Facade design for noise attenuation and thermal comfort through natural ventilation for high-rise office buildings in the Netherlands

Christina Evi Christoforidou

Supervisors: Dr. ir. Martin Tenpierik
ir. Arie Bergsma

Faculty of Architecture and the Built Environment
MSc Building Technology

Delft University of Technology

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Abstract

High-rises are usually ventilated mechanically in order to ensure thermal and acoustic comfort in the indoor environment. Consequently, the energy consumption in summer months is increased while the indoor air quality is usually deteriorated due to poor maintenance of mechanical ventilation systems. The topic of the current thesis is the design of a facade panel which provides natural ventilation while keeping high comfort levels in the indoor environment for high-rise office buildings in the Netherlands. Firstly, literature is reviewed about topics of sound theory, noise propagation in the urban environment, noise propagation through facades, natural ventilation in high-rises and Phase Change Materials. Several case studies are examined while conclusions are formed regarding the existing design strategies for natural ventilation and sound insulation in high-rises. The developed design concept is based on the use of a double skin facade system where sound absorbing materials and PCM are applied in the double skin cavity. Several ventilation strategies are formed in order to ensure that the suggested system functions effectively in an annual basis. To evaluate the developed concept and to make estimations regarding its acoustic and thermal performance calculations are conducted indicating the facade's cavity temperature, the levels of sound insulation and the amount of the provided airflow. After taking into account the calculations' results, several facade typologies are developed and evaluated according to their feasibility, cost and aesthetic value. The most optimum typology is designed in detail while an analysis is conducted regarding its thermal performance, watertightness and maintenance.

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1.1 Introduction

Natural ventilation is one of the most important passive strategies that could be implemented in buildings to reduce cooling loads and improve the indoor air quality (Emmerich et al., 2001). However, in high-rises located in urban congested centers, natural ventilation is not usually preferred due to high noise levels and strong winds (Schreurs et al., 2008). In addition, natural ventilation is commonly associated with indoor discomfort due to draught in winter months. Those factors are of high importance as they limit the application of natural ventilation strategies and as a result buildings' ventilation is realized solely through mechanical ventilation systems. In order to implement natural ventilation strategies in high-rises and deal with the before-mentioned challenges, an innovative facade design concept should be developed as facade is the main building part where natural ventilation is provided through. In the current thesis report, office high-rises in the Netherlands are considered as case study in order to develop a facade design which provides natural ventilation, noise attenuation and thermal comfort in annual basis.

1.2 Problem statement

One of the main problems found currently in the building environment is the inadequate natural ventilation which results in high energy consumption, poor air quality and indoor temperature discomfort in summer months(Emmerich et al., 2001). In the Netherlands, high-rises located in noisy urban environments where facades are exposed to noise levels varying from 50 to 65 dB and high wind pressure, natural ventilation and noise transmission are conflicting and challenging issues as the noise is transmitted through the fresh air to the indoor environment (Schreurs et al., 2008). In the Netherlands the indoor sound pressure level for offices has to be lower than 40 dB(A), therefore the provided sound insulation must be approximately 10-20 dB(A) to deal with the most extreme conditions (Van der Linden et al., 2013). In addition, airflow control is needed to provide the required amount of fresh air of 25 m3/h/person for offices while ensuring that the indoor air velocity is lower than 0.2 m/s (Van der Linden et al., 2013). Several solutions which provide natural ventilation and attenuate noise have been developed such as insulated vents, plenum windows, noise absorbing blinds and resonator panels (Tang, 2017). Apart from plenum windows where air can be preheated by solar loads none of the systems provide thermal comfort as there is a risk of cold draughts and overheating in winter and summer respectively. The combination of PCM with some typologies of the earlier mentioned ventilation system in facades has plenty of potential as PCM could control the provided air's temperature. However, several challenges emerge regarding system's effectiveness in terms of sound insulation, airflow control, levels of transparency, maintenance, thermal performance, water tightness and aesthetic value.

1.3 Research question

In which way a facade panel can provide effectively natural ventilation in annual basis in high-rise office buildings in the Netherlands by utilizing DSF to increase the indoor thermal and acoustic comfort while providing high transparency levels?

Sub questions:

- Which are the design strategies in order to mitigate noise propagation through facades?
- Which design solutions have been developed in order to provide sufficiently natural ventilation in high-rises? Which are the problems encountered in naturally ventilated high-rises?
- How noise propagation through natural ventilation can be minimized? Which design solution has the best performance?
- How can PCM be incorporated in facades to control indoor temperature?
- Which hybrid ventilation strategies can be developed in order to ensure users’ comfort in annual basis by using a DSF where PCM are applied?
- Which is the optimum volume and area of PCM and sound absorbing materials in order to achieve pleasant indoor temperature and high reduction of sound pressure levels?
- Which design typologies are developed including the incorporation of PCM and sound absorbing materials in a double skin facade panel designed for high-rises?
- Which type of double skin facades is the optimum selection for the developed natural ventilation strategy?
- In which way background and summer ventilation can be realized through a DSF panel without increasing its thickness and ensuring water, air tightness and easy maintenance?

1.4 Methodology

The starting point of the current thesis is related to the approach of research for design, considering literature review about sound propagation through façade, natural ventilation strategies for high-rises and the application of PCM in facades. Case studies are reviewed for each different chapter of the literature study in order to gain a better insight about the practical limitations and performance of each strategy. In addition, the function of PCM is analyzed while the available PCM categories in the market are evaluated in terms of cost, performance and compatibility. In order to form conclusions from the literature review, tables are created comparing the available design strategies for the improvement of noise insulation and the provision of natural ventilation in high-rises. Following the theory conclusions, a facade concept is developed including the implementation of sound absorbing materials and PCM in a double skin facade panel while a ventilation strategy is defined in order to specify the panel's function under different weather conditions. In order to confirm the validity of the design concept calculations were accomplished regarding thermal and acoustic performance of the facade panel. After selecting box-window as the most suitable system for the developed facade concept and considering the calculations results several facade typologies are developed presenting different layouts of the system accommodating the sound absorbing materials and PCM. The suggested designs are evaluated in terms of feasibility, transparency, materiality, aesthetic value, maintenance, thermal and acoustic capacity. The design solution presenting the most optimum features is designed in detail while ways of productions, assembly and materialization are analyzed.

1.5 Relevance

The provision of natural ventilation is one of the main strategies that should be implemented in the buildings in order to reduce the energy consumption as it is closely related to cooling loads decrease. In addition, natural ventilation improves the indoor air quality and the user's comfort by introducing fresh air and preventing overheating in summer (Van der Linden et al., 2013). By designing a façade panel which provides natural ventilation, thermal comfort and at the same time attenuates noise, the user will be encouraged to ventilate naturally the indoor space even when high sound pressure levels occur in the outdoor environment. In addition, the proposed design will also regulate the introduced fresh air by decreasing its pressure to minimize user's discomfort due to draught and allowing natural ventilation even in high-rises.

Theory

2.1 Sound theory

Sound is generated by vibrations when a body that vibrates causes pressure difference on a medium around it by compressing and decompressing the medium's particles. As a result, longitudinal waves are created and travel in the same direction of particles' movement in the medium. Waves' characteristics such as frequency (f), speed (c) and length (λ) define the perception and intensity of sound. **(van der Linden, 2006)** The relationship of those characteristics is described by the following formula:

$$c = f \cdot \lambda$$

Where:
c is the propagation speed of the sound in m/s
f is the frequency in Hz
λ is the wavelength in m

The frequency (f) expresses the number of vibrations per second, the sound wavelength (λ) is described as the distance between two points that are in the same phase, while the speed (c) depends only on the properties and temperature of the medium.

Sound pressure levels

As it was mentioned, the vibrations generate pressure differences which can be perceived as sound. The sound pressure is used to define sound's intensity and is calculated by using the formula:

$$Lp = 10log\left(\frac{p_{eff}^2}{p_o^2}\right)$$

Where:
p_{eff} is effective sound pressure in Pa
p_o is a fixed comparison pressure in Pa

The sound pressure levels depend on the type of source and field of propagation, for instance in a free field the source is understood as a point e.g. a car or a line e.g. a busy road. In the case of a point source, the sound propagates spherically while in the line source it propagates cylindrically. In a closed room the sound waves are partially reflected and absorbed by walls and other surfaces. Consequently, the area of sound absorbing materials and the total absorption coefficient determine the sound pressure levels inside a room. **(Ginn, 1978)**

Sound absorption

When sound strikes on an element a proportion will be reflected, absorbed and transmitted through the structure. The following formula is used to calculate the absorbed (α), reflected (r) and transmitted (t) part of sound energy **(van der Linden, 2006)**:

$$a + r + t = 1$$

Sound absorption is defined as the conversion of sound energy to heat. Sound absorption can be realized through friction in porous materials, resonance or the combination of those two phenomena.

Friction

When sound waves enter a porous material, friction occurs between the incoming and outgoing air particles in material's pores. As a result the sound energy is converted to heat and sound is absorbed by the material itself. The thickness of a sound absorbing material is an important factor as it determines its effectiveness and the range of frequencies that can be effectively absorbed. More specifically, the maximum particle speed occurs in quarter wavelength (λ/4), therefore the material's thickness should be greater than λ/4 to block the sound effectively. In case low frequency sound needs to be blocked the use of porous materials is not practical as the wavelengths are quite large and the construction of bulky elements is required e.g. the wavelength of sound in air at 125 Hz is 2.7 m. **(van der Linden, 2006)** Hence, it is recommended to use sound absorbing materials in frequency ranges between 500 and 2000 Hz. In addition, to reduce the amount of used material, cavities having the thickness of λ/4 in combination with porous materials are built to tackle sound propagation. Commonly, the sound absorbing materials are soft and need protection against damage. A quite common method is the addition of a perforated metal or wooden sheet in front of the sound absorbing surface which ensures its durability. Other cases include also the application of porous membranes and foils to reduce the amount of emitted fibers **(Ginn, 1978)**.

Resonance

All object have a natural frequency and when they are exposed to vibrations equal to their natural frequency they start vibrating spontaneously. This phenomenon is used for sound absorption in specific frequencies. An air mass spring system is created having its own natural frequency and when it is exposed to vibrations the air particles are periodically compressed and decompressed. The friction occurring due to the intense motion of air particles results in sound energy absorption. Commonly, those systems are constructed either by the combination of perforated sheets and air cavities or by Helmholtz resonators. Their application is recommended in cases where limited range low and medium frequency sound should be tackled. To increase the effective frequency range sound absorbing materials can be combined with resonators. **(van der Linden, 2006)**

Sound insulation

Sound insulation is defined as the amount of sound energy that is blocked by a specific construction. Sound insulation is divided in two main categories the airborne and structure-borne sound insulation according to the medium which transmits sound. The structure-borne sound insulation is related to the insulation provided for sound waves generated inside materials due to the direct action of a noise source, for instance the case of noise transmission in a building's structure caused by drilling, hammering and walking. The airborne sound insulation deals with sound waves propagated through air from a certain sound source. **(van der Linden, 2006)** A typical example of airborne sound insulation is the effect of noise transmission due to people talking in adjacent rooms and is described by using the following formula for constructions consisting only of one material layer:

$$R = -10\log(t)$$

where:
t is the transmitted part of sound energy allowed to pass through a construction

In addition, the airborne sound insulation is divided in three subcategories which describe the possible transmission paths in a room, the direct, indirect and flanking transmission. The direct sound transmission describes the sound propagation directly through partitions, the indirect transmission refers to transmission through air cavities while the flanking transmission includes the sound waves traveling in flanking building elements such as side walls, floors and ceilings.

The amount of transmitted sound energy through a construction element is proportional to its mass. As a sound wave excites an element it causes vibrations and motions to its particles. According to the second Newton's Law about motion the change of the motion of a mass is directly proportional to the force that is exerted on this mass. Consequently, a component having a greater mass will have a smaller acceleration and thus less vibrations will occur in the element itself and will be transmitted on the other side of it. In case of a composite structure consisting of different materials, each one has its own sound insulation.

Therefore, an average sound transmission should be defined by using the formula:

$$t = \frac{\sum_{i=1}^{n} tiSi}{\sum_{i=1}^{n} Si} = \frac{t1 \cdot Si + t2 \cdot S2 + \cdots + tiSi}{S1 + S2 + \cdots + Si}$$

Where:
t_i is the absorption coefficient of each component
S_i is the area of each component

Thus the formula for the sound insulation is defined as:

$$R = -10\log\left(\frac{S1 \cdot 10^{-\frac{R1}{10}} + S2 \cdot 10^{-\frac{R2}{10}} + \cdots + Sn \cdot 10^{-Rn/10}}{S1 + S2 + \cdots + Sn}\right)$$

However, the sound insulation is dependent on the frequency and direction of sound, so formulas including these properties of sound waves have been developed to define more accurately sound insulation. In the case of single leaf elements the diagram presented in Fig.2.1 is used to predict sound insulation in cases of normal sound incidence. As it can be seen in the graph very low frequencies are excluded as they rarely occur in building acoustics. In addition since normal incident sound is examined no coincidence occurs, consequently the sound insulation is calculated only according to the mass law. **(Nederlof et al.)**

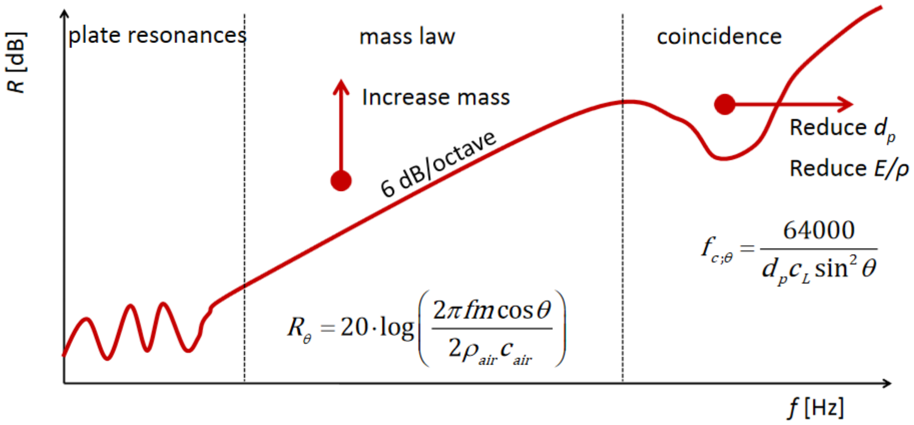


Fig. 2.1. The figure indicates the ways to calculate sound insulation for single leaf constructions, source: Building Acoustics, Airborne Sound Insulation of Single Leaf Constructions, lecture notes of AR1B025

Practically the sound field in front of a facade is diffuse as several sound reflections occur in the urban environment. Therefore, the sound insulation is calculated considering the formula:

$$R_{single\ random} = R_{single\ normal} - 5$$

In case of a cavity construction the sound insulation is estimated according to the following formulas below and above resonance frequency respectively:

$$R = 20\log\left[\frac{m1}{2m2} + \frac{m2}{2m1}\right]$$

$$R = 20\log\left[\frac{\omega m1 cos\theta}{2c_{air}p_{air}}\right] + 20\log\left[\frac{\omega m2 cos\theta}{2c_{air}p_{air}}\right] + 20\log\left[\frac{2\omega d_{cav} cos\theta}{c_{air}}\right]$$

While the sound insulation for random incidence is found according to the formula:

$$R_{single\ random} = R_{single\ normal} - 8.5$$

Urban noise sources in the Netherlands

Industry noise

The noise generated by industries is related to the function of production plants, mechanical equipment, loading and unloading of heavy trucks, refrigerators, construction equipment, electric and pneumatic tools. **(Garcia and Raichel, 2003)** Due to several regulations about urban zones, the heavy industry is located in a great distance from residential areas, however in some cities such as Nijmegen industries can be found close to residential zones. As a result, in the Netherlands around 50000 people experience noise nuisance due to industrial functions. **(European Environmental Agency, 2018)**

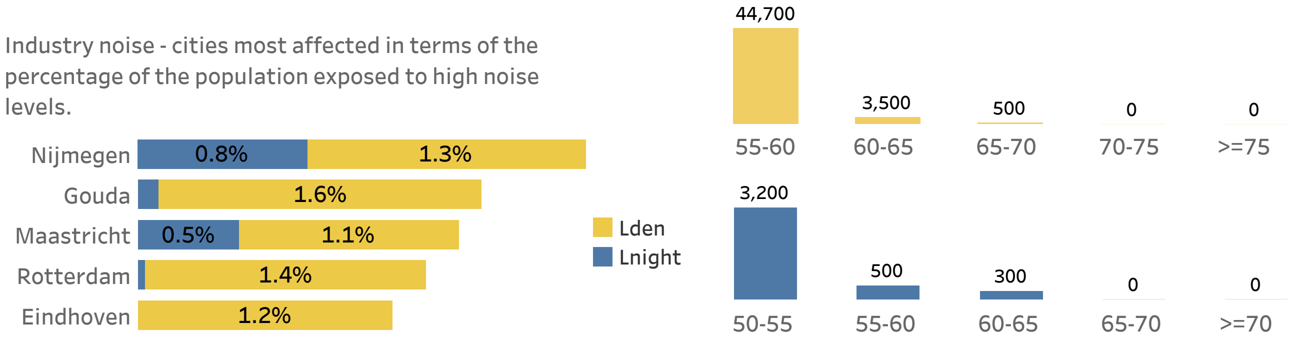


Fig. 2.2. The figure indicates the number of people being exposed to industry noise levels in The Netherlands, source: https://www.eea.europa.eu/themes/human/noise/noise-fact-sheets/noise-country-fact-sheets-2018/netherlands

Road traffic noise

The main noise source found in the Dutch urban centers is traffic occurring either in main urban roads, junctions or highways. **(European Environmental Agency, 2018)** In the term of Traffic noise, sources such as cars, motorcycles, trucks, buses and trams are included. The noise generation is mostly related to tires friction to road, motor engines, exhaust of engines, breaking, accelerating and air displacement due to high speed. **(Bhatia, 2014)** According to **Boer and Schroten (2007)** approximately 210 million people in Europe are exposed to road traffic noise exceeding the 55 dB(A) while around 70% of Dutch houses are exposed to noise levels up to 50 dB(A). The redensification of urban centers increases the number of people being disturbed by noise in offices and residences and at the same time underlines the necessity of adopting noise abatement strategies in the urban environment. The recorded values of sound pressure levels near highways reach the 85-90 dB(A) while in large urban roads the maximum values range between 65-75 dB(A) **(Schreurs et al., 2008)**.

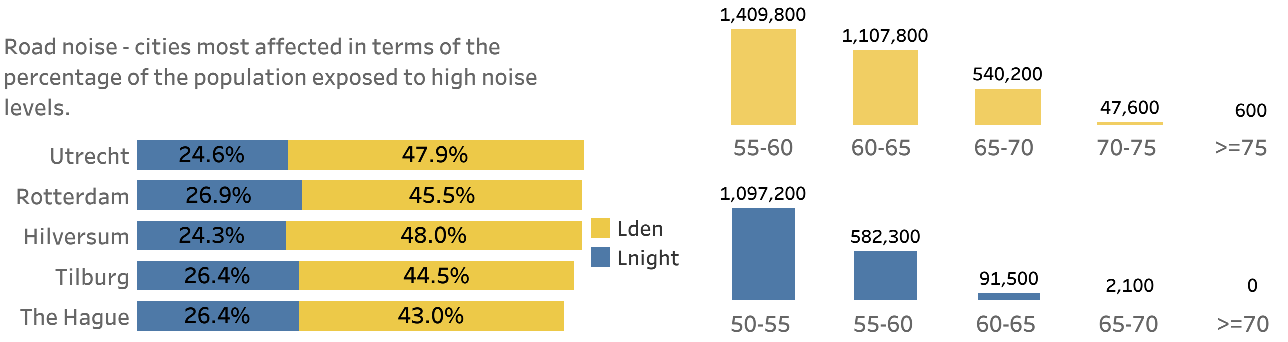


Fig. 2.3. The figure indicates the number of people being exposed to road traffic noise levels in The Netherlands, source: https://www.eea.europa.eu/themes/human/noise/noise-fact-sheets/noise-country-fact-sheets-2018/netherlands

Railway noise

The second most common noise source in the Netherlands is generated by the railway transportation as almost 200.000 people are exposed to sound pressure levels up to 75 dB even during nighttime. **(European Environmental Agency, 2018)** Railway noise is caused by engines, wheels rolling and aerodynamics while the most intensive noise loads are generated in low frequencies. Usually, the areas influenced are located in a 100 m distance from the railways while their function is described mainly as residences and offices. In the Netherlands, the railway noise attenuation is realized by constructing tunnels, noise barrier walls and by enhancing the buildings' facades with noise protection layers, e.g. double skin facades **(Niesten, 2016)**.

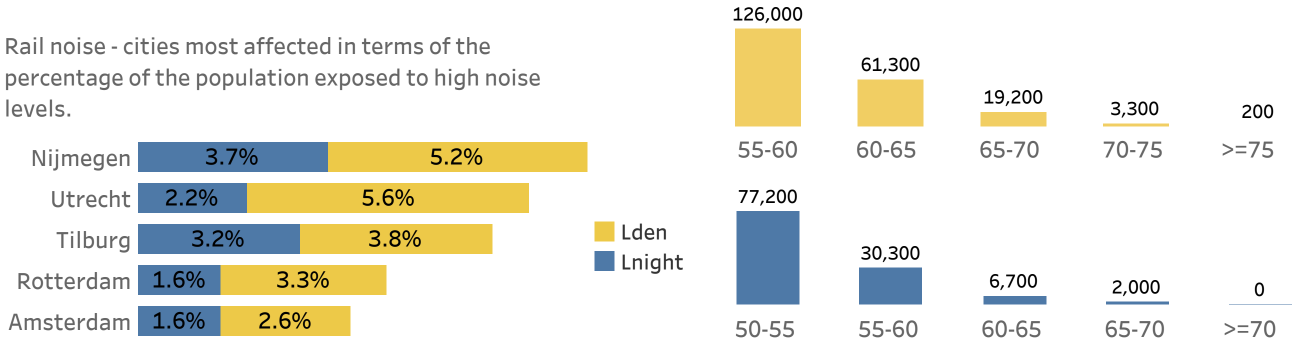


Fig. 2.4. The figure indicates the number of people being exposed to railway noise levels in The Netherlands, source: https://www.eea.europa.eu/themes/human/noise/noise-fact-sheets/noise-country-fact-sheets-2018/netherlands

Aircraft noise

Unlike road traffic and railway noise, aircraft noise is not a regularly found noise source in the urban environment since it causes nuisance only in neighborhoods located close to airports. The noise propagation and levels depend on the distance between the airplane and the built areas, for instance in a distance of 100 m the noise levels exceeds 100 dB. (Lugten M., 2014)

According to the publication of the European Environmental Agency (2018) in the Netherlands approximately 50000 people are affected by aircraft noise mainly in areas near Schiphol airport.

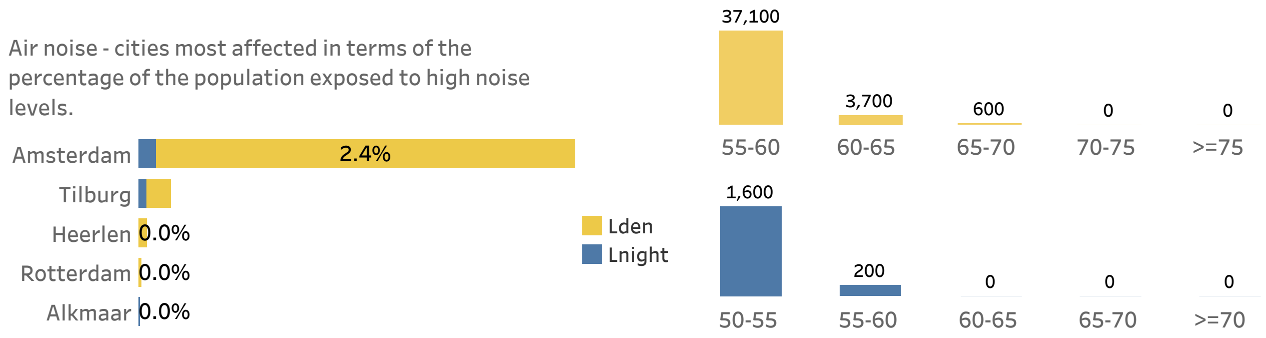


Fig. 2.5. The figure indicates the number of people being exposed to air traffic noise levels in The Netherlands, source: https://www.eea.europa.eu/themes/human/noise/noise-fact-sheets/noise-country-fact-sheets-2018/netherlands

Facades and strategies for reduction of noise propagation

Buildings' envelope is one of the most vulnerable building parts since it is exposed to the outdoor environment including high noise levels and extreme weather conditions. The amount of the transmitted noise depends on the materials used in buildings' envelopes as well as their maintenance frequency. As it was earlier mentioned, one of the most important factors of sound transmission in external walls is their mass. Thus, in old buildings consisting of thick masonry walls the most critical noise leakages occur due to cracks and poor sealing. In addition, the use of single glazing units in windows results in significant sound insulation drop. **(van der Linden, 2006)**

In more recently constructed buildings, the use of sandwich panels and highly insulated windows is quite common. Normally, facades are sealed as much as possible in order to minimize the noise leakage through cracks and openings. However, several design strategies have been developed in order to minimize noise transmission through facades. Some of them include the addition of a second facade layer, sound absorbing screens, balconies and green facades. **(Lugten M., 2014)**

Buildings' shape and balconies

Building's shape and openings' orientation has a critical role in noise transmission. In many cases, facades which include large openings are oriented towards more silent areas such as interior yards, while in facades facing busy roads the amount of openings is minimized. Also, the circulation areas such as corridors and staircases are located in the most noise-exposed facades in order to create a secondary zone between the interior spaces and the outdoor environment. Moreover, the addition of protrusions such as balconies, overhangs and parapets create ''shaded'' areas which decrease facades' direct exposure to high noise levels. Research including simulations and measurements indicated that the before-mentioned facade additions can reduce the noise levels in front of the facade by 2 to 8 dB depending on the materials used as coating on those elements and the height of each floor **Fig. 2.7**. **(Busa et al., 2011)**

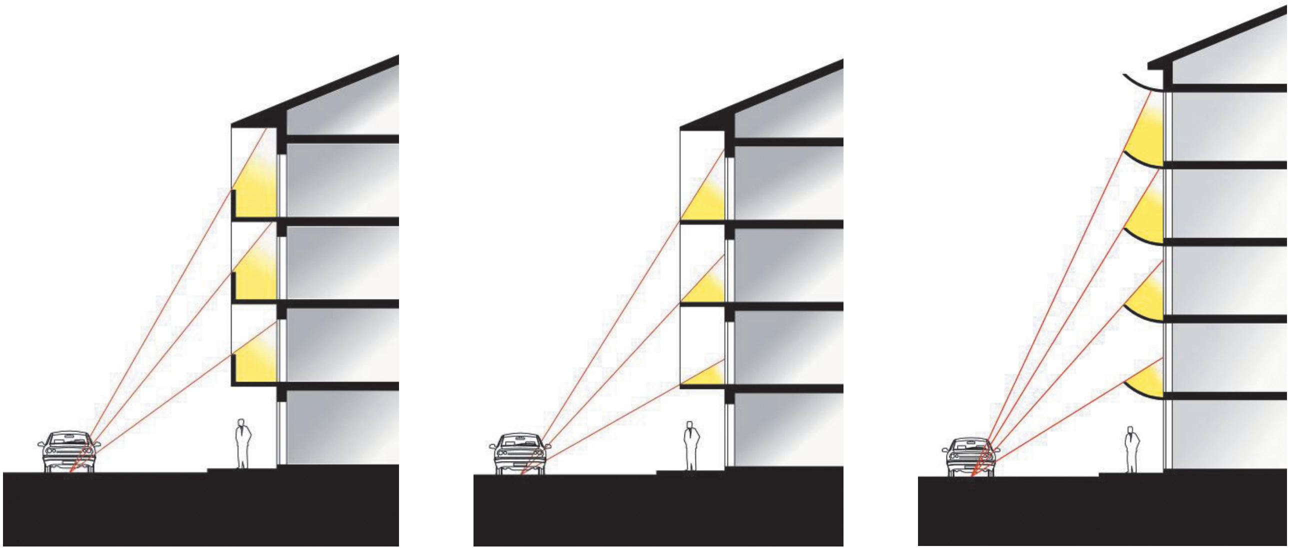
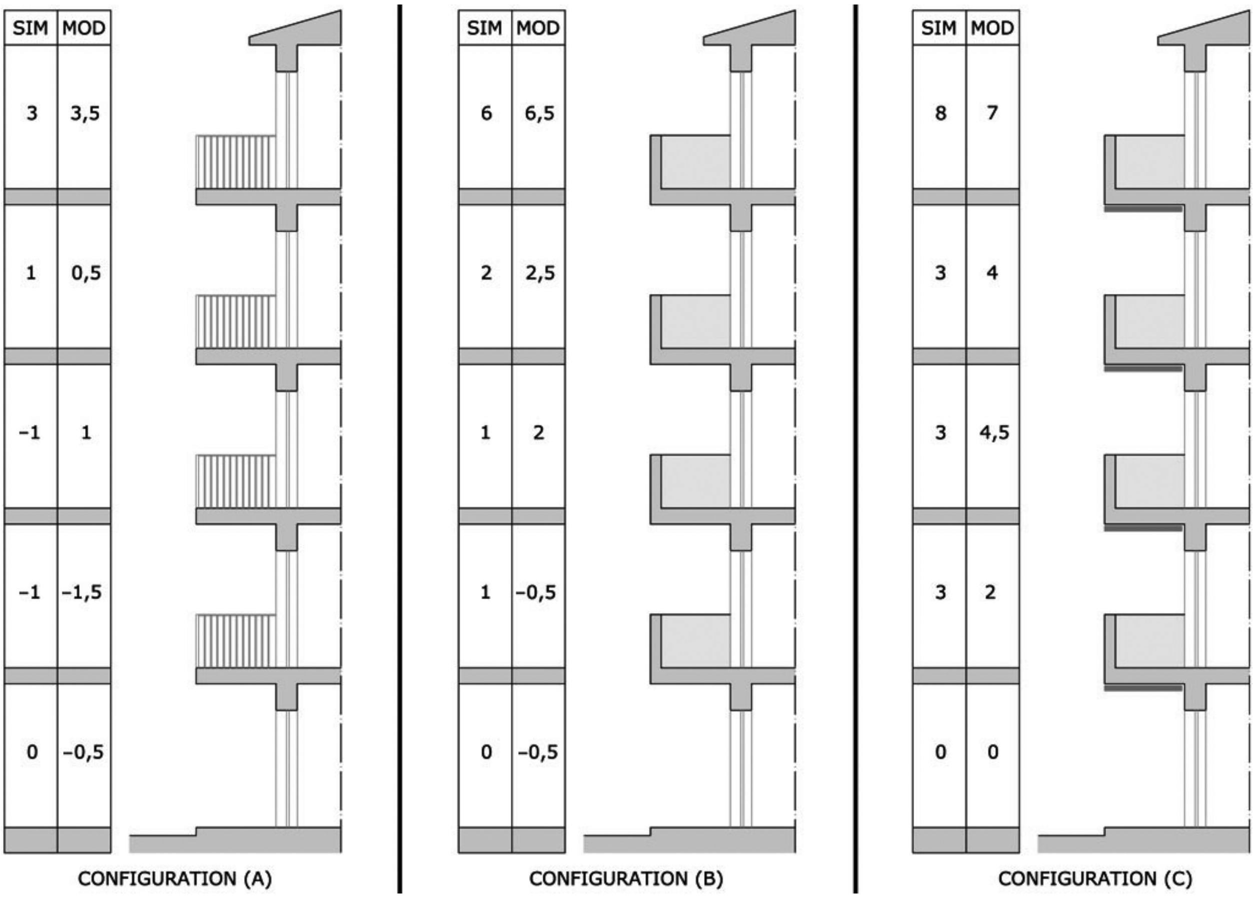


Fig. 2.6. The image indicates noise propagation in facades having overhangs and protrusions, source: Effect of Façade Shape for the Acoustic Protection of Buildings, Busa et al., 2011



CONFIGURATION (A)

SIM	MOD
3	3,5
1	0,5
-1	1
-1	-1,5
0	-0,5

CONFIGURATION (B)

SIM	MOD
6	6,5
2	2,5
1	2
1	-0,5
0	-0,5

CONFIGURATION (C)

SIM	MOD
8	7
3	4
3	4,5
3	2
0	0

Fig. 2.7. The image indicates the noise reduction occurring due to overhangs and balconies, source: Effect of Façade Shape for the Acoustic Protection of Buildings, Busa et al., 2011

Second skin facade

Although double skin facades are commonly used to decrease heating loads in winter, their installation is also suggested in buildings located in noisy areas close to highways and railways to reduce noise propagation. The second glazing facade acts as a noise barrier which reflects sound in the outdoor environment and reduces the transmitted noise. Parameters such as the type of glass, cavity's dimensions and the ventilation provisions have a great impact on the acoustical performance of double skin facades. The installation of a double skin facade results in increase of sound insulation by approximately 35 to 40 dB. **(Urban et al., 2016)**

Fig. 2.8. Double skin facade installed in residences in Delft as sound barrier, source: Building Physics lecture acoustics 1 AR1B025
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Windows enhancement

Windows are one of the most vulnerable building parts in terms of noise transmission due to glass panes' small mass and possible gaps in windows' frames. In order to increase sound insulation without compromising transparency levels the use of triple glazing units can be used. Triple glazing units combine advantages of an excellent thermal and acoustical performance even when low frequency sound should be attenuated. The sound insulation provided by high performance sealed triple glazing facades can reach even 50 dB. **(Pietrzkoa and Mao, 2013)**

Sound absorbing screens

Another common practice is the addition of sound absorbing materials on external facade screens creating a noise barrier in front of windows. This strategy is commonly found in noise insulated grills for ventilation systems which decrease the sound transmission through air. To tackle noise transmission in solid facade parts the combination of soft sound absorbing insulation and perforated metal sheets is regularly found. By using sound absorbing materials on external facade surfaces not only the sound insulation is improved but also the noise levels in the urban environment are decreased as the amount of reflected sound is minimized. **(Cobouw, 2012)**

Green facades

Green facades are preferred because they offer multiple advantages including the enhancement of thermal insulation, the improvement of urban air quality, the biodiversity support and noise abatement. The sound absorption provided by green facades is highly relevant to the thickness and type of growing medium as well as the typology and density of the foliage. Lower and medium frequency sound is more effectively absorbed due to the substrate while higher frequency sound is absorbed by vegetation. **(Wagemans, 2016)**

Case studies

Double skin facade/ Het Kasteel

In the city of Amsterdam housing scarcity leads necessarily to land use close to railways and highways. However, those areas are characterized by high noise levels and are considered unsuitable

Fig. 2.9. Double skin facade in Het Kasteel, source: http://www.hvdn.nl/2111/projecten/0444wte.htm

for the erection of large residential complexes. In Het Kasteel project a second glazing facade was built around the building's envelope to protect the residential spaces by noise generated by trains. In addition, the tilted geometry of facade panels allows natural ventilation inside the double skin cavity. In order to prevent overheating in summer some of the external facade units include foldable openings. In this case, the facade design results not only in noise protection but also in the creation of a unique facade shape which improves the aesthetics of the area. **(hvdn architects, 2008)**

Green facades/ Arup research on green facades

According to a study conducted by Arup in 2016, green facades do not have a great impact on noise reduction in cases where they are located close to noise sources. Their affect is more obvious as the distance increases and the sound becomes more diffuse. Also, simulations indicated that green facades are more effective in buildings having balconies or large overhangs as they trap more sound energy. The sound levels in that case fluctuate between 6 and 10 dB according to the width of balconies. In the models where only flat green facades were simulated the sound levels were partially reduced by approximately 3 to 6 dB(A). Finally, simulations proved that the coverage percentage has a different impact in cases where the noise abatement is required on street and building level. When sound insulation needs improvement the entire facade is suggested to be covered with plants. In contrast, when sound levels should be mitigated in the street level the application of green facades is required only on the ground floor level. **(Arup, 2016)**

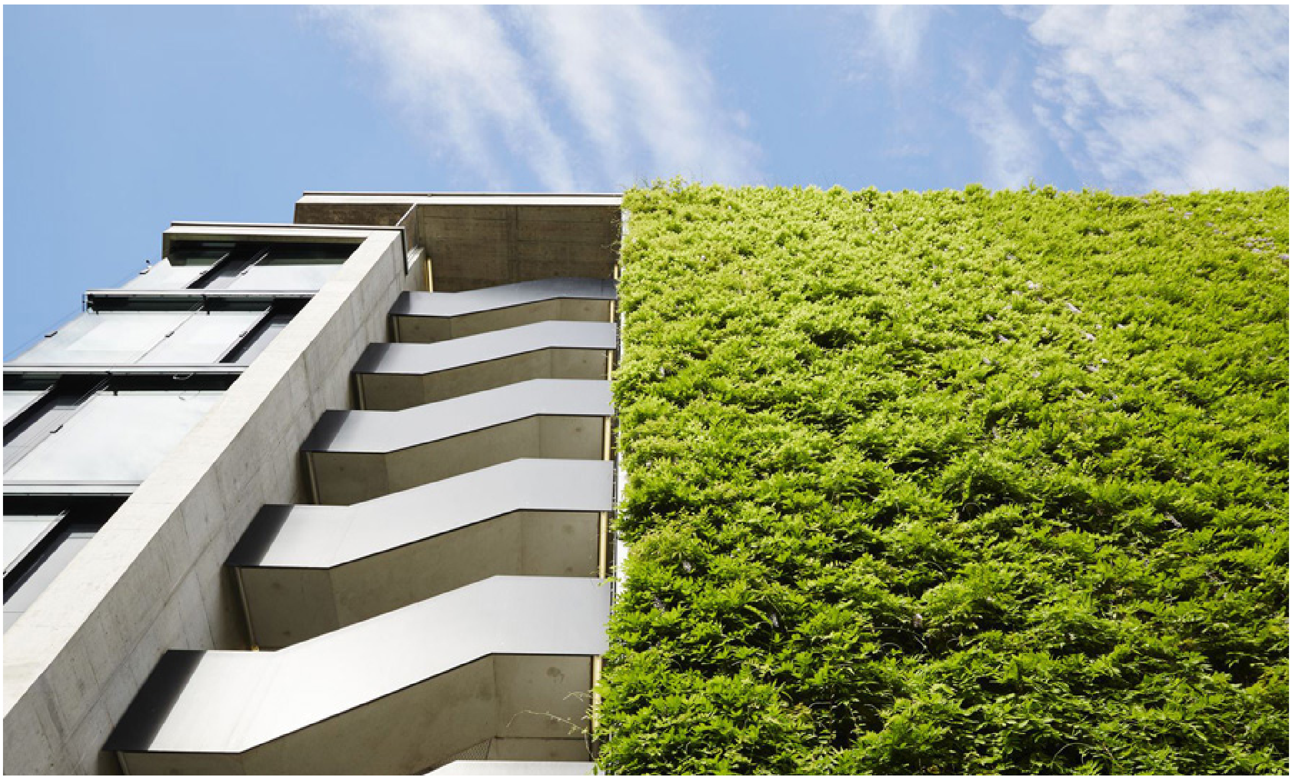


Fig. 2.10. The image indicate a green wall facade in UK, source: https://www.jakob.co.uk/solutions/view/green-walls/

Sound absorbing elements/ Laan van Spartaan housing project

The noise screens known as ‘‘coulissen’’ or ‘‘wings’’ consist of sound absorbing panels made out of perforated metal sheets and rockwool boards. **(Cobouw, 2012)** The panels are hanged from a steel frame in front of galleries or balconies. In the Laan van Spartaan housing project they were used in order to reduce sound levels in front of facades and ensure proper noise levels in the interior living spaces. Their application resulted in a noise level reduction up to 16 dB(A). **(Diersen P., 2012)** The external vertical screens’ layout does not influence the formation of interior spaces and apart from sound abatement it also provides shading. **(Cobouw, 2012)** Nevertheless, the current sound absorbing solution is suggested to be installed in front of corridors and secondary spaces as the dense screen pattern obstructs the view.

