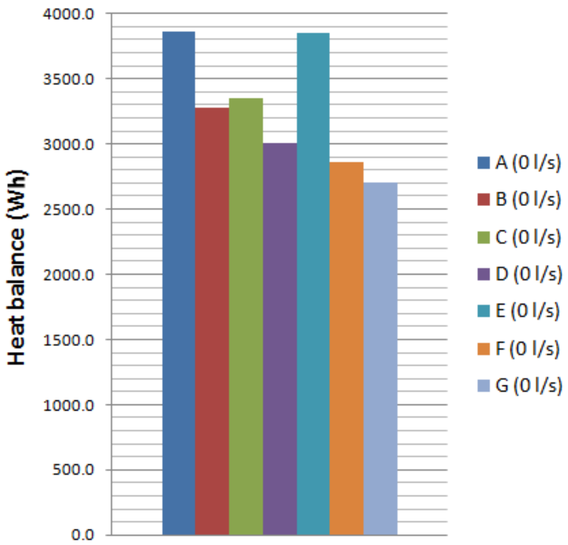

Figure 6.2: Closed cavity summer

The results of energy balance for windows with different layout, with the closed cavity and without shading, calculated during a typical summer and winter day are shown in figures 6.2 and 6.1. In order to compare the simulated alternatives, the first case (A) with 3 clear panes is considered as a reference case. Cases (A) and (E) performs almost the same in summer but due to air being replaced by argon gas, window (E) has a bit better insulation properties in winter. From figure 6.1 it is seen that in case (D) the heat balance is lowest, due to the low E pane placed on the outer skin 4.1. This happens due to temperature increase in the outer skin but there is no convective heat transfer to the inner panes and this makes no positive change in U value. Compared cases (B), (C), (F) and (G) it is seen that low E coating placed on inner skins makes a visible influence on the U value. This can be explained as being due to the larger proportion of solar radiation that is absorbed at the inner skins also the additional insulation that the low E coating provides allows the inner pane to maintain higher temperatures.

As for summer period from figure 6.2 it can be clearly seen that having low E coating on the outer panes (D, F, G) results good results in heat balance. This is due to solar control layer does not allow internal layers to preheat. Also best result in heat balance is showed by window (G). When winter and summer cases are compared it is evident that having low E coating in window pane composition is inevitable in order to get good heat balance results.

6.2 Windows with open cavity

As in previous section for testing 7 different window layout cases the cold and warm periods of the year is used. For testing how windows performs during 24 hour period the calculations on energy balance are made. For windows with ventilated cavity it is chosen to use equation 6.4. The results are shown below.

$$Q = ((I_{s\varphi} + I_{dv}) \cdot g \cdot A) - (T_{in} - T_{out}) \cdot U \cdot A \tag{6.2}$$

where

- Q is heat load (Wh);
- $I_{s\varphi}$ is intensity of direct solar radiation on the vertical window (W/m^2);
- I_{dv} is intensity of diffuse sky radiation (W/m^2);
- g is the value of the pane;
- A is surface area (m^2);
- T_{in} is indoor air temperature (^oC);
- T_{out} is outdoor air temperature (^oC);
- U is heat transfer coefficient $(W/m^2\mathrm{K})$, program WIS gives combined U value- U_{conv}, U_{ir} and U_{vent};
- U_{conv} convective and thermal radiative heat transfer coefficient from room to window $(W/m^2\mathrm{K})$;
- U_{ir} heat transfer coefficient due direct solar radiation $(W/m^2\mathrm{K})$;
- U_{vent} heat transfer coefficient due ventilative heat flow from room to window induced by air entering the room from the cavity, which is heated or cooled under influence of indoor temperature difference $(W/m^2\mathrm{K})$.

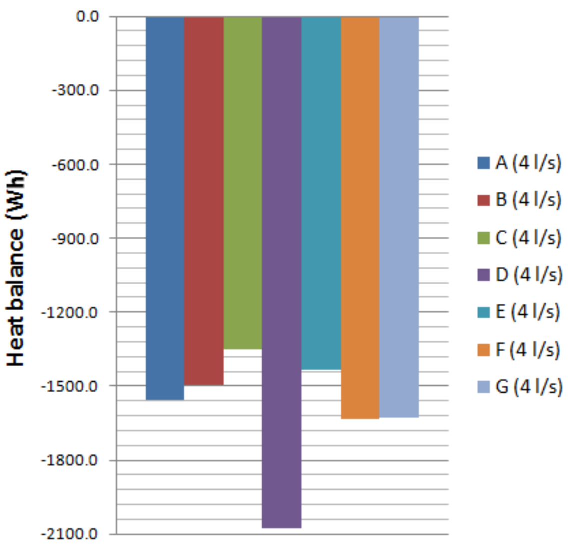

Figure 6.3: Opened cavity winter

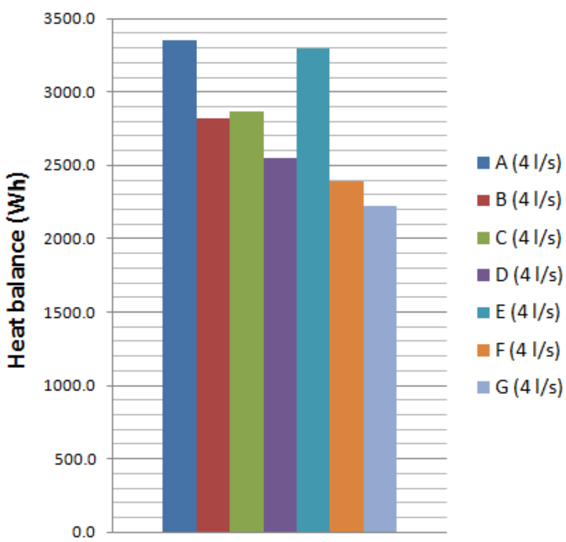

Figure 6.4: Opened cavity summer

As in section 6.1 in order to compare the simulated alternatives, the first case (A) with 3 clear panes is considered as a reference case. When the glass with low E coating replaces the inner clear glass (C), an increase in temperature at the inner pane is found in simulation results. Due to a substantial increase in temperature the air gets preheated from pane while crossing the cavity. Almost the same situation is in case (F) and (G) due to low E coating facing ventilated cavity. Despite there are only clear panes in case (E) the air in the cavity gets preheated by conductive heat exchange. Indoor heat preheats ventilated cavity due to high U value and conductive heat transfer. Considering case (B) it is noticed that low E coating on layer does not make any significant influence on preheating the crossing air. The heat from this pane being radiated to cooler panes but this makes almost no influence on temperature increase in cavity. When case (D) is taken into consideration it is evident that low E coating placed on the outer pane facing outside gives the worst results on energy balance calculations. This happens because the heat being transfered to the outside by conductive and radiative heat exchange. To get a better overview a graph 6.5 with temperature changes at the inlet slot, during winter day, is presented below.

Compared all the cases during warm day it is evident that placing low E coating on the pane(s) makes reasonable influence on heat balance results. The best performance as expected shows cases with low E coatings placed on the pane 1 facing outside. Most of the heat being reflected to the outside, also the conductive heat exchange plays role.

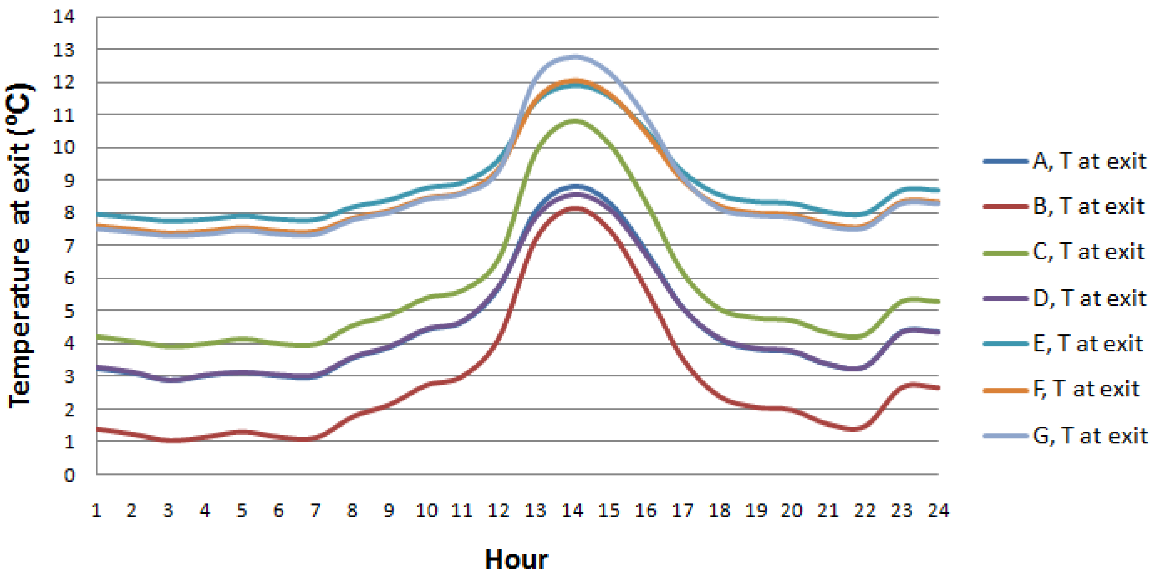

Figure 6.5: Temperatures at exit for all cases using 4l/s air flow in winter day

6.3 Calculation according CEN standards

One of the features of WIS program is to calculate window properties according CEN standards. So the results in this section using CEN mode is described. The calculation is made according European standards dealing with thermal and solar properties of windows. Using CEN calculation mode it is possible to calculate window properties only with closed cavity. Using CEN mode U-value and g-value is calculated for different window configurations. The energy balance for windows with closed cavities is calculated like earlier described in section 6.1. The energy balance is calculated for one summer and winter day hour. The results can be seen 6.6 and 6.7.

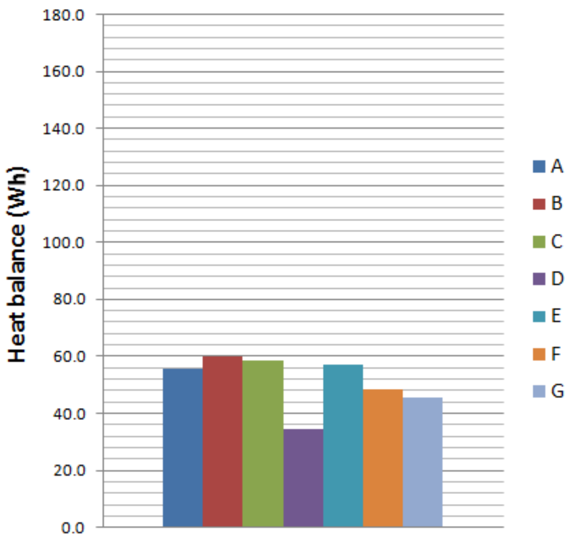

Figure 6.6: CEN winter

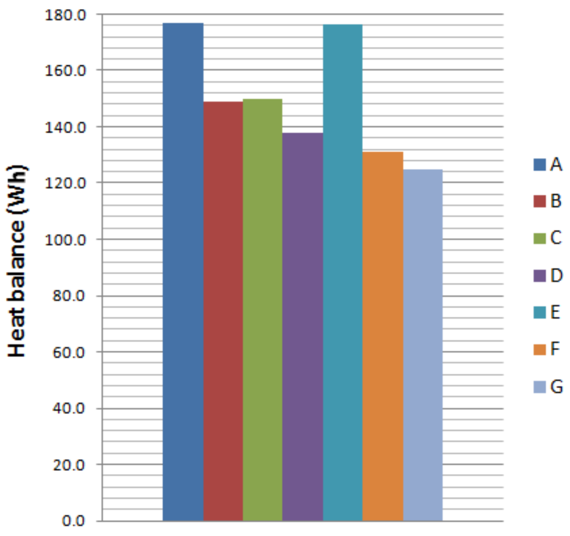

Figure 6.7: CEN summer

It is noticeable that there are similar results which are described in section 6.1. The graphs represents the same trend in amounts of energy in heat balance results, keeping into consideration that simulations are done for one hour.

All seven window configurations are chosen to be tested not randomly. Those cases are most likely to perform best. Through simulations and comparative graphs it has been possible to get an overview of best performing cases and configurations. A focus has been placed on energy balance, heat gains/losses through the window using equations 6.1. Since the window will be performing all year round the simulations has been made both for winter and summer typical day to get an idea how window performs in different temperatures.

6.4 Temperature and air flow dependence

In order to find out how temperature in exit depends on different air flow rates the simulations are done for different windows configurations. Simulations for all 7 window configurations are done without implementing shading device. Also cases A and G are tested with shading. Forced ventilation with and air flow from 0.5 to 4l/s is used. The shading device in case A is located in center of the ventilated cavity, and for case G it is tested in 3 different locations- center, close to inner pane and close to intermediate pane. The simulations are done in two different environments- with and without solar radiation in winter day at 12th hour A.2. The environment parameters are given in A.2, and solar radiation is assumed to be 0. The results are shown in 6.8 and 6.9.

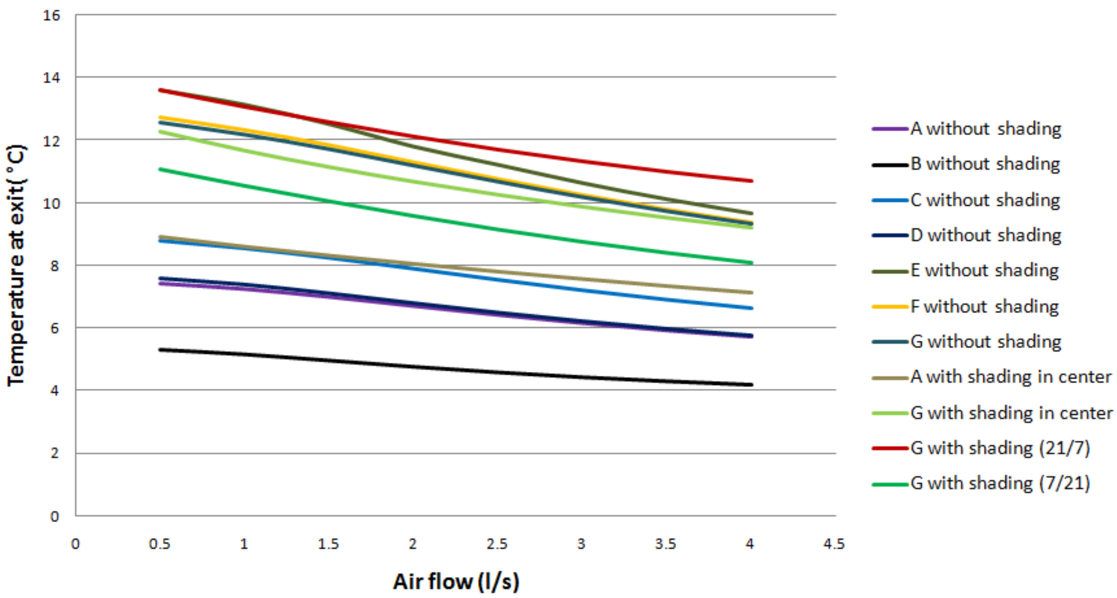

Figure 6.8: Temperature at exit for different air flow rates with solar radiation

In figure 6.8 the exit temperatures for different air flows are presented for a typical winter day with solar radiation. As shown in figure case G with shading device placed close to inside (shading device positioned 21mm from outer pane and 7mm from inside pane) side gives the highest exit temperatures. The environment parameters are given in A.2, and solar radiation is assumed to be 0. The results without solar radiation are shown in 6.9.

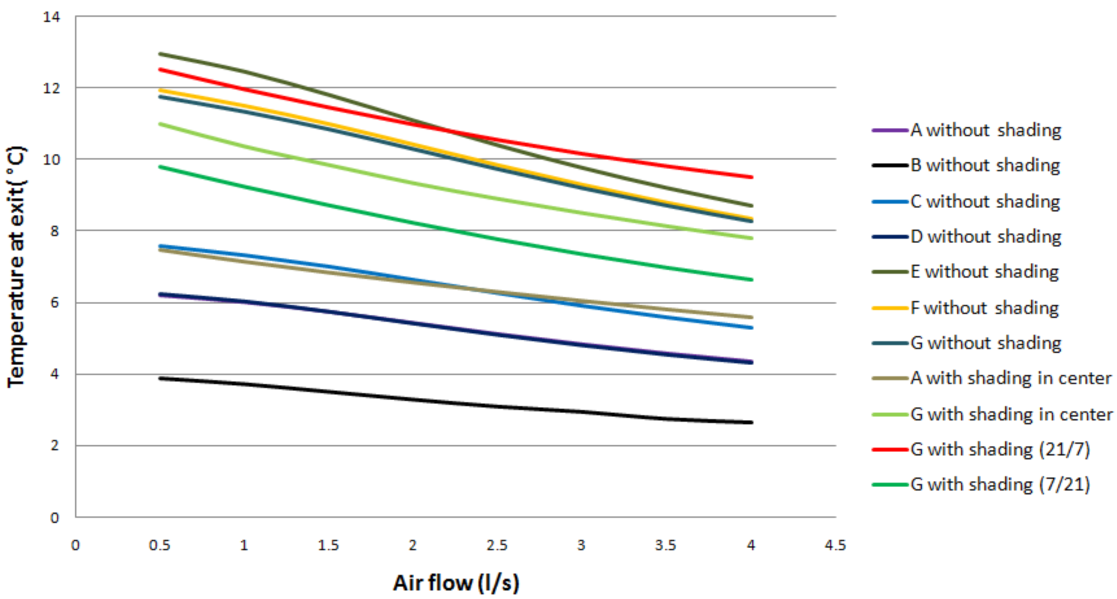

Figure 6.9: Temperature at exit for different air flow rates without solar radiation

The results are slightly different without solar radiation. The outlet temperatures are lower without direct solar radiation. The case G with shading (21/7) and E without shading device gives highest exit temperatures for small air flow rates. For higher air flow rates case G with shading (21/7) gives higher exit temperatures then case E.