Fig. 2.11. The image indicated Laan van Spartaan facade where coulissen are applied to reduce noise exposure, source: http://weekblad.cobouw.nl/digitaleeditie/2012/2/20120316___/1_08/article11.html

Sound absorbers

In order to deal with noise problems in buildings, the application of sound absorbing materials is required on critical internal and external surfaces such as walls, facades, partitions and ceilings. They are applied in cases where the improvement of sound insulation, reverberation time or noise attenuation is needed. Different materials presenting varying properties regarding their effectiveness in sound absorption and the corresponding frequencies can be found in the market. In most of the sound absorbing materials sound absorption is realized through the phenomenon of friction due to materials’ high porosity.

Opaque porous materials

The sound absorption in porous materials is caused due to conversion of sound energy to heat and depends on porosity levels and flow resistance. More specifically, the air is trapped in material’s interconnected cavities and its movement is restricted because of material's flow resistance. Plenty of materials which are available in the market offer a sound absorption coefficient exceeding 0.8 for a wide frequency range while their effectiveness is influenced by their thickness. Their application is suggested in cases where sound frequencies exceeds 500 Hz as the absorption coefficient is increased dramatically above them. However, their limited mechanical strength should always be considered as opaque porous materials are quite fragile and usually should be protected by hard metal or wooden sheets. In addiction, in order to prevent fiber emission to air and to reduce the hydrophilic behavior of porous materials special treatment is required such as the addition of coatings which may decrease materials' sound absorptivity properties(Sagartzazu, 2007). Furthermore, their fire resistance is quite high as the majority of those materials are non-flammable or self-extinguishing. Some examples are rockwool, fiberglass, polyester panels and plastic foam insulation bats.

Fabrics/ textiles

One of the most common strategies to control noise is by airflow resistance as it determines the noise absorption of the medium. They can be found in different forms such as mats, blankets, boards, sheets and open-cell fibre foams. Fabrics' porosity, thickness, tortuosity, elastic modulus, air permeability and flow resistance are properties which determine their acoustic performance (Tang et al., 2018). In fibrous materials the sound energy results in fibres' motion while due fabrics' friction sound energy is converted to heat. Studies have indicated that fabrics' sound absorption coefficient can reach values between 0.4 and 0.7 (Soltani et al., 2013) (Tang et al., 2018). Vescom developed translucent sound absorbing fabrics having a sound absorbing coefficient of 0.5-0.8 due to their porosity and weave (vescom). Their light weight, flexibility and easy maintenance are properties which encourage their use as sound absorbents in offices, conference and teaching rooms.

Microperforated absorbers

Microperforated absorbers have been widely used for sound absorption in sectors of aerospace, mechanical and building engineering. Microperforated plates function either as Helmholtz resonators when they are backed by an air cavity and a sound absorbing layer or as porous materials. Their acoustic performance is affected by the perforation ratio, diameter, panel's thickness and depth of air cavity while their sound absorption coefficient varies between 0.6 and 0.8 (Struiksma et al., 2016) (Kang et al., 2004). Transparent micro-perforated plates have been developed in order to improve sound absorption while offering high levels of transparency due to viscous thermal dissipation and sound distortion caused by apertures having sub-millimeter sizes (Struiksma et al., 2016). However, their high cost due to glass perforation processing and brittleness limits their application. Another more costly effective solution includes the use of microperforated membranes made out of polycarbonate or ETFE foils which combine sufficient sound absorption coefficient, high transparency levels and extremely small weight. Their application is commonly found in front of windows, partitions and ceilings.

Resonators

The most simplified version of resonator absorbers are the Helmholtz resonators. Helmoltz resonators consist of air cavities which are connected to the surrounding environment by small holes named as necks. When sound waves enter the cavity they cause motion of air particles inside the cavity. **(Ginn, 1978)** The air volume behaves as a spring which compresses and decompresses the enclosed air inside the cavity. Due to this movement sound absorption occurs as because of friction sound energy is converted to heat. To increase the effectiveness of resonators and broaden the effective frequencies the application of porous materials inside the cavity is suggested. The maximum absorption coefficient occurs in frequencies close and at the resonant frequency of the system. By changing neck's diameter and cavity's volume the effective frequencies can be adjusted according to the requirements for each space. Resonators' application is suggested for areas where specific sound frequencies occur such as in mechanical rooms, auditoriums and concert halls. **(Adams, 2017)** In addition, facade blocks including Helmholtz resonators are used in occasions where low frequency sound needs to be abated, for instance in areas located close to flight paths where specific sound frequencies occur. Research realized by **Lugten (2016)** indicated that the application of resonator facade blocks provide a 15 dB noise reduction comparing to conventional facade blocks.

2.2 Natural ventilation

Natural ventilation's importance is related to the improvement of indoor air quality as well as temperature control during warm months. By ventilating indoor spaces, air pollutants such as CO2, odors, dust and moisture are removed while large amounts of oxygen are supplied. **(Van der Linden, 2013)**. A good indoor air quality is required in order to ensure people's health, productivity and wellbeing as insufficient ventilation causes headaches, allergies and respiratory problems. Sick building syndrome is a medical condition which describes illness' symptoms related to deterioration of indoor environment which exacerbate or improve according to the spent time inside a building. Usually, users presenting those symptoms live or work in buildings where outdated mechanical ventilation systems are used, polluted outdoor is supplied or noise propagation occurs. **(Shahzad et al., 2016)**

Summer ventilation is the supply of extra air to remove excess heat and control indoor temperature. Its benefits are associated to user's comfort as high temperatures cause discomfort, luck of productivity and faintness. When summer ventilation is provided naturally the outdoor temperature has to be lower than the indoor in order to have an efficient impact on the indoor environment. Therefore, since during daytime outdoor temperature usually exceeds indoor temperature nighttime natural ventilation strategies are commonly applied. In addition, nighttime natural ventilation is of great importance as it also removes heat absorbed by the building's structure itself due to its thermal mass. **(Van der Linden, 2013)**

In winter the main purpose of ventilation is the improvement of indoor air quality without decreasing the indoor temperature. To realize this goal, minimum requirements of fresh air have been set while the ability for regulation is required to be installed in any system type. According to **Buildings Decree** the required amount of fresh air is 25 m^3/h per person while the wind speed in the interior spaces should not exceed 0.2 m/s to prevent discomfort due to draught. In addition, it is suggested to locate operable window parts above 1.8 m to ensure that higher air velocities will not occur on peoples' level. **(Van der Linden, 2013)**

In order to prevent natural ventilation's unpredictability and to ensure stable indoor conditions, mechanical ventilation is provided in most of the buildings. The function of each space as well as its working schedule define the ventilation strategy. Mechanical ventilation offers a lot of advantages including controlled air temperature, standard humidity levels, constant air velocity, the provision of filtered air and sound isolation from the outdoor environment. Also, the application of heat exchangers reduces the consumed energy for air preheating and precooling. **(ter Haar, 2015)** However, the use of mechanical ventilation has negative effects as the poor maintenance of filters and inlets results in the increase of air pollutants in the indoor environment. In addition, complaints have been reported regarding the noise propagation between adjacent rooms through ventilation ducts as well as noise generation due to funs' rotation.

In order to combine the advantages of mechanical and natural ventilation, a hybrid system is often preferred. A hybrid ventilation system is described as a ventilation strategy where mechanical and natural air supply or exhaust are combined either simultaneously or independently. According to van der Linden (2013) the most optimum hybrid combination for residential high-rises is the natural air supply and the mechanical exhaust as fresh air is provided while the air flow rate is regulated by fans installed in the mechanical system. However, the space type and occupancy levels define the system's suitability, for instance meeting rooms where many people gather together require great amount of preheated or precooled fresh air. In addition, a mechanical ventilation system is required in most of the cases and needs to work supplementary to natural ventilation system in order to provide fresh air during harsh weather conditions. When natural ventilation is used, in winter months there is a risk of thermal discomfort due to cold draught, therefore a detailed and careful strategy has to be applied in order to prevent the increase of energy consumption for heating. (Van der Linden, 2013)

Hybrid ventilation in high-rises

Natural ventilation in high-rises is quite limited due to high wind speeds occurring on critical facade parts such as corners and higher floors. Due to large pressure difference caused by cross, stack and even single-sided ventilation the control of air flow rate is impossible. In addition, since high-rises are usually located in condense urban areas, natural ventilation is not preferred due to high noise levels and air pollution. Therefore, the majority of high-rises are either solely mechanically ventilated or are relied on a hybrid ventilation systems. **(Etheridge & Ford, 2008)**

It is important to highlight that a successful hybrid ventilation strategy in a high-rise is based on the interpretation of the conditions' range under which each mode is activated. Different strategies have been developed and are related to the concurrent or independent function of mechanical and natural ventilation. More specifically, the first strategy known as contingency, where a building is designed to be completely air conditioned and at the same time has natural ventilation provisions and vise versa in order to switch between those two modes. The second strategy includes the separation of zones where the ventilation strategy alters in different areas of one building. Finally, the third strategy is named complementary since the design is realized to utilize mechanical and natural ventilation at the same time. **(Wood & Salid, 2012)**

After the suitable ventilation method is selected, proper design strategies should be developed in order to ensure comfortable conditions in the indoor environment. Zones' division in high-rises is a very common strategy used for natural ventilation. Fresh air is induced to an intermediate zone and then fed to the main spaces. Usually these zones have a special behavior as they function either as sunspaces, green zones, acoustic buffer zones or thermal storages. Some examples of these zones are double skin facades and green atria and their function is to preheat, precool, reduce outdoor noise transmission or purify the induced air. **(Pasquay, 2004)** Envelope's design has a significant impact on the efficiency of a naturally ventilated space as natural ventilation is provided through envelope's openings. Therefore, openings' sizes, orientation and materiality are of great importance as they define wind's pressure drop and noise propagation. In most of the cases, a double skin facade is used in order to reduce the exposure to high wind pressure by a second layer. **(Etheridge & Ford, 2008)**

Also, the use of vents is quite common as adjustable grilles minimize or increase the flow rate. In cases where higher pressure occur, i.e. in heights up to 70 m, vents having self-regulating flaps adjust according to wind pressure in order to prevent discomfort caused by draugth. Vents vary on size and technology as they can be just applied on top of windows and be almost invisible or they may have the same size as an operable window. In addition, the use of thermal mass in combination with natural ventilation is quite effective as in warm months the thermal mass absorbs excess heat while nighttime ventilation discharges the thermal mass.

Case studies

KfW Westarkade

KfW Westarkade is an extension of KfW bank headquarters in Frankfurt and it was built in 2010. Its height is 50 meters and the implemented ventilation strategy is a hybrid complementary system. Natural ventilation is realized through a double skin facade including colorful operable flaps on the sides of each facade unit. The double skin facade is segmented in each floor while it is characterized by horizontal continuity. Each facade unit consists of a fixed glazing part, sound absorbing frames and operable hinged flaps which open up to 90°. The internal windows are either operable or fixed in order to supply natural ventilation through the double skin facade to the indoor space. Natural ventilation can be used at approximately 60% of the year a fact that results in 84% energy savings comparing to a solely air-condoned office building in Germany and a total annual energy consumption of 50 kWh/m^2. **(Wood & Salid, 2012)**

Fig. 2.12. The image depicts the KfW facade and the colorful ventilation flaps, source: http://www.sauerbruchhutton.de/en/project/kfw

Highlight towers

Highlight towers accommodate offices and are located in Munich. They belong to a greater plan about the redevelopment of urban land in central Munich. A mixed complementary ventilation strategy has been chosen for the current building. The natural ventilation is realized through a single skin facade including fixed triple glazings and operable one floor high vents. The vents consist of perforated steel plates which decrease the wind pressure, sound absorbing materials to minimize noise transmission and interior glazing flaps. They are operated automatically according to outdoor weather conditions and they are effectively used for nighttime natural ventilation in summer. The annual energy consumption of Highlight towers is 100 kWh/m2 and the energy saving is 69% comparing to an air-conditioned office building in Germany. **(Wood & Salid, 2012)**

30 St. Mary Axe

30 St. Mary Axe is an office high-rise in London built in 2004. It is a well known building as it is a landmark of London's skyline. A hybrid concurrent ventilation strategy is applied on the current building. Natural ventilation is supplied in building's atria by top and bottom hung windows where it is preheated and then provided to offices through internal windows facing the atria. In addition, office spaces can be directly ventilated by a ventilated double skin facade. Cross-ventilation is enhanced by atria located on the windward and leeward building's sides. Natural ventilation can be utilized approximately at 40% of the year which results in 50% energy savings comparing to a conventional office building in UK. **(Wood & Salid, 2012)**

Fig. 2.13. The left and top right image depict the highlight towers and its natural ventilation system, source: http://www.rumausbau.apleona.com/en/apleona-rm-ausbau/references/high-rises/highlight-towers-munich/, Fig 2.14. The picture indicates the openings in atria of 30 st. Mary axe, source: https://www.archute.com/the-gherkin-a-monumental-building-in-the-middle-of-london-by-foster-partners/img13/

Natural ventilation and noise propagation

As it was mentioned earlier, in order to enhance sound insulation, facades are sealed as much as possible to prevent noise leakage through gaps and cracks. In cases where natural ventilation is provided by large facade openings, the sound insulation is reduced significantly as the airflow resistance is very small. The proportion of openings' area in facades affects its overall sound reduction index, e.g. an opening having the area of 1/10th out of the overall facade will cause a 10 dB reduction of the total sound reduction index **Fig. 2.15.** In cases where solutions increasing air flow resistance are applied the effect of natural ventilation is minimized due to the decreased airflow. In addition, the available natural ventilation systems with acoustic treatment provide only background ventilation and cannot be used to remove excess heat in summer. In order to maintain high levels of facade sound reduction index (SRI) while providing natural ventilation, apertures should provide sound attenuation in sound frequencies regularly occurring in the urban environment. **(De Salis et al., 2001)** According to **ISO 717-1 (2013)** frequencies between 250 and 2000 Hz have the largest amount of sound energy due to road traffic, therefore apertures' sound attenuation should mainly occur in this frequency range. Several devices combining sound absorption and fresh air provision have been developed in order to ensure comfortable indoor condition in terms of noise levels and indoor air quality.

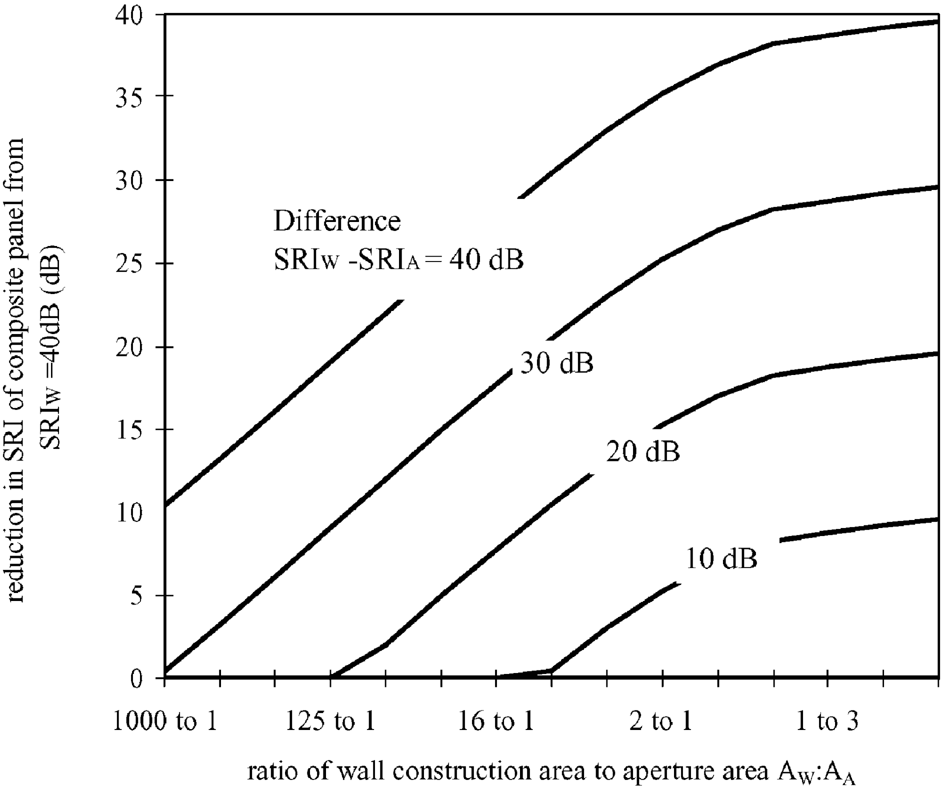


Fig. 2.15 The left diagram indicate the drop of Sound reduction index according to the proportion of openings' area to the total facade area, source: Noise control strategies for naturally ventilated buildings, De Salis et al., 2001

Natural ventilation systems for noise attenuation

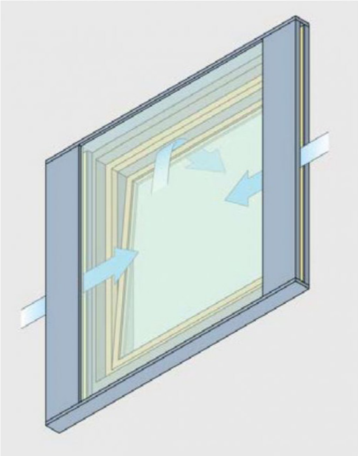
Trickle vents

Trickle vents are also known as background vents and they are commonly located above the windows or they are implemented on the window frame itself fig.2.16. They are easily operated manually or according to pressure difference either by flaps or slots (Biller et al., 2018). The installation of trickle vents is an effective solution for background ventilation as the available products in the market provide the required amount of fresh air (Karava et al., 2003). In addition, the application of sound absorbing materials in the air path results in effective noise attenuation as the sound insulation reaches even the 40-60 dB(A) (Duco, 2015). However, disadvantages emerge regarding heat losses since trickle vents similarly to other window elements are thermal bridges and transfer heat from the indoor to outdoor environment. In addition, although trickle vents are appropriate for supplying background ventilation, they do not sufficiently contribute to cooling loads reduction as the airflow is not enough to remove excessive heat in summer (Asdrubali, 2005).

Box- windows

Box-windows are defined as double skin glazed windows having partial openings on both window panes fig.2.17. The openings are located on different positions in order to prevent direct sound propagation (Tang, 2016). The cavity between the outer and inner pane acts as an air path where sound is attenuated before it enters the room. By replacing a conventional window with a plenum one the sound reduction index reaches 16 dB(A) (Søndergaard et al., 2017). Factors such as openings' size, the cavity's length and the material applied between the two panes can highly affect the window's acoustic performance (Yuya et al., 2009).

Several studies have been conducted in order to increase the window's sound proofness by apply



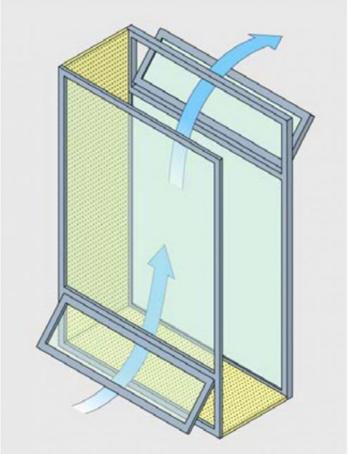


Fig. 2.16 Insulated trickle vent produced by Duco, Source: http://www.duco.eu/en-gb-products/basic-ventilation/window-ventilation Fig. 2.17 The right image indicates the basic function of box-windows, Source: https://www.apexacoustics.co.uk/attenuated-passive-ventilation-options/

ing sound absorbing materials and changing the cavity’s geometry. More specifically, experiments have shown that the application of opaque sound absorbing material on the window frames results in sound insulation improvement of 4-10dB(A). Other alternatives have been tested considering the application of absorbing material on both inlets and windows frames of the system, a strategy that increases the sound insulation by 10 dB(A). **(Søndergaard et al., 2017)**

Resonator panels

The use of resonators is quite common in engines to reduce noise propagation in specific frequencies. Their use in architecture is more often met in concert halls, gymnasiums and mechanical rooms. Many researchers have investigated the potential of using resonators in façade level in ventilation devices. The use of tube-like resonators results in sound insulation of 20 dB(A) while their increased length minimizes the amount of provided natural ventilation **(Tang et al., 2017)**. A façade panel developed by Lee and Kim (2014) included the design of an air transparent soundproof window where resonators are used to attenuate noise transmitted through natural ventilation **fig.2.18**. Their study was based in the theory of sound diffraction and the effect of negative bulk modulus. The resonator was a rectangular cell having two centralised holes. The two holes were connected with an air filter while small elements separated the resonators’ room. The measured sound insulation varied between 20 and 35 dB(A) in frequencies from 700 to 2200Hz **(Kim et al., 2014)**.

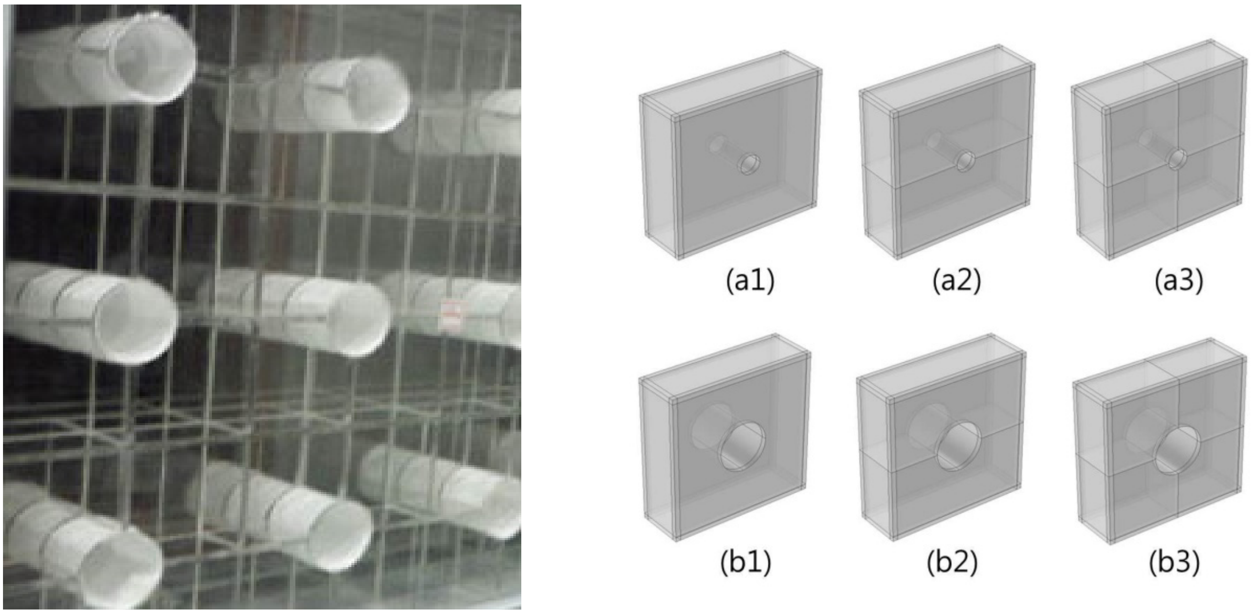


Fig. 2.18, Image indicates Facade rezonators used to provide natural ventilation developed by Kim S.A. and Lee S.H
Source:https://acousticengineering.files.wordpress.com/2013/08/window_that_lets_through_air_but_blocks_sound.jpg?w=500,

2.3 PCM

Thermal energy storage is one of the most common strategies to save energy and is based on storing of latent and sensible heat. Phase change materials (PCM) are used as heat storages as they absorb and release large amounts of latent heat and sensible heat when their physical state changes. The phase transition occurs when material's state change between solid to liquid, solid to solid, liquid to vapor and vise versa, however the liquid to vapor situation is excluded from the current literature research as it includes significant changes in air pressure and its application is not regularly found in the built environment. **(Rahman et al.,2013)** Due to their high heat of fusion, during their melting and solidification large amount of energy are released and absorbed. As long as the PCM is in its solid phase it behaves as a common material such as concrete as it stores sensible heat, at the point that PCM reaches its melting temperature the addition of extra heat does not result in temperature increase as it is stored as latent heat. When the entire volume of PCM has melted, its temperature starts increasing again as heat is stored in a sensible way. During the solidification phase of PCM, the heat which was previously stored during melting is released. **(Alexiou, 2017)**

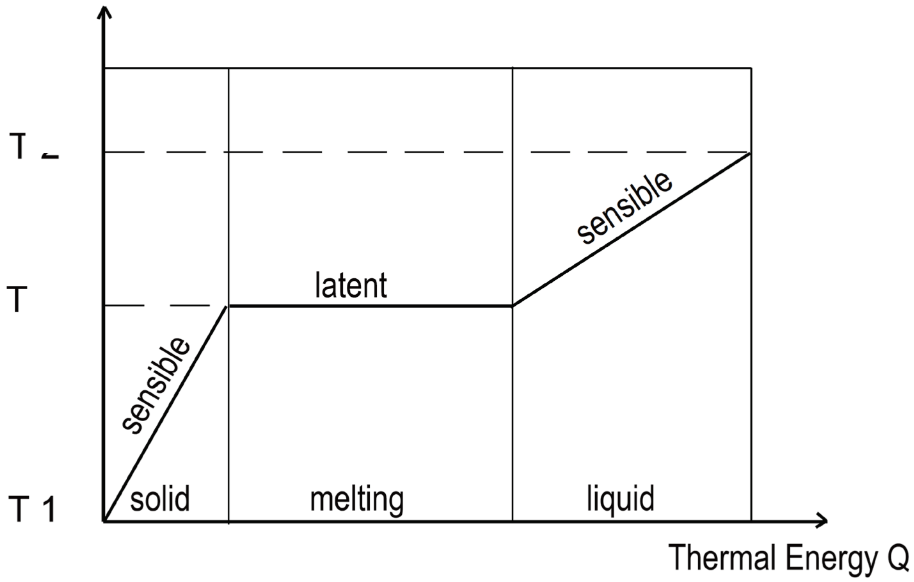


Fig. 2.19, Image indicates the correlation between PCM temperature and Thermal energy during phase transition
Source: Building Physics lecture notes 3, TU Delft, Aart Schuur and Wim van der Spoel

The benefits of PCM are mostly related to temperature stabilization as the range of temperature peaks are decreased due to heat absorption and release. One of the most important characteristics of PCM is their melting temperature, as it defines the temperature that phase transition occurs. The PCM available in the market cover a wide range of temperature between -5^{o}C and 190^{o}C, however, it is suggested to select PCM with melting point close to operable temperature. Therefore, for building applications a PCM should have a melting point between 20-30^{o}C to have an effective impact on the indoor environment. Another very significant property of PCM which defines its performance is its Latent heat capacity. The latent heat capacity determines the amount of heat that is stored and released during the phase transition **(Solarino, 2018**).

Additionally, several properties of PCM should be considered in order to interpret entirely their function. Firstly, the phenomenon of supercooling, where the PCM temperature has to drop significantly below the melting point during the cooling process in order to start the solidification phase. PCM will behave as a common material as long as this supercooling temperature is reached, therefore it will only store sensible heat. Secondly, the phenomenon of hysteresis where the PCM transition phase occurs in different temperatures during the solidification and melting process. Furthermore, the effect of material's phase separation should be included as in case of a non uniform substance the different freezing temperature occur for each of the used component. As a result, under specific conditions, the components will be separated due to the difference in density. **(Alexiou, 2017)**

To calculate the effect of PCM in the indoor temperature in correlation to time the following formulas are used **(Schuur and van der Spoel, 2017)**:

- Before phase transition:

$$T_i(t) = T_e + \frac{W}{H_e}\left(1 - e^{-\frac{H_e}{M}t}\right)$$

- During phase transition:

$$T_i(t^*) = \left(T_{pcm} - \frac{W + H_e T_e + H_{pcm} T_{pcm}}{H}\right) e^{-\frac{H}{M}t^*} + \frac{W + H_e T_e + H_{pcm} T_{pcm}}{H}$$

- After phase transition:

$$T_i\left(t^{\#}\right) = T_e + \frac{W}{H_e} + \left(T_{melt} - T_e - \frac{W}{H_e}\right)\exp\left(-\frac{H_e}{M}t^{\#}\right)$$

Where:

T_e is the outdoor temperature in oC

W is he internal heat production inside the room per time, this consists of the heat produced by people, equipment, lighting and the sun in J

H is the energy loss (or gain) by transmission and ventilation and the energy loss in J

M is the heat accumulation in thermal mass in J

t is the variant of time in s

PCM classification

Organic phase change materials

Paraffins

Paraffins are one of the most common PCM applied in buildings as they combine advantages such as low price, no supercooling, wide temperature range (-20-100°C) and high enthalpy values (approximately 200kJ/kg). However they have several drawbacks since they have a low thermal conductivity approximately 0.2 W/m2K, they are not compatible with encapsulation in plastics and they are moderately flammable. Special treatment with fire retardants is required to reduce fire risk while the encapsulation medium should be carefully chosen in order to prevent pcm leakage. **(Baetens, 2011)**

Non Paraffins

Unlike paraffins non-paraffins do not have specific properties and mostly consists from a number of esters, fatty acids, alcohol's and glycol's. The before-mentioned materials are flammable and they should not be exposed to high temperatures and oxidizing agents. The most suitable non-paraffins for building applications are fatty acids as they have a low temperature range, subcooling does not occur and their volume does not increase significantly during the phase change. However their high cost is of high importance as it prevents their wide application. **(Advanced cooling technologies, 2019)**

Inorganic phase change materials

Studies about Inorganic phase change materials have indicated that their performance is degraded after continuous phase transitions as they undergo supercooling and phase separation. The most popular category of PCM inorganics are Salt Hydrates. They present a higher thermal conductivity of 0.5 W/mK and their latent heat varies between 60 and 300 kJ/kg. **(Advanced cooling technologies, 2019).** Their thermal stability can be improved by adding gelled or thickened mixtures and suitable nucleating materials. **(Alexiou, 2017)**

Eutectics

Eutectics are composed by multiple types of PCM which undergo phase transition concurrently. Since its composition is formed by a mixture of different PCM their properties are dependent on the individual feutures of each of the used typologies. Eutectics are quite promising as they present optimum properties comparing to inorganic and organic PCM in terms of durability, encapsulation, enthalpy and effective temperature range. **(Solarino, 2018**)

Fig. 2.20, The image indicates Parafin wax and salt hydrates PCM Source: Building Physics lecture notes 3, TU Delft, Aart Schuur and Wim van der Spoel

PCM encapsulation methods

There are two ways to encapsulate PCM in building components. One is the microencapsulation and the other is macroencapsulation method. As their names indicate, the microencapsulation method includes the PCM impregnation by physical and chemical processes such as coating and spraying on solid elements. In the macroencapsulation method, PCM is enclosed in containers made out of metal, plastics, glass or foils. The choice of material should be done according to its compatibility with PCM while the containers should be constructed in a way that prevents leakages when PCM is in the liquid state. **(Solarino, 2018**)

Case studies: Facade applications

Paranel, a thermo-responsive glazing system

Paranel is a research project developed to investigate the potential of PCM implementation in double skin facades. The project's aim is to achieve the optimum combination of thermal mass and transparency to improve windows' thermal performance. The system works as a trombe wall as it consists of a ventilated cavity, an external glass layer with shading elements while the internal glass pane includes pcm. The pcm melts due to solar radiation and afterwards when it is solidified it releases heat indoors. The shading pattern was generated using the octapus generative algorithm to define the spacing between the grid cells. The amount of the needed pcm depends on the required pcm volume to achieve effective thermal mass. The paraffin pcm regulates the indoor temperature by reducing it by approximately 15°C. (Chen et al., 2018)

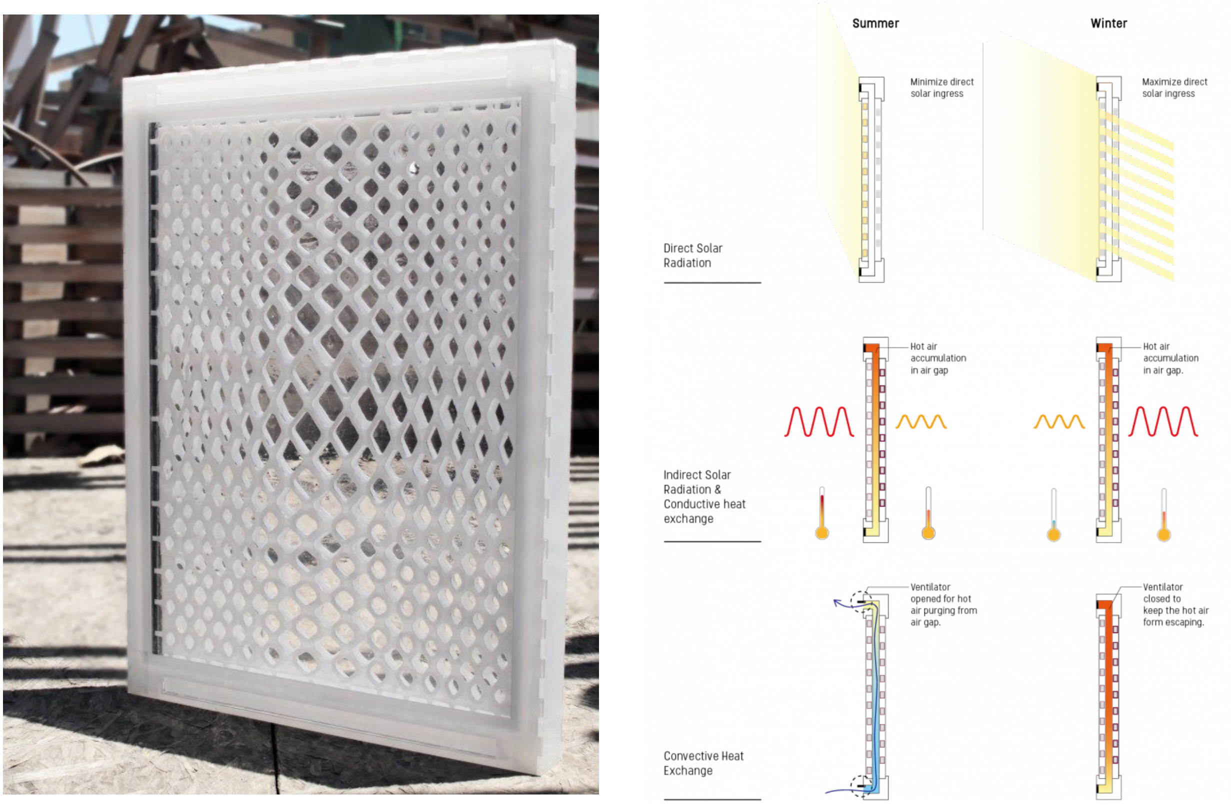


Fig. 2.21, The image indicates Paranel panel and its working principle, source: http://www.iaacblog.com/programs/paranel-phase-change-material-glazing/

DoubleFace: Adjustable translucent system to improve thermal comfort

Doubleface is a project developed by both TU Eindhoven and TU Delft to improve passively the indoor thermal comfort. The system is based on trombe wall principles but it is five times lighter, provides natural light because translucent materials are used and is adjustable in order to maximize the advantages of thermal mass in both summer and winter.

More specifically, the system consists of glass containers filled with translucent pcm while a layer of aerogel is added to enhance the system's thermal performance. In winter the pcm absorbs heat due to solar radiation which is later released indoors by rotating the components inwards. Contrarily, in summer the system accumulates heat from the indoor environment while it is discharged during nighttime to the exterior where the heat loads are removed by means of night ventilation. After the research team conducted measurements and simulations the optimum pcm and aerogel thickness were defined. By implementing the doubleface's passive strategy the total energy consumption is estimated to be reduced by 40% in comparison to a no trombe wall situation. **(Turrin et al., 2014)**

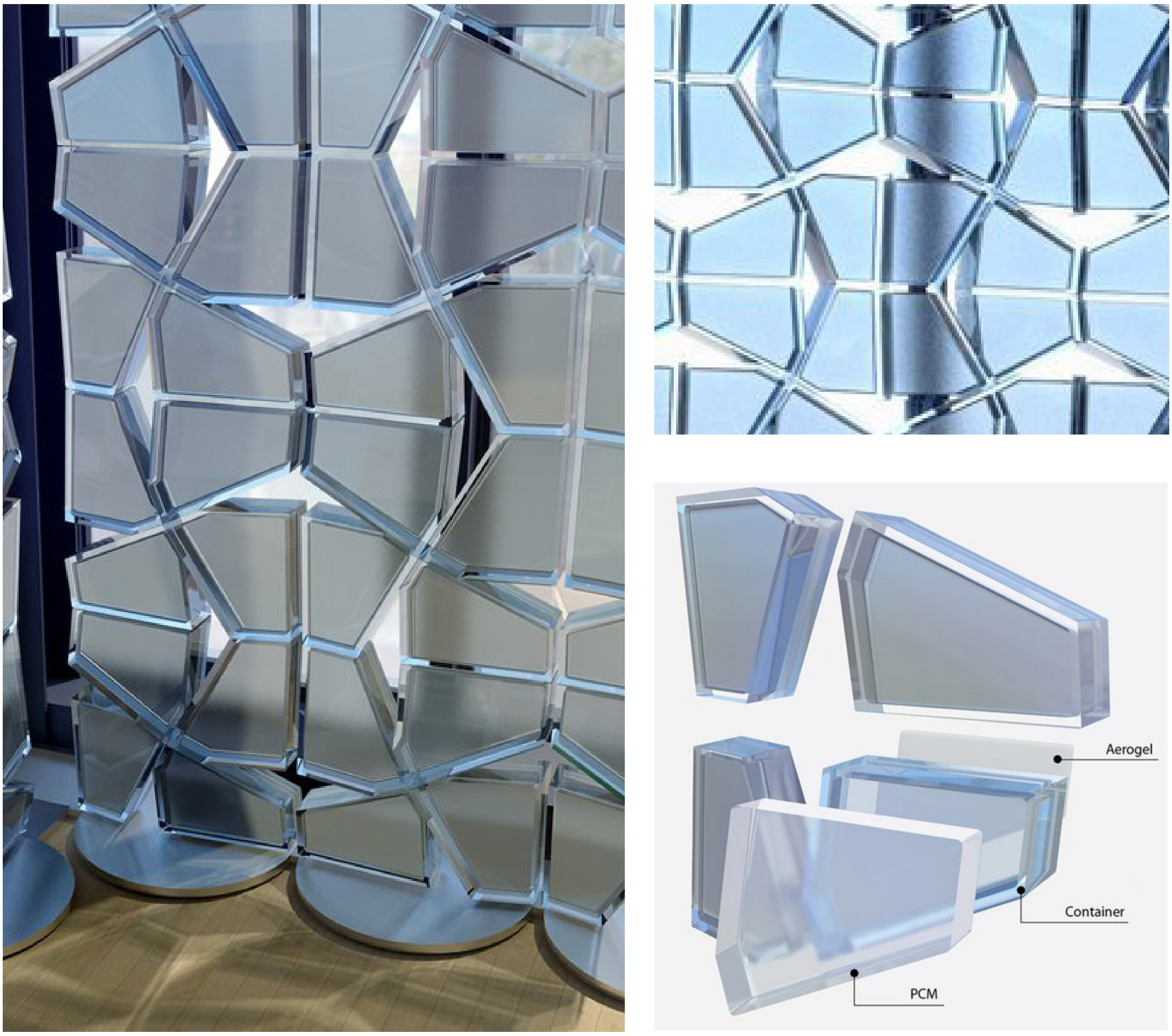


Fig. 2.22, The image indicates double face project, source: https://www.4tu.nl/bouw/en/LHP2014/doubleface/

GlassX

GlassX is a series of window system where PCM is implemented as an additional layer to a double glazing unit. The most popular product is the GlassX crystal where an additional prismatic glass is added on the external skin of the window. The prismatic shape is selected in order to reflect and block solar radiation in summer and prevent PCM overheating, while in winter due to the low height of sun, solar radiation is used to heat PCM. The total Uvalue of the window is 0.48 W/m2K and although its thickness is only 78 mm its heat capacity is equal to the heat capacity of a 200mm thick concrete wall. The main disadvantage of the system is the lack of transparency since when the PCM are in solid state the view is entirely blocked while even when they are in liquid state the prismatic layer does not allow a clear view. **(Greenlite glass systems)**

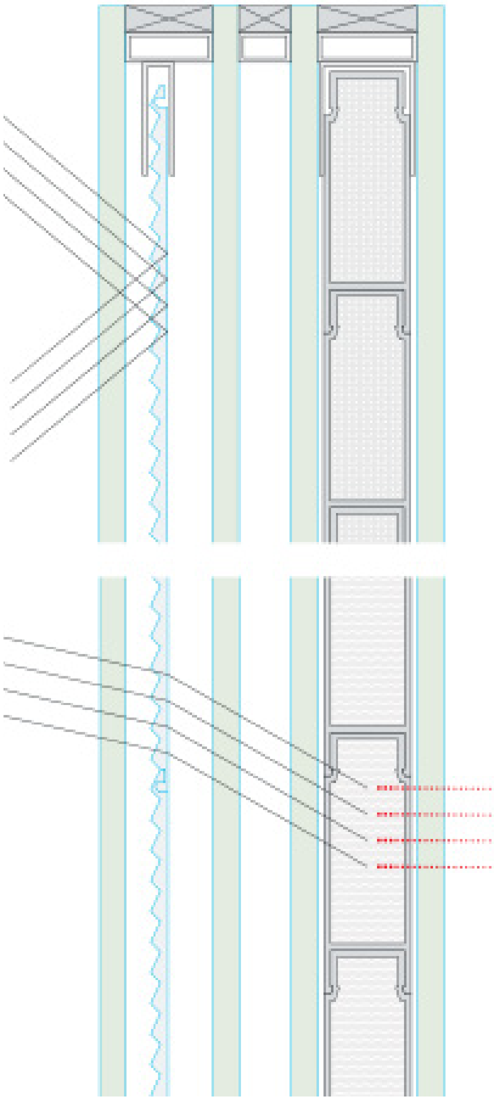


Fig. 2.23, The left image shows glass X system, source: https://www.laros.com.au/glass-x/
Fig. 2.24, The right image indicates the visual result of phase transition of glass X, source: https://www.materialscouncil.com/so-transparent-crystal-palace-reloaded/

Theory conclusions

Sound absorption is used in order to mitigate noise and is realized through friction and resonance where sound energy is converted to heat due to air particles' intense motion. In buildings, sound insulation is needed to minimize noise transmission between adjacent indoor spaces as well as between the indoor and outdoor environment. In the Netherlands, industries, road, railway and air traffic are the most commonly found noise sources in the urban environment. However, the largest number of people experience nuisance due to road traffic noise as they are exposed to noise levels exceeding 50 dB. As facades are one of the most critical building parts in terms of noise transmission, when they are exposed to high noise levels their sound insulation should be enhanced. The most common way to improve facades' sound insulation is to increase the thickness of sound insulating materials applied on external walls. However, the most vulnerable facades' parts are windows, where due to the small mass of glass panes and ineffective sealing, noise is transmitted more easily. Several strategies have been developed to improve window's sound insulation such as triple windows, sound absorbing screens, double skin and green facades. By comparing the before-mentioned strategies the most effective one is triple windows as it combines optimum advantages in terms of sound insulation, maintenance, cost and transparency levels. Double Skin Facades (DSF) and the installation of sound absorbing screens perform very well too however they provide smaller numbers of noise insulation with a higher cost and maintenance for DSF and the view obstruction for the systems with sound absorbing screens. Green facades is the least effective strategy as it presents the smallest values of sound insulation, is not transparent while a high cost is required for maintenance and construction. Regarding the sound absorbing materials, five categories are formed, the opaque porous materials, the MPP plates and membranes, textiles and resonators. Each material presents optimum performance in different conditions as their suitability is defined according to the range of frequencies that have to be tackled. More specifically, according to **table 2.2** in cases where transparency is required MPP plates, membranes and textiles are the most effective solutions, while opaque porous materials are the most preferable case when transparency is not a design requirement.

Facade typology	**Sound insulation increase (dB)**	**Maintenance**	**Cost (E/m^2)**	**Urban impact**	**Transparency levels**
DSF	35-40	+++	680	+	+++
Green facade	3-10	+	800	+++	-
Sound absorbing screens	16	++	N/A	+++	+
Triple windows	50-60	+++	300	+	+++

Table 2.1. In the table the strategies for mitigation of noise transmission in facades are compared. The table is created by the author

Sound absorber	Effective frequencies (Hz)	Absorption coef.	Cost	Transparency levels
Porous opaque materials	500-2000	0.8-1	+++	-
MMP plates	300-1500	0.7-0.9	+	+++
MMP membranes	50-500	0.6-0.8	+++	+++
Textiles/ fabrics	500-2000	0.5-0.8	++	++
Resonators	Varies according to resonators' geometry	0.7-0.9	+	+

Table 2.2. In the table sound absorbers are compared. The table is created by the author

The benefits of natural ventilation are related to improvement of indoor air quality and thermal comfort with minimum energy consumption in summer months. There is a great distinction between background and summer ventilation as the former is used to bring fresh air in indoor spaces during winter while the later's purpose is to remove excess heat in summer. In order to ensure thermal comfort and sufficient indoor air quality the minimum amount of fresh air is 25 m^3/hour/ person while the indoor air speed should be lower than 0.2 m/s. Natural ventilation is a great challenge in high-rises as it is limited due to issues of high wind speeds and noise propagation. Firstly, in order to deal with high wind speeds, design strategies have been developed including the use of DSF, vents and ventilation through other zones. As it can be seen in the **table 2.3**, DSF presents more advantages comparing to the rest strategies in terms of sound insulation, thermal comfort and transparency. To mitigate noise propagation through natural ventilation trickle vents, box-window facades and resonator panels can be used. Each solution presents optimum performance in different climates and building requirements. For instance, resonator panels are the most effective solution in climates where background ventilation is not required due to high temperatures in winter. In contrast, in regions where both background and summer ventilation are required such as the Netherlands, the most suitable solution to provide natural ventilation and mitigate noise propagation is DSF.

Facade typology	Sound insulation	Maintenance	Cost (E/m^2)	Thermal comfort	Transparency
DSF	+++	+	$$$	+++	+++
Vents	+++	++	$	+	++
Ventilation through other zones	+	N/A	$$$	+++	+++

Table 2.3. In the table design strategies for ventilation in high-rises are compared . The table is created by the author

Sound absorber	Background ventilation	Summer ventilation	Sound insulation (dB)	Transparency levels
Trickle vents	+	-	50-60	-
Box-window facades	+	+	20- 25	+
Resonator panels	-	+	20-35	+

Table 2.4. In the table design natural ventilation systems for noise attenuation are compared . The table is created by the author

PCM absorb and release heat when their physical state changes. For buildings application the use of PCM which change between solid and liquid and vice versa is suggested as the phase transition from liquid to vapor includes differences in pressure and is not easily encapsulated. Three main PCM categories are found, the organic, inorganic and euthetics. Paraffin waxes are most commonly used in buildings due to their low cost, high enthalpy values and wide range of applicable temperatures, however their low thermal conductivity, high flammability and incompatibility with plastics should be taken into consideration. Non paraffins present slightly better properties than paraffins while their cost is approximately 5 times greater. Inorganics such as salt hydrates have been applied on projects such as Glass X present a better thermal conductivity, are not flammable and have a high latent heat. Regarding the encapsulation methods PCM can be microencapsulated in materials as a coating or be impregnated during their production process. When PCM are applied in facades, they are usually macroencapsulated in transparent or opaque containers made out of polycarbonate or glass in order to allow transparency when they are on liquid state.

Classification	Paraffins	Non paraffins	Inorganics	Eutectics
Melting temperature (°C)	-20-100	5-120	0-100	Depends on the mixture
Thermal conductivity (W/mK)	0.2	0.3	0.5	Depends on the mixture
Latent heat (kJ/kg)	200-280	90-250	60-300	Depends on the mixture
Flammability	Flammable	Non-flammable	Flammable	Depends on the mixture
Compatibility	not suitable for plastics	Mildly corrosive	Corrosive	Depends on the mixture
Cost	$$	$$$$$$	$	Depends on the mixture

Table 2.5. The main pcm categories are compared . The table is created by the author

Consequently, by comparing the tables 2.1-2.5 the DSF is the most suitable system for Dutch climate for mitigation of noise transmission and natural ventilation provision as it presents the most effective features in terms of sound insulation, thermal comfort, transparency levels, summer and background ventilation. However, further treatment is required to maintain the acoustic performance of the DSF since noise will be propagated through natural ventilation. Also, to improve system's thermal performance during different weather conditions, PCM can be implemented in DSF to control the temperature developed inside the cavity and reduce the temperature peaks occurring daily in a ventilated DSF. Since in facades great transparency levels are required to maximize visual contact with the outdoor environment, PCM should be encapsulated in transparent containers. According to **table 2.5** the most suitable PCM for facades applications are Paraffins and Inorganics. However, paraffins should be treated in order to reduce their flammability while in inorganics, gelled or thickened mixtures and suitable nucleating materials should be added to improve their thermal stability.

Design concept

3. Design development

3.1 Concept

Considering the results of the literature review, the design is based on the use of a ventilated double skin facade where sound absorbing materials and PCM are implemented in the DSF cavity to control sound propagation and air temperature. The design concept was based on the creation of a facade air channel consisting of small transparent pockets. Since the main design goal is related to user's comfort improvement in terms of noise transmission, indoor air quality and thermal comfort, those pockets were perceived as small ventilation boxes which control the air temperature and attenuate noise. The air channel is a system of interconnected pockets while its length determines its effectiveness as the time that air travels inside the channel is increasing, more amount of sound energy is converted to heat and more heat exchange occurs due to solar loads and PCM **Fig. 3.1**.

The air channel's multiple function is realized by adding sound absorption treatment and pcm on pockets' sides. PCM were selected as a passive strategy to control cavity's air temperature and to improve the thermal performance of the air channel by preheating or precooling the supplied air. Ideally, one block/pocket could combine the incorporation of both sound absorbers and pcm on its sides. Therefore, as air travels inside the block, heat exchange occurs due to PCM and solar loads while noise is attenuated by sound absorbing treatment. As far as water and air tightness are concerned, both of them are realized by the implemented vents as well as the external and internal glazing sides of the air channel.

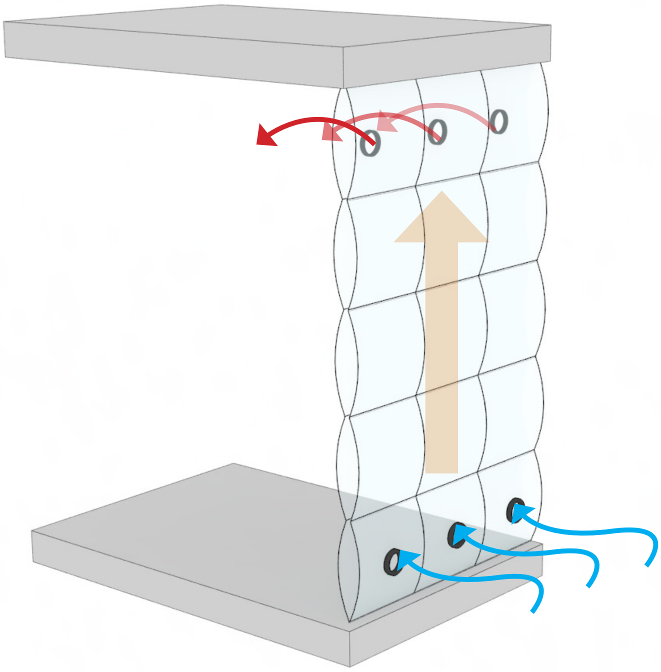


Fig. 3.1. The diagram represents the air channel's function of heat exchange and the effect of sound absorption , the image is created by the author

To minimize the complexity regarding the production process, assembly as well as the maintenance of a transparent facade element which combines at the same time the function of sound absorption, heat exchange, water and air tightness, the functions were divided in different facade layers and units **Fig 3.2**. The first layer consists of an external glazing skin and vents which are implemented at the bottom of the glazing pane. The second layer includes a system of sound absorbing and PCM units which is installed in the in-between cavity, several air brunches are created inside the cavity leading to those two box typologies. Finally, in the third layer an external glazing skin and vents are incorporated.

As the function of pcm and sound absorption is separated in two different units, the air does not pass through each pocket anymore but travels in the cavities created between them. The sound absorbing unit can be made out of opaque sound absorbing materials i.e. rockwool or transparent microperforated plates to increase the overall facade light transmittance. In the typologies where porous opaque materials are used, an extra layer of perforated foil or plate is added to prevent fibers emission and protect them from weather exposure. Regarding the pcm implementation, the macro-encapsulation method is selected. Box units, which are made out of transparent or translucent materials such as polycarbonate or glass, are filled with pcm. In addition, the units' shape and area can be determined according to the requirements for noise reduction and indoor temperature. The outdoor conditions, more precisely the solar radiation and outdoor temperature, define the needed PCM volume to achieve effective cavity temperatures.

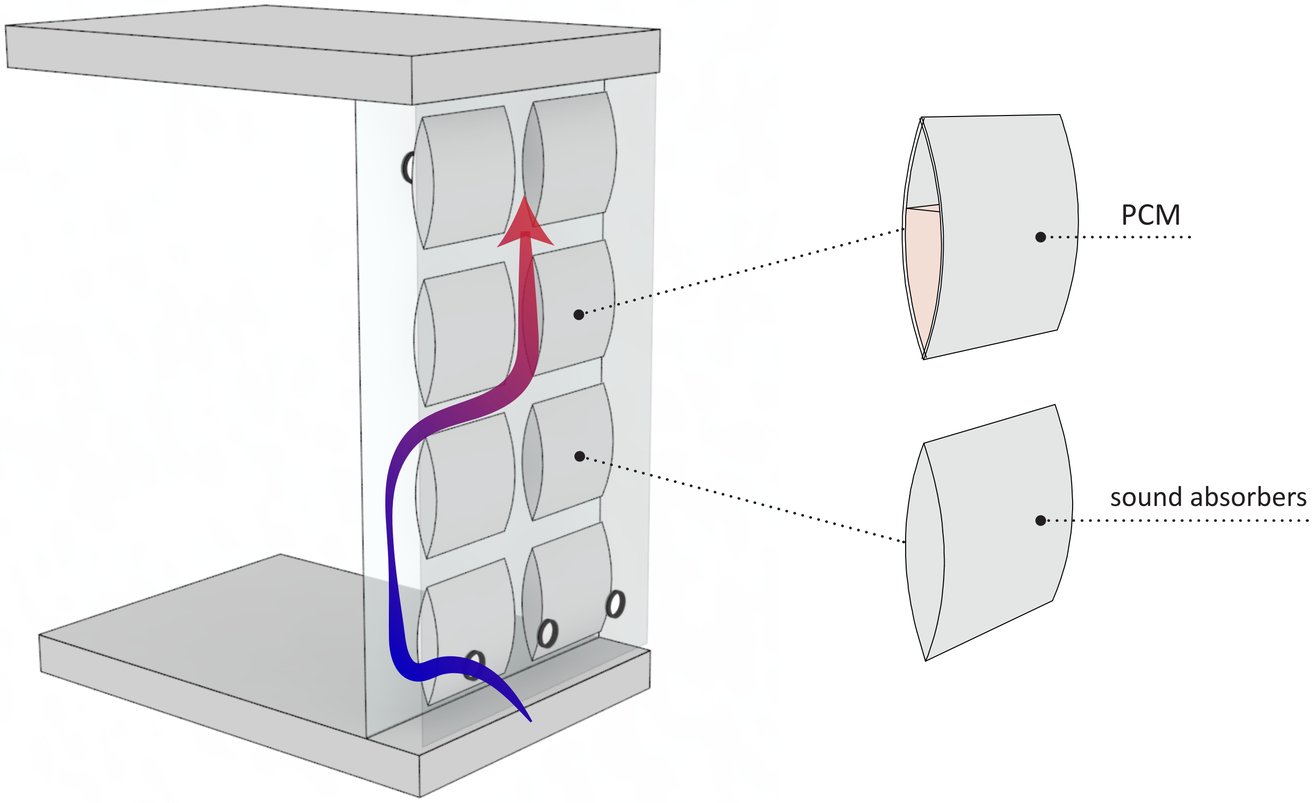


Fig. 3.2 The diagram presents the different facade layers and blocks incorporating PCM, the image is created by the author

3.2 Natural ventilation strategy

A ventilation hybrid strategy was developed about different weather conditions in order to ensure indoor comfort in annual basis. Since the design aim is to rely only on passive strategies, different concepts were developed according to varying weather conditions. In winter, the system provides only background ventilation as long as the outdoor temperature does not drop below 5°C, while in summer natural ventilation is provided as long as the outdoor temperature is lower than 27°C. During windy days when wind speed exceeds 20 m/s, fresh air is supplied mechanically and the facade's openings are sealed to minimize heat exchange between the indoor and outdoor environment. Regarding the operating schedule, since Dutch office high-rises are considered as case studies the occupancy hours are 09.00-18.00 during workdays while the occupancy level is defined by Dutch standards as 0.10 people/m². **(van der Linden, 2010)**

Winter months

T_{out} < 5°C or/and v_{wind} >20m/s

As the outdoor weather conditions are quite harsh, in order to minimize the heat losses due to background ventilation the natural ventilation system is not activated. Both internal and external openings are closed and the double skin facade functions as a thermal barrier which decreases the heat losses through the glazing units. The interior space is only ventilated with mechanically supplied warm air while the air extraction is also realized mechanically and ends up to a heat recovery system. **Fig 3.3**

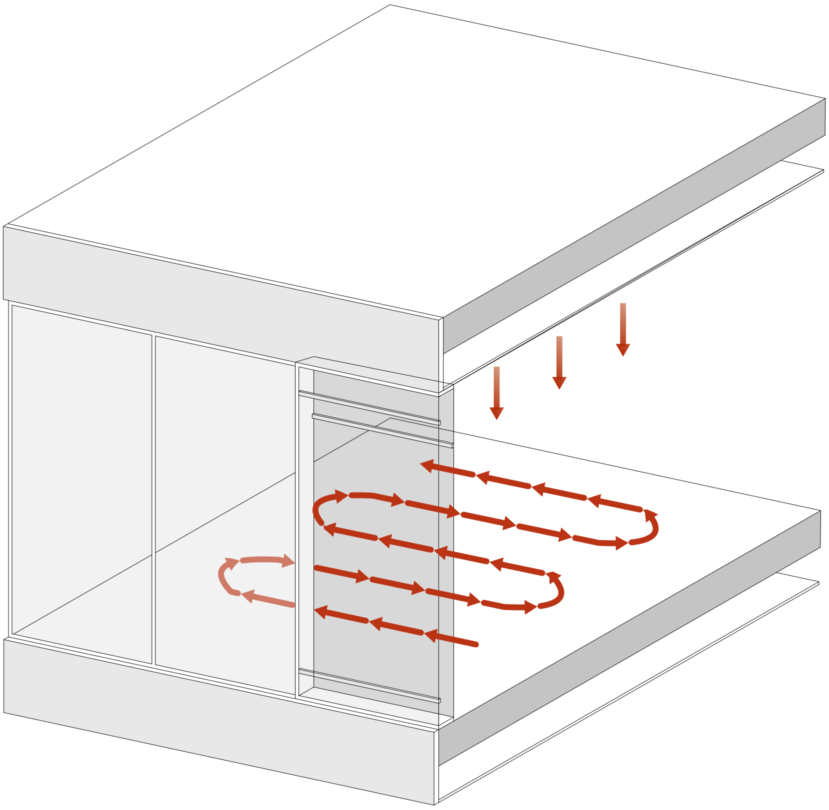


Fig. 3.3. Winter ventilation strategy when the Tout< 5oC and/or wind spreed > 20 m/s, the image is created by the author

Winter months

$T_{out} > 5oC$ and/or $v_{wind} <20$ m/s

Under these weather conditions the natural ventilation system provides continuously background ventilation. The implemented PCM inside the double skin cavity in combination with solar loads preheat the air before it is supplied to the indoor environment. The indoor space is heated by a floor heating system to ensure comfortable conditions for the building's users. The air is extracted mechanically and is transferred to a heat recovery system. The users have the freedom to operate the indoor and outdoor openings if they want to increase the airflow to the indoor environment **Fig. 3.4.**

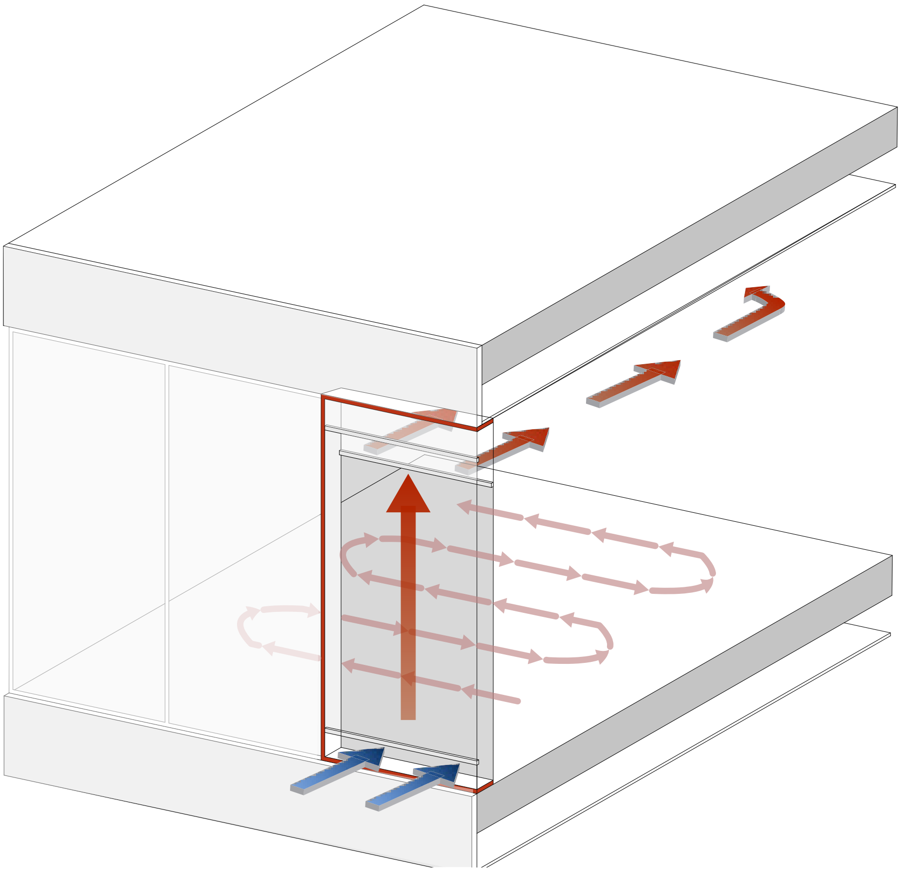


Fig. 3.4. Winter ventilation strategy when the Tout> 5oC and/or wind spreed < 20 m/s, the image is created by the author

Summer months

$T_{out} < 27^{o}$C and/or wind speed< 20 m/s

During summer months, the natural ventilation system is activated to its maximum as both external and internal openings are open to increase as much as possible the airflow inside the cavity. In addition, in days where there is a low wind pressure the natural airflow is enhanced by increased air exhaust rate. During daytime, PCM absorb heat from the naturally supplied air and pre-cool it before it is brought indoors **Fig. 3.5.** The night summer ventilation has two phases, during the first one the cavity is ventilated in order to cool down and discharge pcm **Fig. 3.6.**

After the pcm are entirely solidified, the second phase of nighttime ventilation begins, where cold air is brought indoors through the cavity in order to decrease the indoor temperature and create a pleasant indoor environment during morning **Fig. 3.7.**

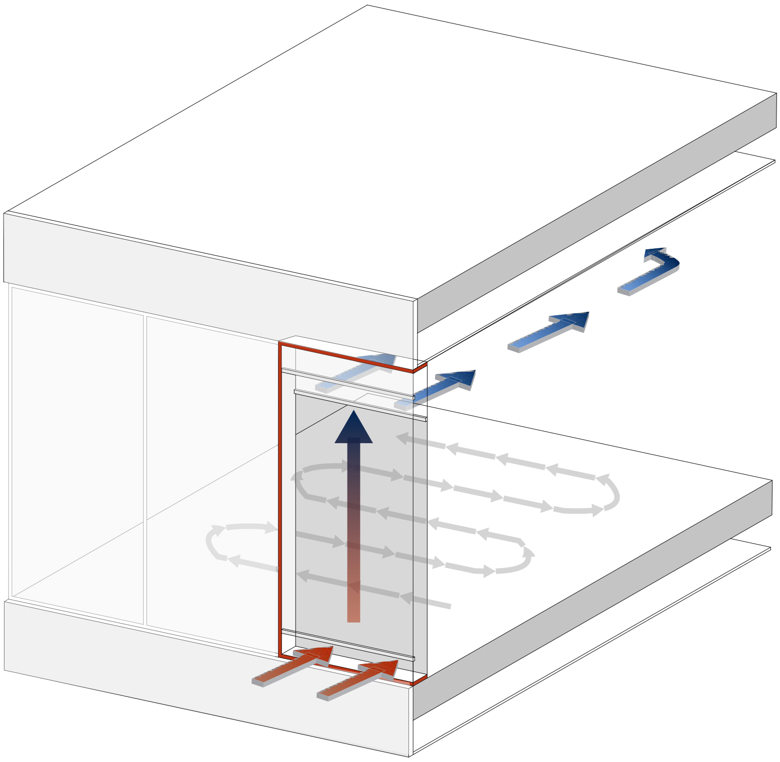


Fig. 3.5 Summer daytime ventilation strategy when the Tout< 27°C, the image is created by the author

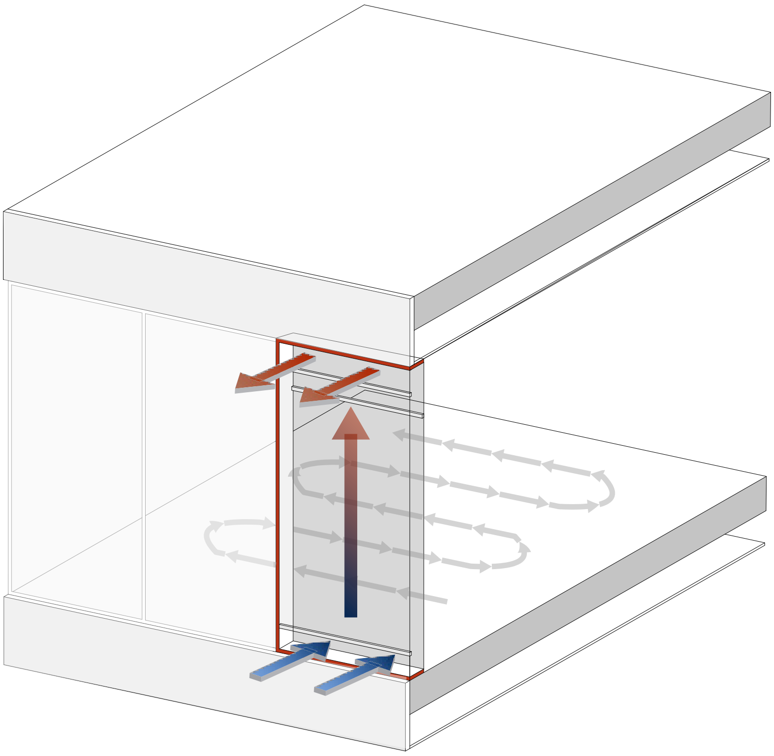


Fig. 3.6 First phase of summer nighttime ventilation strategy, the image is created by the author

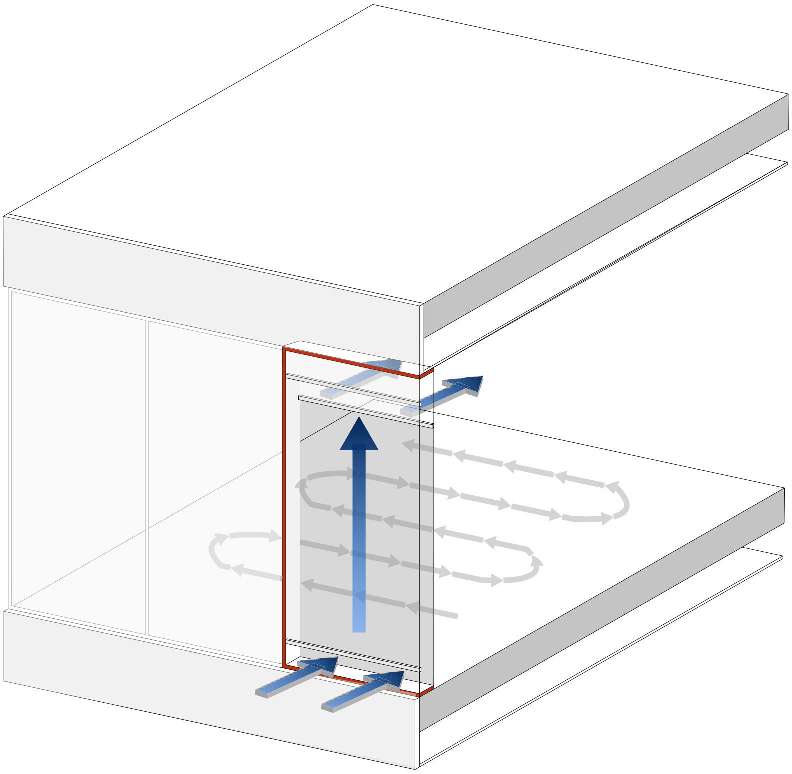


Fig. 3.7 Second phase of summer nighttime ventilation strategy, the image is created by the author

Summer months

Outdoor temperature > 27°C and/or wind speed> 20 m/s

When the temperature exceeds 27°C or the wind speed is higher than 20 m/s , the indoor environment has a constant temperature of 26°C because of floor cooling while mechanical ventilation supplies cool air. The air is extracted mechanically and fed to a heat recovery system. In addition, both top and bottom external openings are kept open and provide continuously air in the cavity to prevent overheating **Fig. 3.8**.