6.5 Heat recovery efficiency

The heat recovery efficiency is calculated for all window configurations with and without shading device by the following equation. The results are shown in 6.10 and 6.11.

$$\mu_t = \frac{t_{exit} - t_{out}}{t_{ind} - t_{out}} \cdot 100\% \tag{6.3}$$

where

- t_{exit} is the air temperature at exit after preheating $[^oC]$;
- t_{out} is the outdoor air temperature $t_{out} = 2.7$, $[^oC]$;
- t_{ind} is the indoor air temperature $t_{ind} = 20$ $[^oC]$.

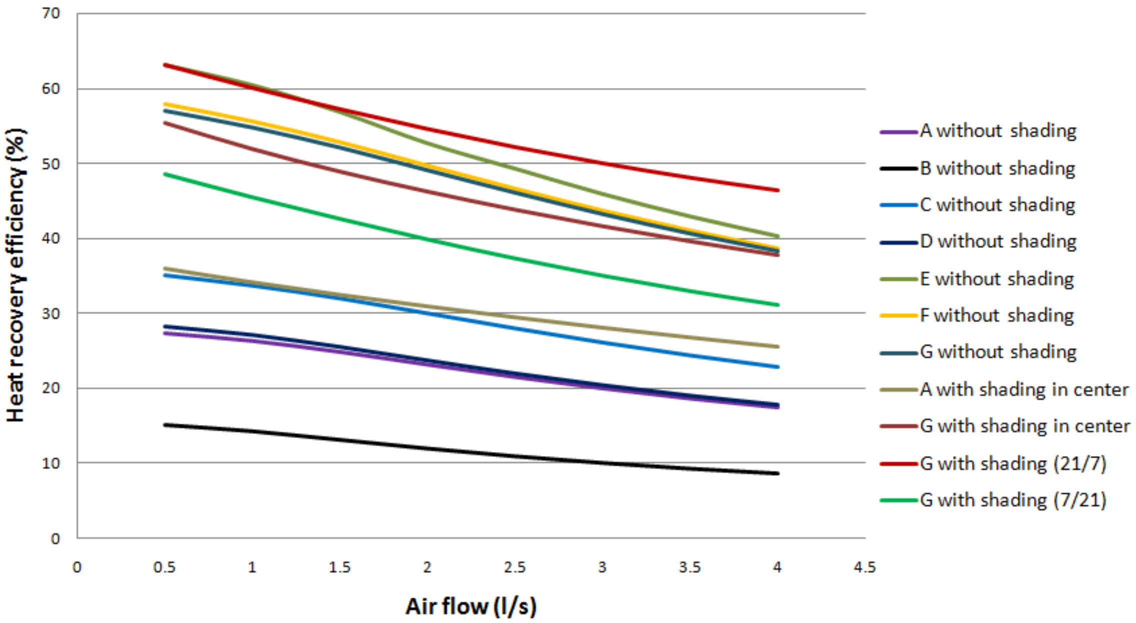

Figure 6.10: Heat recovery efficiency for different flow rates with solar radiation

From results presented in 6.10 it is seen when air flow is increased the percentage of recovered energy decreases. The calculation is done for a typical winter day with solar radiation. It is seen that case G with shading (21/7) gives the better heat recovery efficiency than other cases. Also it is seen that the case E without shading performs almost the same for low air flow. The results are similar without solar radiation 6.11.

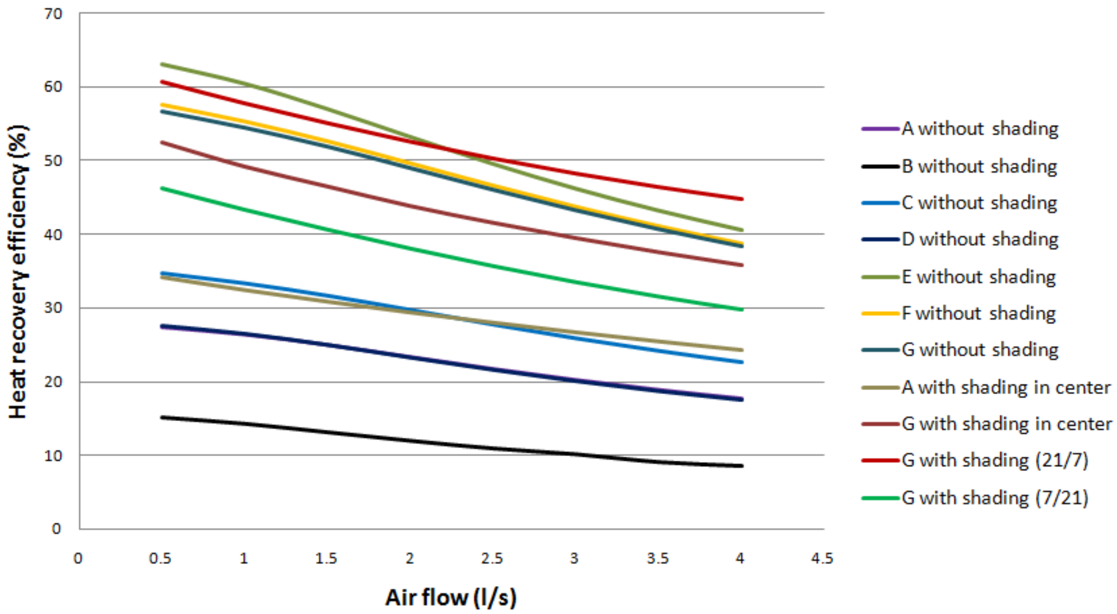

Figure 6.11: Heat recovery efficiency for different flow rates without solar radiation

The results of heat recovery efficiency for windows with different layout, with different air flow in gap and in few cases with shading, calculated during a typical winter night without solar radiation are shown in figure 6.11. Case E without shading gives the best heat recovery efficiency for small air flow rates also keeping into consideration that simulations are done only in cold period. Situation changes increasing air flow in G composition with shading (21/7) gives better heat recovery efficiency.

6.6 Comparison of energy balance for windows with different air flow and preheating

In this section comparison of four different cases is done. The energy balance for ventilated windows (C and F) with an air flow of 2; 4 l/s with preheating and 2; 4 l/s without preheating is calculated. In first situation, air gets preheated in window cavity and in second situation air is supplied directly from outside i.e. by bypass. This is done in order to get an idea of how much energy it is possible to gain/loose from environment. For energy balance calculations it is chosen to use 6.4 equation, but U value has to be split as it is known from previous section 5 the equation 6.5 consists of three components two components is calculated with WIS and ventilative heat transfer coefficient is calculated manually. In case with preheated air, for calculating energy losses due ventilation, the supply air temperature is used. In case with non preheated air, the outdoor air temperature is applied. The results are presented below.

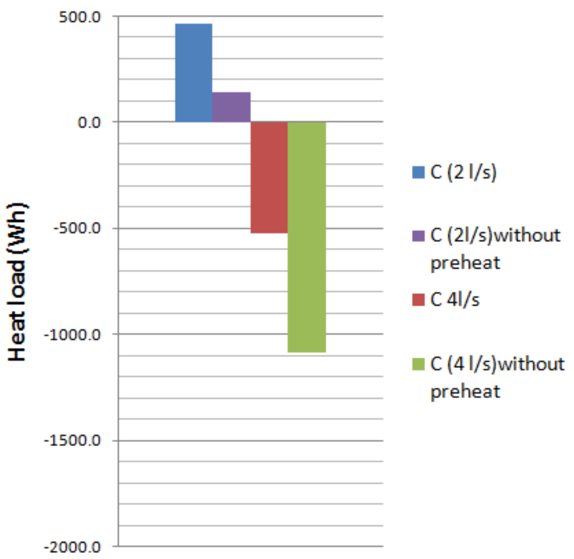

Figure 6.12: Heat load in winter for window C

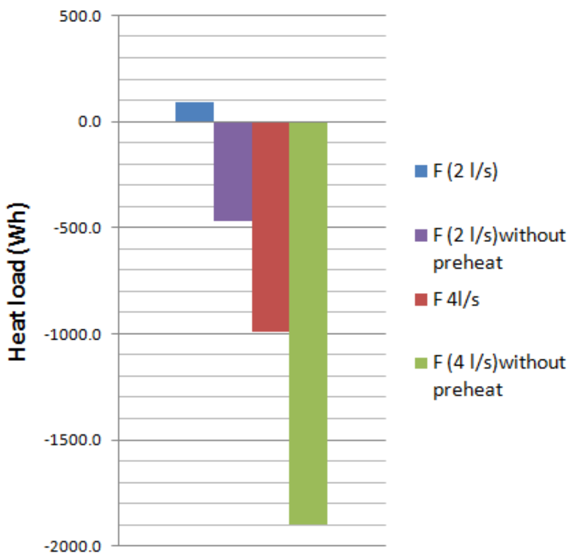

Figure 6.13: Heat load in winter for window F

From the results presented above, it is seen that when windows have ventilation of 2l/s the heat losses during day are significantly smaller compared with ventilation of 4l/s. Also it is noticeable that with cavity preheated air it is possible to save energy. When air is preheated and with air flow of 2 l/s it is possible to reduce about 75% of energy losses due ventilation. But with higher air flow energy savings decrease and results show savings about 50%. During cold period the temperature at outlet can be increased by reducing air flux or vice versa without compromising unnecessary energy losses.

The energy balance for window cases C and F, for summer with closed air gap and forced ventilation with 2, 4 l/s is calculated. The calculations are made using same methodology as for winter situation- using split U value when cavity is ventilated. The results are presented below.

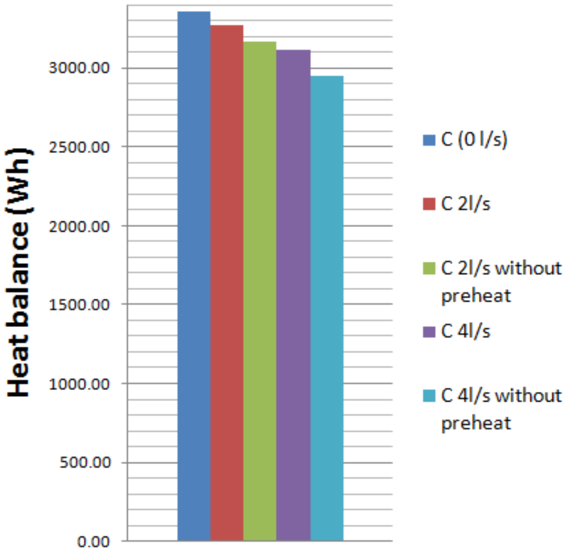

Figure 6.14: Heat balance in summer for window C

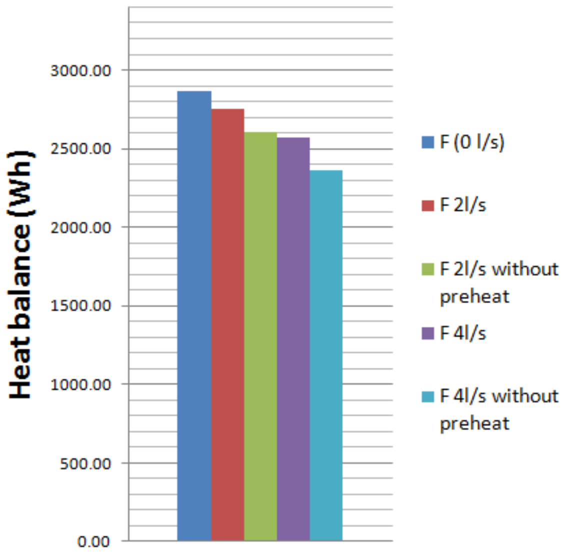

Figure 6.15: Heat balance in summer for window F

From results presented in 6.14 and 6.15 it is seen that it is possible to reduce heat gains using ventilated gap. Reduction in heat gains can be also noticed when air is supplied directly from outdoors with high air flux, without crossing ventilated cavity. Calculations concerning control strategies is presented later.

To sum up all the results presented above it must be stressed that implementing low E coating to windows has a significant positive impact on heat balance. The usage of coating shows positive results in summer as well as for the winter. Through simulations and result comparison it is easy to get an overview of energy amounts which will be saved when using double ventilated windows. For other simulations the case G, with low E coating facing ventilated cavity, is chosen to use as a best performing window configuration. Later in the project the shading device will be implemented in window configuration G.

6.7 Influence of the position of shading device for energy balance

The position of shading devices inside the cavity can have a huge impact on the energy and thermal performance of ventilated window. In order to find out how results in heat balance calculations depends on different position of shading device, a cavity of 28mm depth is selected and window configuration G, with shading positioned in center of the cavity, case G with shading device positioned 7mm from outer pane and 21mm from inside pane, and case G with shading device positioned 21mm from intermediate pane and 7mm from inside pane, are simulated. The comparison of these 3 different shading positions both for summer and winter days is done using heat balance calculations.

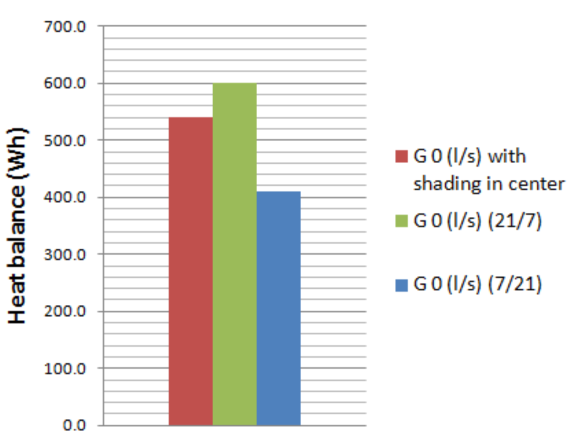

Figure 6.16: Heat balance for window G with closed air gap and different shading positions in winter

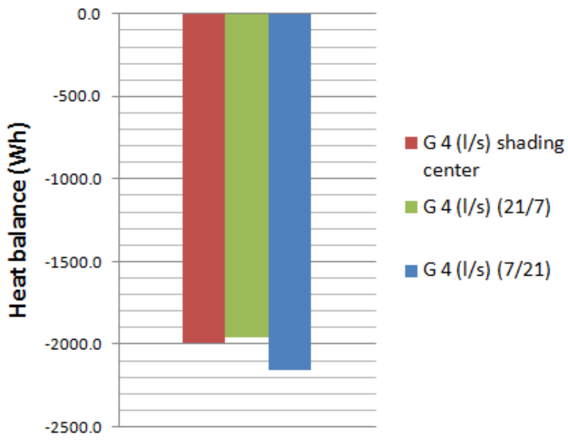

Figure 6.17: Heat balance for window G with 4(l/s) forced ventilation and different shading positions in winter

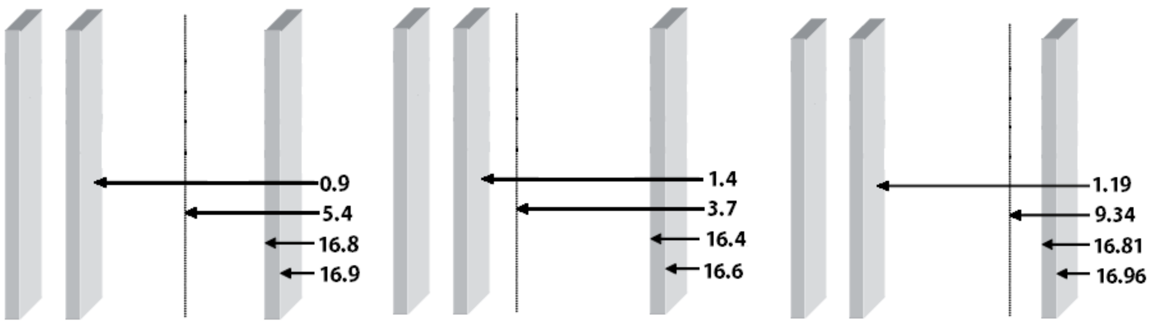

Figure 6.18: temperatures in window case G with air flow of 4l/s for winter night

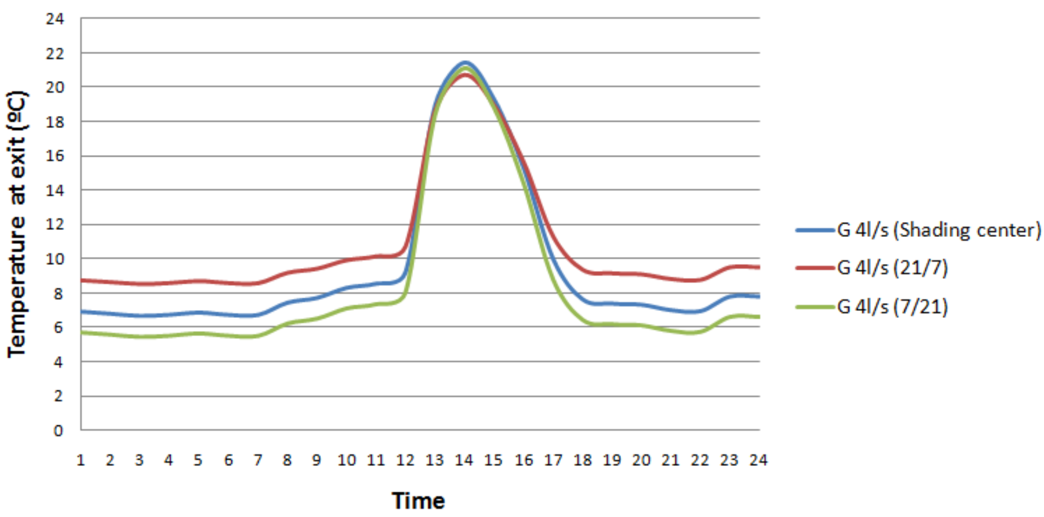

Figure 6.19: outlet temperatures with different shading position in case G for winter day

In figures 6.16 and 6.17 the heat load for different shading positions is presented. The main aim of this comparison is to investigate the influence of shading device position for heat balance. From the results for winter situation it is seen that it is possible to save energy when shading device is closer to internal pane. Even bigger difference between shading positions can be seen when air gap is ventilated. In figure 6.18 temperature in different layers of window is presented. The impact of shading device is visible- having it closer to inside pane, causes the reduction of transmission losses. More heat from inside is absorbed in shading unit and then by air flux is recovered back to inside. Figure 6.19 gives an idea of shading performance during cold day. In point where the sun radiation is highest the outlet temperatures gets equal, but in all other time of the day case with shading placed close to inside pane gives highest outlet temperatures. On the other hand the results are different for summer.

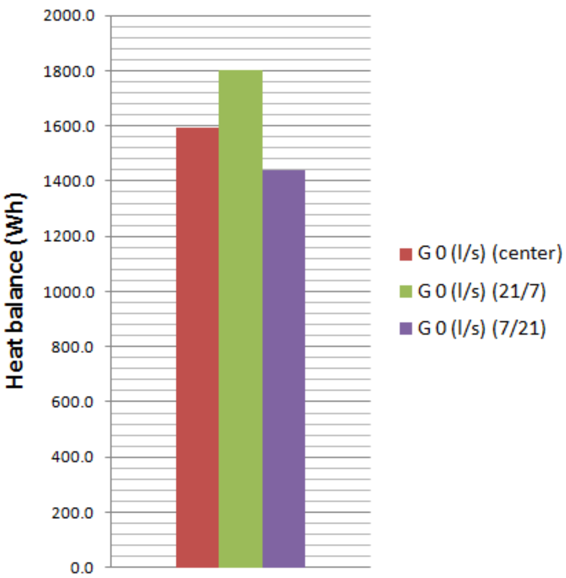

Figure 6.20: Heat load for window G with closed air gap and different shading positions in summer

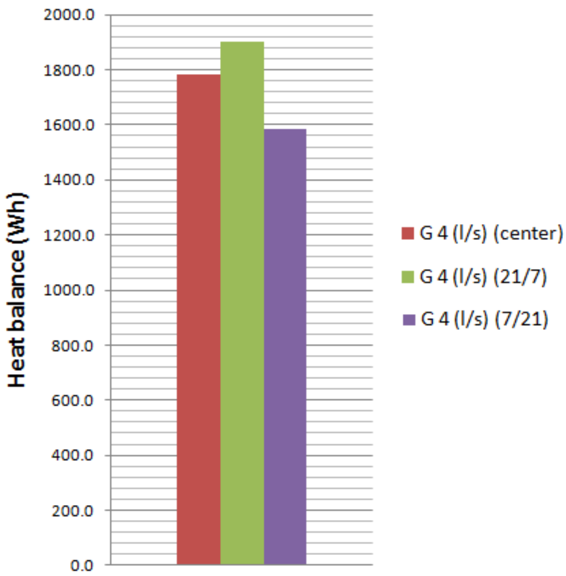

Figure 6.21: Heat load for window G with 4 (l/s) forced ventilation and different shading positions in summer

As shown in the figure 6.20 it is seen that it is possible to save energy when shading device is closer to intermediate pane. From the above it can be concluded that the shading device position in the ventilated cavity is important for window thermal performance. Due to radiative heat transfer the most efficient shading position for cold period is closer to indoor pane and for summer vice versa. With appropriate choice of positioning shading device for different seasons, or climates it is possible to reduce heat gains in summer or heat losses in winter.

6.8 Comparison of energy balance for windows with shading device and without shading device

The importance of presence and absence of shading device in ventilated or not ventilated window is of interest in this section. In order to compare heat load the case G with shading device and without shading device is simulated and then using energy balance, for window with closed cavity and window with opened cavity, equations are used. The comparison both for summer and winter is done.

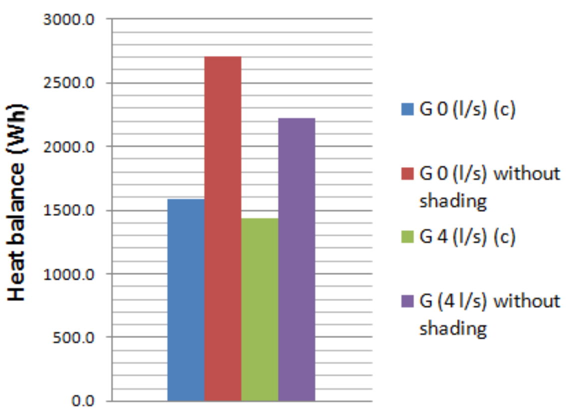

Figure 6.22: Heat balance for window with closed air gap with shading and without shading in summer

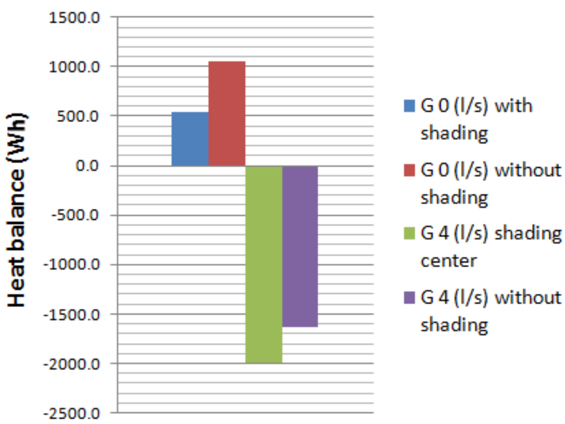

Figure 6.23: Heat balance for window with an air flow of 0 (l/s) and 4 (l/s) with shading and without shading in winter

In figures 6.22 and 6.23 the heat load for summer and winter is presented. From the results for summer it is evident that having shading device in the air gap results best results in heat balance. On the other hand, having it in cavity in winter time causes less heat gains from outside. The difference of heat load for windows with closed cavity is bigger when cavity is ventilated. From the above it can be concluded that the presence and absence of shading device in the ventilated cavity is important for window thermal performance and should be controlled in order to get desired results.

6.9 Comparison of energy balance for windows with different shading device and without shading device

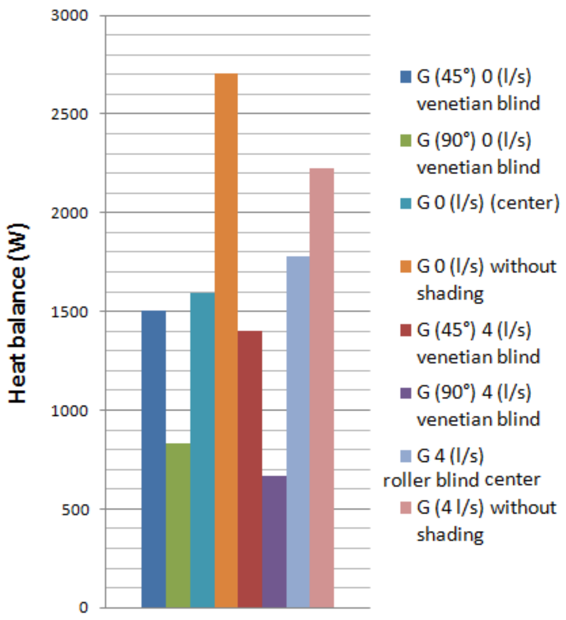

Figure 6.24: Heat balance for window with different shading device type and without shading device in summer

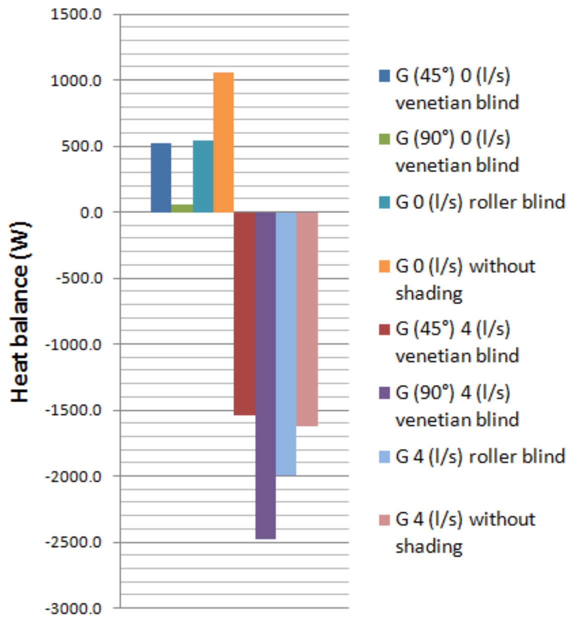

Figure 6.25: Heat balance for window with different shading device type and without shading device in winter

One of aspects of shading device performance that is investigated by this series of simulations are made in order to define the best performing solution for ventilated window case. Simulations are done to test and compare the performance of two type of shading devices. The roller blind and venetian blind are chosen as most common types of shadings. Simulations with venetian blind are done in two ways- first it is tried to check the performance when shading is fully blinded (90^o) and half blinded (45^o).

From results presented above it is obvious that having a shading device in warm period is a must in order to prevent heat gains. The best performance of venetian blind is seen in all three cases when there is no air flow in the window cavity, when there is air flow of $4l/s$ and a blind is set to 45^o and 90^o angle. The case for winter time is shown for comparable reasons- from previous simulations the results shows that there is no need for shading device. The outlet temperatures for ventilated cases are give in appendix C.

6.10 Control strategy

Previous studies have shown that the use of controlled windows could lower the energy consumption of buildings. Considering that the main function of windows is providing day light, transparency and in this case fresh air, the control of these contributors is needed. Looking at energy perspective, it is almost always good to have as low-transparency as possible. This can be applied when energy demand for cooling is taken into consideration. In this section the simple control strategy is applied to window case G. The shading device is implemented in window cavity to check which position gives best results in energy balance for summer. Calculations are done using thermal balance method and implementing thermal loss due to ventilative heat flow.

Energy optimization means that the windows are always kept in the state that is best from a heating and cooling perspective. So the aim of this test is to check how much energy it is possible to save using roller blind and grills with bypass, if the bypass opens when the cavity temperature exceeds 20^oC. When the temperature reaches 20^oC air flow of 3l/s from outside comes directly trough bypass and 1l/s through ventilated cavity. It is impossible to close grills completely 8.

$$Q = ((I_{s\varphi} + I_{dv}) \cdot g \cdot A) - (T_{in} - T_{out}) \cdot U \cdot A - \rho \cdot c_p \cdot q_v \cdot (T_{in} - T_{inlet}) - \rho \cdot c_p \cdot q_v \cdot (T_{in} - T_{out}) \tag{6.4}$$

where

- Q is heat load (Wh)
- $I_{s\varphi}$ is intensity of direct solar radiation on the vertical window (W/m^2)
- I_{dv} is intensity of diffuse sky radiation (W/m^2)
- U is heat transfer coefficient (W/m^2K), program WIS gives combined U value- U_{conv}, U_{ir}
- U_{conv} convective and thermal radiative heat transfer coefficient from room to window (W/m^2K)
- U_{ir} heat transfer coefficient due direct solar radiation (W/m^2K)
- g is the g-value of the pane
- A is surface area (m^2)
- T_{in} is indoor air temperature (^oC)
- T_{out} is outdoor air temperature (^oC)
- ρ is is the air density $(1,2kg/m^3)$
- c_p is the specific heat capacity of air $(1005J/kg^oC)$
- q_v is is the calculated ventilation in (m^3/s)
- T_{inlet} is air temperature at the inlet slot (^oC)

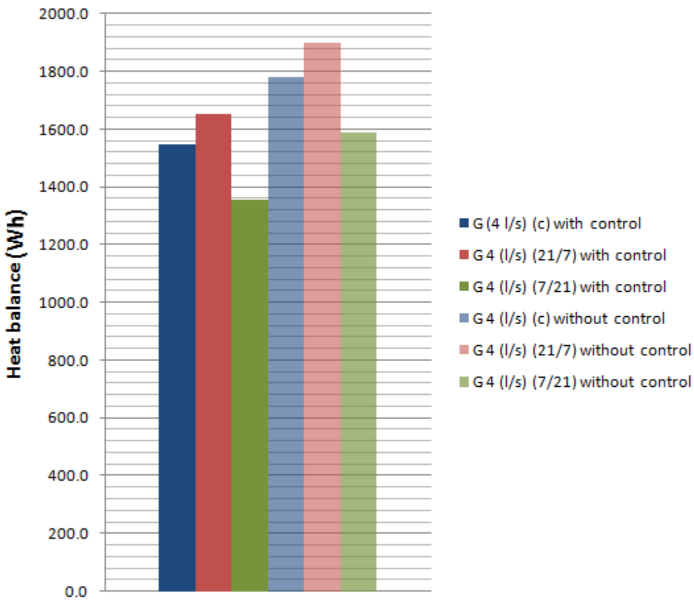

Figure 6.26: With and without control strategy in window case G

In the simulations the window is kept in a low-transparent state by using shading device (roller blind). For the energy simulations it is important to note that the results show the energy balance caused by the window only. The different colors (transparent represent same window configuration but without control strategy) in the figure represent different window G configurations. The graph shows the energy balance of window G during 24 hours of the warm day. To be able to compare results between window G configuration with shading device 6.21 without control strategy and with control strategy, the U value calculated by program WIS had to be split. Splitting U value is done for both methods- with and without control strategy. Afterwards the heat balance with the flow of 4l/s for non controlled window is calculated using equation 6.5

$$Q = ((I_{s\varphi} + I_{dv}) \cdot g \cdot A) - (T_{in} - T_{out}) \cdot U \cdot A - \rho \cdot c_p \cdot q_v \cdot (T_{in} - T_{inlet}) \tag{6.5}$$

The intention of using this equation is to manually add the flow of 4l/s through the cavity to inside of the building. The results represents the changes in heat balance with and without control strategy, and the best configuration for warm period is having shading device close to intermediate pane. The control strategy shows approximately 14% better results in heat balance results.

6.11 Temperature distribution in windows

Due to results in section 6.4 it is decided to plot some results from WIS simulations. For plotting results it is chosen to show solar radiations affect to window layers in all the cases. The results are taken from simulations in winter using solar radiation and without it, also it is chosen to use 2l/s air flow in the cavity. WIS does not take diffuse sun radiation into consideration.

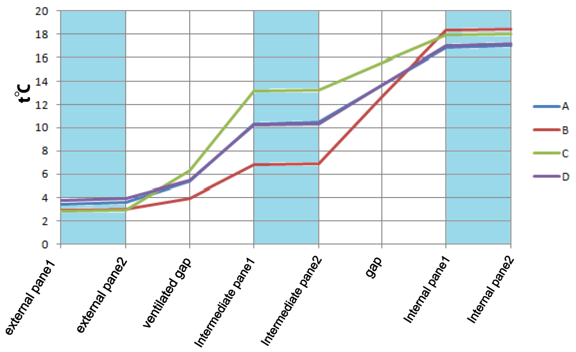

Figure 6.27: Temperature distribution through windows A, B, C and D when exposed with solar radiation

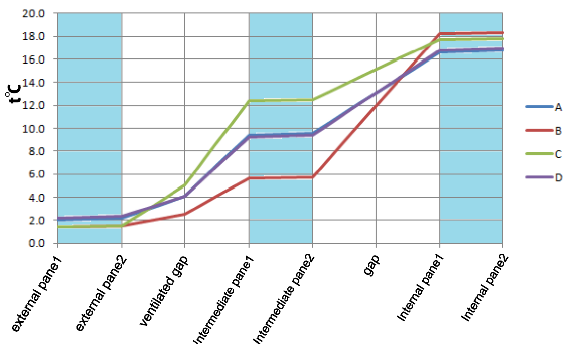

Figure 6.28: Temperature distribution through windows A, B, C and D without solar radiation

In the figures above the temperature distribution is presented in window layouts where the ventilated cavity is located closer to outside. It is noted that in cases with solar radiation, the temperature in ventilated cavity is slightly higher than in cavity without solar radiation applied. The highest temperature in ventilated cavity is reached in case C, due the low E coating located on intermediate pane1. The temperature difference between cases C and B (no low E coating in ventilated cavity) in cavity is $6.8^{o}C$ with solar radiation and $6.3^{o}C$ without solar radiation. The temperature difference, between cases with and without sun radiation, in case C on boarder of pane with low E coating is $0.7^{o}C$. Also a steep increase in temperature is noted in the cavity close to inside. This happens due to convective heat transfer from indoors.

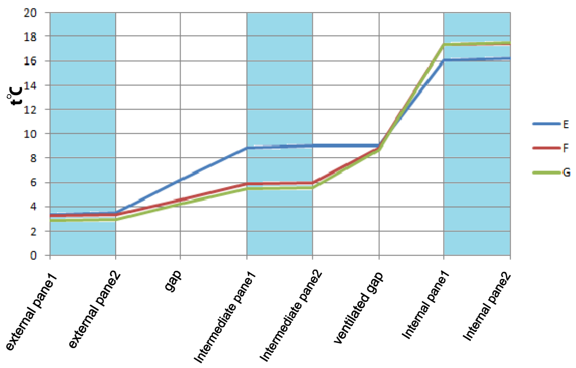

Figure 6.29: Temperature distribution through windows E, F, and G when exposed with solar radiation

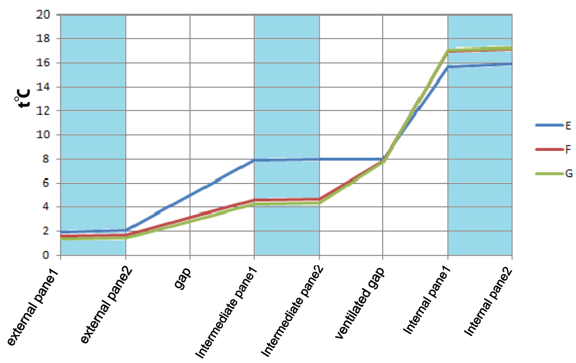

Figure 6.30: Temperature distribution through windows E, F, and G without solar radiation

In figures 6.29 and 6.30 the temperature distribution is presented in window layout cases E, F and G. Here the ventilated cavity is located closer to indoors. The situation in the middle layer is almost the same as in previous cases A, B, C and D- the temperature is slightly higher when exposed to solar radiation. The steepest temperature increase is seen in ventilated cavity. The biggest influence to temperature increase in ventilated cavity is made by convective heat transfer from indoors.