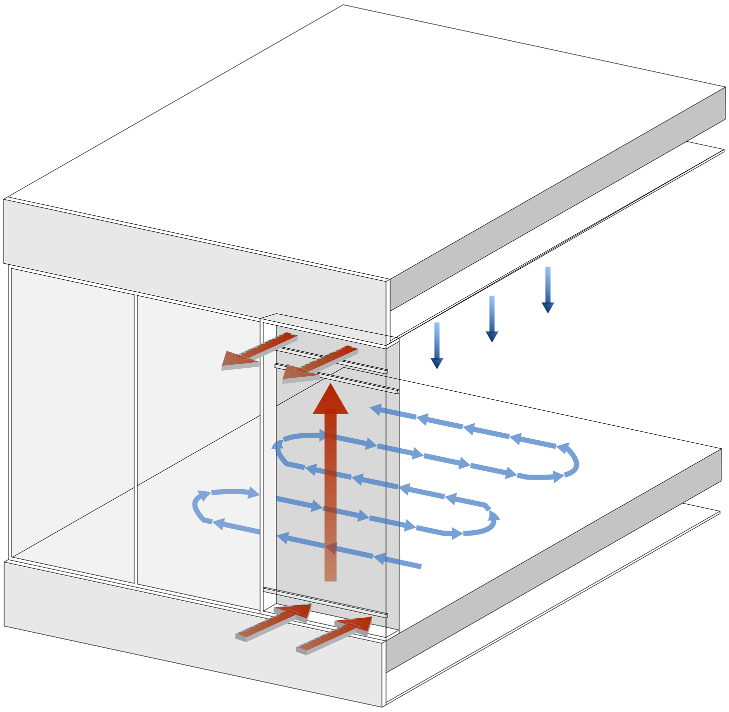


Fig. 3.8. Summer ventilation strategy when Tout> 27°C, the image is created by the author

Building physics

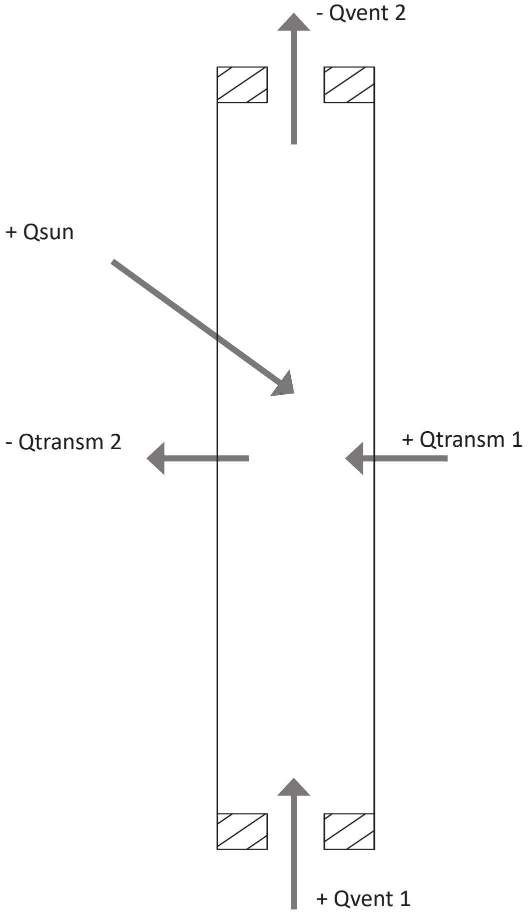
4. Calculations

To make an estimation about the thermal and acoustic performance of the developed concept, a case study of a double skin facade panel having the dimensions of 3x 1.5x 0.15 m was analyzed.

4.1 Thermal calculations

Firstly, calculations were accomplished to estimate the temperatures that will be developed inside the cavity. Different weather conditions were considered presenting varying outdoor temperatures and solar radiation values which were retrieved by Climate consultant's weather data for the Netherlands. The double skin panel is perceived as a solar collector and the assuming medium where heat transfer occurs is air instead of water. Several heat flows occur from the indoor and outdoor environment Fig.4.1 . (appendix 1)

Five heat transfers occur, two of them are because of ventilation (Qvent 1, Qvent 2), the other two due to heat transmission through the glazing panes and one due to solar loads. In order to get more accurate results, the solar collector was divided in smaller zones of 0.5 m to predict the temperature gradient inside the box-window cavity in different heights Fig.4.2.



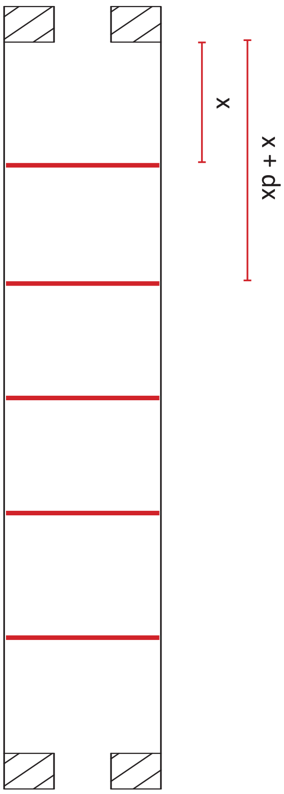


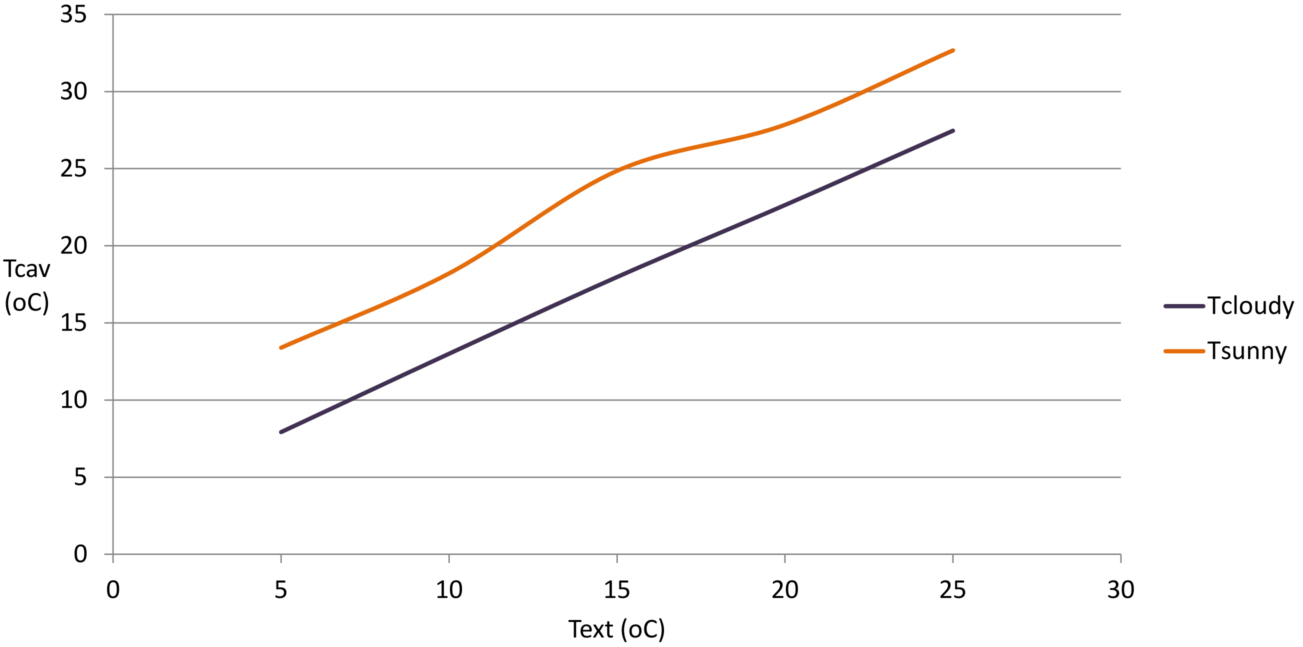
Fig. 4.1. The diagram indicates the Heat flows from and to the facade panel, the image is created by the author

Fig. 4.2. The diagram illustrates small divisions of the facade panel, the image is created by the author

In order to calculate the developed temperatures inside the cavity the following formula was used:

$$Tx = \frac{\frac{Te}{Re}dx + \frac{Ti}{Ri}dx + Atq_{sun}dx + vwpcT_{x-dx}}{\frac{dx}{Re} + \frac{dx}{Ri} + vwpc}$$

Different weather conditions were considered in calculations where the outdoor temperature varied between 5°C and 25°C. In addition, the solar radiation levels included for sunny days were 300 W/m^2 and 500 W/m^2 and 100 W/m^2 for cloudy days. In the following table the temperature extracted from the cavity in correlation to the outdoor temperature is plotted.



Graph 4.1. The graph illustrates the cavity temperatures during sunny and cloudy days in relation to external temperature, the image is created by the author

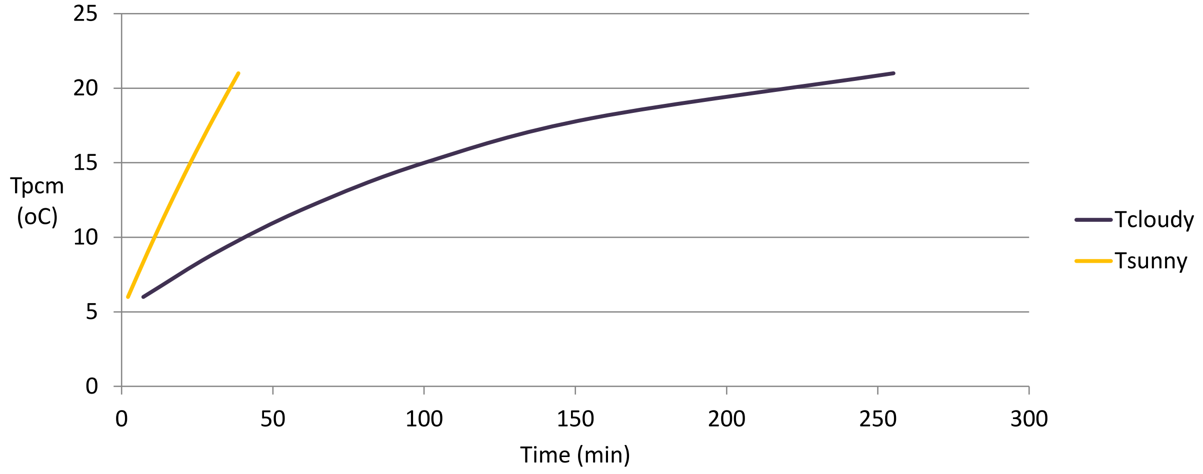
As it can be seen from the graph 4.1, the cavity temperature is dependent on solar loads. Especially during winter, the temperature may be doubled in sunny days comparing to the outdoor temperature. Even during cloudy days when the solar loads drops to 100 W/m^2 there is a temperature increase of 2°C. This fact minimizes the risk for indoor discomfort due to draughts and ensures pleasant indoor conditions in a naturally ventilated space. However, when the external temperature increases above 20°C, the cavity is overheated since its temperature exceeds 26°C and it is not suitable anymore for providing natural ventilation. Consequently, it is necessary to apply a strategy which at the same time provides high temperatures in winter and minimizes the risk of overheating in summer. **(appendix 2)**

Another concern is associated to the daily solar radiation fluctuations. More specifically, it is quite common to have in the same day significant changes between sunny and cloudy weather. Since the cavity is continuously ventilated, the air temperature cannot be stable and it will change according to the outdoor conditions. In order to control daily temperature fluctuations, a strategy implementing PCM inside the cavity is applied on the design. The goal of this strategy is to stabilize the cavity air temperature and decrease its dependency on solar loads. Of course as the system relies on passive ways to improve thermal comfort it can never be entirely independent from solar loads. The only factor which can be improved is the time that the system works effectively and be extended without being influenced by the outdoor conditions. The considered PCM volume is 0.04 m^3 and Rubitherm SP21EK was selected in order to control the cavity temperature and its properties were used to calculate the PCM effect in the cavity temperature **(appendix 3)**.

Firstly, the time required for PCM to reach its melting temperature is calculated according to the following formula, in order to understand the effectiveness and the suitability of the PCM strategy for the suggested design concept. To simplify the PCM temperature calculations in accordance to time, the PCM temperature is considered equal to the cavity air temperature. In real conditions, the pcm and air temperature are different as PCM needs more time to heat up comparing to air.

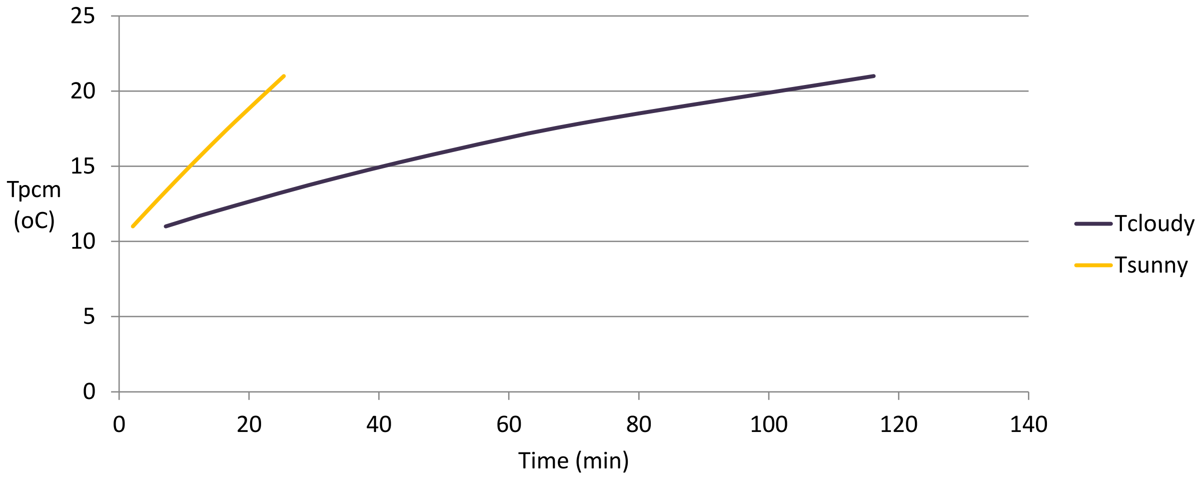
$$t = -\frac{M}{H}\ln\left(W - \frac{(Tpcm - Tout)H}{W}\right)$$

Time required to reach 21°C when Tout= 5°C, $Q_{suncloudy}$= 100 W/m^2 and $Q_{sunsunny}$= 400 W/m^2



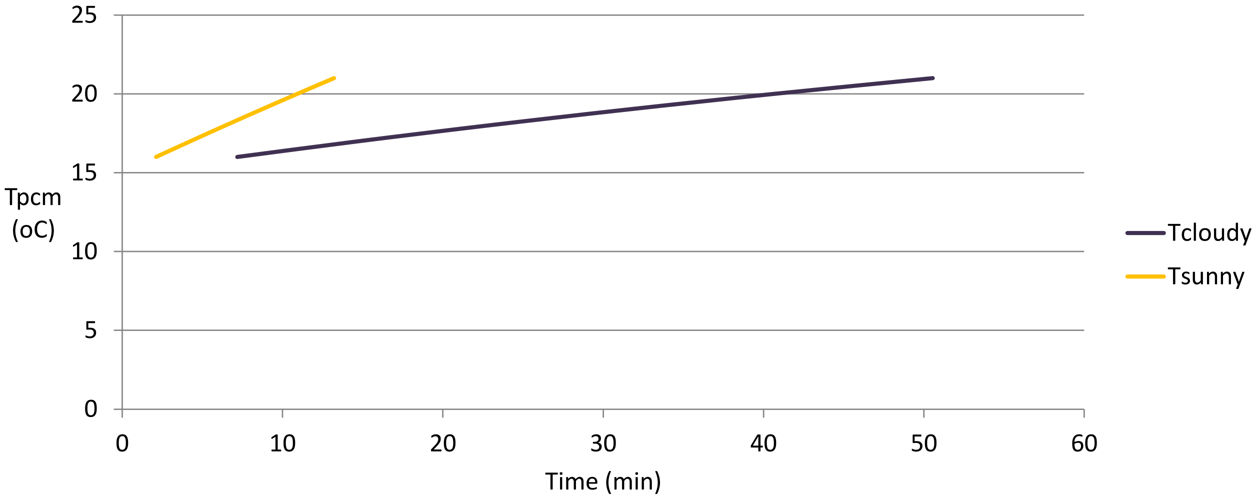
Graph 4.2. The graph illustrates the correlation between Tpcm and time when Tout is 5oC during a sunny and cloudy day, the image is created by the author

Time required to reach 21°C when Tout= 10°C, $Q_{suncloudy}$= 100 W/m^2 and $Q_{sunsunny}$= 400 W/m^2



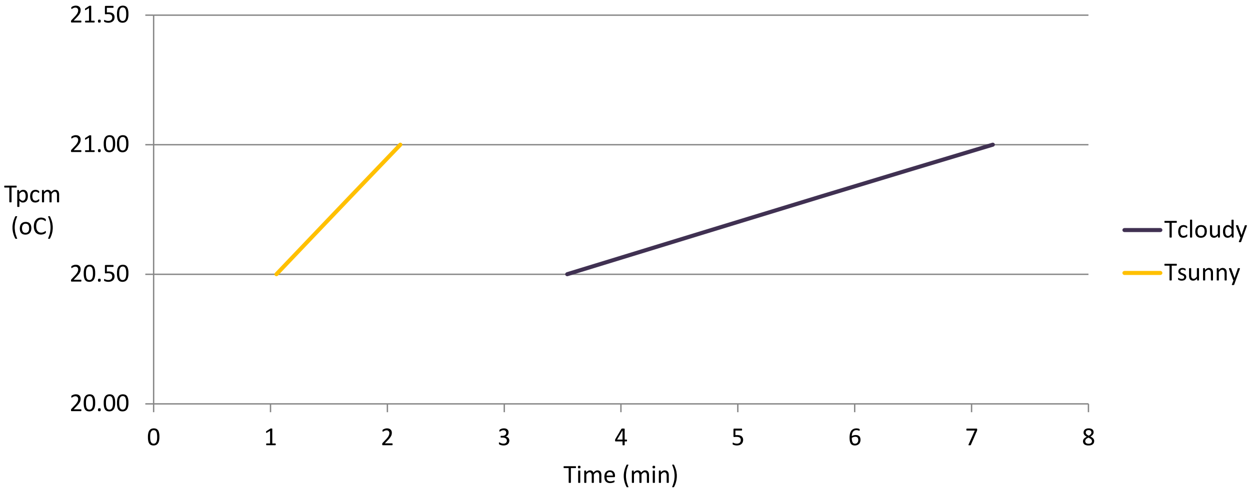
Graph 4.3. The graph illustrates the correlation between Tpcm and time when Tout is 10oC during a sunny and cloudy day, the image is created by the author

Time required to reach 21°C when Tout= 15°C, $Q_{suncloudy}$= 100 W/m² and $Q_{sunsunny}$= 400 W/m²



Graph 4.4. The graph illustrates the correlation between Tpcm and time when Tout is 15oC during a sunny and cloudy day, the image is created by the author

Time required to reach 21°C when Tout= 20°C, $Q_{suncloudy}$= 100 W/m² and $Q_{sunsunny}$= 400 W/m²



Graph 4.5. The graph illustrates the correlation between Tpcm and time when Tout is 20oC during a sunny and cloudy day, the image is created by the author

As it can be seen in graphs 4.2-5, in winter when the outdoor temperature fluctuates between 5°C and 10°C the PCM temperature will reach 21°C after 250 and 120 minutes in a cloudy day. In case of a sunny winter day the required time is 40 and 25 minutes respectively. When the outdoor temperature rises to 15°C and 20°C, the time needed for pcm to reach the melting point is reduced significantly especially during sunny days when the corresponding time is 11 and 2 minutes. Under the same temperature conditions and with lower levels of solar radiation the respective time is 50 and 8 minutes.

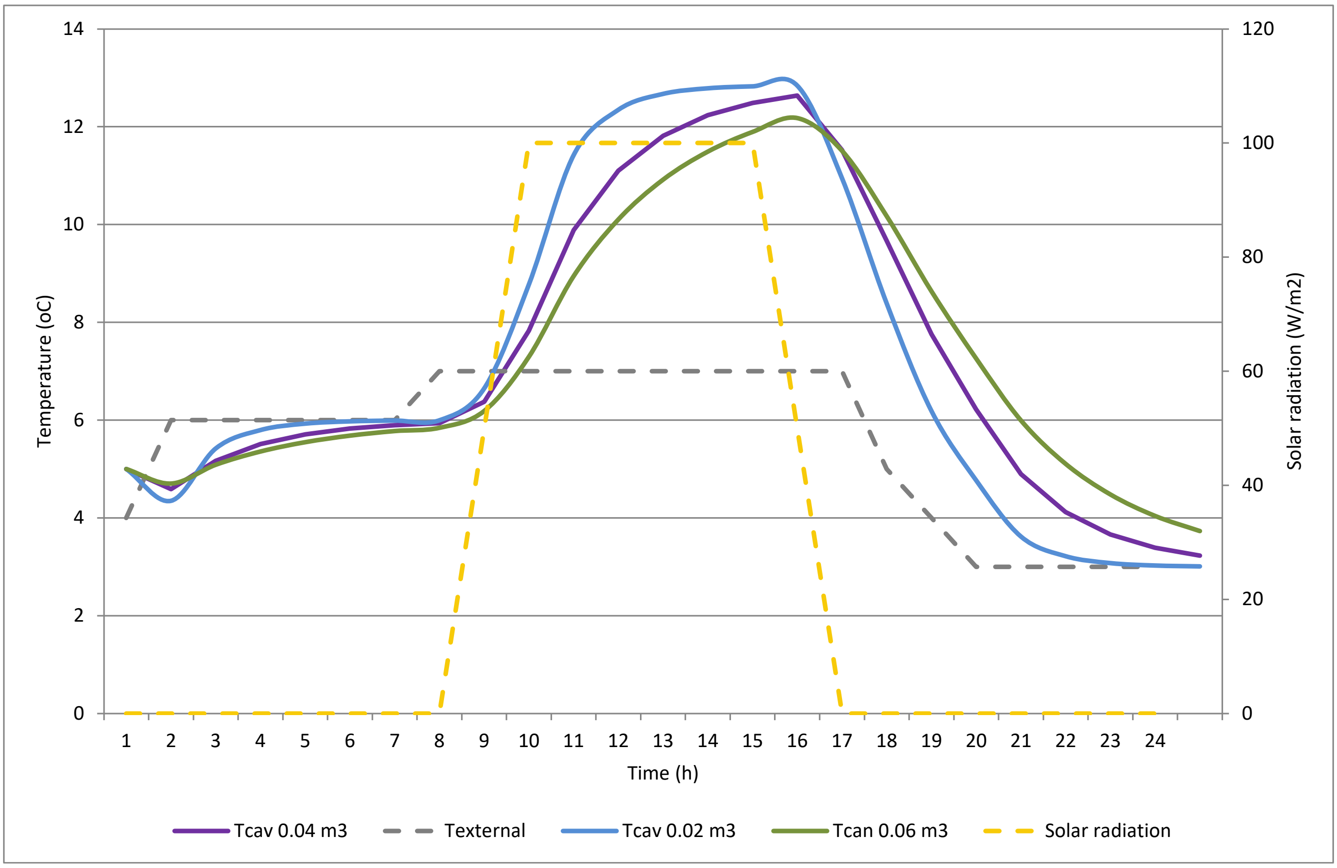
Although this formula was quite helpful to make estimations regarding the air temperature fluctuations and its relationship to time, the effectiveness of PCM transition in the air temperature has to be determined. This calculation is quite complicated as factors such as material's thermal capacity and indoor temperature are constantly changing according to time, outdoor air temperature and solar loads.

The following formula was used to calculate the indoor temperature, which is again assumed equal to PCM temperature for simplification reasons. **(appendix 4)** In calculations three PCM volumes, 0.02 m^3, 0.04 m^3 and 0.06 m^3, where tested in order to define which is the optimum volume for the design to control cavity temperature.

$$T_i(t_n) = T_i(t_{n1}) + \left(\frac{W}{He} + T_e(t_n) - T_i(t_{n-1})\right)\left(1 - e^{-\frac{He}{M}\Delta t}\right)$$

Winter cloudy day

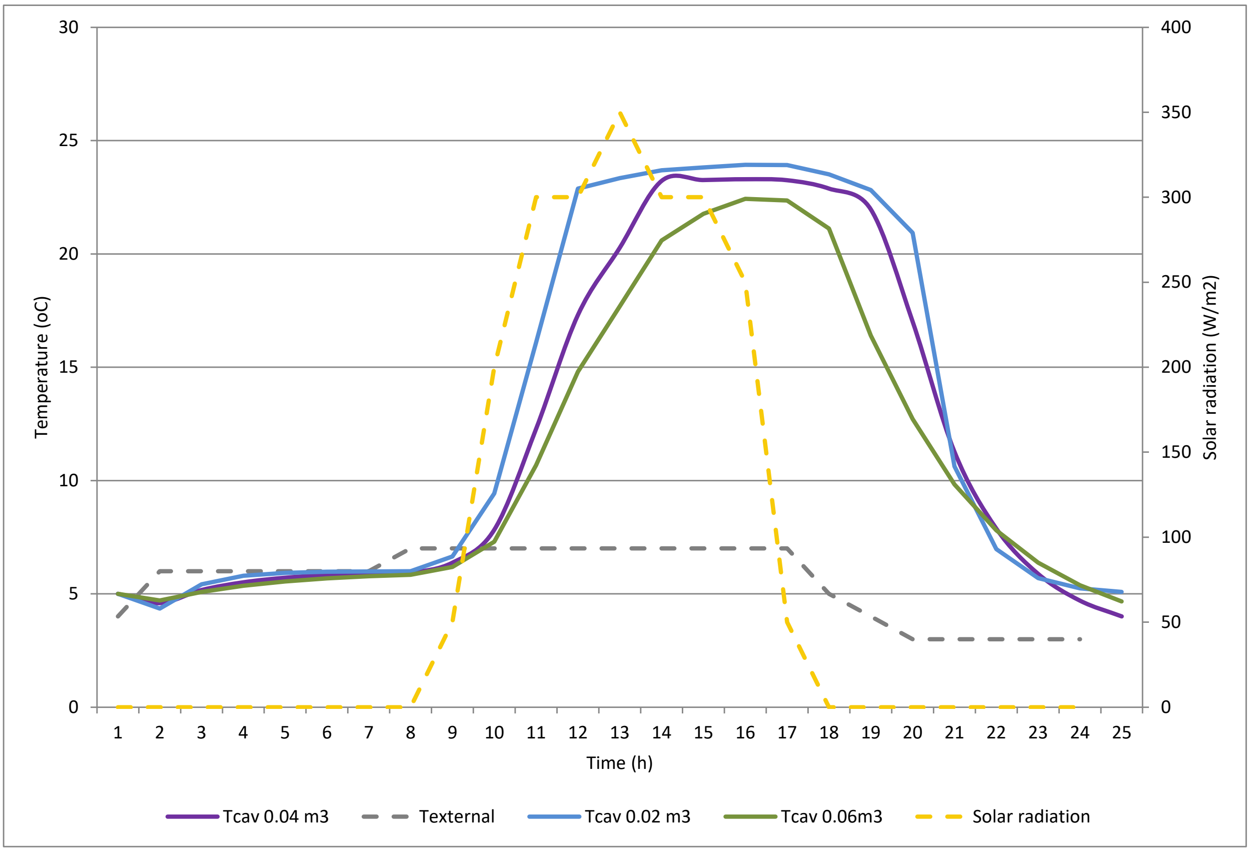
In a winter cloudy day when the T$_{out}$ fluctuates between 3 and 8^{o}C and the solar radiation does not exceed 90 W/m^2, the average cavity temperature is approximately 11^{o}C between 09.00-18.00. Under the indicated weather conditions, the most effective option is the application of 0.02 m^3 of PCM, as it presents the fastest and highest temperature increase. Also, the cavity temperature drops after 18.00 which is the end of a working day. The other two examined cases include the application of 0.04 and 0.06 m^3 of PCM and present a very similar effect in the cavity temperature control. In both of the cases, the temperature increases above 10^{o}C after 11.00 A.M. while the maximum temperature of 12^{o}C is only reached around 16.30 **Graph 4.6**.



Graph 4.6. In the graph the cavity temperature resulting from using volumes of 0.02, 0.04 and 0.06m3 of pcm are compared in relation to solar radiation and time in one day , the image is created by the author

Winter sunny day

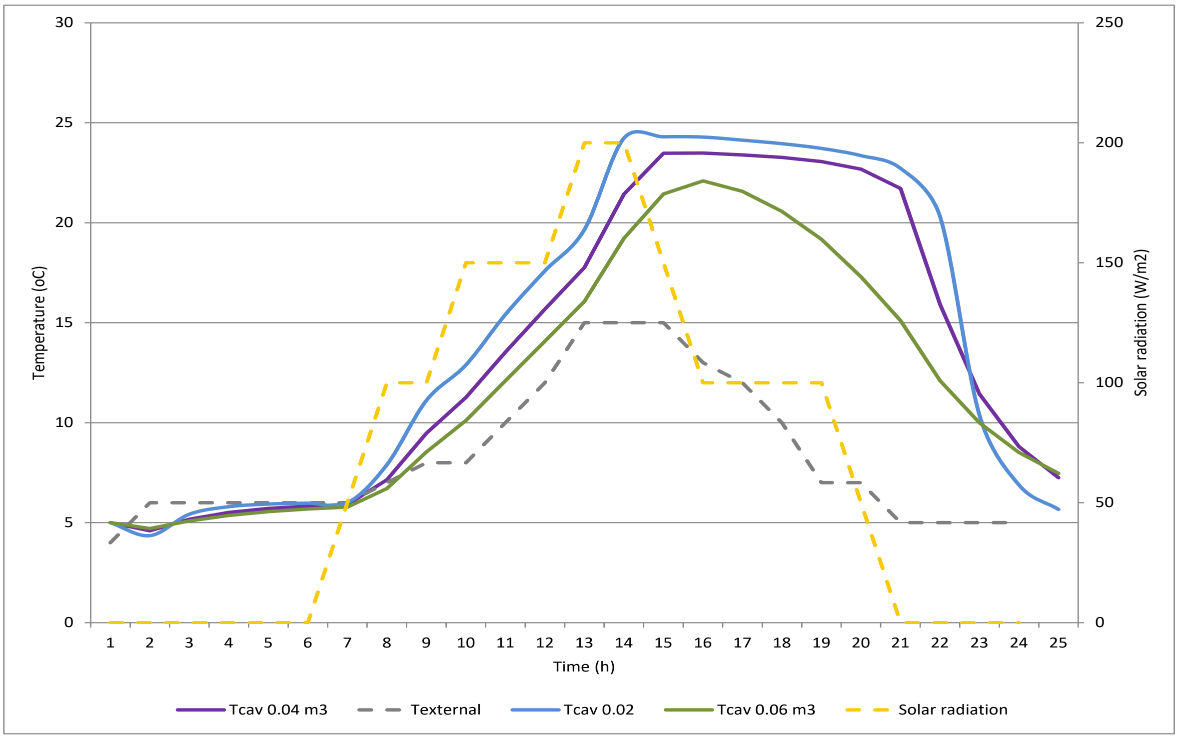
In a winter sunny day when the T_{out} varies from 3 to 8°C and the solar radiation reaches 350 W/m^2, the average cavity temperature is around 18°C between 09.00-18.00. Under the before-mentioned weather conditions, the most suitable solution includes the application of 0.02 m^3 of PCM as the temperature increases faster and reaches even 24°C, while high temperatures occur until 20.00. The other two examined cases of 0.04 and 0.06 m^3 of PCM present sufficient results as the cavity temperature fluctuate approximately between 15 and 21°C during the working hours **Graph 4.7**.



Graph 4.7. In the graph the cavity temperature resulting from using volumes of 0.02, 0.04 and 0.06m3 of pcm are compared in relation to solar radiation and time in one day , the image is created by the author

Spring/ Autumn cloudy day

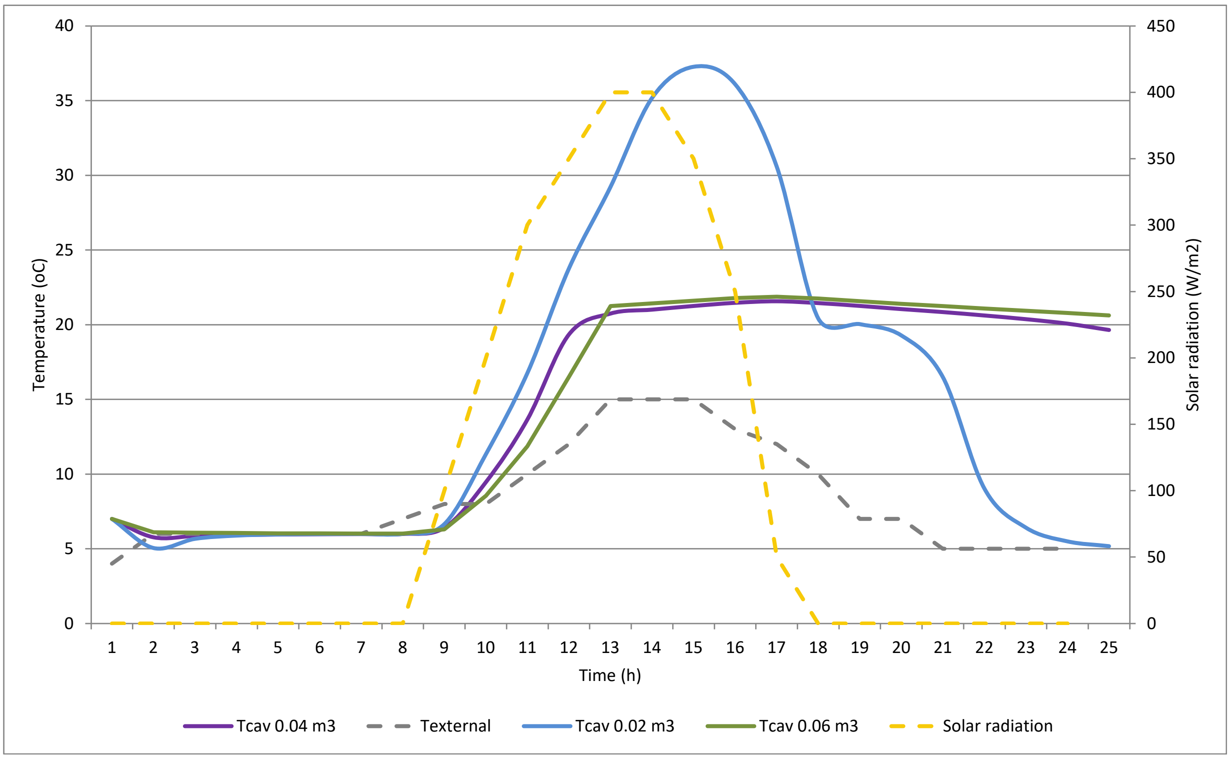
During a Spring or Autumn cloudy day the T_{out} varies from 5 to 15°C and the solar radiation is up to 200 W/m^2, the average cavity temperature is 20°C in the working hours. The most effective option is the application of 0.02 m^3 as the cavity temperature exceeds 15°C even from 10.00 A.M.. The maximum calculated temperature in this case is 24°C when the outdoor temperature reaches 15°C. In addition, due to phase transition the cavity temperature is higher than 20°C when there are no solar loads. The other two presented cases indicate quite similar results, however, due to the increased PCM volume the temperature rise is much smaller while the maximum cavity temperature is approximately 21°C **Graph 4.8**.