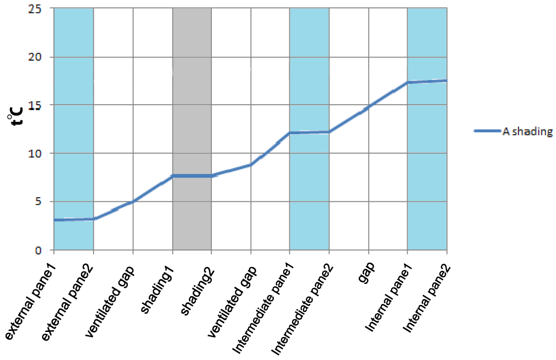

Figure 6.31: Temperature distribution through window A using roller blind

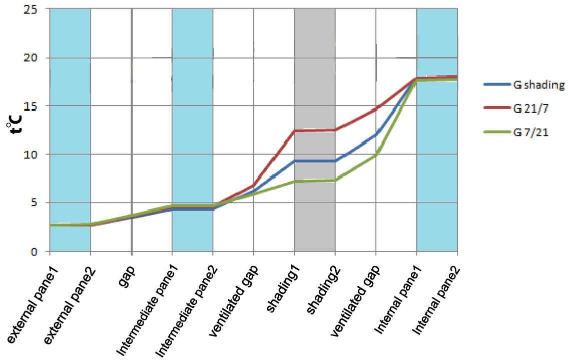

Figure 6.32: Temperature distribution trough window G using different positions of roller blind

In order to show how windows behave concerning temperature distribution, using shading device, it is chosen cases A (shading device placed in the middle of ventilated cavity) and G (shading device is placed in three different places of ventilated cavity) for plotting results. The highest temperature of $12.5^{o}C$ in cavity is reached when shading device is placed 21mm from outdoor side of ventilated cavity. In all cases, with shading device, plotted above, windows are exposed to sun radiation.

Chapter 7

Simple calculation method

Another way to predict energy performance of ventilated window is simple calculation method. Using this method it is possible to calculate real energy consumption of all building or building part. In this method the impact of ventilated window on the overall energy demand of building is applied. This calculation method should offer sufficient accuracy of the thermal behavior and the energy performance of the analyzed system. This tool helps set future targets and identify measures to reduce energy consumption. The following equations are used [11]:

Energy need for heating and cooling is given in 7.1 and 7.2.

$$Q_{H,nd} = Q_{ls} - \eta_{gn} \cdot Q_{gn} \tag{7.1}$$

$$Q_{C,nd} = Q_{gn} - \eta_{ls} \cdot Q_{ls} \tag{7.2}$$

where

- Q_{ls} is the heat losses$[kWh]$, Equation 7.3;
- Q_{gn} is the heat gains$[kWh]$, Equation 7.4;
- η_{gn} is the gain utilization factor for heating, Equation 7.8, 7.9;
- η_{ls} is the gain utilization factor for cooling, Equation 7.15, 7.16.

Heat losses are calculated as in 7.3.

$$Q_{ls} = Q_{tr} + Q_{ve} \tag{7.3}$$

where

- Q_{tr} are the total transmission heat losses$[kWh]$, Equation7.5;

- Q_{ve} are the total ventilation heat losses$[kWh]$, Equation 7.6.

Total heat gains are calculated as in 7.4.

$$Q_{gn} = Q_{int} + Q_{sol} \tag{7.4}$$

where

- Q_{int} is the sum of the internal heat gains over a given period, it is assumed that it is $0[kWh]$;
- Q_{sol} is the sum of the solar heat gains over a given period$[kWh]$, Equation7.7;

The total transmission heat losses are calculated as in 7.5.

$$Q_{tr} = A \cdot U \cdot (T_{ind} - T_{out}) \tag{7.5}$$

where

- A is the area of the component of the surface separating the evaluated building zone from the unheated glazed annex $[m^2]$;
- U is the U-value of window $[W/(m^2K)]$;
- T_{ind} is indoor air temperature, it is assumed that it is 20 $[^oC]$;
- T_{out} is outdoor air temperature $[^oC]$.

The total ventilation heat losses are calculated as in 7.6.

$$Q_{ve} = \rho \cdot c_p \cdot q_v \cdot (T_{in} - T_{inlet}) \tag{7.6}$$

where

- T_{in} is indoor air temperature $[^oC]$;
- ρ is is the air density $[1, 2kg/m^3]$;
- c_p is the specific heat capacity of air $[1005J/kg^oC]$;
- q_v is is the calculated ventilation in $[m^3/s]$;
- T_{inlet} is air temperature at the inlet slot $[^oC]$.

The sum of the solar heat gains over a given period is calculated as in 7.7.

$$Q_{sol} = F_{F,iu} \cdot A \cdot g \cdot F_{F,ue} \cdot \tau_{e,ue} \cdot I_s \cdot t \tag{7.7}$$

where

- $F_{F,iu}$ is the correction factor accounting for the proportion of the frames of the internal glazing, it is assumed that it is 0.9;
- $F_{F,ue}$ is the correction factor accounting for the proportion of the frames of the external glazing, it is assumed that it is 0.9;
- $\tau_{e,ue}$ is the transmittance of the external glazing (is calculated using WINDOW5 program and is different for direct and diffuse solar radiation) ;
- I_s is the global solar radiation intensity for the orientation of the respective dividing surface $[W/m^2]$;
- t is time, it is assumed that it is 1 $[h]$.

The gain utilization factor for heating is calculated as in 7.8 or 7.9.

if $\gamma_H \neq 1$ then

$$\eta_{H,gn} = \frac{1-\gamma_H^{a_H}}{1-\gamma_H^{a_H+1}} \tag{7.8}$$

if $\gamma_H = 1$ then

$$\eta_{H,gn} = \frac{a_H}{a_H+1} \tag{7.9}$$

where

$$\gamma_H = \frac{Q_{gn}}{Q_{ls}} \tag{7.10}$$

$$a_H = a_{0,H} + \frac{\tau_H}{\tau_{0,H}} \tag{7.11}$$

- γ_H is the dimensionless gain or loss ratio for the heating mode;
- a_H is the dimensionless numerical parameter depending on the time constant τ_H;
- $a_{0,H}$ is the dimensionless reference numerical parameter;
- τ_H is the time constant of a building or building zone $[h]$;

- $\tau_{0,H}$ is the reference time constant.

Time constant for a building or building zone is calculated 7.12:

$$\tau_H = \frac{C_m/3{,}6}{H_L} \tag{7.12}$$

where

$$C_m = \sum_j \cdot \sum_i \cdot \rho_{ij} \cdot c_{ij} \cdot d_{ij} \cdot A_j \tag{7.13}$$

- H_L is heat transfer coefficient, Equation 7.14;
- ρ_{ij} is the density of the material of a layer i in element j $[kg/m^3]$, for brick wall 1700;
- c_{ij} is the specific heat capacity of the material of a layer i in element $[kJ/kgK]$, for brick wall 0.84 ;
- d_{ij} is the thickness of a layer i in element j $[m]$ for the utilization factor calculation, 0,4 $[m]$;
- A_j is the area of element i of the building envelope $[m^2]$;
- U_{wall} is the U value of the building envelope $[W/(m^2K)]$, 2,13;
- A_{wall} is the area of the building envelope $[m^2]$.

$$H_L = U_{wall} \cdot A_{wall} \tag{7.14}$$

The gain utilization factor for cooling is calculated as in 7.15 or 7.16.

if $\lambda_C \neq 1$ and $\lambda_C > 0$ then

$$\eta_{C,ls} = \frac{1-\lambda_H^{a_H}}{1-\lambda_H^{a_H+1}} \tag{7.15}$$

if $\lambda_C = 1$ then

$$\eta_{C,ls} = \frac{a_H}{a_H+1} \tag{7.16}$$

if $\lambda_C < 0$ then $\eta_{C,ls} = 1$

The mean air temperature in the ventilated window cavity is calculated according to EN ISO 13789 7.17,

$$\vartheta_u = \frac{\varphi_u + \vartheta_i (H_{T,iu} + H_{V,iu}) + \vartheta_e (H_{T,ue} + H_{V,ue})}{H_{T,iu} + H_{V,iu} + H_{T,ue} + H_{V,ue}} \tag{7.17}$$

where

- φ_u is heat gains affecting the ventilated window cavity (what stays in ventilated cavity)$[W]$;
- ϑ_i is the indoor air temperature in $[K]$;
- ϑ_e is the outdoor air temperature in $[K]$;
- $H_{T,iu}$ is the heat transfer coefficient of transmission of the components between the zone being evaluated and the adjacent unheated building zone (ventilated window gap)in $[W/K]$;
- $H_{T,ue}$ is the heat transfer coefficient of transmission of the building components between the unheated building zone (ventilated window gap)and the exterior in $[W/K]$;
- $H_{V,iu}$ is the heat transfer coefficient of ventilation between the building zone being evaluated and the adjacent unheated building zone (ventilated window)(normally, $H_{V,iu} = 0$ can be assumed)in $[W/K]$;
- $H_{V,ue}$ is the heat transfer coefficient of ventilation between the adjacent unheated building (ventilated window)zone and the outside atmosphere in $[W/K]$.

The outlet temperature in the ventilated window can be estimated as 7.18,

$$\vartheta_{out} = \vartheta_e + 2 \cdot (\vartheta_u - \vartheta_e) \tag{7.18}$$

7.1 Simple calculation method calculated for 24 hours

In this chapter the energy consumption for court building, located in Herredsfoged, both for summer and winter is calculated for 24 hours. The calculations are done implementing simple calculation method. The energy need for cooling and heating is calculated for simplified building model i.e. this analyzed model has the same size windows 1,4 m wide and 1,09 m hight and outer walls are made from red bricks 0,4 m thickness, roof is also 0,4 m thickness. The outer wall area is $377.54m^2$, roof area $227m^2$. The building ventilated area is $293m^2$ and including non ventilated area the total building area is assumed to be $350m^2$. This area is cooled/heated. Also it is assumed that this building has 10 windows facing south, 9 facing north, 5 - east and 8 windows are facing west direction. The diffuse and direct solar radiation is recalculated at the respective directions [10]. Additionally calculation is done using the energy labeling method for windows [13]. This method should help to reduce total heating and cooling needs. The energy need for cooling and heating is calculated weighting the heat gain/loss for the defined window orientations(it is called labeling method) south

41%, north 26%, east and west 33%. In this section U-value, g-value and outlet temperature for the ventilated window are calculated using WIS program. All calculations are done using equations which are explained in chapter 7. The results of energy need for cooling and heating for all building with different window layouts, is calculated with 4 l/s air flow in the ventilated air cavity and without control strategy, during a typical summer day. The comparison of results using energy labelling method for window areas and window areas set as in referance building, located in Herredsfoged is shown in figures 7.1 and 7.2 and for typical winter day results are shown in figure 7.3.

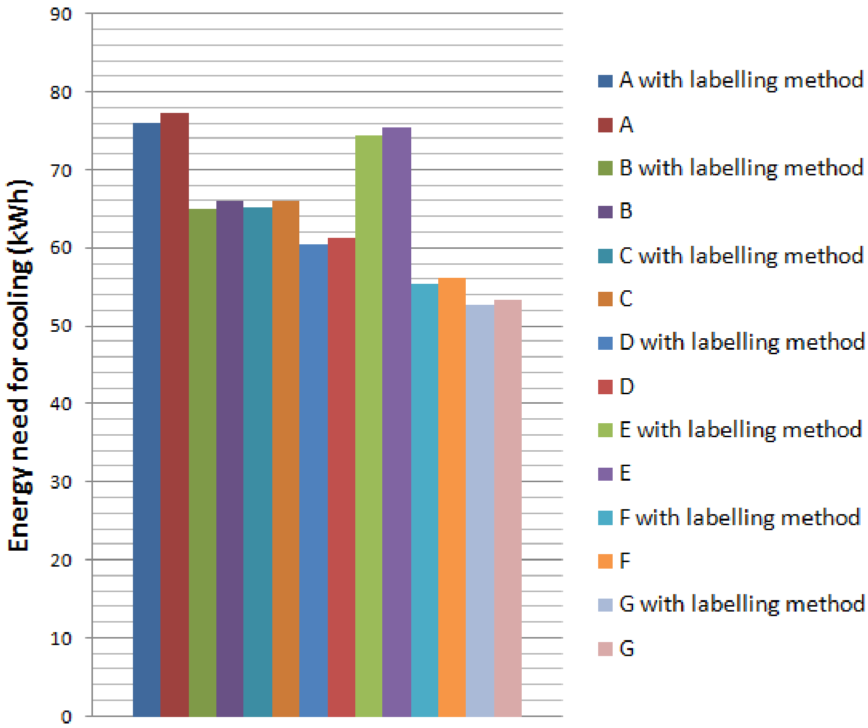

Figure 7.1: The comparison of energy need for cooling and for 24 hours in typical summer day for different ventilated window configurations

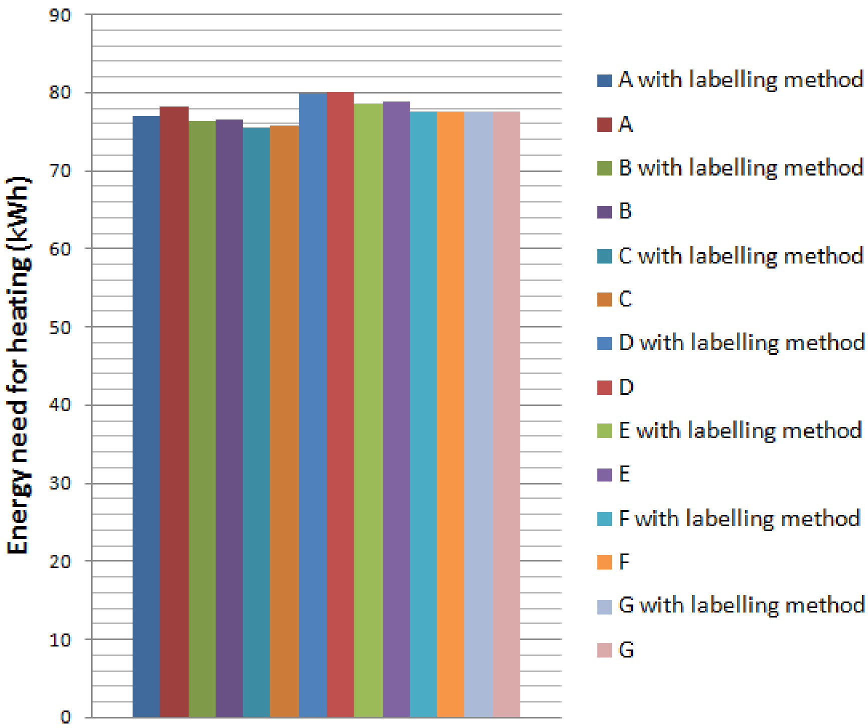

Figure 7.2: The comparison of energy need for heating and for 24 hours in typical summer day for different ventilated window configurations

In figures 7.1 and 7.2, the difference in energy use for cooling and heating is compared between the different window configurations. Also the comparison between two different methods is done. The output of simple calculation method for 24 hours shows that for cooling window G performs best. The main reason why G window configuration gives the lowest energy need for cooling that it has the lowest g value. But the results for heating need are different window configurations B and C give almost the same result. The window configuration C performs best from these 7 different window configurations because it has the optimal U and g values combination. Furthermore using labeling method it is possible to save 1.5% of total energy need for cooling for case G and just 0.15% of total energy need for heating for case C. It is possible using this method to save energy both heating and cooling need in all window configurations.

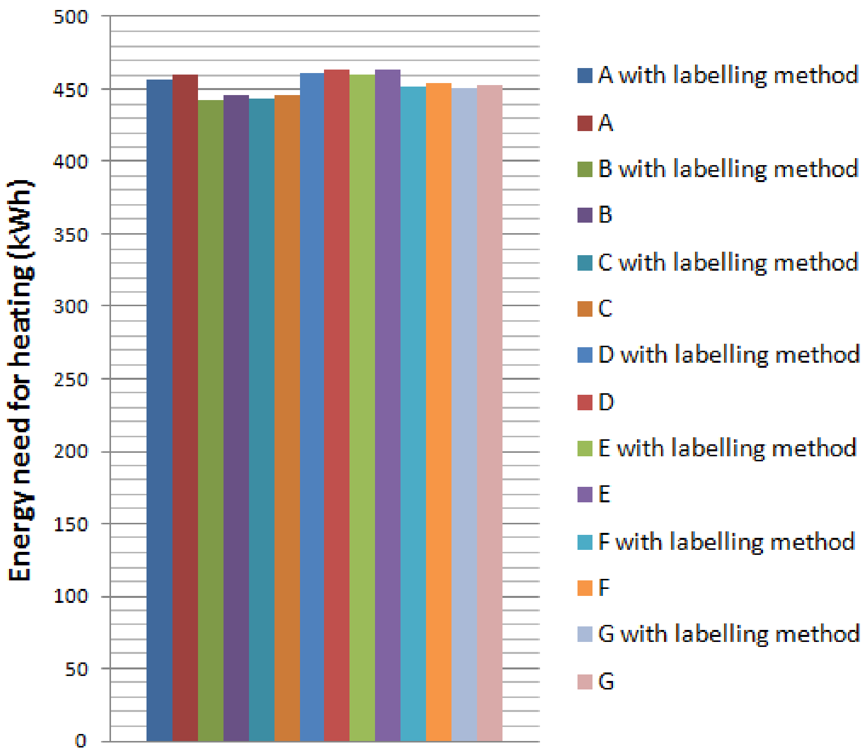

Figure 7.3: Energy need for heating and 24 hours in typical winter day for different ventilated window configurations

The calculations are done not only for typical summer but also for typical winter day. The energy need for cooling is 0 $[kWh]$in typical winter day. The results show that for heating need the same window configurations B and C are leading. But the energy need for heating increases more than 5 times. Also results show that C window configuration performs best and gives the lowest energy need for heating. The reason of this result is quite low U value and hight g value of this window configuration. Also it is seen that using labeling method is useful not only for summer but also winter time.

7.2 Simple calculation method calculated for 24 hours with split CEN

In this section U and g values are calculated using WIS program as in section 7.1. But the outlet temperature for the ventilated window is estimated using simple calculation method equation 7.18. In order to calculate outlet temperature it is necessary to find mean temperature of the ventilated cavity equation 7.17 to do that the heat transfer coefficients are specified for window layer which separates ventilated air gap with outside air and ventilated air gap with indoor air. The U-value is calculated for interior and exterior side of the window in CEN mode with program WINDOW5. The $U_{exterior}$ and $U_{interior}$ values are given in table 7.1.

Window Case	$U_{exterior}$	$U_{interior}$
A	5.733	2.839
B	5.733	1.307
C	5.733	2.667
D	5.733	2.667
E	2.653	5.799
F	2.653	5.799
G	2.653	5.799

Table 7.1: U-values for different window configurations

The results of energy need for cooling and heating for all building with different window layouts, is calculated with 4 l/s air flow and without control strategy, with split CEN, during a typical summer day results are shown in figures 7.4 and 7.5 and for typical winter day results are shown in figure 7.6. The results are compared with results which are estimated using outlet temperature from WIS simulation and without labeling method 7.1.

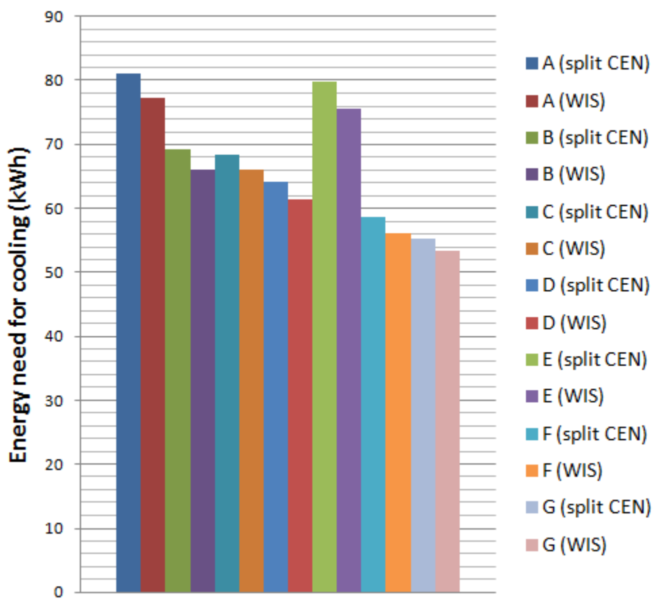

Figure 7.4: Energy need for cooling and 24 hours in typical summer day for different ventilated window configurations calculated using outlet temperature using simple calculation method and compared with results from section 7.1

The energy need for cooling calculated as explained above is bigger then is calculated in section 7.1. The bigger energy need for cooling is because using simple calculation method and equation 7.18 the outlet temperatures are bigger then calculated with program WIS. The energy need for cooling is bigger $7.1\% - 18.4\%$ differance depends on window configuration.

Also results show that G window configuration performs best and gives the lowest energy need for cooling.

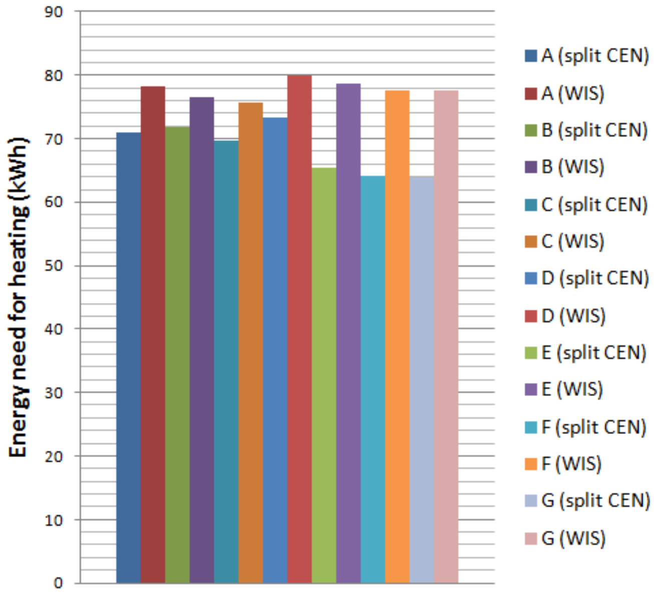

Figure 7.5: Energy need for heating and 24 hours in typical summer day for different ventilated window configurations calculated using outlet temperature using simple calculation method and compared with results from section 7.1

As it is noticeable the heating need is smaller then in section 7.1,because of bigger temperature in ventilated air outlet. The energy need for heating is smaller 3.4% − 4.8%. Also it is seen that G window configuration performs best and gives the lowest need for heating. The results are different comparing with sections 7.1 results. The C window configuration gives the lowest energy need for heating in chapter 7.1. The differance occure between two methods because of quite big outlet temperature difference figure 7.7. The results are shown not only for typical summer day but also for typical winter day figure 7.6.

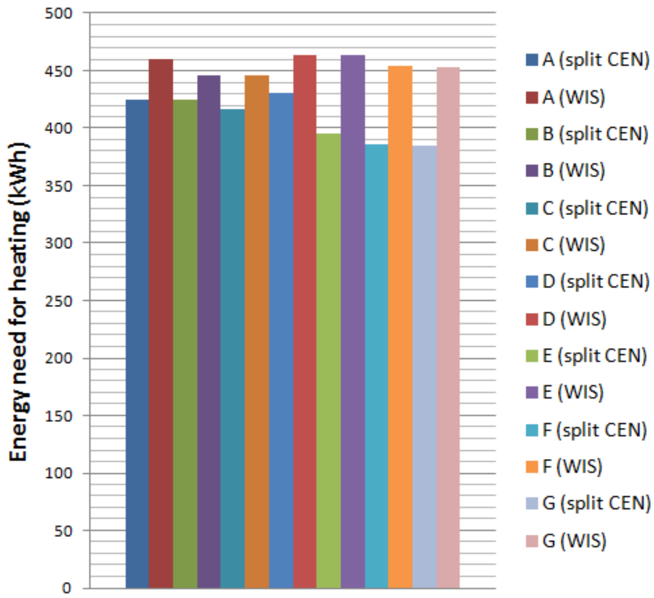

Figure 7.6: Energy need for heating in typical winter day for different ventilated window configurations calculated using outlet temperature using simple calculation method and compared with results from section 7.1

The energy need for cooling is 0 $[kWh]$in typical winter day. The need for heating shown in 7.6 is also smaller then is calculated in 7.3. The outlet temperatures calculated using two different methods for window configurations A and G are shown in figure 7.7. This figure shows how temperature changes in 24 hours.

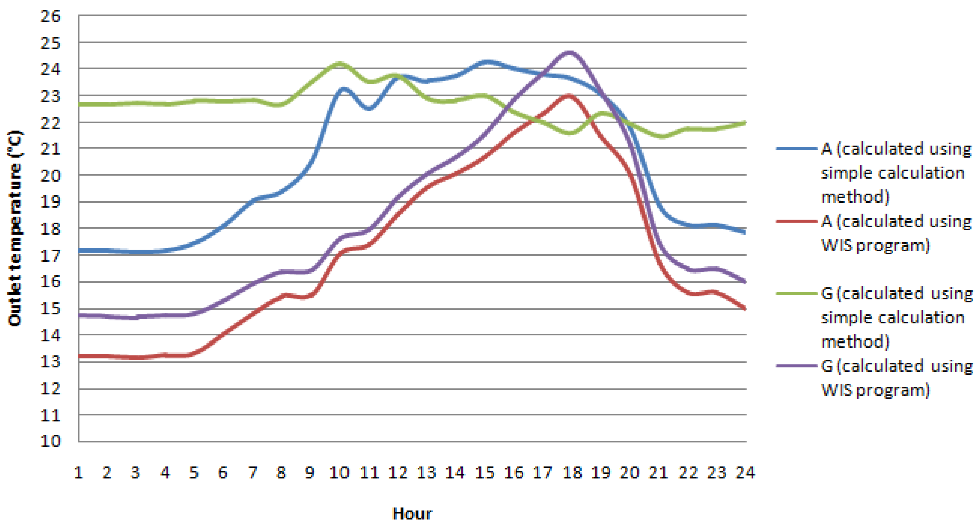

Figure 7.7: The comparison of the outlet temperatures calculated using WIS program and using simple calculation method

As is shown in 7.7 it is quite big outlet temperature difference between calculation methods. The outlet temperature calculated with WIS fluctuates more, while temperatures calculated using simple calculation method looks more stable during 24 hours. This gives an overview that WIS program more responds to environment changes in simulations.

7.3 Simple calculation method calculated for all year with split CEN

The energy consumption for analyzed building is calculated for all year using DRY data. The U and g values are estimated with WIS program in CEN mode. The U value is given in tables 4.1 and 4.2. The outlet temperature is found in the same way like it is explained in section 7.2. In this section calculations are done without control strategy. It means that through all ventilated windows $4l/s$ of fresh air is supplied. The air is preheated using ventilated air gap. This calculations are done in order to be able to compare results with applied control strategy and find benefit of it. The results are shown in figures 7.8 and 7.9.

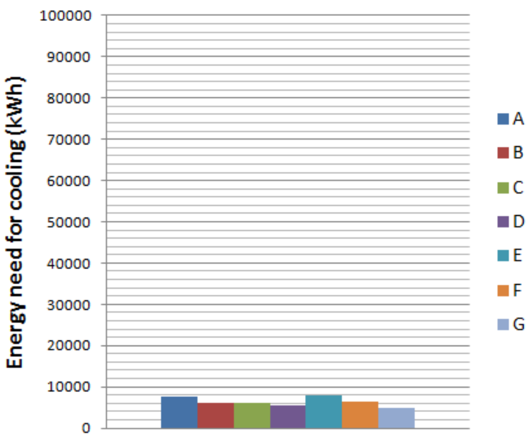

Figure 7.8: Energy need for cooling for different ventilated window configurations for all year

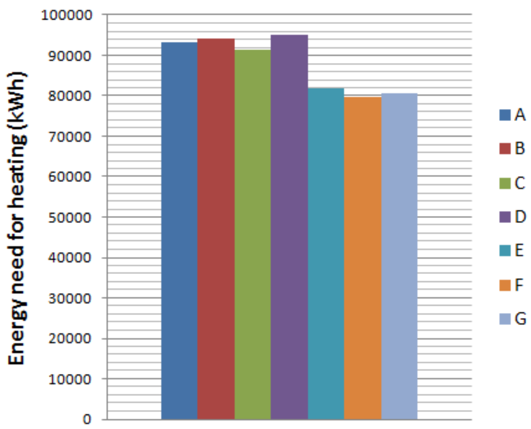

Figure 7.9: Energy need for heating for different ventilated window configurations for all year

As for energy need for cooling from figure 7.8 it is seen that case G gives the best result. This is due to lowest U, g values and quite low calculated outlet temperature. But for the heating, the window configuration F performs best because of quite high calculated outlet temperatures. The energy need for cooling and heating for each month separately is shown in figure 7.10. The results are given without control strategy for all ventilated window configurations.

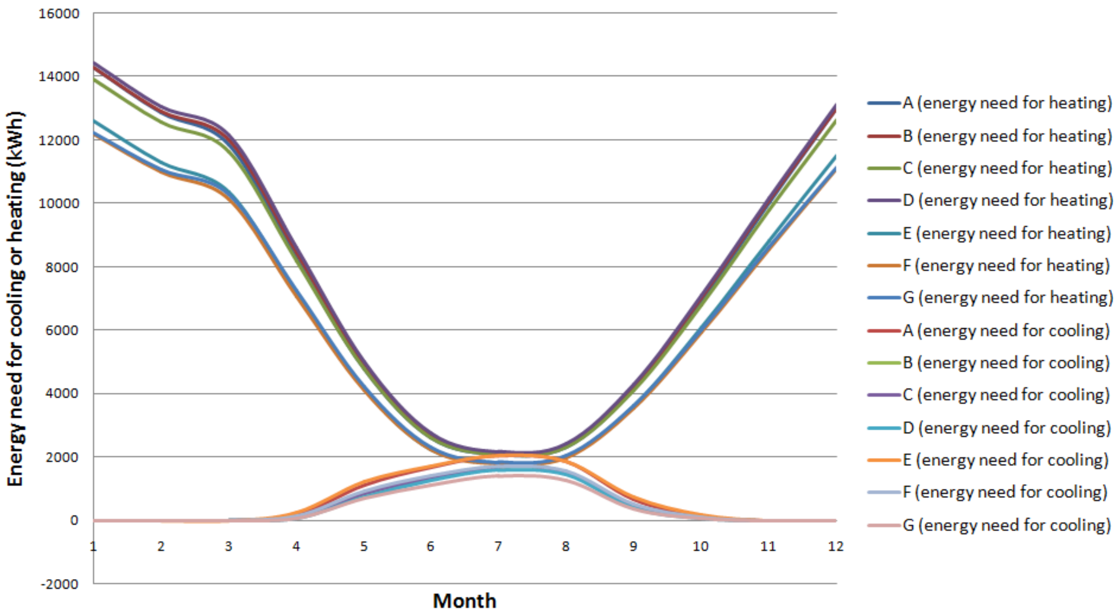

Figure 7.10: The energy need for cooling and heating for each month without control strategy

The results show what the biggest heating need for analyzed building is in January. The F window configuration performs best and has the lowest energy need for heating in this month and for all year 7.9. Also the biggest energy need for cooling is in August. The G window configuration has the lowest energy need for cooling in this month and for all year 7.8. The G window shows the best results for cooling because it has the lowest U, g values and also quite low calculated outlet temperatures 7.11. These temperatures are calculated for summer 24 hours and for all window configurations using equation 7.18.

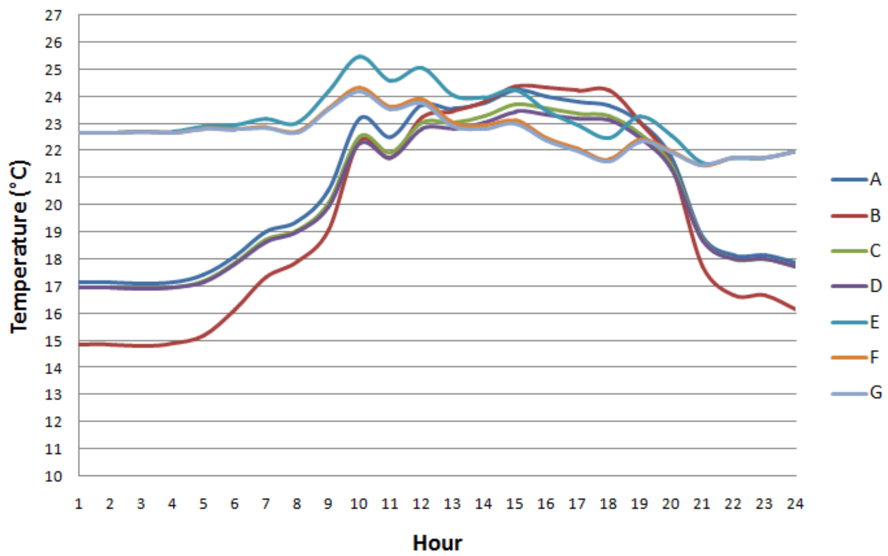

Figure 7.11: The outlet temperatures calculated with simple calculation method for summer 24 hours and for all window configurations

The reason why temperatures are shown for 24 hours instead for all the year, it is impossible to plot such amount of data. But the outlet temperature difference between window configurations remains stable for all year. The outlet temperatures are shown also for winter 24 hours in figure 7.12.

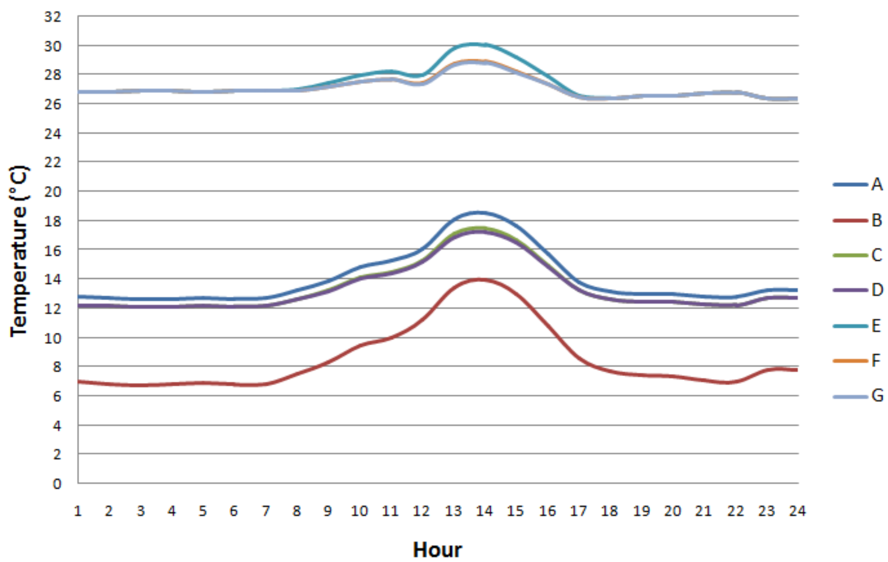

Figure 7.12: The outlet temperatures calculated with simple calculation method for winter 24 hours and for all window configurations

Comparing summer and winter outlet temperatures 7.11 and 7.12 for window configurations E, F, G it is strange that outlet temperatures are higher for winter even though outside temperatures are lower. This big difference occur using equation 7.18. It seems that it is better to use the mean air temperature calculated 7.17 instead of using outlet temperature calculated with equation 7.18. The outlet temperatures for window case G calculated with simple calculation method and WIS program are shown in 7.13. Additionally, the mean temperature of ventilated cavity calculated using equation 7.18 is given.