Graph 4.8. In the graph the cavity temperature resulting from using volumes of 0.02, 0.04 and 0.06m3 of pcm are compared in relation to solar radiation and time in one day , the image is created by the author

Spring/ Autumn sunny day

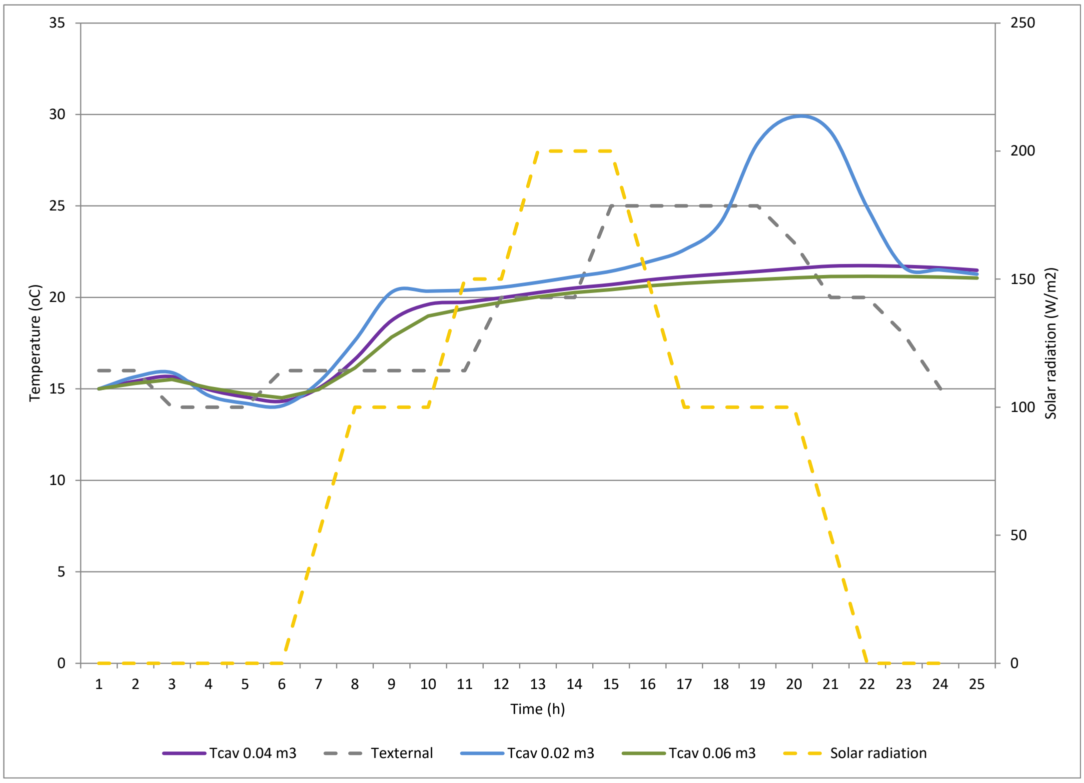
In a Spring or Autumn sunny day when the T_{out} is between 5 to 15°C and the solar radiation rises to 400 W/m^2, the PCM impact is more significant than the previously presented cases. The application of 0.02 m^3 of PCM is not effective anymore since it cannot control the cavity temperature as it reaches almost 37°C around 14.00. Both the cases of 0.04 and 0.06 m^3 of PCM control sufficiently the cavity temperature as it is kept lower than 21°C **Graph 4.9**.



Graph 4.9. In the graph the cavity temperature resulting from using volumes of 0.02, 0.04 and 0.06m3 of pcm are compared in relation to solar radiation and time in one day , the image is created by the author

Summer cloudy day

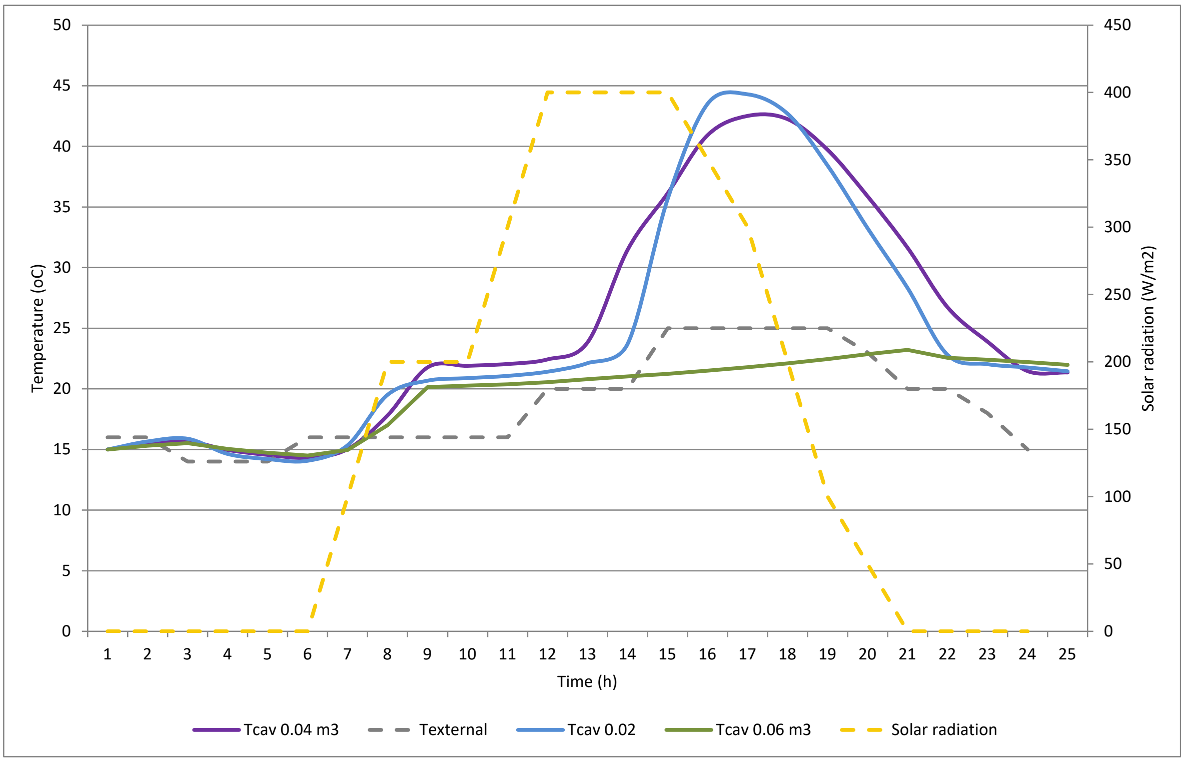
During a Summer cloudy day when the T_{out} fluctuates from 15 and 25°C and the solar radiation reaches 200 W/m², the examined cases present a similar behavior between 9.00 and 18.00. More specifically, the cavity temperature does not exceed 22°C even when the outdoor temperature is 25°C. However, after 18.00 in the case including 0.02 m³ of PCM the cavity temperature increases to 30°C due to phase transition. The application of 0.04 and 0.06 m³ of PCM results in constant temperatures which are stabilized at approximately 21°C when the external temperature is 25°C **Graph 4.10**.



Graph 4.10. In the graph the cavity temperature resulting from using volumes of 0.02, 0.04 and 0.06m3 of pcm are compared in relation to solar radiation and time in one day , the image is created by the author

Summer sunny day

In a Summer sunny day when the T_{out} varies between 15 and 25°C and the solar radiation increases to 400 W/m², during the working hours the cavity temperature is effectively controlled only in the case where 0.06 m³ of PCM is implemented. The case including 0.02 m³ has the worst performance as the cavity temperature reaches 45°C at 15.00. When 0.04 m³ are applied, the cavity temperature is kept constant at approximately 22°C, however, after three hours of exposure to solar radiation of 400 W/m², at 16.00, the temperature rises to 35°C. The application of 0.06 m³ of presents the most optimum results since the temperature does not exceeds 24°C during the entire day **Graph 4.11**.



Graph 4.11. In the graph the cavity temperature resulting from using volumes of 0.02, 0.04 and 0.06m3 of pcm are compared in relation to solar radiation and time in one day , the image is created by the author

4.2 Acoustic calculations

To calculate the reduction of sound pressure levels due the application of sound absorbing materials in the cavity, the double facade panel is assumed as an air duct which is acoustically treated. The external opening is interpreted as a sound source, the interior opening is the point of measurement and the panel's height is the distance between those two openings. To simplify the calculation process, the points are collinear and located on two parallel edges of the air duct **Fig. 4.3**. The sound pressure level on the point source is equal to the sound pressure level created in front of the facade due to traffic noise. The reduction of sound pressure level is calculated in order to define the required area and thickness of sound absorbing elements inside the cavity, the most suitable type of sound absorbers and the range of frequencies where maximum sound absorption occurs.

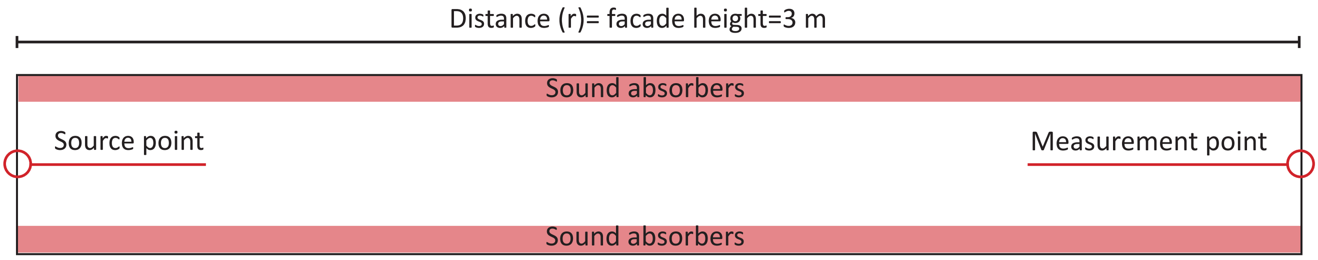


Fig. 4.3. The diagram indicates the simplification of facade panel to an air duct, the image is created by the author

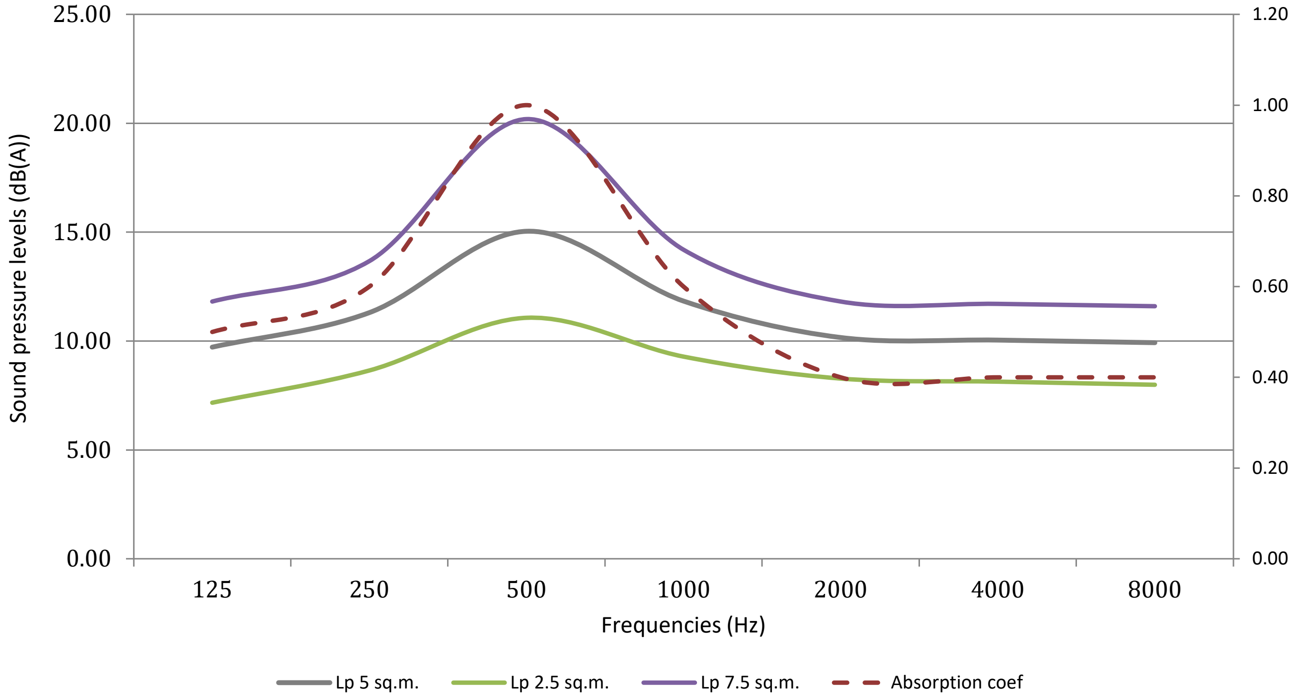
According to systemair's brochure about acoustic calculations (2013) the following formula is used to calculate the sound pressure reduction in enclosed places such as an air duct:

$$Lp = Lw - 10log\left(\frac{Q}{4\pi r^2} + \frac{4(1-\alpha)}{\alpha S}\right)$$

In order to estimate the sound pressure reduction resulted from the application of different materials, the before-mentioned formula was used while the impact of area and absorption coefficient were examined for each material. Three different materials were considered. More specifically, rockwool was selected as opaque porous material since it is one of the most widely chosen material for sound absorption. In addition, the effectiveness of microperforated glass and membranes is estimated to interpret the impact of transparent sound absorbers. The areas which are considered in the calculations are 2.5, 5 and 7.5 m^2 for the sound absorbers, while the total area of the facade element is 10.35 m2. **(appendix 5)**

Microperforated glass

The microperforated glass sound absorption coefficient varies between 0.4 to 1 while in contrast to the rest considered materials it presents higher values in low frequencies. The highest sound pressure level reduction achieved when the area of microperforated glass is 7.5 m^2 since values reach 20 dB(A) close to 500 Hz. The average sound reduction is approximately 15 dB(A) when a maximum of 7.5 m^2 of microperforated glass is applied on facade's cavity. Lower values are calculated for when the area is decreased to 5 m^2 and 2.5 m^2.

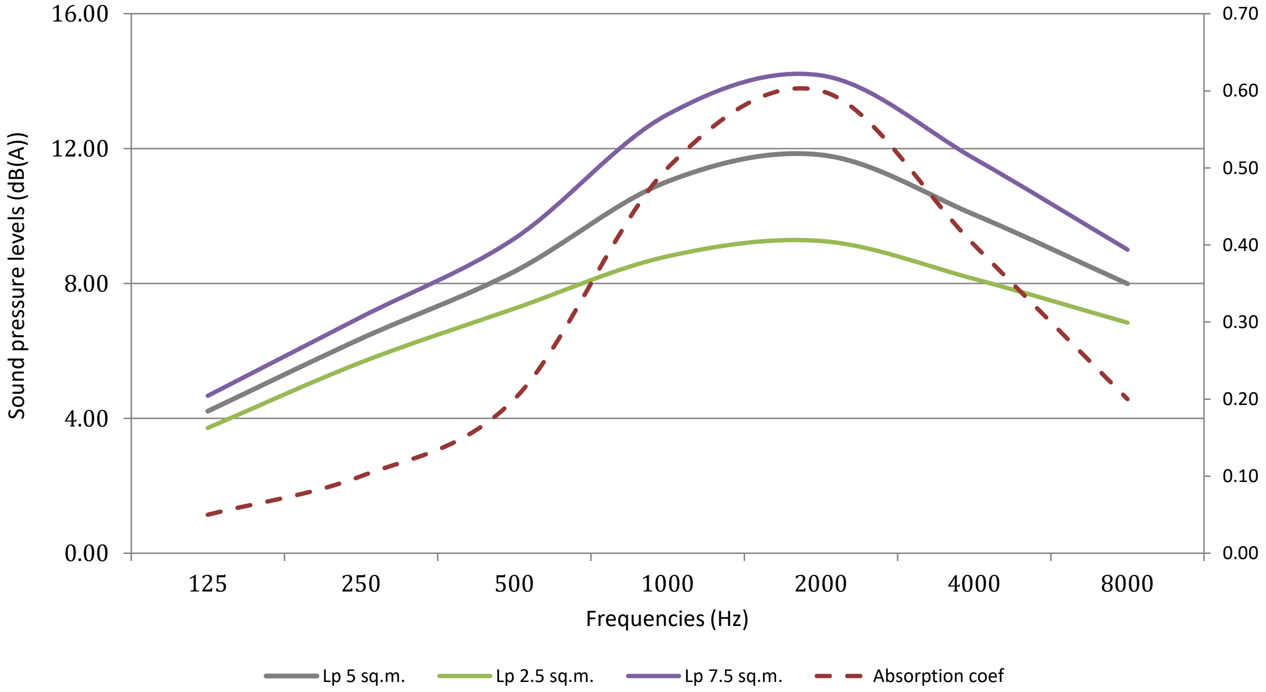


Graph 4.12. In the graph the reduction of sound pressure resulting from applying of 2.5, 5 and 7.5 m2 of pcm are compared in relation to absorption coef. and sound frequencies in one day , the image is created by the author

The average sound pressure reduction is 12 dB(A) and 9 dB(A) respectively. In all of the displayed the cases, a significant increase is presented in frequencies between 300 and 1000 Hz **Graph 4.12**.

Microperforated membranes

Microperforated membranes have a smaller sound absorption coefficient comparing to the rest materials presented as it varies between 0.05 and 0.6. Their application is more effective when frequencies between 1000 and 4000 Hz have to be tackled since their absorption coefficient increases to 0.4 and 0.6 in this range of frequencies **Graph 4.13**.

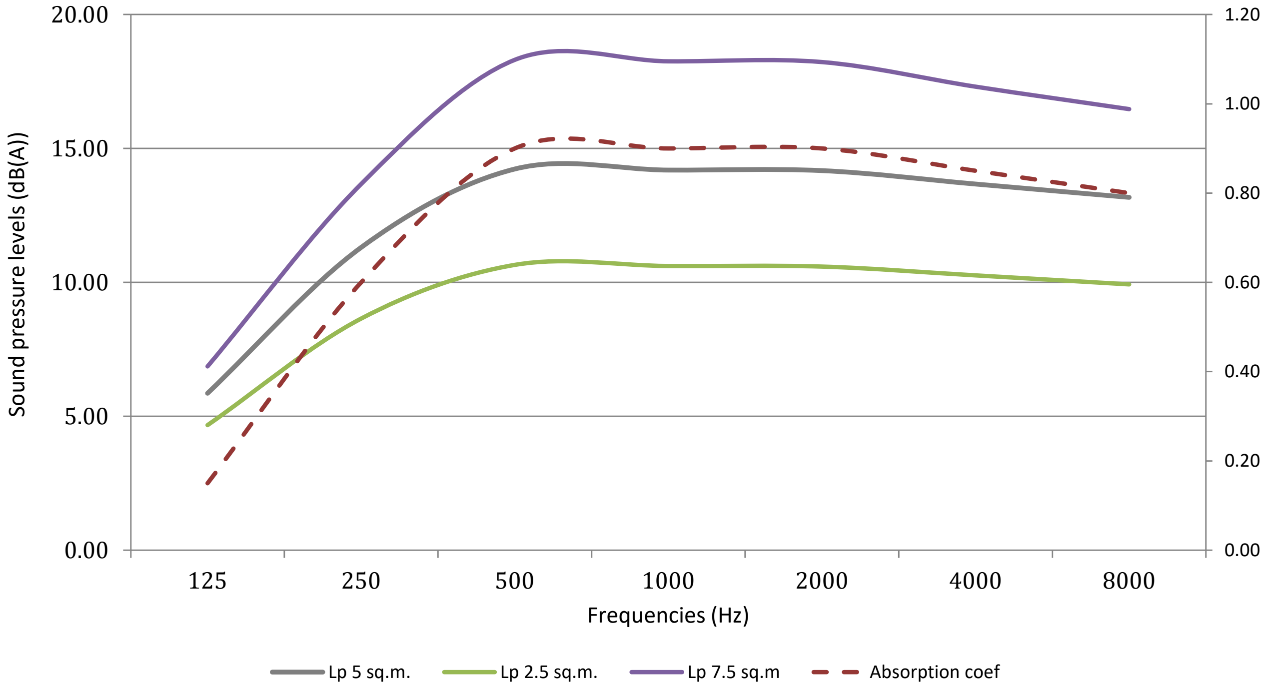


Graph 4.13. In the graph the reduction of sound pressure resulting from applying of 2.5, 5 and 7.5 m2 of pcm are compared in relation to absorption coef. and sound frequencies in one day , the image is created by the author

The most optimum results are obtained when 7.5 m^2 of microperforated membranes are applied in the system's cavity as the average reduction of sound pressure levels is 9 dB(A). When the area is decreased to 2.5 and 5 m^2, the effectiveness is reduced to approximately to 7 and 5 dB(A) correspondingly.

Rockwool

Rockwool presents high absorption coefficient in frequencies exceeding 250 Hz as in frequencies between 500 and 8000 Hz its values vary between 0.7 and 1. When the area of rockwool is increased to 7.5 m^2 the average reduction of sound pressure levels is 18 dB(A) in frequencies above 300 Hz. Even when the area is reduced to 2.5 and 5 m^2 high values are achieved as the average reduction of sound pressure levels is 14 and 10 dB(A) respectively. In addition rockwool presents optimum values in a wider frequency range which are the most commonly found frequencies in road traffic noise.



Graph 4.14. In the graph the reduction of sound pressure resulting from applying of 2.5, 5 and 7.5 m2 of pcm are compared in relation to absorption coef. and sound frequencies in one day , the image is created by the author

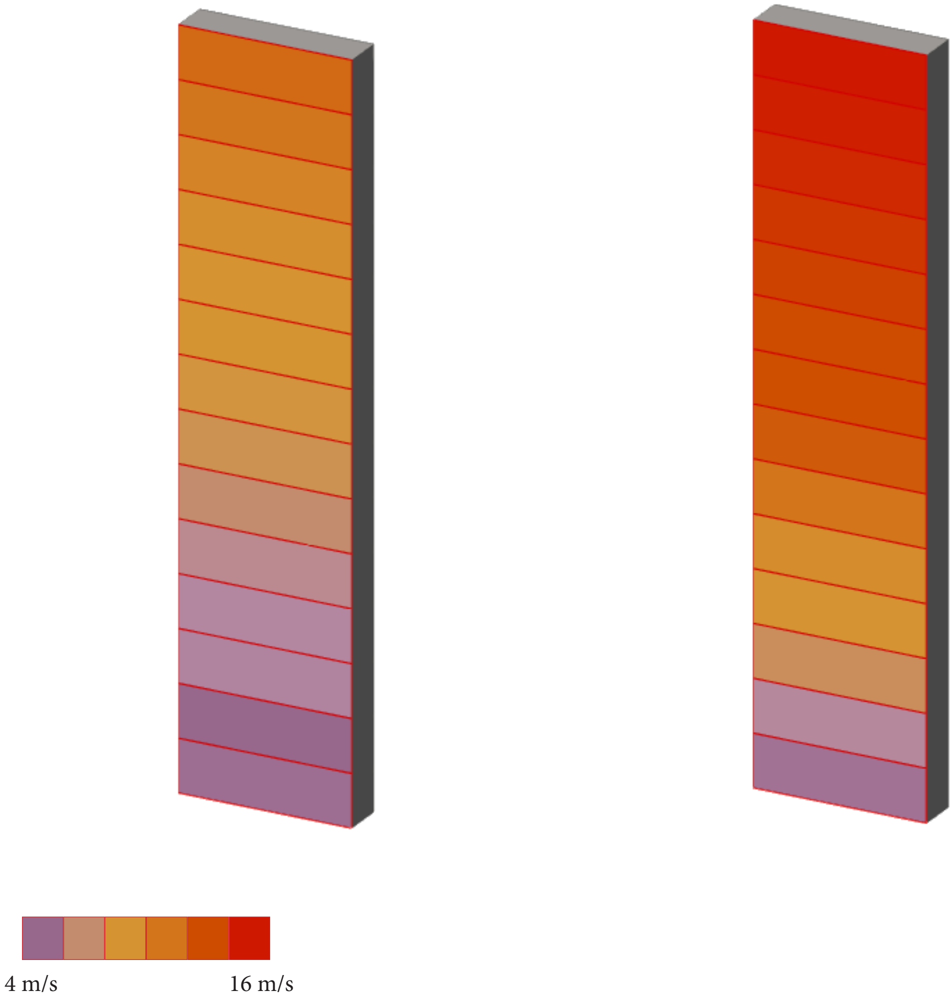
4.3 Air flow calculations

In order to interpret the provided air flow from the suggested design concept, firstly the developed wind speeds in front of the facade of a high-rise in the Netherlands were calculated. In the calculations an average wind speed of 4.5 m/s at the height of 10 m was considered according to the Dutch climate data.**(appendix 1)** Different heights were assumed varying between 10 and 140 m. The following formula was used:

$$v(z) = v(G)\left(\frac{Z}{G}\right)^{\alpha}$$

where:

z is the height from the ground (m)
v is the wind speed in m/s
G has a standard value of 500 m for urban areas
α is 0.36 for urban areas with high-rises



Graph 4.15. In the graph the different wind speeds developed in a high-rise of 140 m in the Netherlands. The left and the right gradient represent the developed wind speed when the wind speed at 10 m is 4.5 m/s and 6 m/s respectively the image is created by the author

As it can be seen in the graph 4.15, when a wind speed of 4.5 m/s occurs at the height of 10 m, which is recorded as an average wind speed for spring and summer months in the Netherlnads, the maximum wind velocity reaches 11.8 m/s (67 Pa) at the top floor of a 140 m high building. During winter and autumn the average wind speed at the height of 10 m is 6 m/s, in this case the maximum wind speed occurring on the facade is 16 m/s (119 Pa). **(appendix 6)**

Following, the calculations of wind speeds, the amount of fresh air provided by the proposed facade panel was calculated. Firstly, a fixed value 0.01 m^2 was defined as the effective area of openings for the cold months, independently from the variant of height from the ground. The formula below was considered to calculate the airflow:

$$Q = 0.5A_{eff}\sqrt{\frac{2\Delta p}{\rho}}$$

where:

Aeff is the effective area of openings (m^2)
Δp is the total pressure difference (Pa)
ρ is the air density (kg/m^3)

To determine the total pressure difference the pressure difference caused by wind and stack effect should be calculated by using the following formulas:

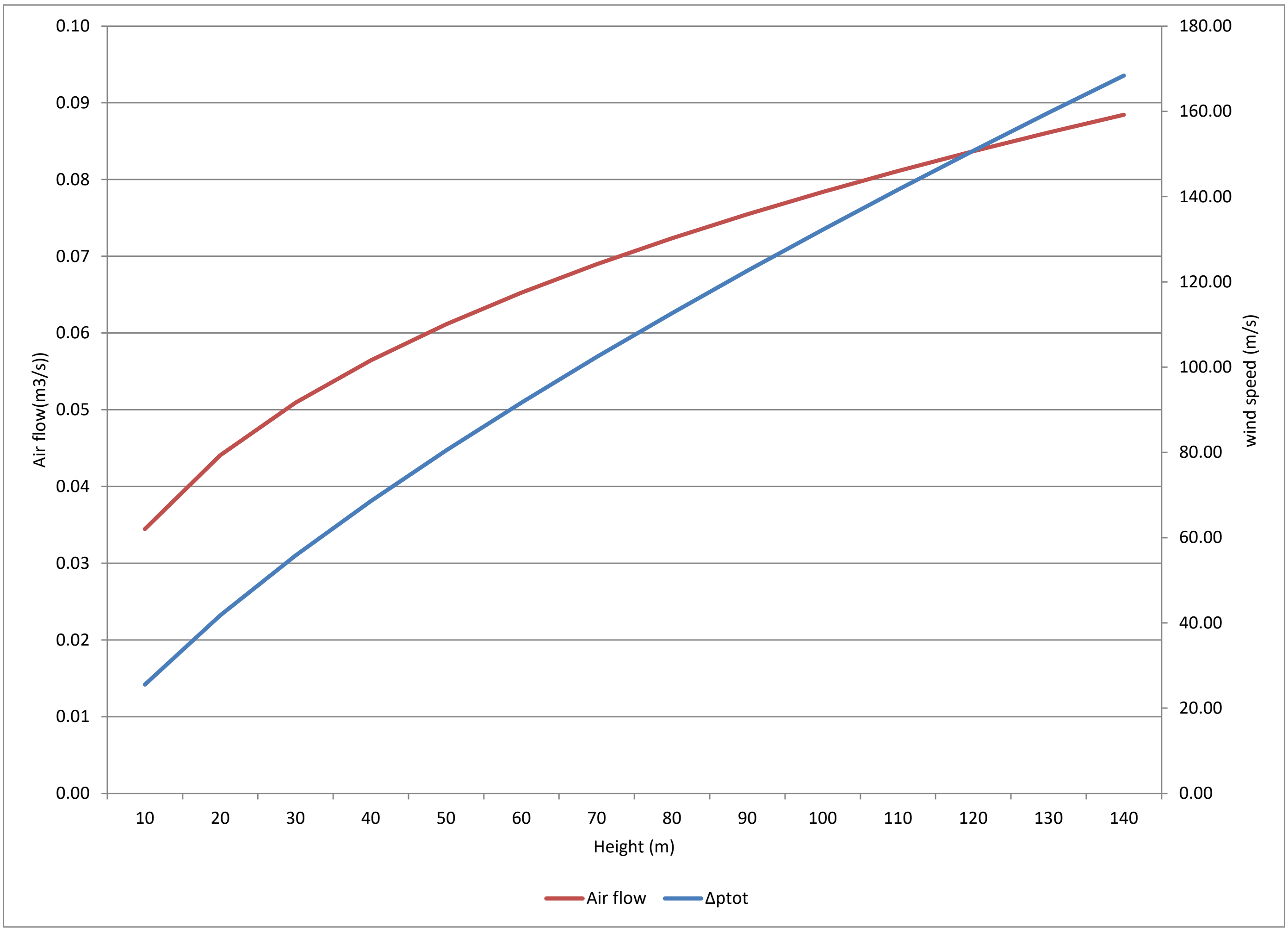
$$\Delta p_{wind} = C_d \rho v^2 (C_{p1} - C_{p2})$$

$$\Delta p_{stack} = \rho g n h \left(\frac{\Delta T}{T_{ext}}\right)$$

where:

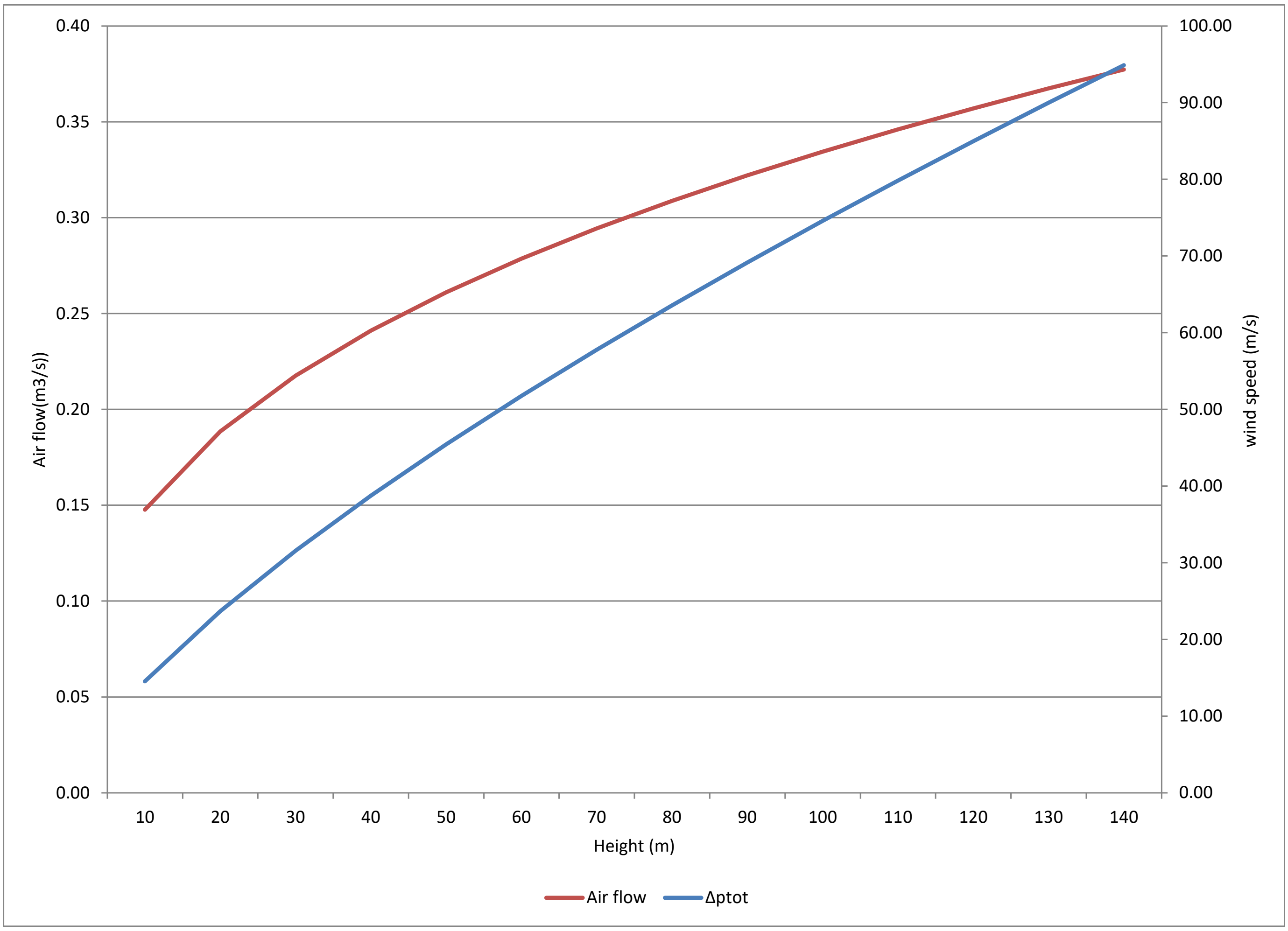
Cp is the pressure coefficient
ρ is the air density (kg/m^3)
v is the wind speed (m/s)
g is the gravity acceleration (m/s^2)

n is the number of floors
h is the floor height
ΔT is the temperature difference (K)
Text is the outdoor temperature (K)



Graph 4.16. In the graph the provided airflow during clod months is plotted in correlation to the pressure difference the image is created by the author

As it can be seen in the graph 4.16, the airflow is proportional to the pressure difference between the indoor and outdoor environment which is increased according to the building's height. The graph 4.16 illustrates the airflow values for background ventilation supplied during cold months. The average wind speed at the height of 10 m is 6 m/s while the temperature difference between the DSF cavity and the outdoor environment is 4 degrees and the outdoor temperature is 8°C. The airflow varies between 0.02 and 0.08 m^3/s which is enough to supply fresh air for 6 to 15 people respectively. **(appendix 6)** Since the airflow increases proportionally to the pressure difference, varying effective areas should be used according to the corresponding height. This problem can be easily solved by installing pressure regulated ventilation grilles.