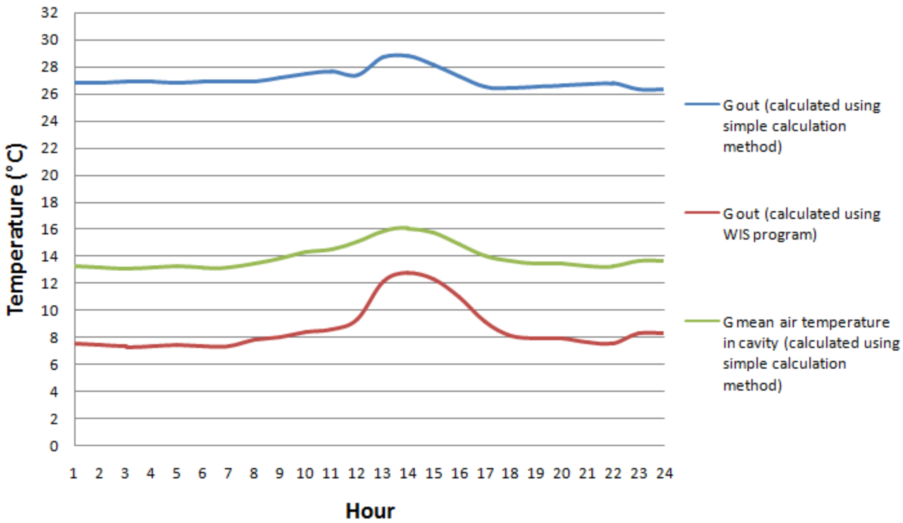

Figure 7.13: The outlet temperature and mean temperature calculated with simple calculation method for winter 24 hours and for all window configurations

The figure above shows that deviation between WIS calculated outlet air temperatures and mean temperatures of the cavity is smaller then calculated outlet temperatures with 7.18. Also it can be concluded that it is necessary to improve the equation 7.18 in simple calculation method. Instead of that the equation 7.18 for chapters 7.2, 7.3, 7.4 is used.

7.4 Simple calculation method calculated for all year with control strategy

As in previous section the energy consumption for all building is calculated using simple calculation method for all year. The values for calculations are used and calculation sequence is like in chapter 7.3. The only difference is that in this chapter cooling and heating need for building is found using control strategy. The ventilated window supplies $1l/s$of air if outside temperature is below 12 degrees, $4l/s$ of air if the outside temperature is between 12-20 degrees, $3l/s$ of air is supplied through bypass and $1l/s$ of air through cavity if outside temperature is above 20 degrees. The regulation temperatures are chosen not accidentally, but due to experiment which are done in laboratory with ventilated window grills and explained in chapter 8.

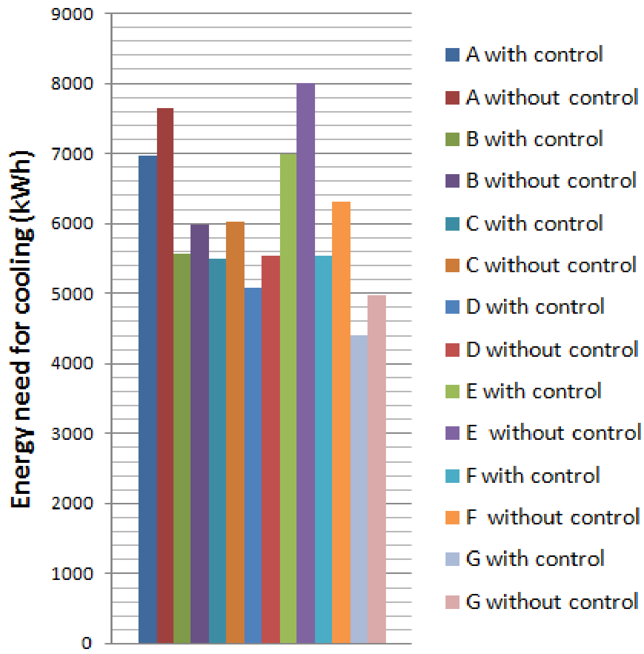

Figure 7.14: Comparison of energy need for cooling for all year, without control strategy

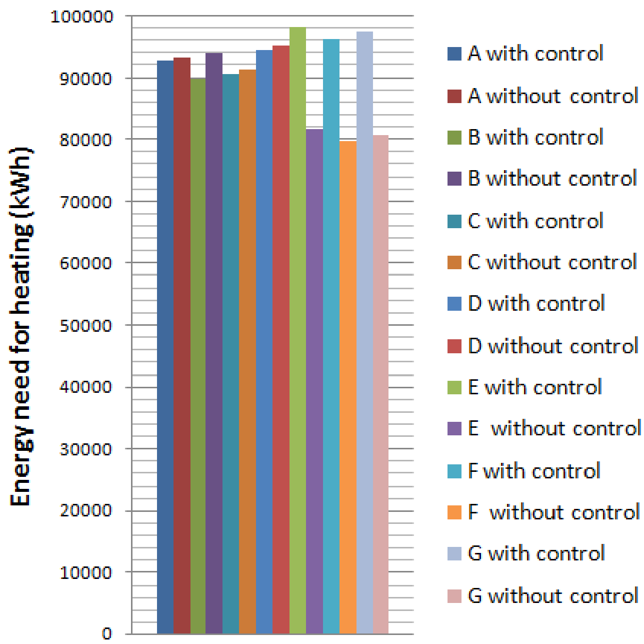

Figure 7.15: Comparison of energy need for heating for all year, without control strategy

The results of energy consumption for windows with different layout, with and without control strategy during all year are shown above. Because of negligible difference between two strategies the results are put together. The energy savings for cooling is 7.2-12.2 percents it depends on case and it possible to save 2 percents of energy for heating using control strategy for A, B, C, D cases. For cases E, F and G it is not worth to use control strategy because it is possible to lose about 20 percent of energy need for heating. From the results it is seen that sometimes with ventilation control strategy it is possible to lose energy. Furthermore annual energy need for cooling and heating per one square meter for analyzed building is calculated the results are given in table 7.2

Window Case	**Energy need for heating** (kWh/m^2)	**Energy need for cooling** (kWh/m^2)
A	265	20
B	256	16
C	259	16
D	270	15
E	281	20
F	275	16
G	278	13

Table 7.2: Annual energy need for heating and cooling per square meter

In order to compare results the amount of energy needed for cooling/heating one square meter of area is chosen to use. The results are incompatible with danish regulations because in calculations all heat gains due to internal sources are neglected 7.4. All results and calculations can be found in enclosed CD.

Chapter 8

Experiments

8.1 Test facility

In order to carry out experiments regarding performance of the window, ventilation grills (and air preheating efficiency) a full size construction is subjected to several experiments. The experimental studies were carried out in the test cell shown in figure 8.1.

Figure 8.1: View of the test cell

8.2 Setup of the window

The window being tested is fitted into a wooden box with dimensions of 0.415m width, 1.255m length and 1.51m hight. Basically it is a window frame, extended to have an empty space in indoor side of the window. The system under investigation is composed by commercially available window mounted in the frame. An air inlet with a total area of $14cm^2$ is installed at the bottom of the frame. Also automatically-opening grills with an option of bypass are installed in the top of the frame. Grills automatically opens depending on temperature. The graph with a grill opening dependence on temperature is presented below. All this composition is placed and all the experiments are done in the room, where the environment temperature can be kept constant for certain time.

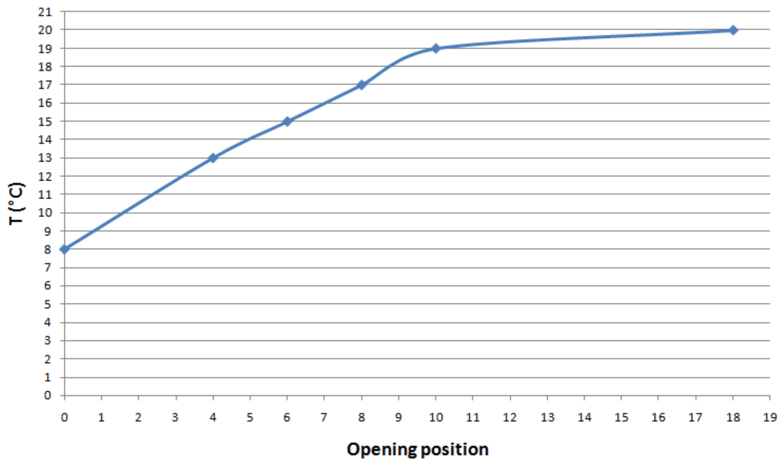

Figure 8.2: Grill opening dependence on temperature

To have a better overview of how the tested window looks like the exterior view and the section of the test cell is presented in figure 8.3.

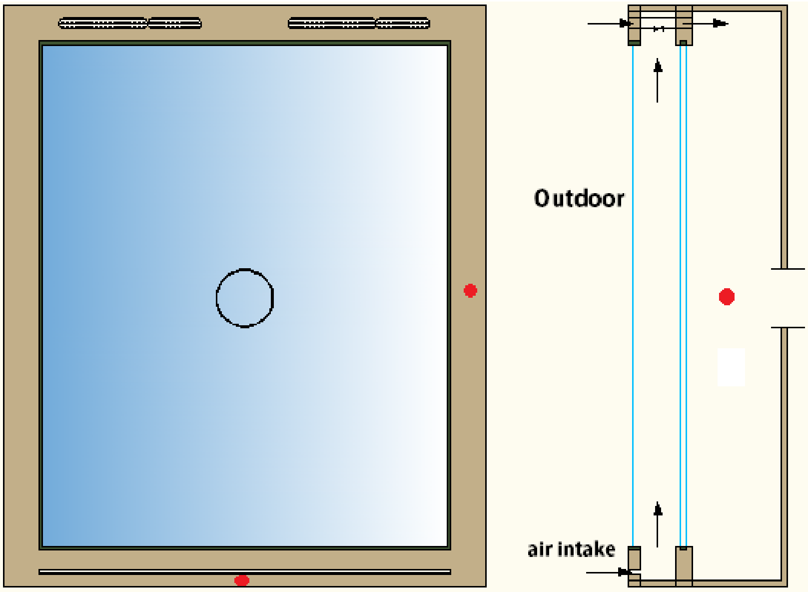

Figure 8.3: Exterior view and section of tested window

8.3 Air resistance in window system

The ventilated window can be used in both naturally and mechanically ventilated rooms. As it is known from previous studies about natural ventilation, in order to provide sufficient amount of fresh air into the building the opening between indoors and outdoors must be as air permeable as possible. Also the same rule goes to all the air path. It means that resistance losses in the inlet opening, the openings between different areas and in the outlet opening must be as low as possible. It is not so essential when talking about mechanically ventilated areas.

In this experiment the main task is to measure the resistance losses in automatically-opening grills and all window system. Grills are tested using mechanical ventilation. Considering that grills change opening position due temperature changes, the experiments are done in temperature range from 8^oC to 24^oC. At 8^oC grills are fully closed. This means that by pass are totally closed but fresh air still comes into the room trough small gaps which are left in the bottom of grills. At temperature of 24^oC grills are fully opened. That means that by pass are fully opened, the bottom of grills are left opened 50%- the air goes trough the window cavity to the outside and to the inside at the same time. In this situation the room are still provided with fresh air, but some of the hot air goes outside. Results concerning reistance losses is presented below.

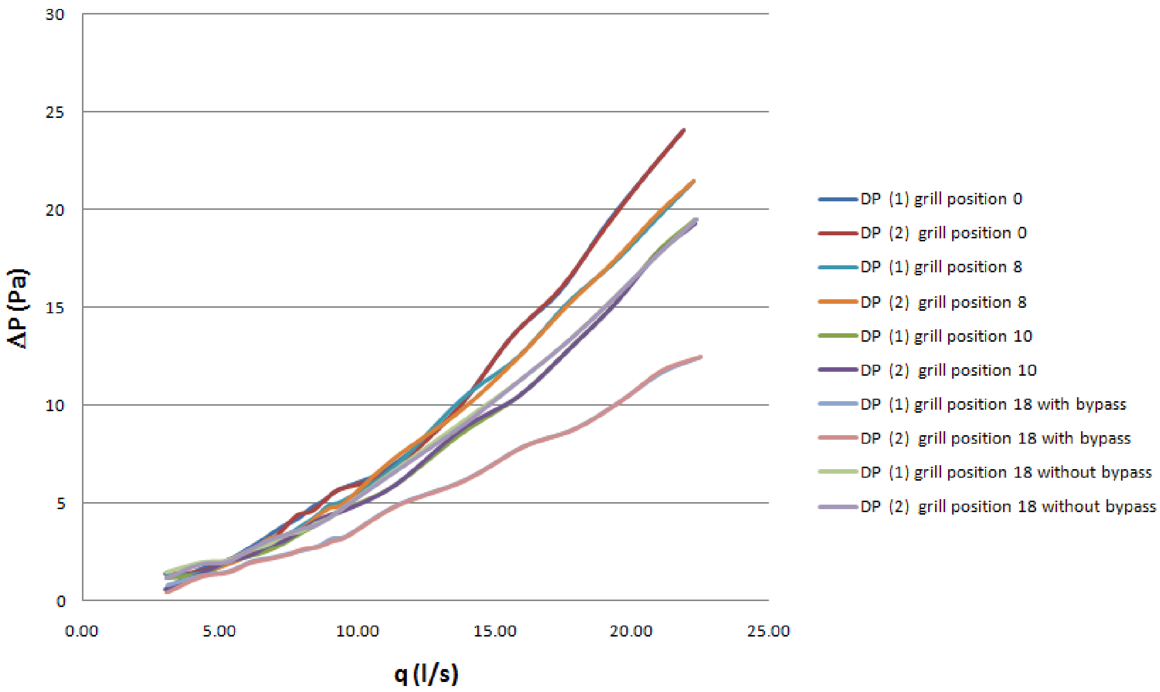

Figure 8.4: Resistance losses in the grills

In the experiment grills are tested in flow range from $3l/s$ to $22l/s$. The resistance losses is considered as pressure difference between outside of the window and inside. This difference is measured using micro manometer- placing two measuring tubes in front of the window and third tube mounting in the cavity inside the window. The location of measuring tubes is shown in figure 8.3 marked as red dots. From results introduced above the dependence of resistance losses due grill opening position and flow rate. The pressure difference is very low considering debit of air flow.

Chapter 9

Building in Herredsfoged

Calculations of required amount of supply and exhaust air for the building which is located in Herredsfoged. The building is used to be court house but now the purpose is changed to residential building. For calculations there are used [4] and Danish building regulations [17]. The results are shown in tables below.

Room Nr.		m^3	m^2	l/s	m^3/h	n h^{-1}
1	kitchen	148.1	50.22	-28	-100.8	0.7
4	bathroom/ WC	60.4	20.46	-20	-72	1.2
11	kabinet	50.8	17.22	24.1	86.8	1.7
12	library	76.2	25.84	38.8	139.5	1.8
13	living room	104.7	35.50	53.3	191.7	1.8
20	loft room	132.7	54.16	75.8	273.0	2.1
23	shower	9.2	3.75	-20	-72	7.8
24	WC	33.2	13.55	-14	-50.4	1.5
25	room	29.1	11.89	16.6	59.9	2.1
27	room	30.9	12.60	17.6	63.5	2.1
29	room	29.4	12.00	16.8	60.5	2.1
30	bedroom	88.8	36.25	52.6	189.2	2.1

Table 9.1: Calculations of required amount of supply and exhaust air. Category I, Danish standards DS/EN 15251

Room Nr.		m^3	m^2	l/s	m^3/h	n h^{-1}
1	kitchen	148.1	50.22	-20	-72	0.5
4	bathroom/ WC	60.4	20.46	-15	-54	0.9
11	kabinet	50.8	17.22	17.2	62.0	1.2
12	library	76.2	25.84	28.4	102.3	1.3
13	living room	104.7	35.50	40.8	147.0	1.4
20	loft room	132.7	54.16	54.2	195.0	1.5
23	shower	9.2	3.75	-15	-54	5.9
24	WC	33.2	13.55	-10	-36	1.1
25	room	29.1	11.89	11.9	42.8	1.5
27	room	30.9	12.60	12.6	45.4	1.5
29	room	29.4	12.00	12.0	43.2	1.5
30	bedroom	88.8	36.25	39.2	140.94	1.6

Table 9.2: Calculations of required amount of supply and exhaust air. Category II, Danish standards DS/EN 15251

Room Nr.		m^3	m^2	l/s	m^3/h	n h^{-1}
1	kitchen	148.1	50.22	-20	-72.0	0.5
4	bathroom/ WC	60.4	20.46	-15	-54.0	0.9
11	kabinet	50.8	17.22	6.0	21.7	0.4
12	library	76.2	25.84	9.0	32.6	0.4
13	living room	104.7	35.50	12.4	44.7	0.4
20	loft room	132.7	54.16	19.0	68.2	0.5
23	shower	9.2	3.75	-15.0	-54.0	5.9
24	WC	33.2	13.55	-15.0	-54.0	1.6
25	room	29.1	11.89	4.2	15.0	0.5
27	room	30.9	12.60	4.4	15.9	0.5
29	room	29.4	12.00	4.2	15.1	0.5
30	bedroom	88.8	36.25	12.7	45.7	0.5

Table 9.3: Calculations of required amount of supply and exhaust air. Danish building regulations

Chapter 10

Conclusion

This project has been dealing with thermal behavior and the energy performance of ventilated window with solar shading/night blind and solar control units (low emissivity coating). This has been carried out with different energy analyzing methods such as energy balance calculation, simple calculation method and supported by simulation programs WIS and WINDOW 5.

A preliminary phase has dealt with literature review. The reviewed literature gave an idea for the project where an attention has to be payed. On reviewed literature basis we started to understand problems related with performance assessment and modeling of ventilated window. Also we got an idea how this analyzed window should look like. We decided to test triple glazing system placing coating in different positions. For Scandinavian climatic conditions during summer and winter months, in order to have well insulated buildings envelope, windows with low thermal transmittance are indispensable. In simulations performed in the project, weather data from danish reference year is used.