Graph 4.16. In the graph the provided airflow during summer months is plotted in correlation to the pressure difference
the image is created by the author

During summer months, the effective area is increased to 0.06 m^2. The included wind speed at the height of 10 m is 4.5 m/s and the external temperature is 25oC. The temperature difference between the cavity and the outdoor environment is 2°C since PCM control the cavity temperature, therefore the effect of pressure difference due to stack effect is small. For office buildings and factories there is a limitation about summer natural ventilation in order to ensure comfortable indoor conditions. The provided air volume per hour should not be higher than five times the air volume of the room. According to the graph 4.16 the supplied air volume is for the suggested effective area is complies with the previously mentioned limitation even for heights exceeding 100 m. **(appendix 6)**

To calculate the pressure drop caused by the DSF, the facade panel is approximated as an air channel which has two openings on its opposite sides **Fig. 4.3**. The length of the air channel has a specific resistance which causes further pressure drop. The pressure was calculated in four critical points located on the external and internal part of the openings. The assumed area of the air channel is 0.18 m^2.

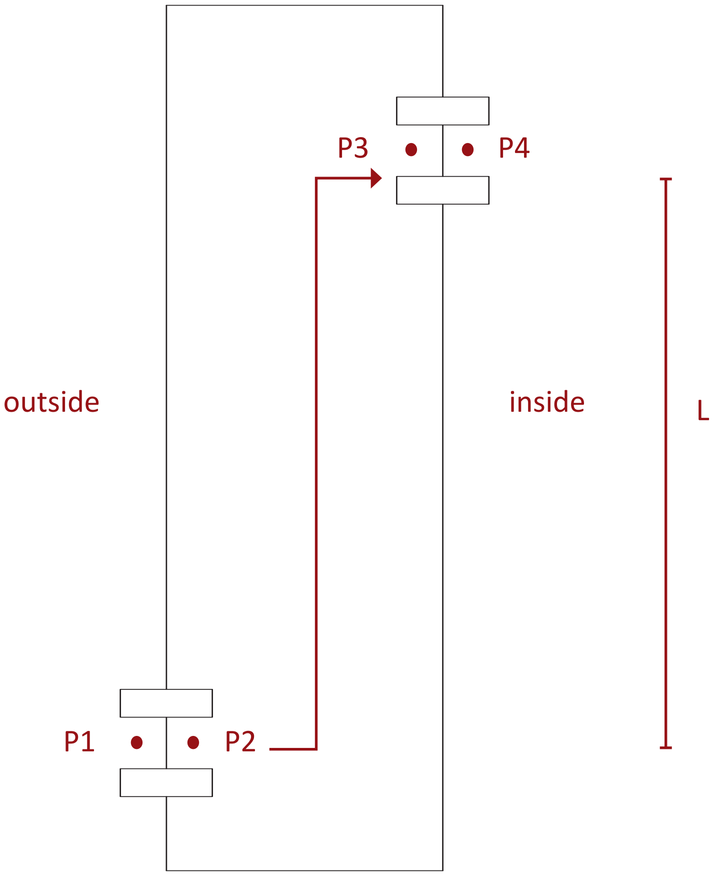


Fig. 4.3. The diagram illustrates the facade approximation as an air channel to calculate pressure drop, the image is created by the author

Different formulas are used to calculate the pressure in each point, more specifically:

$$p1 = \frac{1}{2}C_{p1}pv^2$$

$$p2 = p1 - \frac{1}{2}C_{d1}pv^2$$

$$p3 = p2 - 4f\frac{L}{D_h}pv^2$$

$$p4 = p3 - \frac{1}{2}C_{d2}pv^2$$

Where:

Cp is the pressure coefficient
v is the wind speed (m/s)
p is the air density (kg/m3)
L is the length of the air channel (m)
Dh is the ratio of 4A/S
4f is equal to 0.316Re^-1/4

The pressure drop caused by the DSF system is 22 Pa and it is independent from the external wind speeds. **(appendix 7)** However, to evaluate the effect of the pressure drop more parameters such as the indoor pressure and the effect of the use of mechanical ventilation should be known and considered. These parameters could be examined in a further research and go beyond the scope of the current thesis.

Calculations' conslusions

Thermal calculations

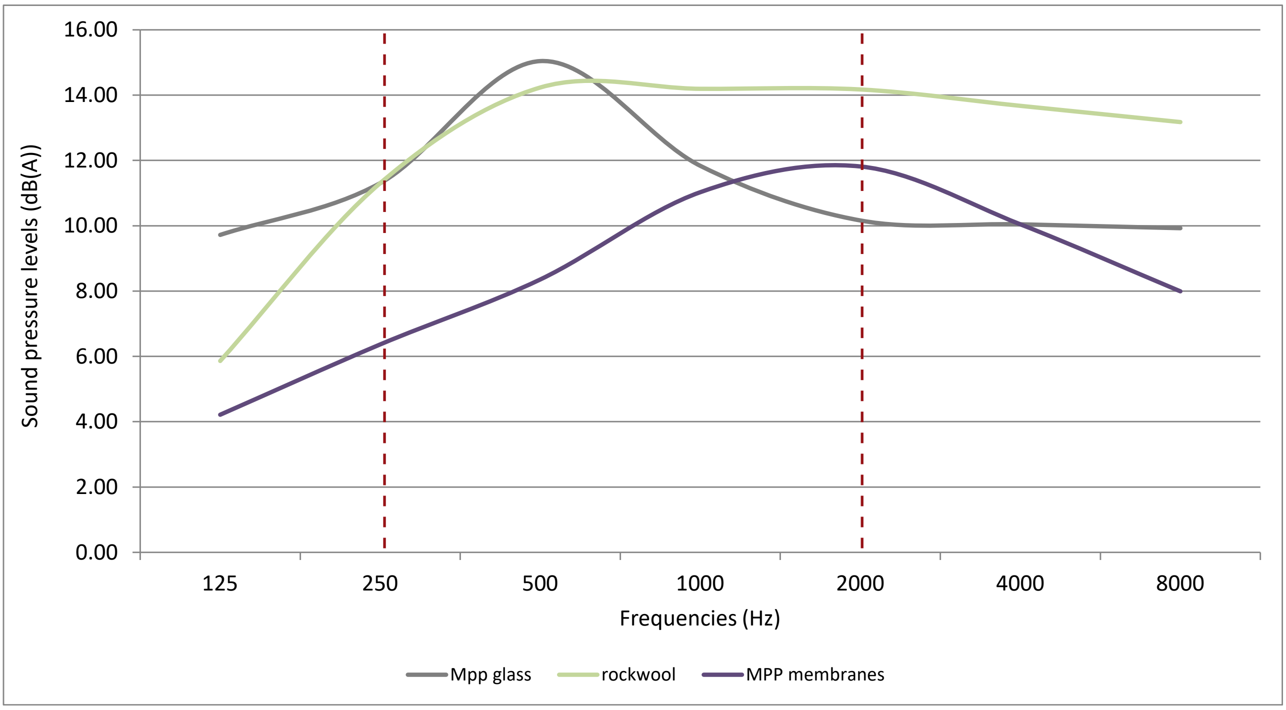
As it can be seen in the following table, each case performs differently according to the outdoor conditions. In winter the pest performance is presented in the case where 0.02 m^3 of PCM is applied in facade's cavity. Contrarily, during spring, autumn and summer the cases of 0.04 and 0.06 m^3 have a better impact in cavity's temperature as it is stabilized between 21 and 24°C during working hours. The case of 0.02 m^3 is considered unsuitable for the current facade concept as during summer and sunny spring days the cavity temperature reaches 45 and 35°C respectively. When 0.04m^3 of PCM are applied in the cavity, the temperature under most of the examined weather conditions fluctuates between 10 and 23°C. However in a sunny summer day when the outdoor temperature increases to 25°C and solar loads are 400 W/m^2, the system is not effective anymore as the cavity temperature exceeds 30°C. Only the case of 0.06 m^3 is effective under all of the tested weather conditions as it stabilizes the cavity temperature to temperatures between 10°C and 25°C. Therefore to ensure thermal comfort when a double skin facade is used to provide natural ventilation in a high-rise office building in the Netherlands at least 0.06 m^3 of PCM should be applied in facade's cavity.

Pcm volume	**0.02 m^3**	**0.04 m^3**	**0.06 m^3**
Winter cloudy day	optimum	sufficient	sufficient
Winter sunny day	optimum	sufficient	sufficient
Spring/ Autumn cloudy day	optimum	sufficient	sufficient
Spring/ Autumn sunny day	not suitable	optimum	sufficient
Summer cloudy day	not suitable	optimum	sufficient
Summer sunny day	not suitable	not suitable	optimum

Table 4.1 The table indicated the effectiveness of PCM volume under several weather conditions, the image is created by the author

Acoustic calculations

As it is presented in **Graph 4.17** the greatest sound pressure level reduction occurs when rockwool is applied in facade's cavity as an average of 13dB(A) is calculated for 5 m^2 of rockwool. Similar values are calculated when 7.5 m^2 of perforated glass is added on the cavity. In cases where microperforated membranes are used the sound pressure level is reduced by approximately 9 dB(A) when 7.2 m^2 are applied. The frequencies where the largest sound pressure levels occur in road traffic noise are between 250 and 2000 Hz, therefore, the values in this spectrum should be evaluated in order to estimate the acoustic performance of each material. Rockwool performs better in between 250 and 2000 Hz as the reduction of sound pressure levels reaches 14 dB(A). Lower values are calculated for microperforated membranes and glass as the respective values for the before-mentioned spectrum fluctuates from 6 to 10dB(A) and 11 to 15dB(A) accordingly. However, since the thermal calculations indicated that shading should be provided in order to prevent cavity's overheating and PCM quick melting, the microperforated glass and membranes will not be considered as suitable materials for the current facade design.



Graph 4.17. In the graph the reduction of sound pressure levels by applying 5m2 of rockwool, MPP glass and membranes are compared , the image is created by the author

Air flow calculations

The suggested design concept can provide effectively both background and summer ventilation even when the wind speeds reach 20 m/s, which means that it could provide natural ventilation in a high-rise of 140 m when the wind speed at the ground level is 6m/s. In addition, all the operable facade parts should offer several effective areas in order to minimize or maximize the provided air flow. Regarding the background ventilation, pressure regulated grilles must be used to control the opening's area according to the wind pressure in front of the facade. When the facade system supplies summer ventilation the effective openings' area should be regulated according to height, therefore an operable window which has some standard open areas should be chosen for the external facade skin to comply with varying wind pressure in different floors.

Realization

5.1 Double skin facade typologies

In order to select the most suitable double skin facade typology for the developed facade concept a review was accomplished regarding the available double skin facade systems in the market. Four main categories are found including the second skin, box-window, corridor and shaft-box facade.

The second skin facade consists of a fixed external glazing skin covering the entire area of the internal facade. The double skin cavity is ventilated by openings located on the top and bottom of the external skin. **Fig. 5.1** Although the second skin facade has the optimum acoustic performance and the most simple assembly and construction process, the risk of overheating even in winter months in combination with the limited users' freedom to control the cavity temperature defines the system unsuitable for the realization of the developed design concept. The box-window facade system includes an external and internal glazing skin with operable openings on the top and bottom of them **Fig. 5.2**, this fact provides the freedom of indoor environment control to users. The box window system has horizontal and vertical dividers which separate each unit from the adjacent facade spaces. The corridor facade system is quite similar to the box-window system, the only difference between them is the lack of horizontal dividers. The greatest disadvantage of this system is the noise transmission through the horizontally continuous cavity between spaces in the

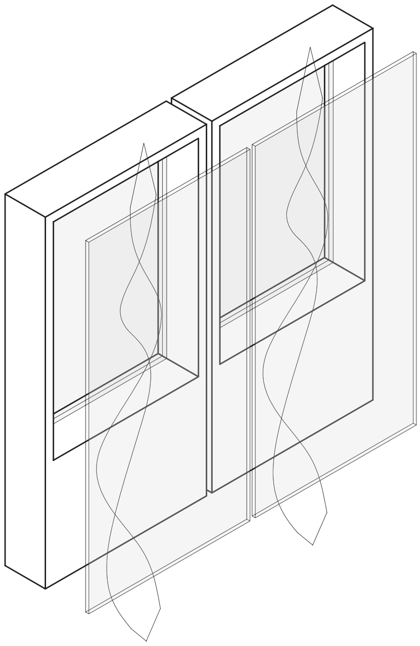
Typology	Second skin facade
	Acoustic performance: excellent Thermal performance: risk of overheating Ventilation: poor Feasibility: easy construction and assembly processes. Users' freedom: limited as they cannot control the temperature developed in the double skin cavity.

Table 5.1, The table presents the second skin advantages and disadvantages.
Fig. 5.1 indicates the ventilation strategy of second skin facade, source: Knaack, U., Klein, T., Bilow, M., Auer, T., (2007), Façades: Principles of Construction, Birkhäuser

the same floor. Finally, the shaft-box facade typology is one of the most efficient typologies as the cavity ventilation is enhanced by the connection of box-window systems to large facade shafts. However, the system's construction complexity is the main reason that limits its application. **(Knaack et al., 2007)**

The box window system was selected as it presented optimum features in terms of acoustic, thermal and ventilation performance comparing to other design solutions. The box window system is set as a principal of the design while several configurations have to be applied in order to achieve better sound insulation values in combination with sufficient ventilation provision, air preheating and precooling.

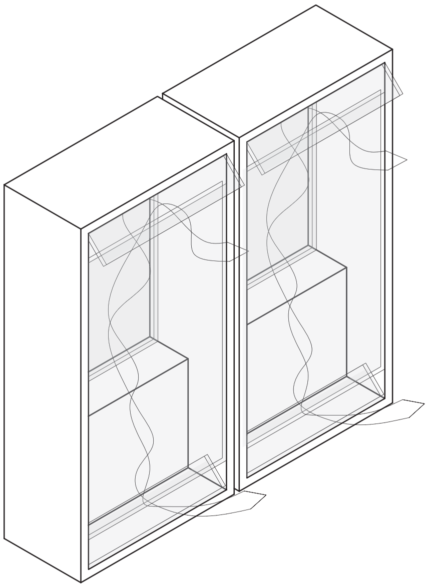
Typology	Box-window facade
	Acoustic performance: good Thermal performance: risk of overheating if the airflow is not sufficient in summer Ventilation: sufficient airflow rate Feasibility: easy construction and assemply processes Users' freedom: users have the freedom to open the external and internal openings to control the indoor and cavity temperature

Table 5.2, The table presents the box-window facade advantages and disadvantages.
Fig. 5.2 indicates the ventilation strategy of second box-window, source: Knaack, U., Klein, T., Bilow, M., Auer, T., (2007), Façades: Principles of Construction, Birkhäuser

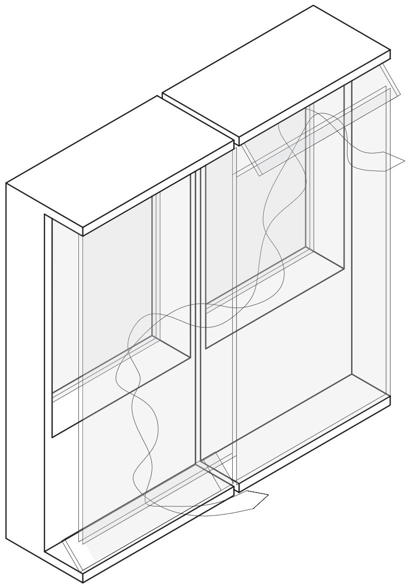
Typology	Corridor facade
	Acoustic performance: poor Thermal performance: risk of overheating if the airflow is not sufficient in summer Ventilation: sufficient airflow rate Feasibility: easy construction and assembly processes. Users' freedom: users have the freedom to open the external and internal openings to control the indoor and cavity temperature

Table 5.3, The table presents the second skin advantages and disadvantages.
Fig. 5.3 indicates the ventilation strategy of corridor facade, source: Knaack, U., Klein, T., Bilow, M., Auer, T., (2007), Façades: Principles of Construction, Birkhäuser

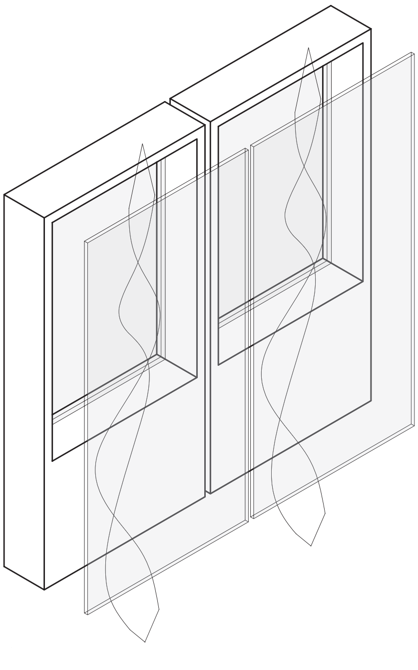
Typology	Shaft-box facade
	Acoustic performance: good Thermal performance: good Ventilation: good air flow rate due to the enhancement of shafts. Feasibility: high complexity due to a lot of engineering control to ensure the effective system's function Users' freedom: limited as mostly the function of shafts is controlled by Building management systems.

Table 5.4, The table presents the second skin advantages and disadvantages.
Fig. 5.4 indicates the ventilation strategy of shaft-box facade, source: Knaack, U., Klein, T., Bilow, M., Auer, T., (2007), Façades: Principles of Construction, Birkhäuser

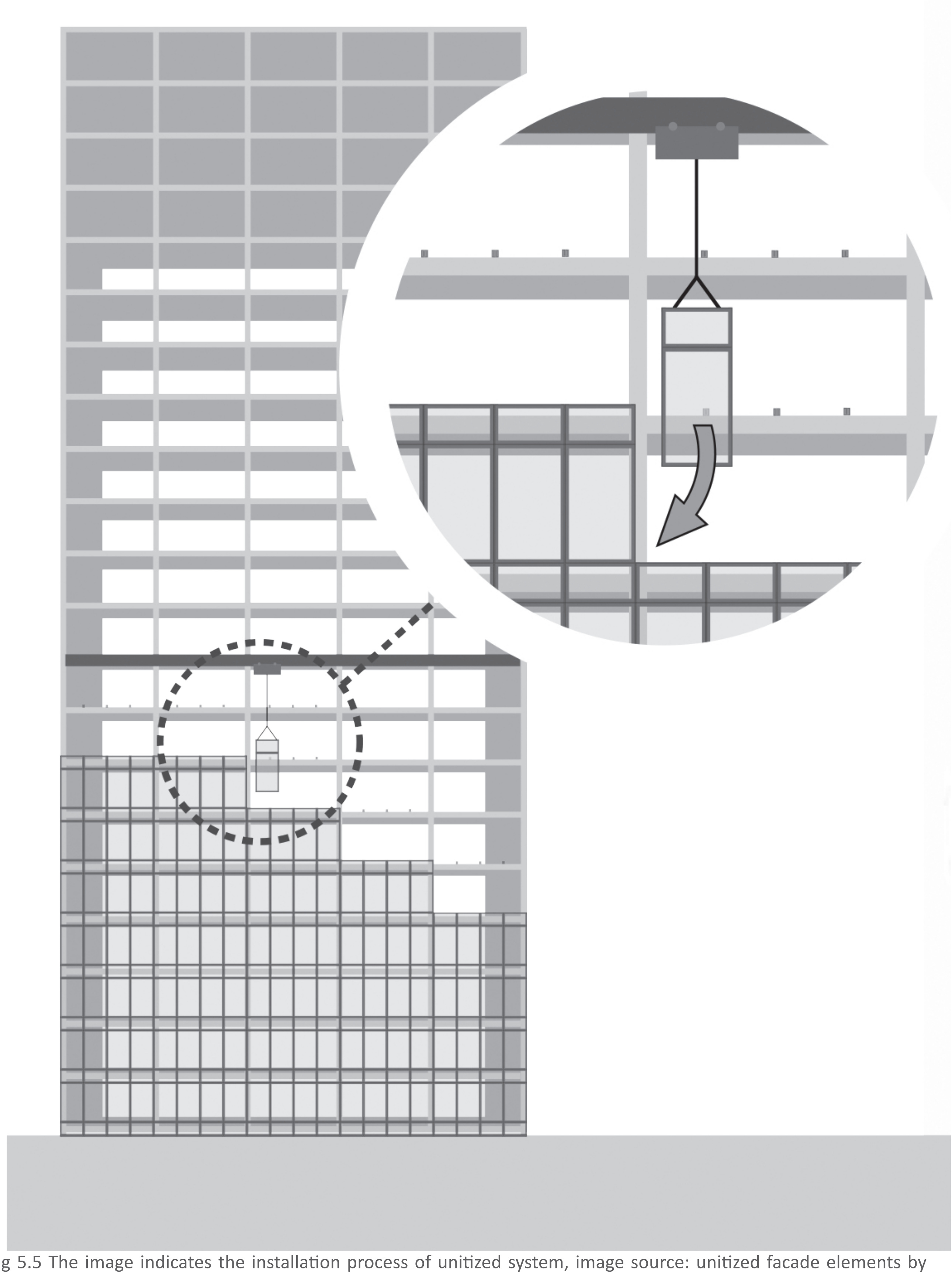


Fig 5.5 The image indicates the installation process of unitized system, image source: unitized facade elements by Reynaers

5.2 Unitized facade system

In order to realize the above-mentioned design concepts, the use of unitized facade system was chosen. A unitized system includes entirely prefabricated facade panels which are added on the building during the initial construction stages. The prefabricated panels are transported on site and then installed on top of each other by cranes and fixed on pre-installed brackets by workers. Fig. 5.6. Each panel has its own load-bearing system in order to ensure rigidity during transportation, installation and daily function. **(Knaack et al., 2007)**

Since the facade panels are prefabricated the possible mistakes are minimized as the air and water tightness as well as the elements' assembly are realized in controlled conditions. In addition, this system provides time efficiency for high-rises construction, comparing to a stick system, as the time needed for facade construction is decreased due to easy installation process. At the same time, after the facade is added on the lower floors, the construction of the interior spaces can start as they are protected by the outdoor weather conditions. Furthermore, unitized systems offer plenty of freedom in function and aesthetics such as ventilation, energy generation, shading, thermal and acoustic performance. **(Knaack et al., 2007)**

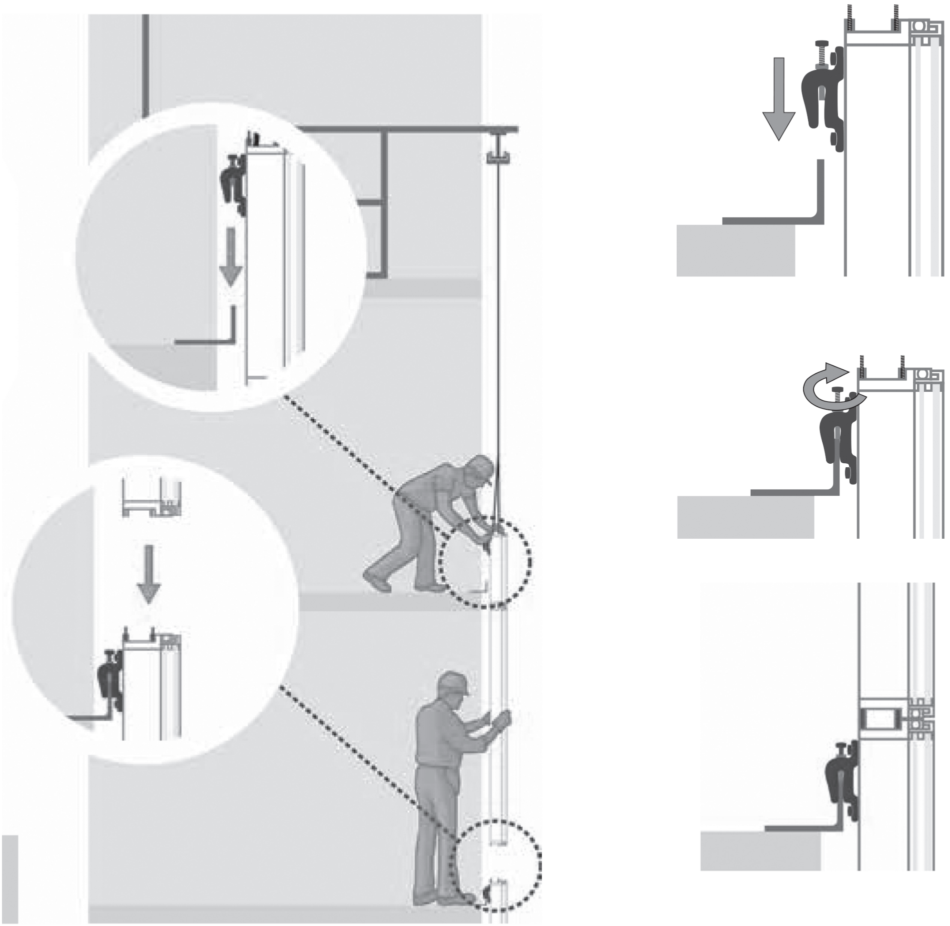


Fig 5.6 The image indicates the installation process of unitized system, image source: unitized facade elements by Reynaers

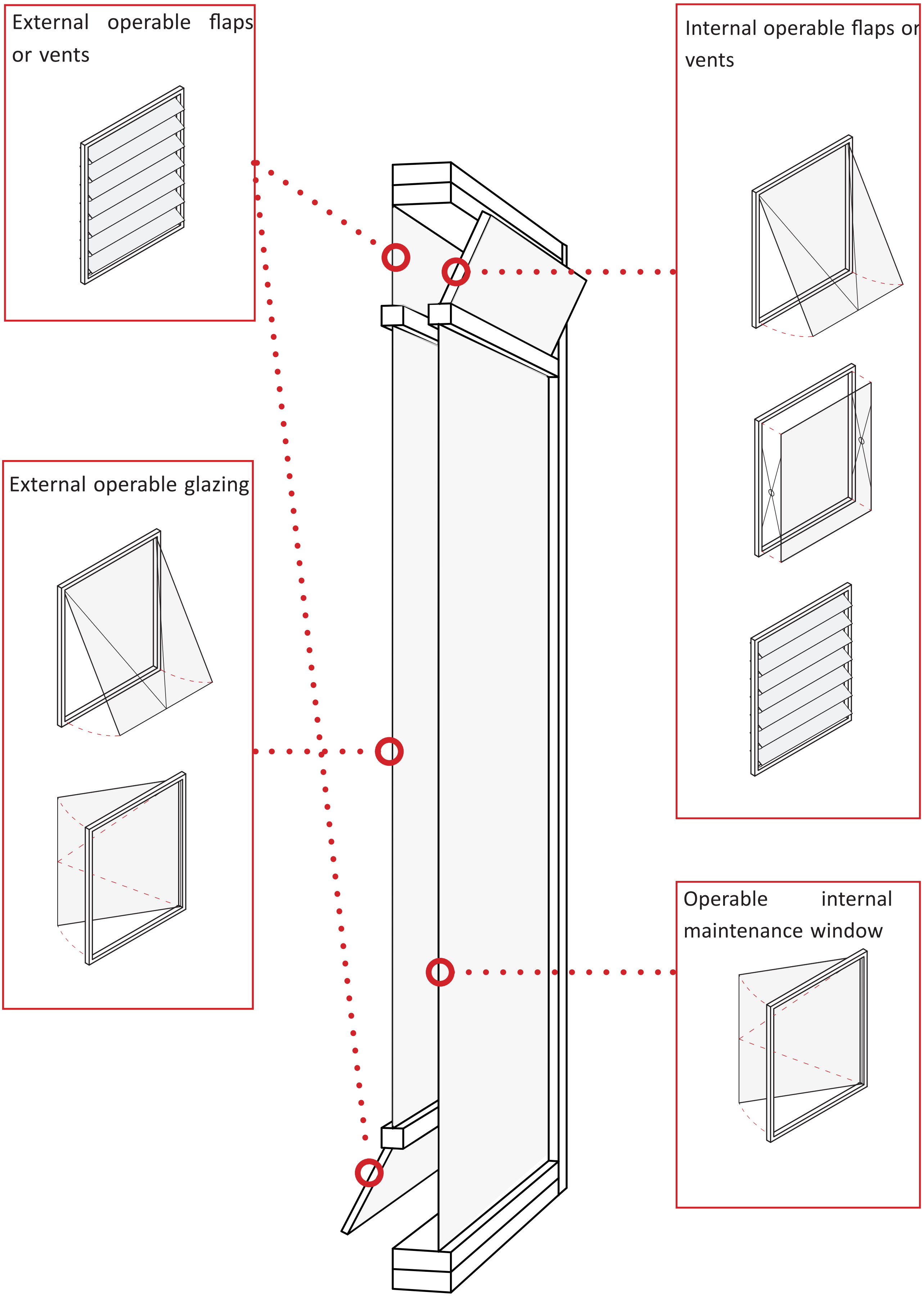


Fig 5.7 The image indicates the components of a box-window as well as suitable typologies of operable parts

5.3 Operable parts

In order develop further the design, several decisions should be formed regarding the typology of external and internal openings. Therefore, the box-window facade panel is divided into smaller components while the available opening systems in the market are reviewed to examine the possible alterations that can be generated through them. A standard box-window typology usually consists of two operable external parts located on the top and bottom of the external skin, and two operable openings on the internal skin. **Fig. 5.7** The interior openings have a different function, as the bottom one is used for maintenance reasons while the top one supplies natural ventilation indoors.

The external operable parts have a quite important function as they define the amount of air that is provided inside the cavity, therefore they should be adjustable according to the wind speed, outdoor temperature and indoor requirements for fresh air and thermal comfort.

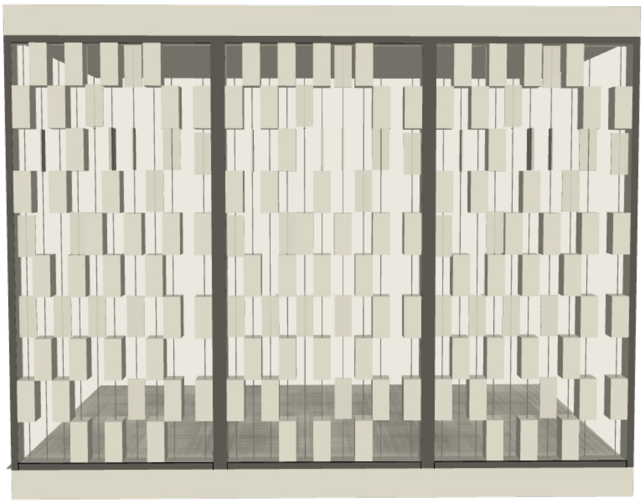
There are several opening directions such as tilt, swing, turn and parallel displacement. Their suitability is defined according to their levels of adjustability and the possibility for installation in a unitized facade system for high-rises. The projected window, downwards tilted window and ventilation flaps are the most suitable window typologies for the external operable parts as their opening area is highly adjustable. The tilted window typology can be applied on buildings reaching the height of 80 m even when the average wind speed is 4.8 m/s, ie. the Manitoba Hydro Place and KfW headquarters in Hamburg. In addition their application is quite common in double skin facades as the width of window frames is quite small and can be easily combined with a second interior skin. The parallel projected window can be applied in high-rises up to 70 m such as the Festo’s Automation Center building in Esslingen where the average wind speed is 3.5 m/s. Finally, the louvered openings are regularly preferred in double skin facades, as they can be easily adjustable while they can be used in heights up to 127 m as in RWE headquarters in Essen **(Wood & Salid, 2012)**. In addition, pressure regulated flaps are used in order to close entirely in case of high wind speed.

Regarding the top internal openings, their typology is highly affected by the selection of external openings as the later determine the wind velocity as well as the provided airflow inside the cavity. High adjustability is required for the internal openings as they should be able to switch between the background and summer ventilation. The ventilation mode should be the same in both external and internal openings except of the cases when the outdoor temperature is higher than 27°C and the interior space is mechanically ventilated while the facade system is continuously ventilated to prevent its overheating.

5.4 Sound absorbing and PCM system

Several design layouts of the PCM and sound absorbing units inside the cavity were created in order to explore the aesthetics in combination with the thermal and acoustic potentials of the design concept. By changing the area and the position of the cavity components the acoustic and thermal performance of the system is affected, since the area defines the total sound absorption coefficient of the cavity while their position mostly influences the PCM performance as shading and adjacency define their temperature and state.

The suggested design layouts will be evaluated in terms of PCM and sound absorbers capacity as according to the acoustic calculations presented in the previous chapter, the required area for sound absorbing material is 5 m^2 in order to achieve more effective values in sound pressure level reduction while the optimum PCM volume is 0.06 m^3 to control effectively the cavity temperature. The following tables present the suggested designs and their advantages and disadvantages in terms of aesthetics, functionality, feasibility, thermal and acoustic performance.

Typology	Hanging boxes
	Description: The system is formed by small rectangular pcm containers and sound absorbing boxes. Those elements are hanged by vertical cables which are mounted on the top and bottom transoms. Max. pcm volume, Sound absorption area ,transparency percentage: 0.02 m^3, 7.3 m^2, 55% Feasibility: The current design presents the highest complexity comparing to the rest suggested designs. The use of cables to minimize the visual impact of the structure results in intensive labor and slow assembling processes. In addition, the maintenance of this complex system requires a lot of time since each element should be cleaned separately and carefully. Materiality: aluminum boxes were chosen to encapsulate pcm to make mounting on cables more easy.

Typology

Hanging boxes

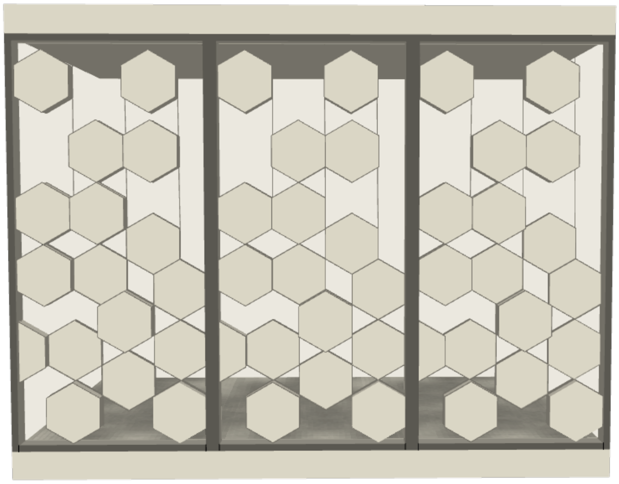
Cost: high cost due to complexity and customization, the reuse possibilities of this system are quite limited

Performance: shading has to be implemented to prevent pcm overheating

Aesthetics: Interesting visual pattern and invisible structure

Typology

Hexagons



Description: Pcm and sound absorbing units are separated and placed on a metal structure inside the cavity. The pcm are enclosed in transparent hexagonal boxes which are also supported on the before-mentioned structure.

Max. pcm volume, Sound absorption area , transparency percentage: 0.02 m^3, 4.5 m^2, 50%

Feasibility: high complexity due to hexagonal shape of transparent pcm containers, high complexity in mounting pcm glass boxes on a supporting structure.

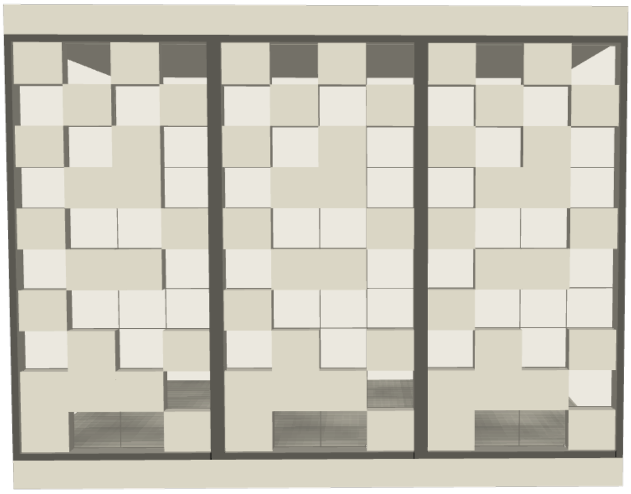
Cost: high cost due to the need of custom-made products

Performance: shading has to be implemented to prevent pcm overheating

Aesthetics: Interesting visual pattern

Typology

Square pixels



Description: The system is similar to the hexagons typology, the only difference is the rectangular shape of the sound absorbing and pcm elements

Max. pcm volume & Sound absorption area, transp. level : 0.03 m^3, 5 m^2, 50%

Feasibility: the complexity is minimized due to the rectangular shape, however, still there is a difficulty in mounting pcm glass boxes on the supporting structure.

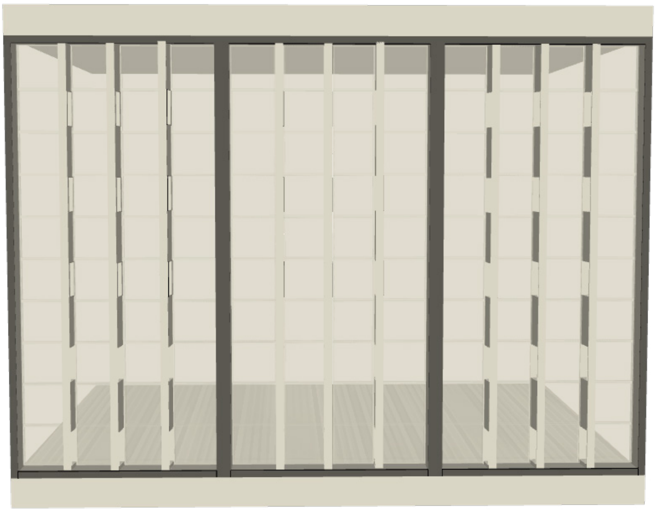
Cost: customization is still required but is minimized because of the rectangular pattern.

Performance: shading has to be implemented to prevent pcm overheating

Aesthetics: Interesting visual pattern

Typology

Vertical louvers



Description: Since in the previously presented designs there was a complexity regarding the pcm boxes' mounting, in the current design the pcm boxes are incorporated in the window frame as an additional layer to the internal glazing skin. This decision provides freedom about the possible cavity layouts and the pcm volume. Sound absorption is realized by vertical louvers which have several openings to allow air flowing in the entire cavity volume.

Max. pcm volume & Sound absorption area, transp. level : 0.03 m^3, 5 m^2, 40%

Typology

Vertical louvers

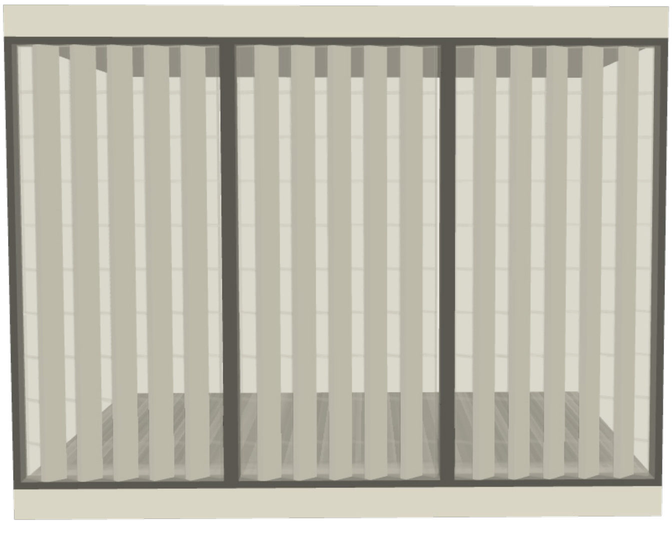
Feasibility: the complexity is minimized significantly comparing to the other presented designs. The sound absorbing louvers can slide and interlock on the window frame. Therefore, the maintenance and production process is simplified.

Cost: the above-mentioned simplifications reduce the production and maintenance cost while the facade elements can be easily reused in other building as they are not highly customized.

Performance: optimum acoustic and thermal performance due to increase of pcm and absorbing area and volume.

Aesthetics: simplified visual pattern

Typology



Inner skin stripes

Description: In this system both sound absorbing elements and pcm boxes are implemented in the internal skin. Two vertical stripe typologies are created, the one includes sound absorbers and the other consists of pcm boxes. Both typologies are implemented on the window frame in order to ensure air tightness.

Max. pcm volume & Sound absorption area, transp level : 0.05 m^3, 2 m^2, 30%

Feasibility: The most complex part is the connection of the two stripe typologies as in order to ensure air tightness, proper sealing should be realized between the pcm boxes and the sound absorbing elements.

Typology	Inner skin stripes
	Cost: cost increases due to the multiple sealed connections between the tripes. Performance: sunshade should be applied in the cavity. The acoustic performance is decreased comparing to the rest designs as the absorbing area exposed on the supplied air is minimized. Aesthetics: view is obstructed by the vertical sound absorbing elements in case opaque porous materials are chosen for their construction.

By comparing the presented design layouts, the most feasible and effective designs are the square pixels and vertical louvers typologies as they combine optimum acoustic and thermal performance and are more easily constructed and assembled comparing to the rest design proposals. More specifically, their performance is evaluated according to the PCM and sound absorber capacity of each design system while their feasibility is defined by the level of complexity in the maintenance and production process. However, in order to improve the PCM capacity of the square pixels typology the PCM boxes will be installed as a third semi-transparent layer to the double glazing interior skin similarly to the vertical louvers typology.

5.4.1 Square pixels

The sound absorbing system is created by an aluminum structure which accommodates the sound absorbing boxes. Aluminum is selected for the construction of this structure as it is an easily processed and lightweight material which can be shaped in several forms. Extruded interlocking aluminum rectangular profiles are connected and form a pixelated structure where opaque sound absorbing materials such as basotect are applied. This connection method is selected as the connections can be simply assembled and disassembled for future uses. This structure apart from the before-mentioned function also provides shading to the PCM boxes located behind them. Therefore, when PCM are in solid state the sound absorbing structure is almost invisible while when they are in liquid state a shading system is visible and an interesting light pattern is generated. The maintenance of the current system is realized by rotating inwards the sound absorbing system which is supported by a hook system fixed on the panels' mullions **Fig. 5.10**.

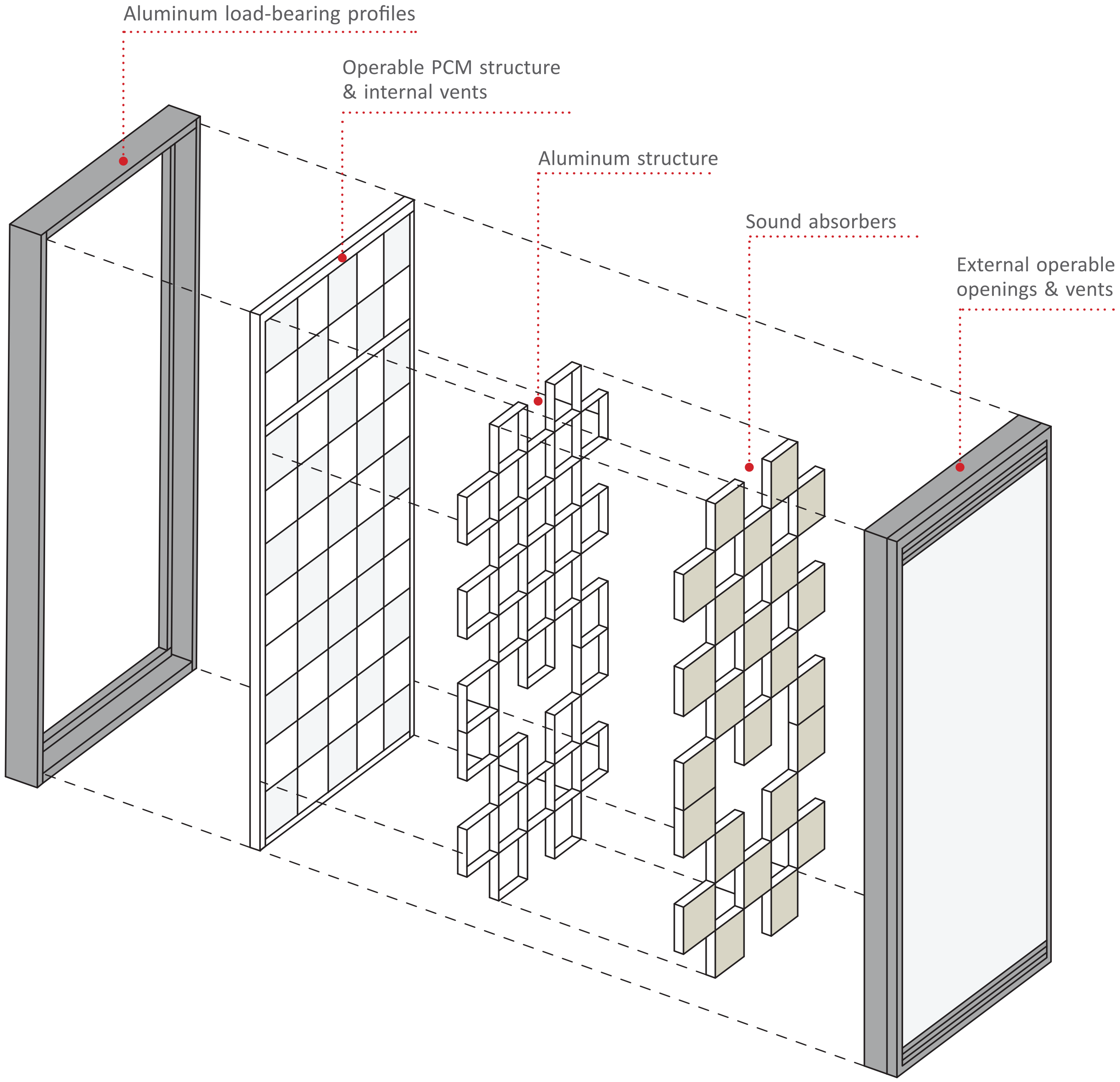


Fig 5.10 Exploded view of square pixel layout, the image is created by the author

5.4.2 Vertical louvers

Although the initial design concept of the vertical louver typology included the use of rotatable vertical sound absorbing louvers, in order to decrease the panel's thickness the sound absorbing material is implemented on rectangular blinds which can be regulated vertically for maintenance and cleaning reasons. The system is hanged by a mechanism fixed on the top and bottom transoms of the panel. Since the vertically movable blinds can provide shading only in specific parts of the PCM structure, the PCM should be placed in a vertical layout according to the position of the sound absorbing blinds. **Fig. 5.11**.

5.5 PCM boxes

As it was mentioned earlier, in order to maximize the space needed for the sound absorbing system and to decrease mounting complexity the PCM system is incorporated as a third semi-transparent layer to the insulated internal glazing skin. Following the design principle of Glass X project, the PCM layer consists of rows and columns of hollow transparent boxes. Some of the boxes are filled with PCM while others are empty to provide sunlight. There are several ways and materials which can be used to produce the PCM layer. Firstly, the boxes can be produced individually by glueing glass sheets together. Then the boxes can be glued on top and sides of each other to form the layer's rows and columns. However, a lot of time is needed to glue all the pieces together, therefore, this joining process is not suitable for a mass produced product which is something required for the current design. Another solution is to shape the entire layer by creating a 3D hollow mould and then injecting a thermoplastic material such as polycarbonate or PEI. In the next stage, holes are drilled in boxes and then PCM is placed in them **Fig.5.13**.

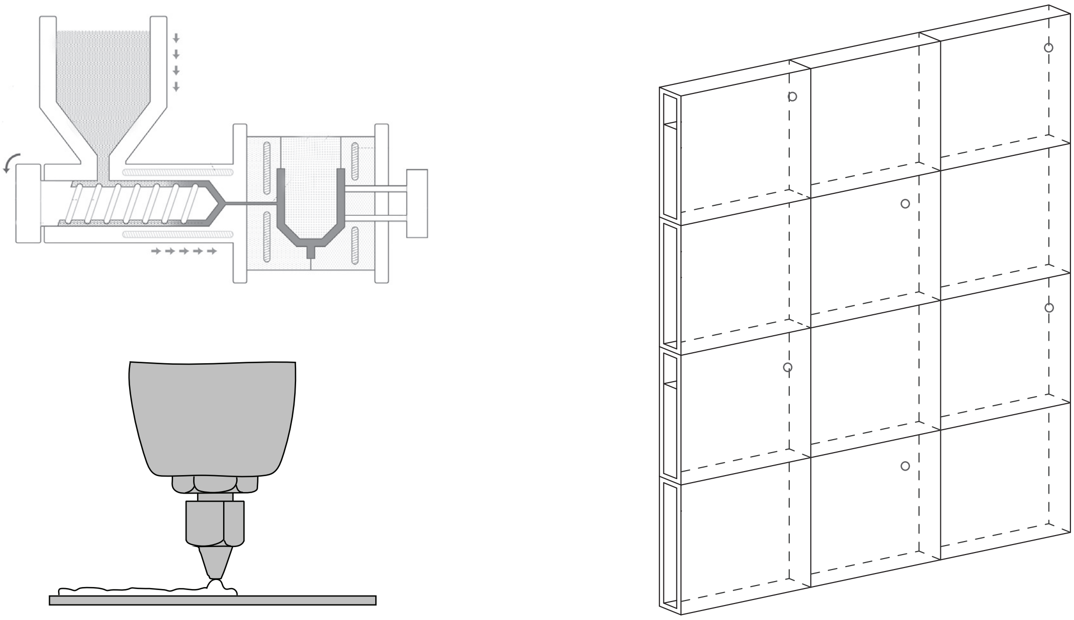


Fig. 5.13 the diagram illustrates the production process of glueing and injection molding as well as the PCM structure, the image is created by the author

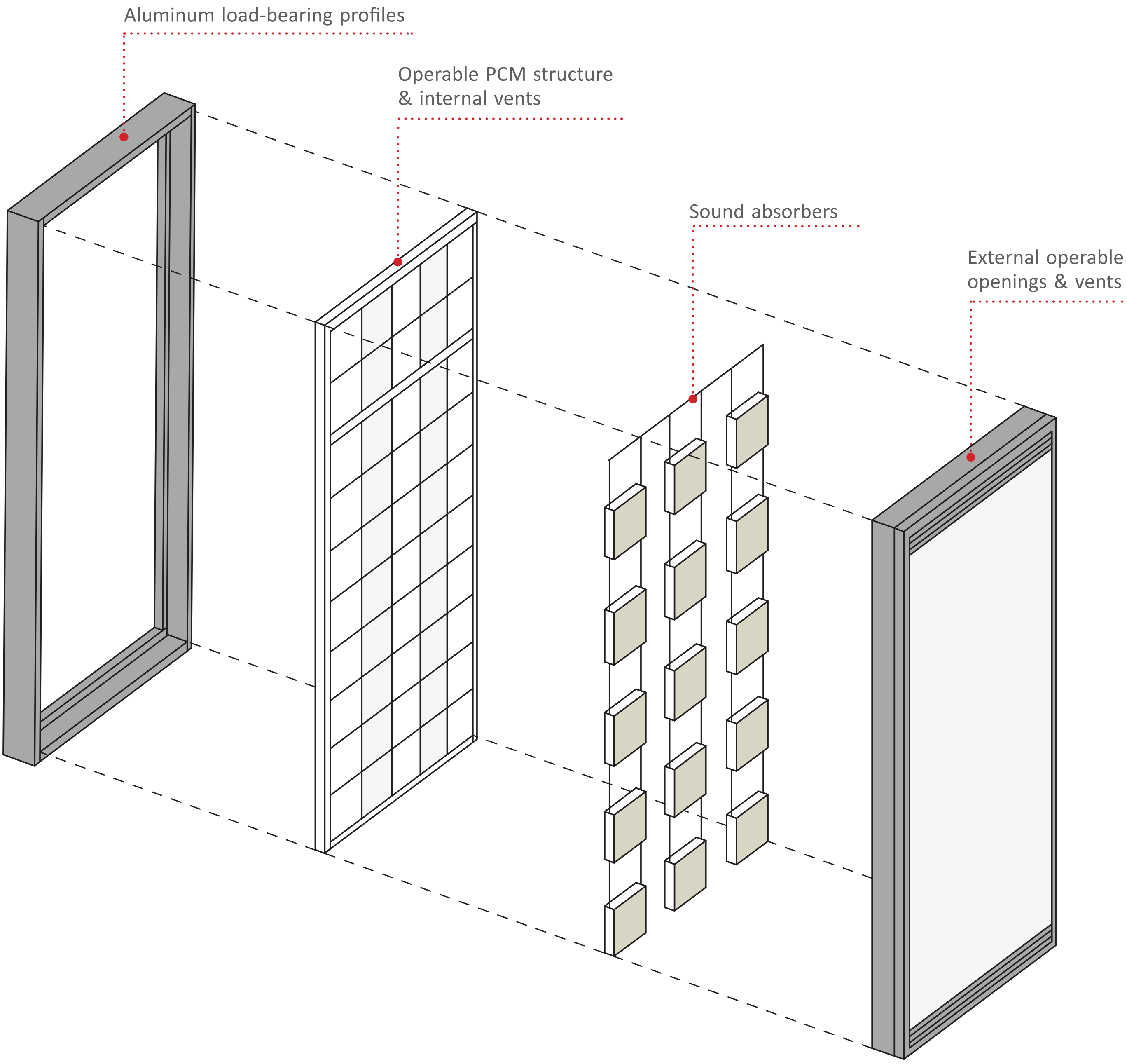
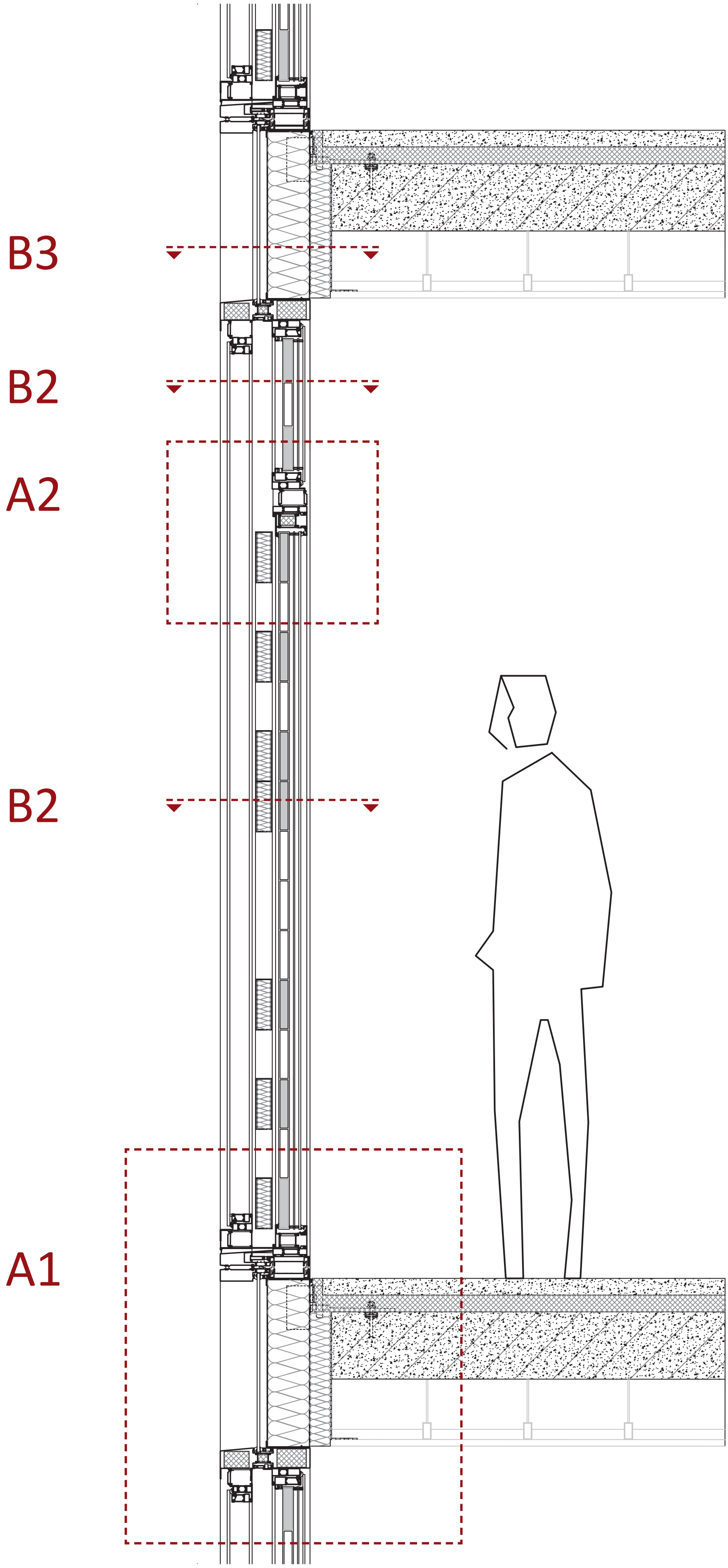


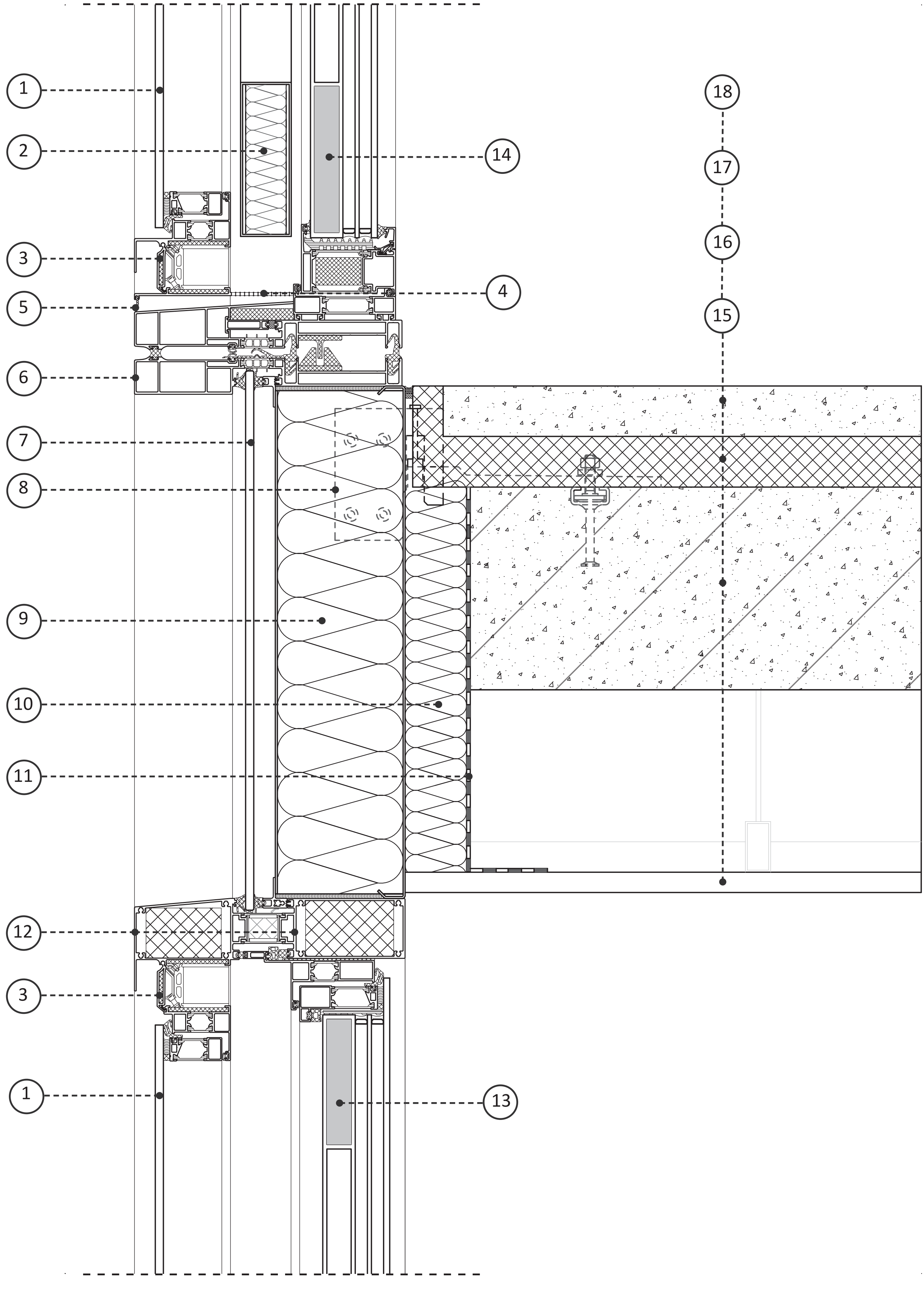
Fig 5.11 Exploded view of vertical louver layout, the image is created by the author

Drawings

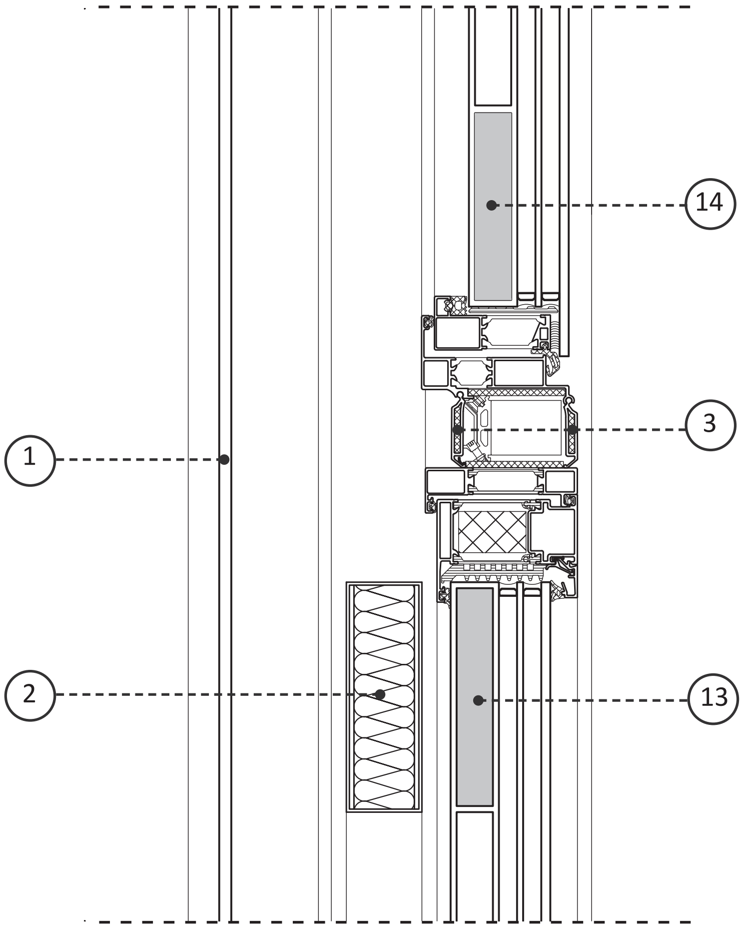
Facade cross section
Scale 1:20



Detail A1
Scale 1:5



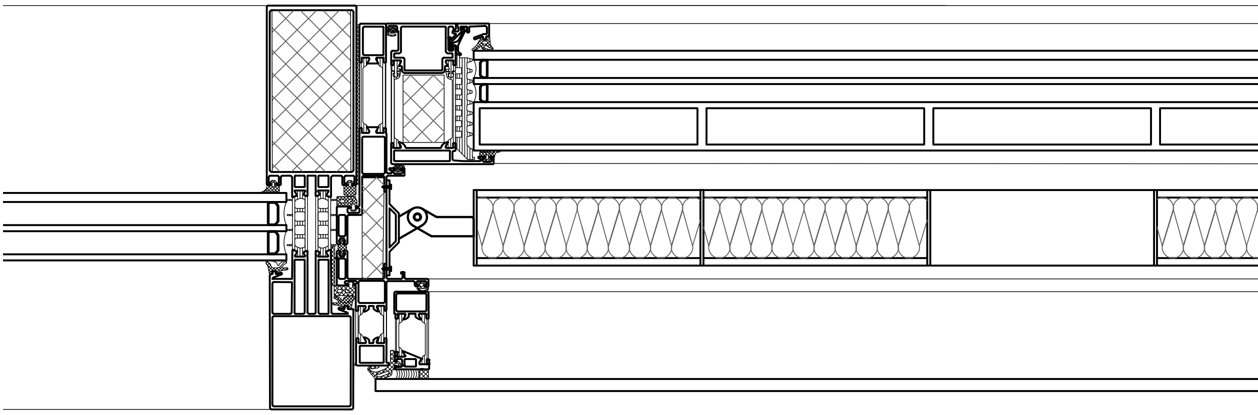
Detail A2
Scale 1:5



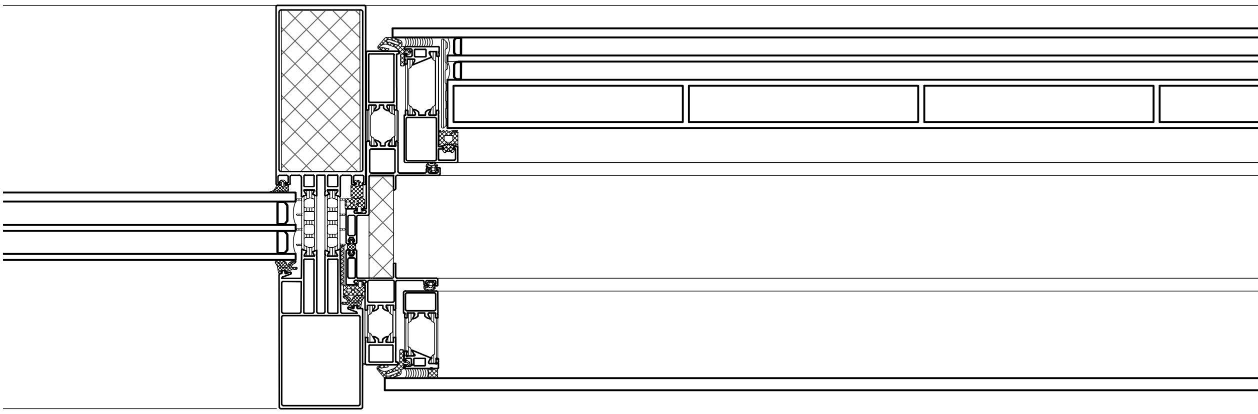
Legend

1. Laminated glass in an openable aluminum window frame (6 mm)
2. Basotec (50 mm)
3. Pressure regulated vent
4. Perforated aluminum plate for water draining
5. Gasket in the draining system allowing water leaking
6. Female/male connection between two different panels
7. Translucent laminated glass (6 mm)
8. Halfen steel hook and plate
9. Sandwich spandrel panel (2mm al. sheet/ 120 mm rockwool/ 2mm al.sheet)
10. Rockwool (60mm)
11. Vapor barrier
12. Insulated aluminum transoms with thermal break
13. PCM box structure incorported to a double glazing unit (projected window frame)
14. PCM box structure incorported to a double glazing unit (openable window frame)
15. False ceiling (20mm)
16. Reinforced concrete slab (200mm)
17. XPS insulation (50mm)
18. Concrete screed (50mm)

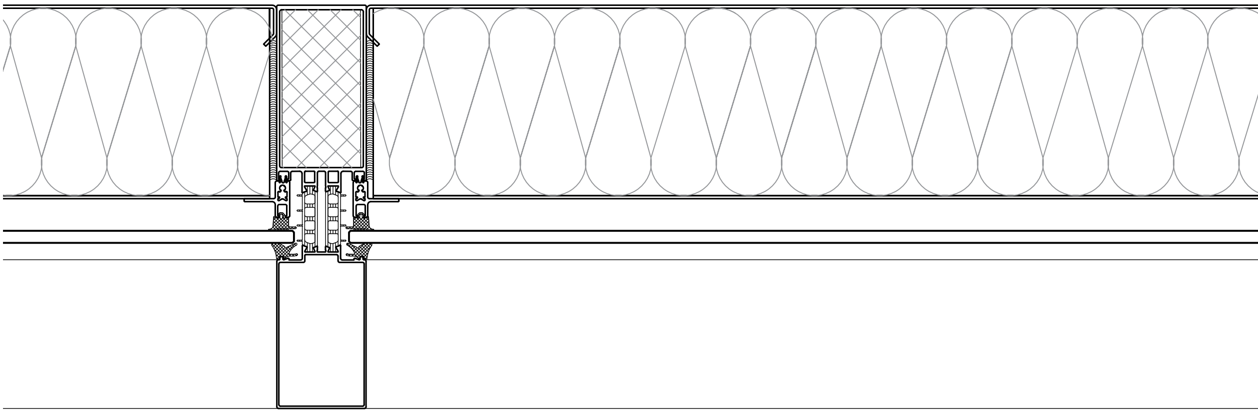
Detail B1
Scale 1:5

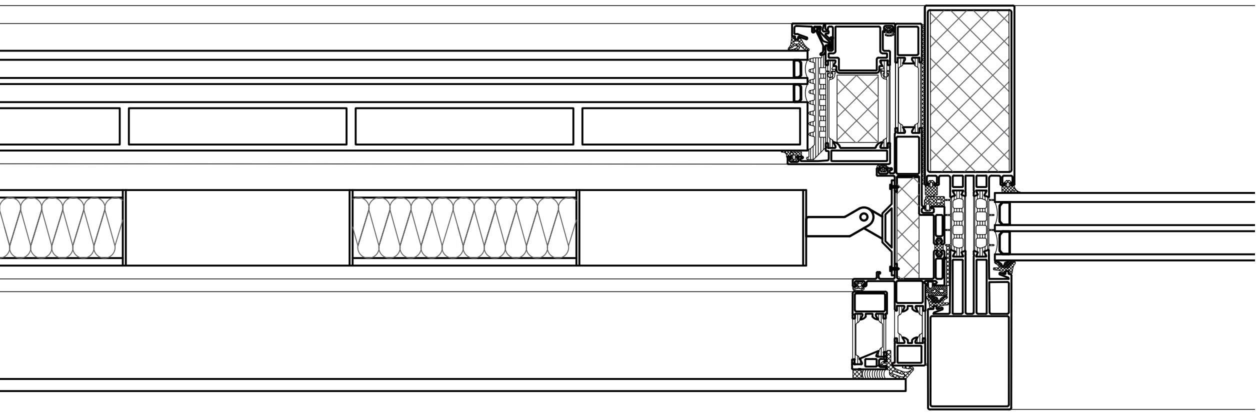


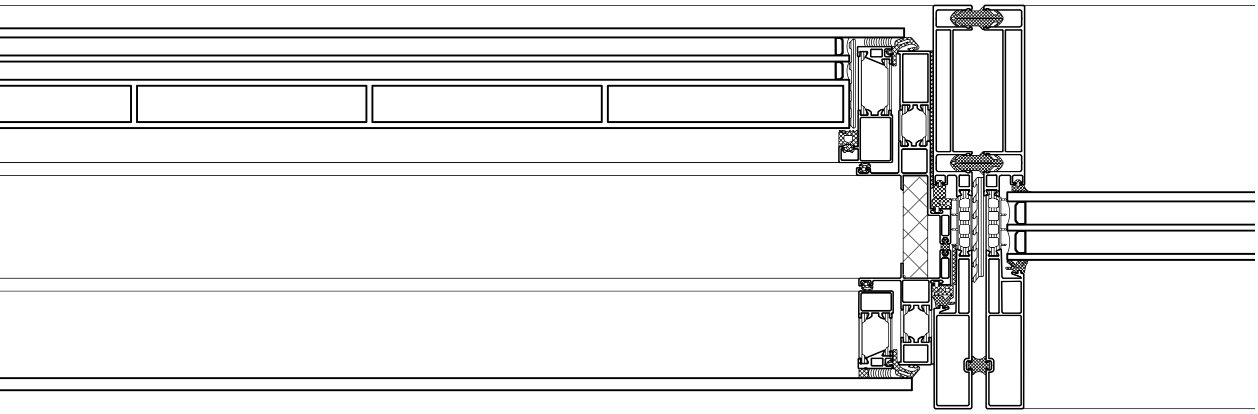
Detail B2
Scale 1:5

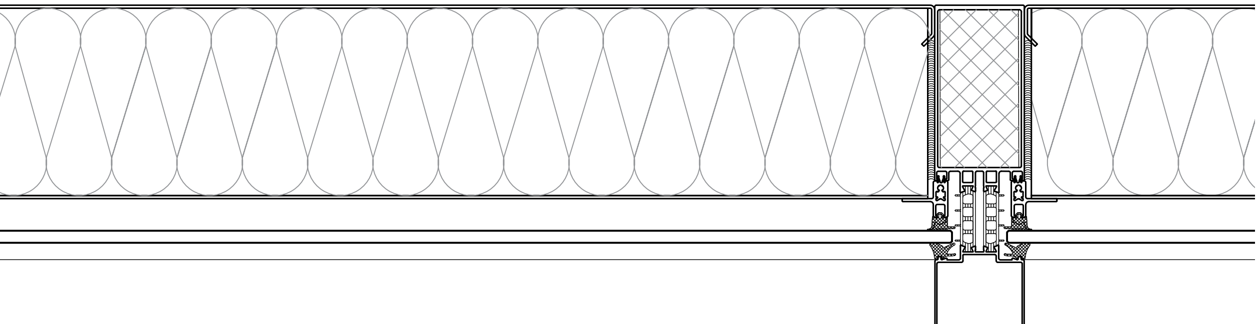


Detail B3
Scale 1:5









Thermal lines

First thermal line

Since the system’s function is based on the preheating and precooling of air in the DSF cavity, there is a need to insulate both the cavity and the indoor environment from the outdoor weather conditions. Therefore, as it can be seen in the Fig. 6.1 there is a continuous thermal line on the outermost facade layer.