To be able to compare different window configurations many static computational simulations were done using program WIS. The remarkable impact on energy use have properties such as U, g values. Those were calculated as well as outlet temperatures. In this way energy balance for every chosen case were estimated. It was chosen to analyze window with closed air gap or with forced ventilation ventilated window gap. The different window configurations were compared. The results showed that window configuration with coating facing into gap performs best in summer time both for ventilated and non'ventilated cavity. To summarize results for window configuration without shading solar control coating CU placed as middle glazing layer performs best in winter time. Next stage was the implementation of shading units, testing their performance. The different shading positions were tested. The results for winter with shading device can be neglectable, because desirable solar heat gains can not pass through shaded window. From energy balance calculation the position of shading device placed closer to intermediate pane gives the best results. Furthermore heat recovery efficiency is determined for specific cases.

Besides energy balance calculation the simple calculation method was implemented for renovated building in Herredsfoged. The main aim of this tool is to find thermal behavior and energy performance of all building. The all window configurations were tested. The method was applied using all year weather data. As well as in heat balance method it was tried to use control strategy. The results showed that it is essential to apply control strategy in some cases, but can not be stated that one of those is best. Before applying control strategy many factors have to be taken into consideration.

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Part I

Appendix

Appendix **A**

Appendix A

The outdoor air and radiant temperatures also recalculated direct, diffused solar radiation both for summer and winter days for 24 hours are shown in tables A.1 and A.2.

Hours	**Outdoor air temperatures in** ^oC	**Outdoor radiant temperatures in** ^oC	**Direct solar radiation** W/m^2	**Diffuse solar radiation** W/m^2
1	12.00	10.60	0.00	0.00
2	12.00	10.40	0.00	0.00
3	11.90	10.60	0.00	0.00
4	12.00	10.70	0.00	1.0
5	12.10	10.70	0.00	25.0
6	13.00	11.70	0.00	66.0
7	14.00	11.40	0.00	131.0
8	14.70	13.10	0.00	143.0
9	14.70	13.10	10.37	268.0
10	16.70	13.60	4.61	493.0
11	17.00	13.50	25.12	363.0
12	18.00	13.70	88.46	280.0
13	19.30	13.70	90.99	196.0
14	19.70	13.40	134.64	125.0
15	20.00	12.80	211.55	131.0
16	20.80	9.20	308.47	69.0
17	21.20	9.20	389.13	65.0
18	21.70	9.70	432.58	73.0
19	19.70	12.30	405.23	81.0
20	18.80	12.60	257.21	62.0
21	16.10	13.90	27.11	7.0
22	14.80	14.20	0.00	0.00
23	14.80	14.50	0.00	0.00
24	14.00	13.70	0.00	0.00

Table A.1: The outdoor air, radiant temperatures, direct and diffused solar radiation for summer days

Hours	Outdoor air temperatures in ^oC	Outdoor radiant temperatures in ^oC	Direct solar radiation W/m^2	Diffuse solar radiation W/m^2
1	-0.30	-2.70	0.00	0.00
2	-0.50	-2.70	0.00	0.00
3	-0.70	-2.80	0.00	0.00
4	-0.60	-2.70	0.00	0.00
5	-0.40	-2.50	0.00	0.00
6	-0.60	-2.80	0.00	0.00
7	-0.60	-3.00	0.00	6.0
8	0.00	-2.20	10.63	32.0
9	0.40	-1.80	11.20	83.0
10	1.00	-1.20	17.79	144.0
11	1.30	-0.90	19.32	170.0
12	2.70	0.40	11.98	194.0
13	3.00	0.70	326.63	161.0
14	3.30	1.00	404.28	130.0
15	3.30	1.00	331.97	117.0
16	2.40	0.20	218.18	60.0
17	1.50	-0.60	62.56	7.0
18	0.80	-1.30	0.00	0.00
19	0.40	-1.50	0.00	0.00
20	0.30	-1.60	0.00	0.00
21	-0.20	-1.90	0.00	0.00
22	-0.30	-1.70	0.00	0.00
23	1.00	-0.10	0.00	0.00
24	1.00	-0.10	0.00	0.00

Table A.2: The outdoor air, radiant temperatures, direct and diffused solar radiation for winter days

Appendix B

Appendix B

U and g values for different window configurations. Using WIS program many static simulations are done. Program gives U and g values for each simulated situation. The U and g values for all window configurations both for summer and winter days for 24 hours with ventilated air gap and not ventilated air gap are shown in figures B.5,B.6,B.7,B.8,B.1,B.2,B.3,B.4. Also exact values are given in tables B.1, B.2, B.3, B.4, B.5, B.6, B.7, B.8.

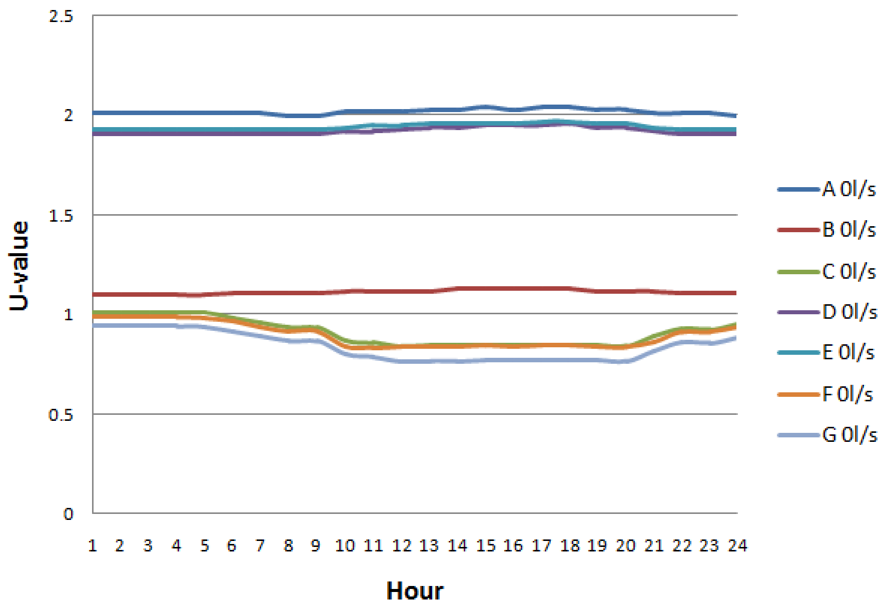

Figure B.1: U values for window with not ventilated air gap for 24 hours in summer

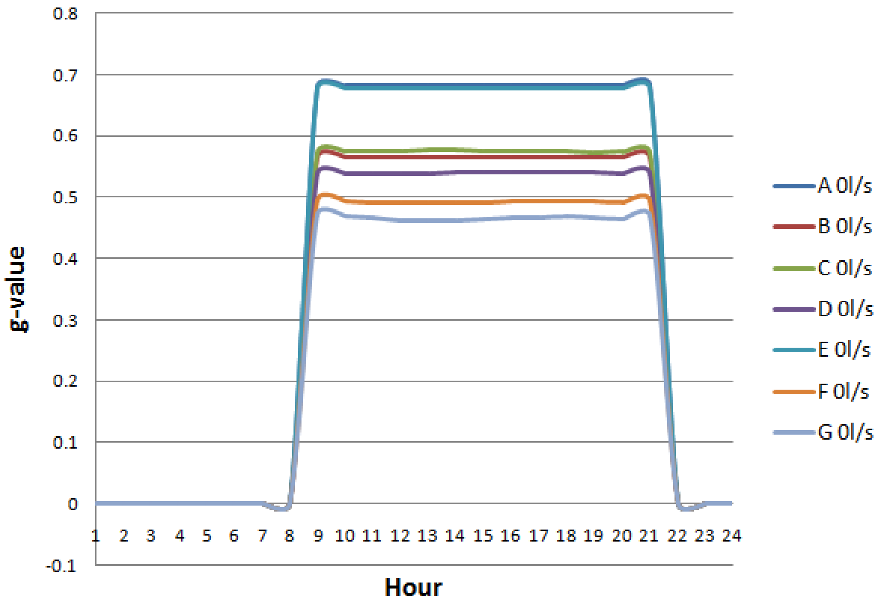

Figure B.2: g values for window with not ventilated air gap for 24 hours in summer

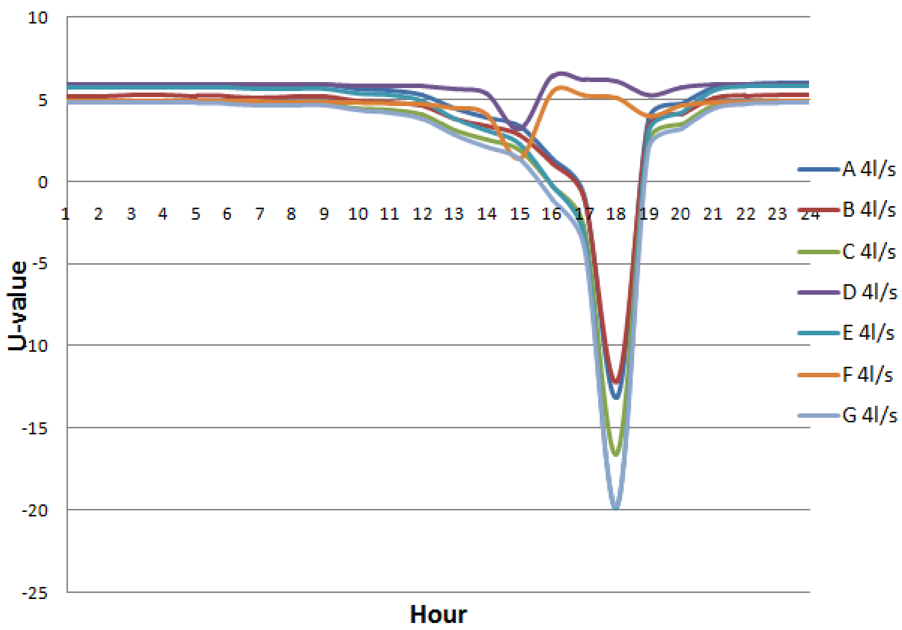

Figure B.3: U values for window with ventilated air gap for 24 hours in summer

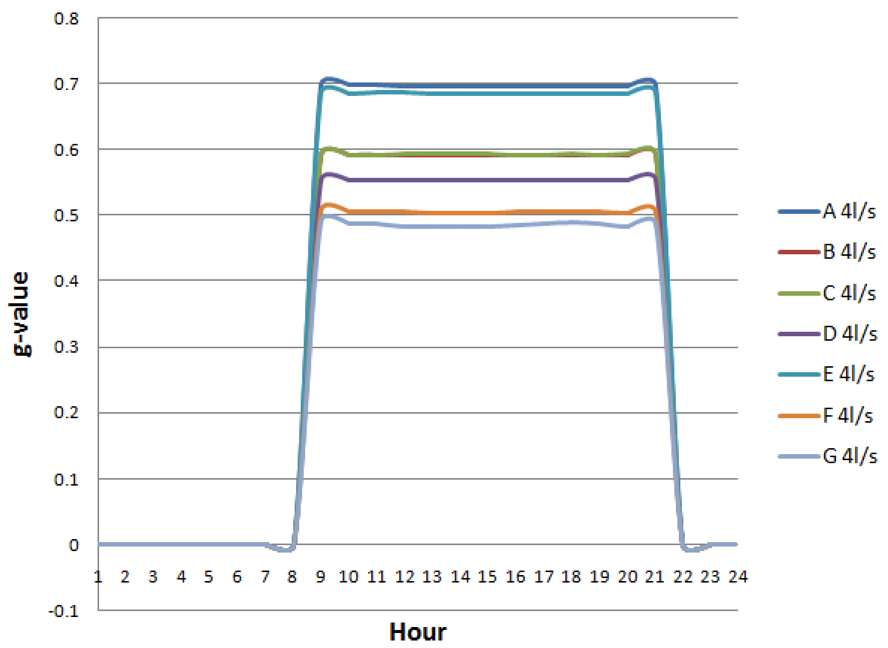

Figure B.4: g values for window with ventilated air gap for 24 hours in summer

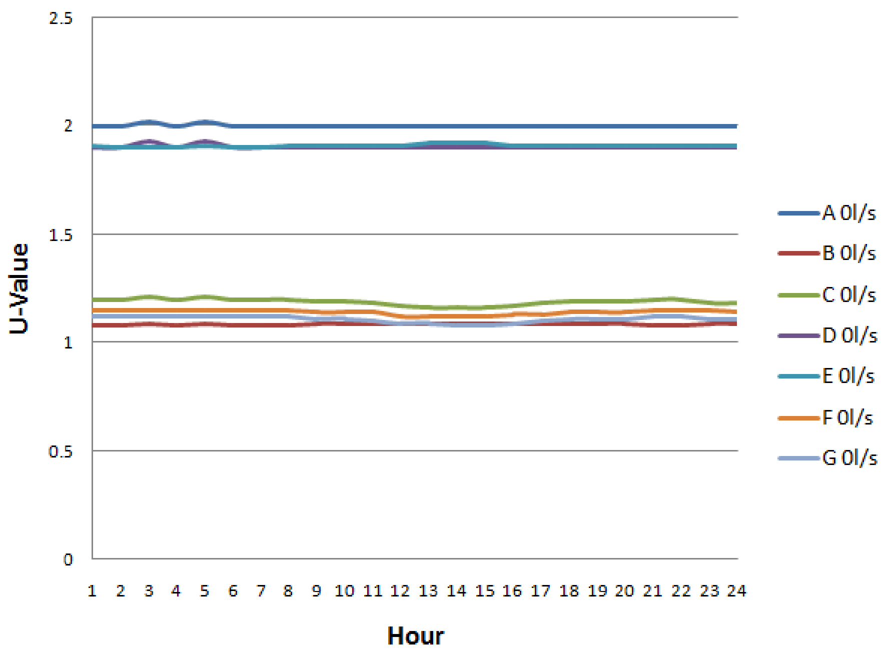

Figure B.5: U values for window with not ventilated air gap for 24 hours in winter

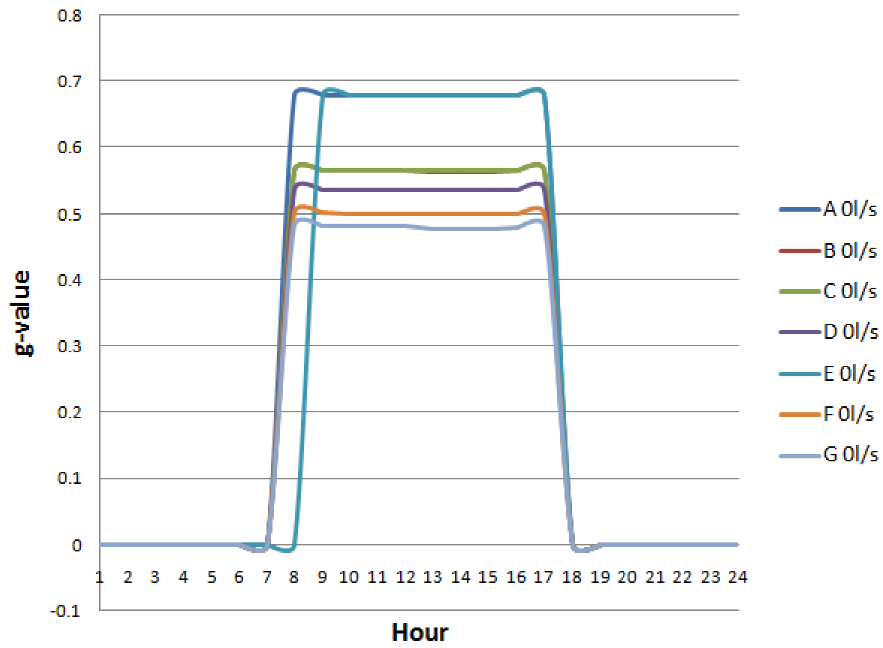

Figure B.6: g values for window with not ventilated air gap for 24 hours in winter

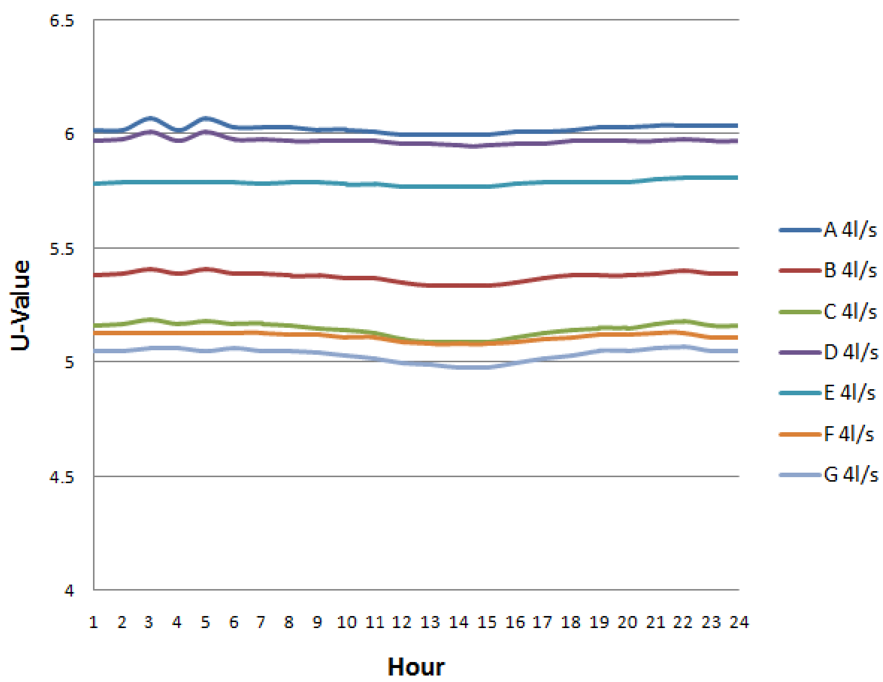

Figure B.7: U values for window with ventilated air gap for 24 hours in winter

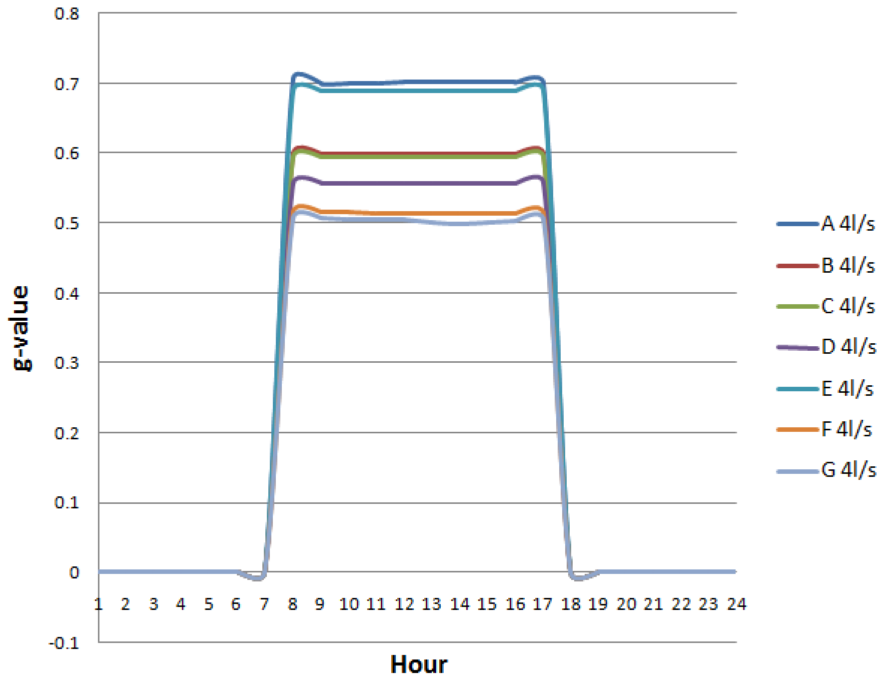

Figure B.8: g values for window with ventilated air gap for 24 hours in winter

Hour	A 0l/s	B 0l/s	C 0l/s	D 0l/s	E 0l/s	F 0l/s	G 0l/s
	U-value	U-value	U-value	U-value	U-value	U-value	U-value
1	2	1.08	1.2	1.9	1.91	1.15	1.12
2	2	1.08	1.2	1.9	1.9	1.15	1.12
3	2.02	1.09	1.21	1.93	1.9	1.15	1.12
4	2	1.08	1.2	1.9	1.9	1.15	1.12
5	2.02	1.09	1.21	1.93	1.91	1.15	1.12
6	2	1.08	1.2	1.9	1.9	1.15	1.12
7	2	1.08	1.2	1.9	1.9	1.15	1.12
8	2	1.08	1.2	1.9	1.91	1.15	1.12
9	2	1.09	1.19	1.9	1.91	1.14	1.11
10	2	1.09	1.19	1.9	1.91	1.14	1.11
11	2	1.09	1.18	1.9	1.91	1.14	1.1
12	2	1.09	1.17	1.9	1.91	1.12	1.09
13	2	1.09	1.16	1.9	1.92	1.12	1.09
14	2	1.09	1.16	1.9	1.92	1.12	1.08
15	2	1.09	1.16	1.9	1.92	1.12	1.08
16	2	1.09	1.17	1.9	1.91	1.13	1.09
17	2	1.09	1.18	1.9	1.91	1.13	1.1
18	2	1.09	1.19	1.9	1.91	1.14	1.11
19	2	1.09	1.19	1.9	1.91	1.14	1.11
20	2	1.09	1.19	1.9	1.91	1.14	1.11
21	2	1.08	1.2	1.9	1.91	1.15	1.12
22	2	1.08	1.2	1.9	1.91	1.15	1.12
23	2	1.09	1.18	1.9	1.91	1.15	1.11
24	2	1.09	1.18	1.9	1.91	1.14	1.11

Table B.1: The U-values for winter 24 hours and not ventilated air cavity

Hour	A 0l/s	B 0l/s	C 0l/s	D 0l/s	E 0l/s	F 0l/s	G 0l/s
	g-value	g-value	g-value	g-value	g-value	g-value	g-value
1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0
8	0.678	0.565	0.565	0.537	0	0.501	0.483
9	0.679	0.565	0.565	0.537	0.679	0.501	0.482
10	0.679	0.565	0.565	0.537	0.679	0.5	0.482
11	0.679	0.565	0.565	0.537	0.679	0.5	0.482
12	0.679	0.565	0.566	0.537	0.679	0.5	0.481
13	0.679	0.564	0.566	0.537	0.679	0.499	0.478
14	0.679	0.564	0.566	0.537	0.679	0.499	0.477
15	0.679	0.564	0.566	0.537	0.679	0.499	0.477
16	0.679	0.565	0.566	0.537	0.679	0.5	0.479
17	0.679	0.565	0.566	0.537	0.679	0.5	0.481
18	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0

Table B.2: The g-values for winter 24 hours and not ventilated air cavity

Hour	A 4l/s	B 4l/s	C 4l/s	D 4l/s	E 4l/s	F 4l/s	G 4l/s
	U-value	U-value	U-value	U-value	U-value	U-value	U-value
1	6.02	5.38	5.16	5.97	5.78	5.13	5.05
2	6.02	5.39	5.17	5.98	5.79	5.13	5.05
3	6.07	5.41	5.19	6.01	5.79	5.13	5.06
4	6.02	5.39	5.17	5.97	5.79	5.13	5.06
5	6.07	5.41	5.18	6.01	5.79	5.13	5.05
6	6.03	5.39	5.17	5.98	5.79	5.13	5.06
7	6.03	5.39	5.17	5.98	5.78	5.13	5.05
8	6.03	5.38	5.16	5.97	5.79	5.12	5.05
9	6.02	5.38	5.15	5.97	5.79	5.12	5.04
10	6.02	5.37	5.14	5.97	5.78	5.11	5.03
11	6.01	5.37	5.13	5.97	5.78	5.11	5.02
12	6.00	5.35	5.10	5.96	5.77	5.09	5.00
13	6.00	5.34	5.09	5.96	5.77	5.08	4.99
14	6.00	5.34	5.09	5.95	5.77	5.08	4.98
15	6.00	5.34	5.09	5.95	5.77	5.08	4.98
16	6.01	5.35	5.11	5.96	5.78	5.09	5.00
17	6.01	5.37	5.13	5.96	5.79	5.10	5.02
18	6.02	5.38	5.14	5.97	5.79	5.11	5.03
19	6.03	5.38	5.15	5.97	5.79	5.12	5.05
20	6.03	5.38	5.15	5.97	5.79	5.12	5.05
21	6.04	5.39	5.17	5.97	5.80	5.13	5.06
22	6.04	5.40	5.18	5.98	5.81	5.13	5.07
23	6.04	5.39	5.16	5.97	5.81	5.11	5.05
24	6.04	5.39	5.16	5.97	5.81	5.11	5.05

Table B.3: The U-values for winter 24 hours and with 4 l/s ventilated air cavity

Hour	A 4l/s	B 4l/s	C 4l/s	D 4l/s	E 4l/s	F 4l/s	G 4l/s
	g-value	g-value	g-value	g-value	g-value	g-value	g-value
1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0
8	0.706	0.6	0.594	0.556	0.69	0.515	0.506
9	0.699	0.6	0.594	0.557	0.69	0.515	0.506
10	0.7	0.599	0.594	0.556	0.69	0.515	0.505
11	0.7	0.599	0.594	0.556	0.69	0.514	0.505
12	0.701	0.599	0.594	0.556	0.69	0.514	0.504
13	0.701	0.599	0.594	0.556	0.689	0.513	0.5
14	0.701	0.599	0.594	0.556	0.689	0.513	0.498
15	0.701	0.599	0.594	0.556	0.689	0.513	0.5
16	0.701	0.599	0.594	0.556	0.69	0.514	0.502
17	0.7	0.599	0.594	0.557	0.69	0.514	0.504
18	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0

Table B.4: The g-values for winter 24 hours and with 4 l/s ventilated air cavity

Hour	A 0l/s	B 0l/s	C 0l/s	D 0l/s	E 0l/s	F 0l/s	G 0l/s
	U-value	U-value	U-value	U-value	U-value	U-value	U-value
1	2.01	1.1	1.01	1.91	1.93	0.987	0.943
2	2.01	1.1	1.01	1.91	1.93	0.987	0.943
3	2.01	1.1	1.01	1.91	1.93	0.989	0.944
4	2.01	1.1	1.01	1.91	1.93	0.986	0.942
5	2.01	1.1	1.01	1.91	1.93	0.984	0.94
6	2.01	1.11	0.984	1.91	1.93	0.963	0.917
7	2.01	1.11	0.962	1.91	1.93	0.937	0.895
8	2	1.11	0.936	1.91	1.93	0.915	0.868
9	2	1.11	0.936	1.91	1.93	0.915	0.868
10	2.02	1.12	0.869	1.92	1.94	0.837	0.798
11	2.02	1.12	0.858	1.92	1.95	0.834	0.787
12	2.02	1.12	0.84	1.93	1.95	0.837	0.765
13	2.03	1.12	0.843	1.94	1.96	0.839	0.767
14	2.03	1.13	0.843	1.94	1.96	0.84	0.767
15	2.04	1.13	0.844	1.95	1.96	0.844	0.768
16	2.03	1.13	0.843	1.95	1.96	0.842	0.768
17	2.04	1.13	0.844	1.95	1.97	0.843	0.77
18	2.04	1.13	0.845	1.96	1.97	0.843	0.769
19	2.03	1.12	0.843	1.94	1.96	0.841	0.768
20	2.03	1.12	0.842	1.94	1.96	0.838	0.766
21	2.01	1.12	0.888	1.92	1.94	0.864	0.818
22	2.01	1.11	0.927	1.91	1.93	0.911	0.859
23	2.01	1.11	0.925	1.91	1.93	0.911	0.857
24	2	1.11	0.95	1.91	1.93	0.935	0.883

Table B.5: The U-values for summer 24 hours and with closed air cavity

Hour	A 0l/s	A 0l/s	A 0l/s	A 0l/s	A 0l/s	A 0l/s	A 0l/s
	g-value	g-value	g-value	g-value	g-value	g-value	g-value
1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0
9	0.681	0.566	0.572	0.539	0.678	0.496	0.472
10	0.682	0.566	0.574	0.539	0.678	0.495	0.469
11	0.682	0.566	0.574	0.539	0.678	0.492	0.467
12	0.682	0.566	0.575	0.539	0.678	0.492	0.463
13	0.682	0.566	0.577	0.539	0.678	0.492	0.463
14	0.682	0.566	0.577	0.54	0.678	0.492	0.463
15	0.682	0.566	0.576	0.54	0.678	0.492	0.464
16	0.682	0.566	0.575	0.54	0.678	0.493	0.466
17	0.682	0.566	0.574	0.54	0.678	0.494	0.468
18	0.682	0.565	0.575	0.54	0.678	0.495	0.469
19	0.682	0.565	0.573	0.54	0.678	0.493	0.467
20	0.682	0.566	0.574	0.539	0.678	0.492	0.464
21	0.682	0.566	0.573	0.539	0.678	0.495	0.47
22	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0

Table B.6: The g-values for summer 24 hours and with closed air cavity

Hour	A 4l/s	B 4l/s	C 4l/s	D 4l/s	E 4l/s	F 4l/s	G 4l/s
	U-value	U-value	U-value	U-value	U-value	U-value	U-value
1	5.94	5.24	4.89	5.91	5.75	4.93	4.8
2	5.93	5.23	4.88	5.91	5.74	4.93	4.79
3	5.94	5.25	4.89	5.91	5.76	4.94	4.81
4	5.94	5.25	4.89	5.91	5.76	4.93	4.81
5	5.94	5.24	4.88	5.91	5.75	4.93	4.8
6	5.93	5.23	4.86	5.91	5.75	4.91	4.78
7	5.83	5.13	4.73	5.9	5.63	4.88	4.63
8	5.88	5.17	4.76	5.9	5.69	4.87	4.68
9	5.88	5.17	4.76	5.9	5.69	4.87	4.68
10	5.64	4.93	4.45	5.87	5.38	4.79	4.33
11	5.56	4.87	4.36	5.86	5.29	4.78	4.23
12	5.29	4.61	4.06	5.83	4.93	4.73	3.86
13	4.47	3.86	3.14	5.66	3.83	4.51	2.81
14	3.92	3.36	2.52	5.36	3.1	4.13	2.11
15	3.33	2.82	1.87	3.23	2.31	1.41	1.36
16	1.4	1.05	-0.288	6.43	-0.287	5.49	-1.11
17	-0.816	-0.968	-2.76	6.24	-3.27	5.25	-3.95
18	-13.1	-12.1	-16.5	6.13	-19.8	5.11	-19.7
19	3.85	3.29	2.45	5.29	3	4.04	2.02
20	4.76	4.13	3.47	5.74	4.22	4.62	3.19
21	5.77	5.06	4.61	5.89	5.56	4.82	4.51
22	5.95	5.23	4.84	5.91	5.8	4.87	4.76
23	5.98	5.26	4.86	5.91	5.83	4.88	4.79
24	5.98	5.27	4.89	5.91	5.83	4.9	4.82

Table B.7: The U-values for summer 24 hours and 4 l/s ventilated air cavity

Hour	A 4l/s	B 4l/s	C 4l/s	D 4l/s	E 4l/s	F 4l/s	G 4l/s
	g-value	g-value	g-value	g-value	g-value	g-value	g-value
1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0
9	0.698	0.593	0.594	0.554	0.687	0.508	0.491
10	0.698	0.593	0.593	0.554	0.686	0.506	0.488
11	0.698	0.593	0.593	0.554	0.687	0.505	0.487
12	0.697	0.592	0.594	0.554	0.687	0.505	0.484
13	0.697	0.592	0.595	0.554	0.686	0.504	0.484
14	0.697	0.592	0.595	0.553	0.686	0.504	0.483
15	0.697	0.592	0.594	0.554	0.686	0.504	0.484
16	0.697	0.592	0.593	0.554	0.686	0.505	0.486
17	0.697	0.592	0.593	0.554	0.686	0.506	0.488
18	0.697	0.592	0.594	0.554	0.686	0.506	0.489
19	0.697	0.592	0.593	0.553	0.686	0.505	0.487
20	0.697	0.592	0.594	0.553	0.686	0.504	0.484
21	0.698	0.593	0.594	0.554	0.687	0.506	0.488
22	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0

Table B.8: The g-values for summer 24 hours and 4 l/s ventilated air cavity

Appendix C

Appendix C

The outlet temperatures calculated for window configuration G with different shading types. Outlet temperatures are given for 24 hours winter and summer typical day C.1 and C.2.

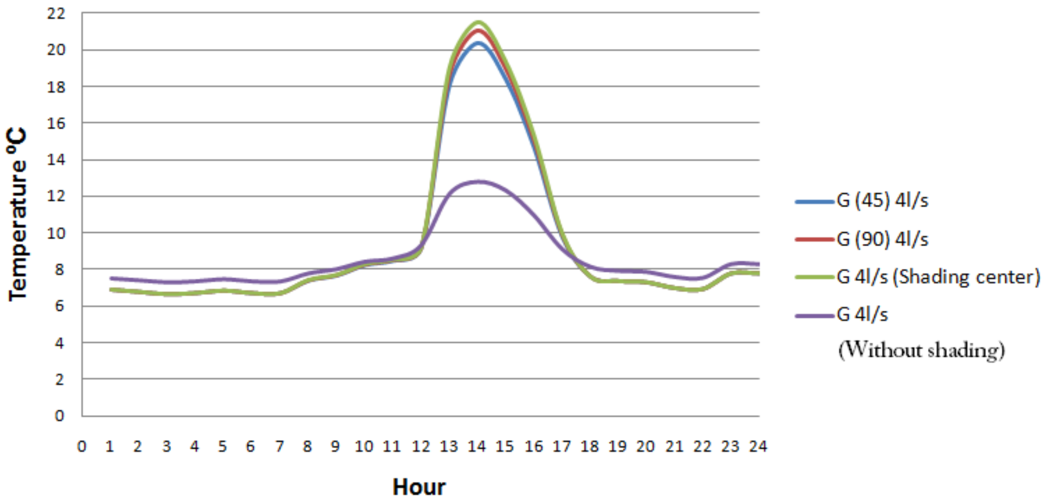

Figure C.1: outlet temperatures with different shading types in case G for winter day

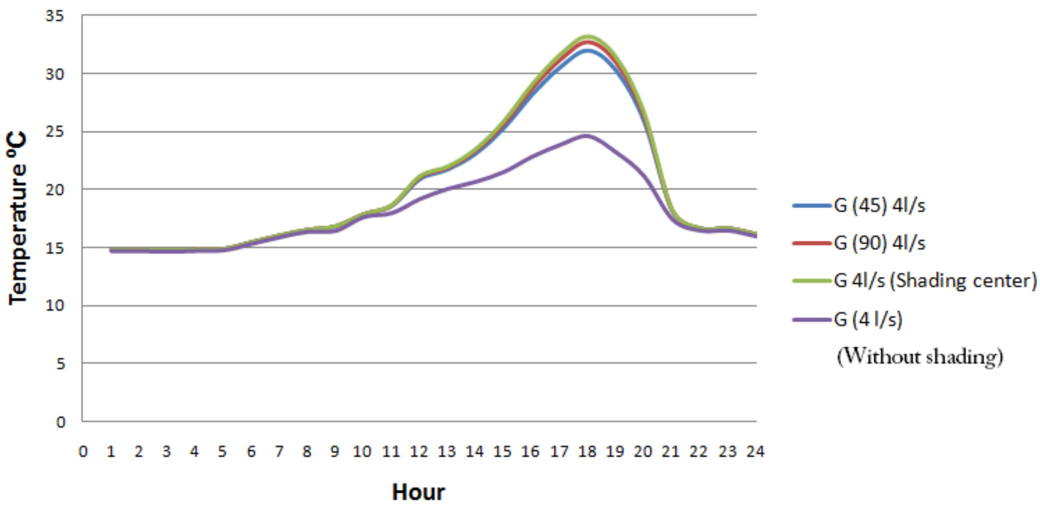

Figure C.2: outlet temperatures with different shading types in case G for summer day