The first thermal line consists of the rockwool insulation layer located in the spandrel sandwich panel, the gaskets and hard insulation placed between and inside the aluminum transoms, the laminated external glass, the insulated vents and the gaskets and insulation layer located in the panels female/male connections.

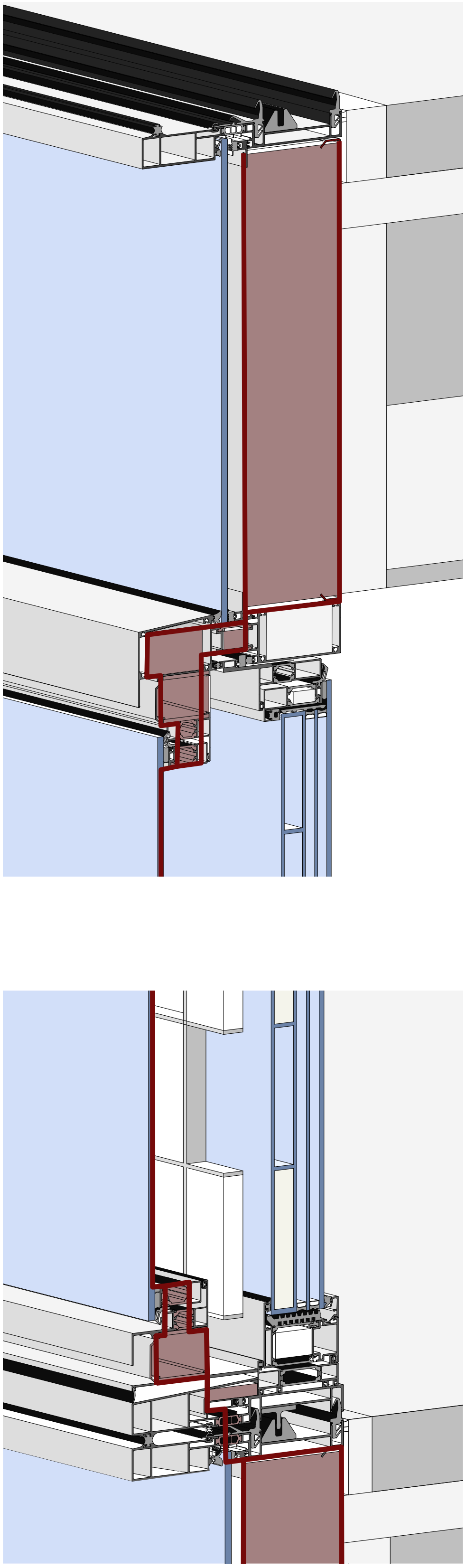
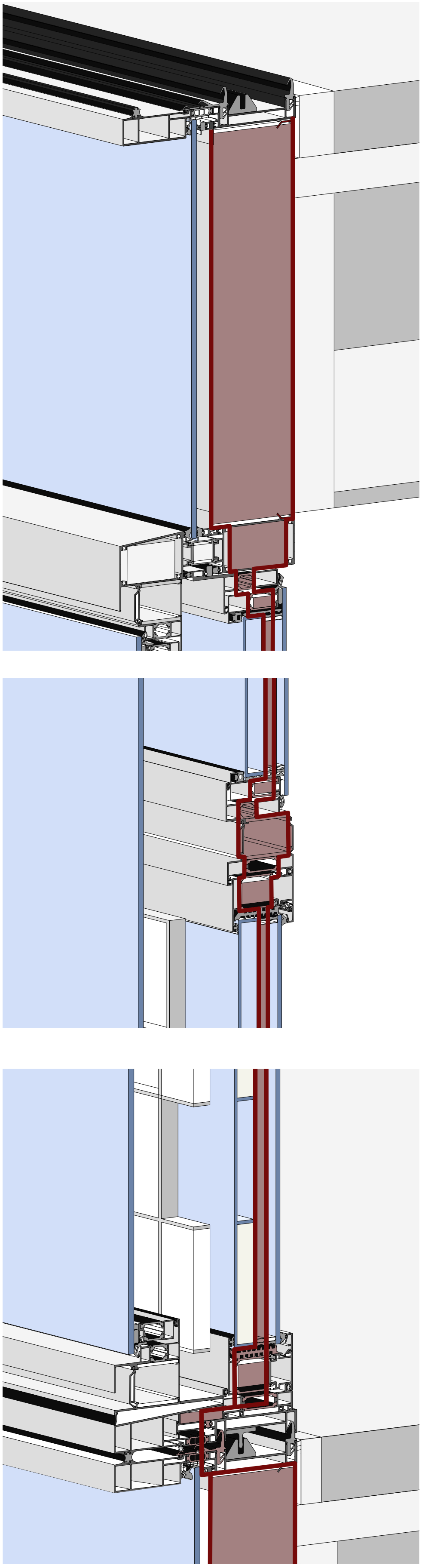


Fig 6.1 The image represents the continuity of the first thermal line, the image is created by the author



Second thermal line

According to the calculations conducted about the possible developed temperatures in the DSF cavity, there will be occasions where the indoor environment should be isolated from the cavity to prevent heat losses or heat gains. Therefore, a second thermal line is required in order to preserve indoor pleasant conditions.

The second thermal line consists of the rockwool insulation layer located in the spadrel sandwich panel, the hard insulation and gaskets located inside the window frames and the facade transoms, the argon filled insulated glass where the PCM structure is implemented in and the gaskets and insulation layers incorporated in the female/male connection between two different facade panels **Fig. 6.2**.

Fig 6.2 The image represents the continuity of the second thermal line, the image is created by the author

Water tightness

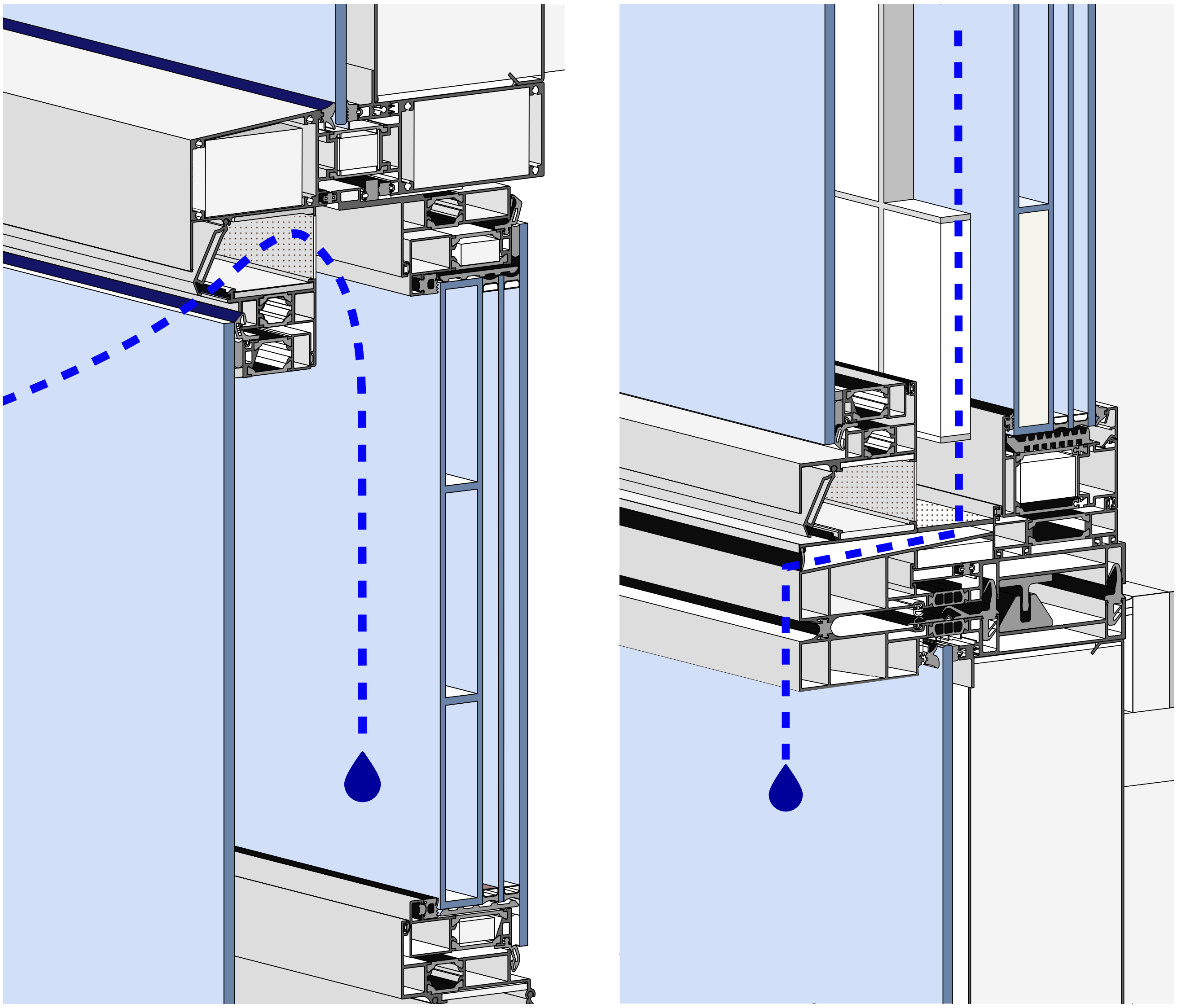


Fig 6.3 The image illustrates the facade draining system, the image is created by the author

In high-rises one of the main problems emerging from natural ventilation is related to water penetration due to high pressure differences between the indoor and outdoor environment. In the suggested design, the cavity is a pressure equalization zone which prevents water penetration and allows natural ventilation. Inevitably water will be leaking inside the cavity either due to rain or condensation since the cavity will be ventilated during the majority of weather conditions **Fig 6.3**. Therefore at the bottom part of the facade panel a perforated plate is located allowing water to weep out from the cavity through a water inclined channel. The perforated plate is placed between the external and internal window frames in order to be easily cleaned and fixed in case of damage.

Maintenance

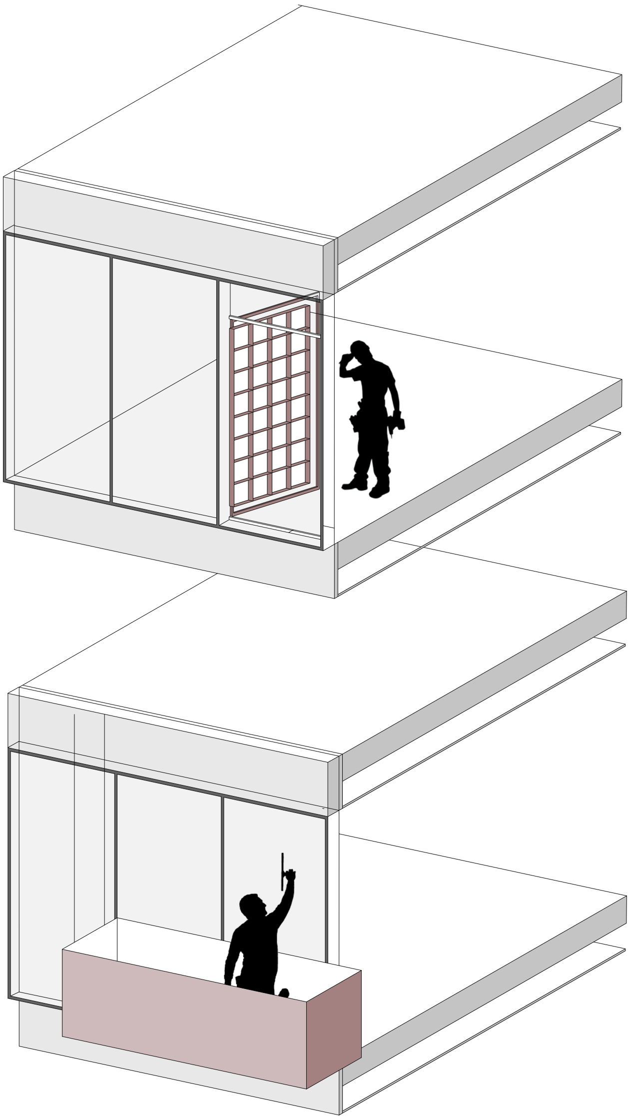
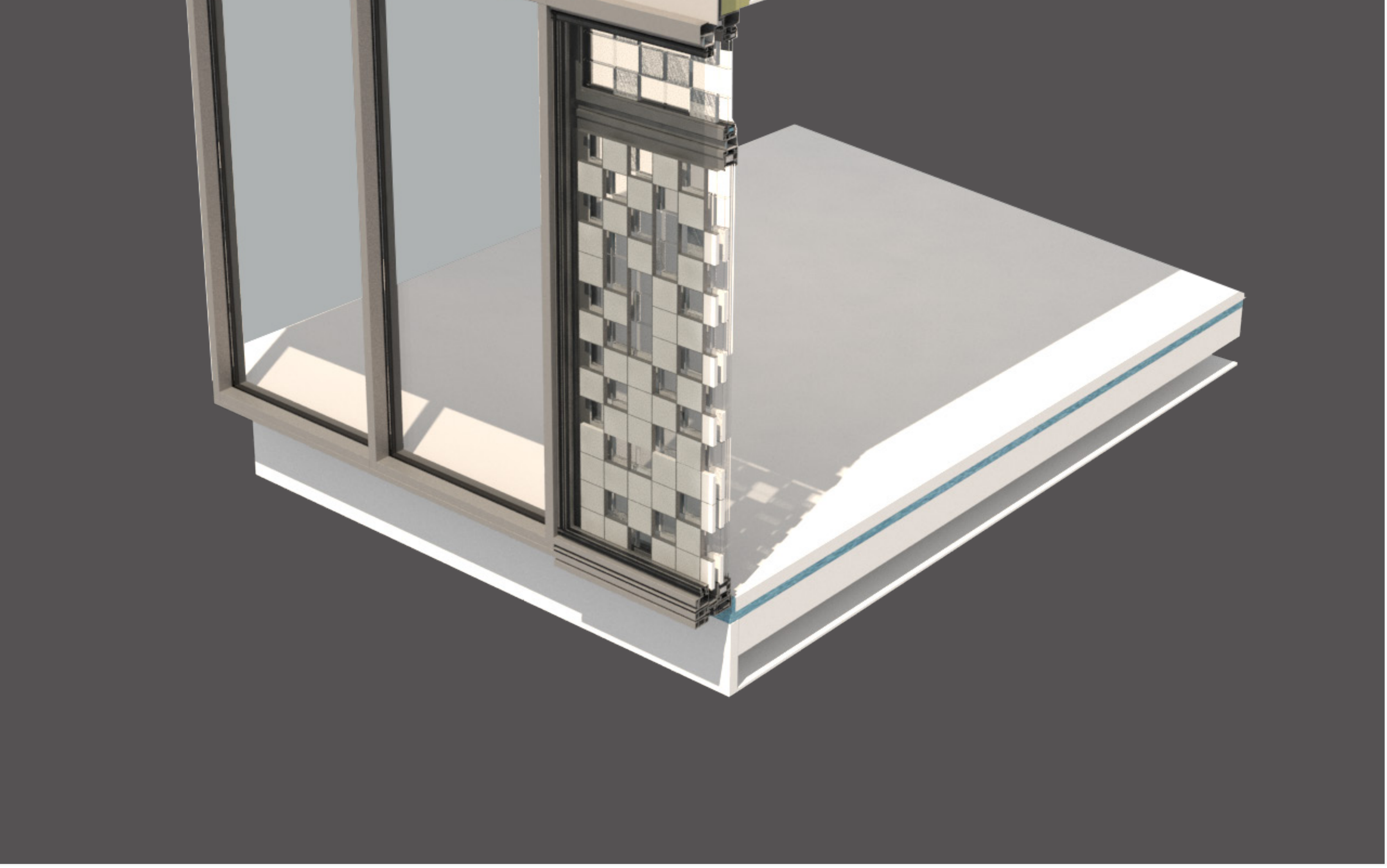


Fig 6.4 The image illustrates the facade maintenance strategies, the image is created by the author

In order to provide easy access in the facade's cavity for cleaning and maintenance purposes the indoor window frame is operable and can be tilted inwards. Similarly, the structure accommodating the sound absorbing materials is rotatable inwards as it is supported by hooks on the facade's mullions. Access to the external facade layers is provided by a crane located on the top floor of the high-rise and aerial platforms carrying cleaners **Fig.6.4**.

Facade visualizations



Coclusions

Conclusions

In the Netherlands in high-rise office buildings natural ventilation is not usually preferred because it causes problems related to acoustic and thermal discomfort. Several solutions have been developed in order to minimize noise propagation through natural ventilation such as vents, double skin facades and resonator panels. In high-rises in order to tackle discomfort problems related to natural ventilation and strong wind pressures, design strategies including the use of buffer zones, ventilation boxes and double skin facades are commonly applied. The main disadvantages are related to the reduction of transparency levels and the provision of either background or summer ventilation since the suggested systems are not efficient in an annual basis. The typology of a ventilated double skin facade was chosen as the design basis, however in order to improve the acoustic performance sound absorbing materials are applied in the cavity of the DSF. In addition, since there is a need to control the temperature of the provided air the application of PCM in the double skin cavity is suggested. A design concept including the use of an air channel where PCM and sound absorbing pockets are implemented in was developed while a hybrid ventilation strategy was formed in order to ensure good levels of indoor comfort independently from the outdoor weather conditions. To evaluate the suggested design concept calculations were conducted regarding the developed cavity temperatures with and without the PCM implementation. The results indicated that by applying 0.06 m^3 of PCM in a double skin facade panel of 0.15 x 1.5 x 3 m, the cavity temperature ranges between 10 and 20^{o}C in winter, while during summer and spring months the cavity temperature is stabilized between 15 and 25^{o}C. Furthermore, both the area and the type of sound absorbing material was chosen according to calculations which indicated that the most effective option is the application of 5 m^2 of 50 mm thick opaque sound absorbing materials. Opaque materials were chosen in order to be used as sun shading for the PCM and prevent overheating in summer. Finally, calculations about the developed wind speed, air flow and pressure drop were realized in order to estimate the effective opening's areas and whether the suggested design will provide adequately natural ventilation annually.

Following the results of the before-mentioned calculations, different typologies regarding the PCM and sound absorbing material layout were developed. Two of them were selected as the most optimum design solutions in terms of feasibility,cost and performance. After considering the need for natural background and summer ventilation as well as for easy maintenance and production method, the final facade design consists of a unitized box-window facade system including operable indoor and outdoor openings, such as windows and vents, a PCM layer incorporated in the indoor glazing unit and a sound absorbing structure located in the ventilated cavity. In the detailing process aspects such as the thermal insulation of both the cavity and the indoor environment were considered by applying thermal breaks and layers of rockwool and hard insulation in the spandrel panel as well as in the load bearing elements of the facade. In addition, in the detailing the watertightness and water drainage of the facade were included since the aluminum profiles are designed in such a way to prevent water penetration and allow water draining in cases of condensation and water penetration through ventilation in rainy days. Finally, the maintenance of the suggested design is solved by providing easy access from the operable indoor opening and sound absorbing structure to the cavity.

Reflection

The aim of the current thesis is to explore solutions in façade level in order to provide natural ventilation while keeping high comfort levels in the indoor environment in high-rise office buildings in the Netherlands. This topic was selected because it combines the extensive knowledge of building physics about acoustics and thermal analysis and at the same time requires the development of a technically smart façade design. The goal of this thesis is closely related to sustainability as the purpose of the design is to preheat and precool the fresh air and at the same time to allow natural ventilation even in noisy urban centers.

The research results indicated that there is a potential in the application of pcm and sound absorbing materials in the cavity of box-windows. In order to make proper estimations about the feasibility and the effectiveness of the developed concept, calculations were realized about the temperature variations in the cavity during different weather conditions while the sound pressure level reduction was calculated by considering several materials and the respective areas. Although the choice of the implementation of PCM in the cavity of the double skin facade panel resulted in effective temperature control in the cavity, especially during summer months, the process of calculating the behavior of PCM in correlation to factors such as solar radiation and the provided airflow was quite time consuming and challenging. Consequently, due to the limited time, the conducted calculations were not verified by realizing measurements in a prototype or by simulating a model in a computer software. Therefore, those steps could be accomplished in a further research where measurements and simulations will indicate the design's performance under several weather conditions.

In addition, in further research the design could be implemented in a more complicated facade where composite will be used as load bearing components. Also, other solutions including the use of other materials such as wood could be explored. Finally, the performance of the suggested design could be tested in several regions while implementing new design improvements to meet indoor comfort levels for different climates.

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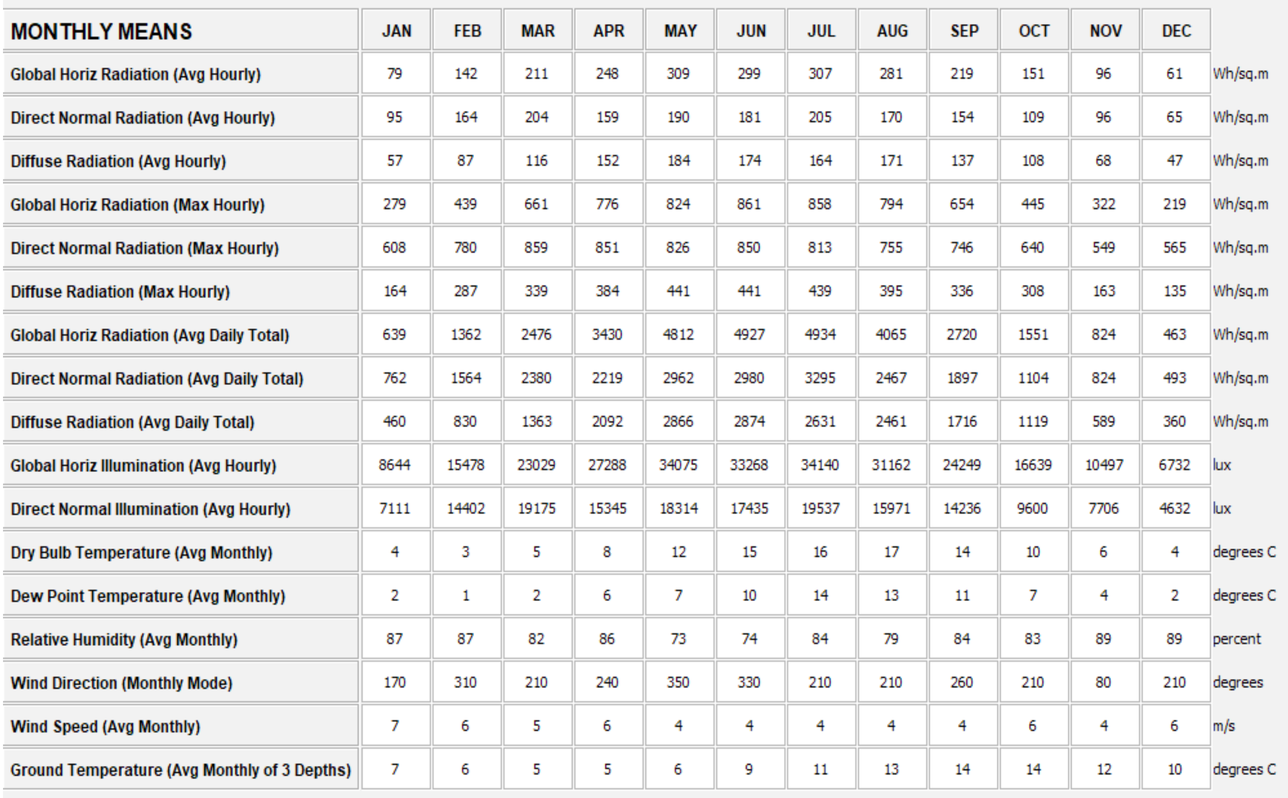
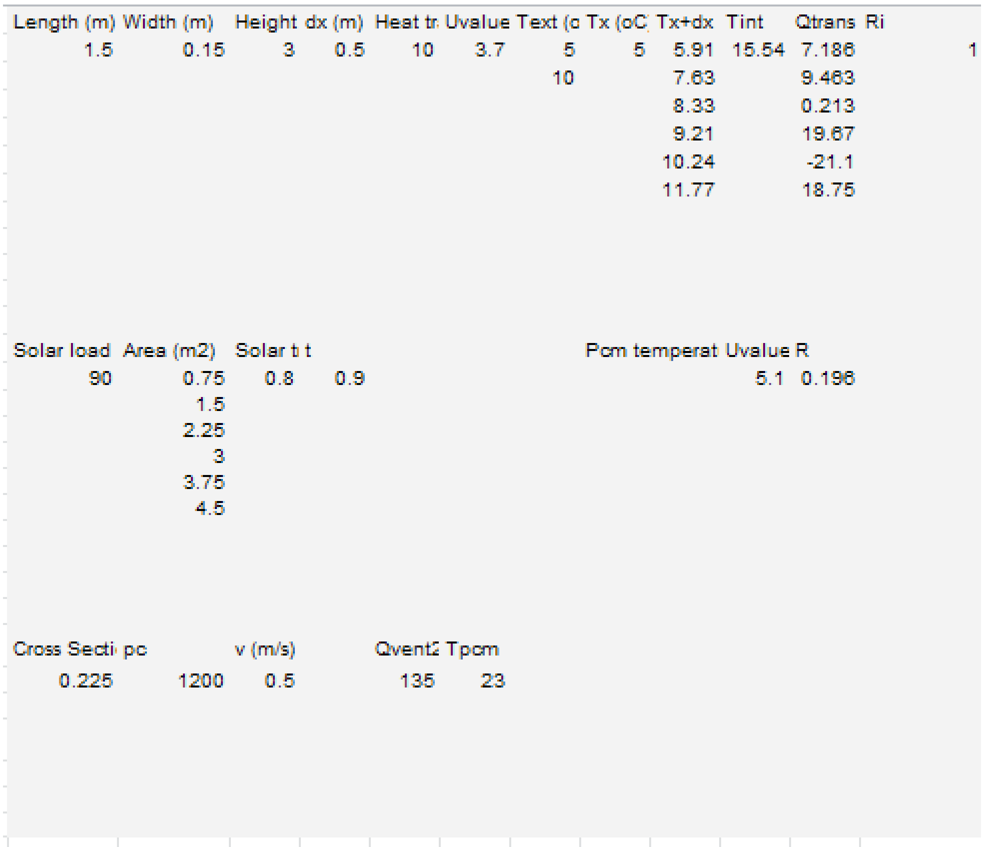
Appendix 1



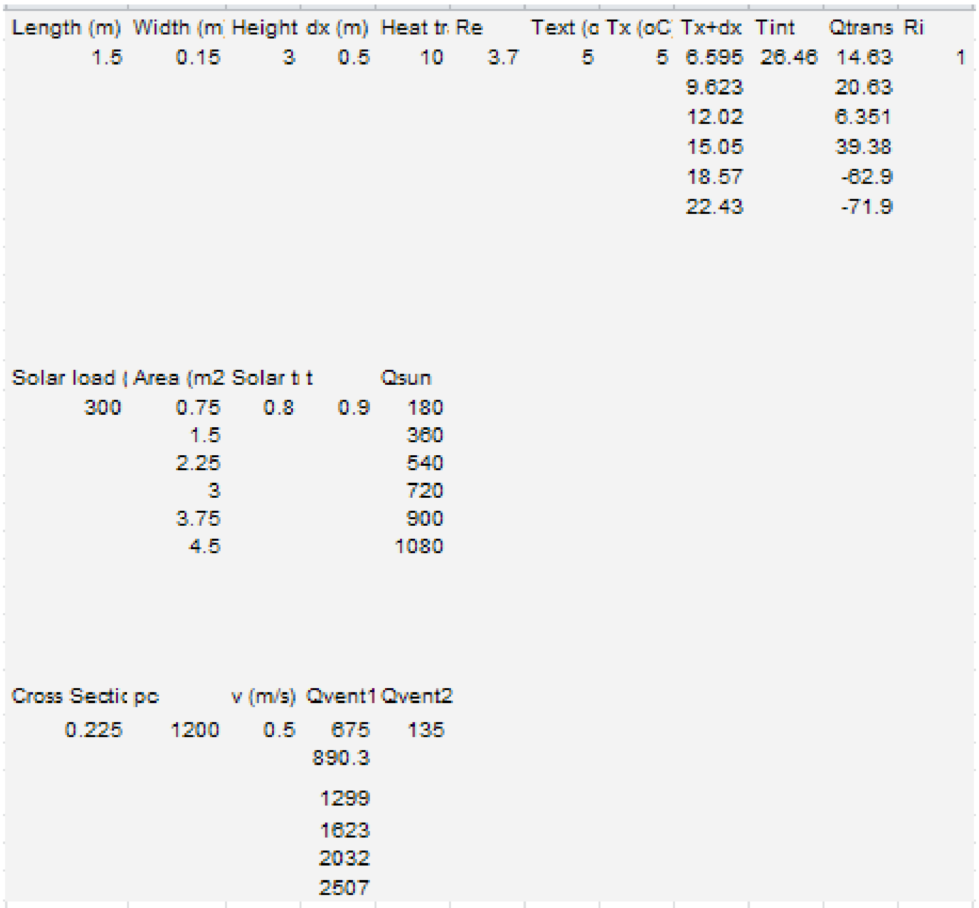
MONTHLY MEANS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Global Horiz Radiation (Avg Hourly)	79	142	211	248	309	299	307	281	219	151	96	61	Wh/sq.m
Direct Normal Radiation (Avg Hourly)	95	164	204	159	190	181	205	170	154	109	96	65	Wh/sq.m
Diffuse Radiation (Avg Hourly)	57	87	116	152	184	174	164	171	137	108	68	47	Wh/sq.m
Global Horiz Radiation (Max Hourly)	279	439	661	776	824	861	858	794	654	445	322	219	Wh/sq.m
Direct Normal Radiation (Max Hourly)	608	780	859	851	826	850	813	755	746	640	549	565	Wh/sq.m
Diffuse Radiation (Max Hourly)	164	287	339	384	441	441	439	395	336	308	163	135	Wh/sq.m
Global Horiz Radiation (Avg Daily Total)	639	1362	2476	3430	4812	4927	4934	4065	2720	1551	824	463	Wh/sq.m
Direct Normal Radiation (Avg Daily Total)	762	1564	2380	2219	2962	2980	3295	2467	1897	1104	824	493	Wh/sq.m
Diffuse Radiation (Avg Daily Total)	460	830	1363	2092	2866	2874	2631	2461	1716	1119	589	360	Wh/sq.m
Global Horiz Illumination (Avg Hourly)	8644	15478	23029	27288	34075	33268	34140	31162	24249	16639	10497	6732	lux
Direct Normal Illumination (Avg Hourly)	7111	14402	19175	15345	18314	17435	19537	15971	14236	9600	7706	4632	lux
Dry Bulb Temperature (Avg Monthly)	4	3	5	8	12	15	16	17	14	10	6	4	degrees C
Dew Point Temperature (Avg Monthly)	2	1	2	6	7	10	14	13	11	7	4	2	degrees C
Relative Humidity (Avg Monthly)	87	87	82	86	73	74	84	79	84	83	89	89	percent
Wind Direction (Monthly Mode)	170	310	210	240	350	330	210	210	260	210	80	210	degrees
Wind Speed (Avg Monthly)	7	6	5	6	4	4	4	4	4	6	4	6	m/s
Ground Temperature (Avg Monthly of 3 Depths)	7	6	5	5	6	9	11	13	14	14	12	10	degrees C

Appendix 2

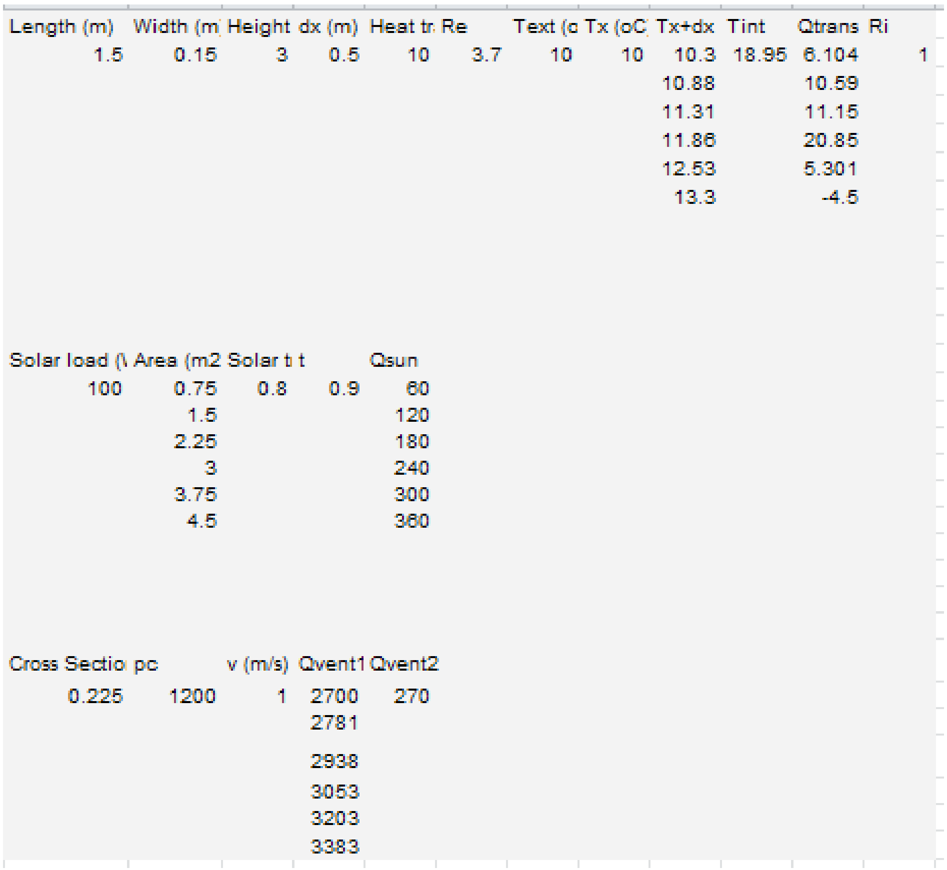
Cavity temperature in different weather conditions



Length (m)	Width (m)	Height	dx (m)	Heat tr	Uvalue	Text (o	Tx (oC	Tx+dx	Tint	Qtrans	Ri
1.5	0.15	3	0.5	10	3.7	5	5	5.91	15.54	7.186	1
						10		7.63		9.463	
								8.33		0.213	
								9.21		19.67	
								10.24		-21.1	
								11.77		18.75	
Solar load	Area (m2)	Solar t t					Pcm temperat		Uvalue	R	
90	0.75	0.8	0.9						5.1	0.196	
	1.5										
	2.25										
	3										
	3.75										
	4.5										
Cross Secti	pc	v (m/s)		Qvent2	Tpcm						
0.225	1200	0.5		135	23						



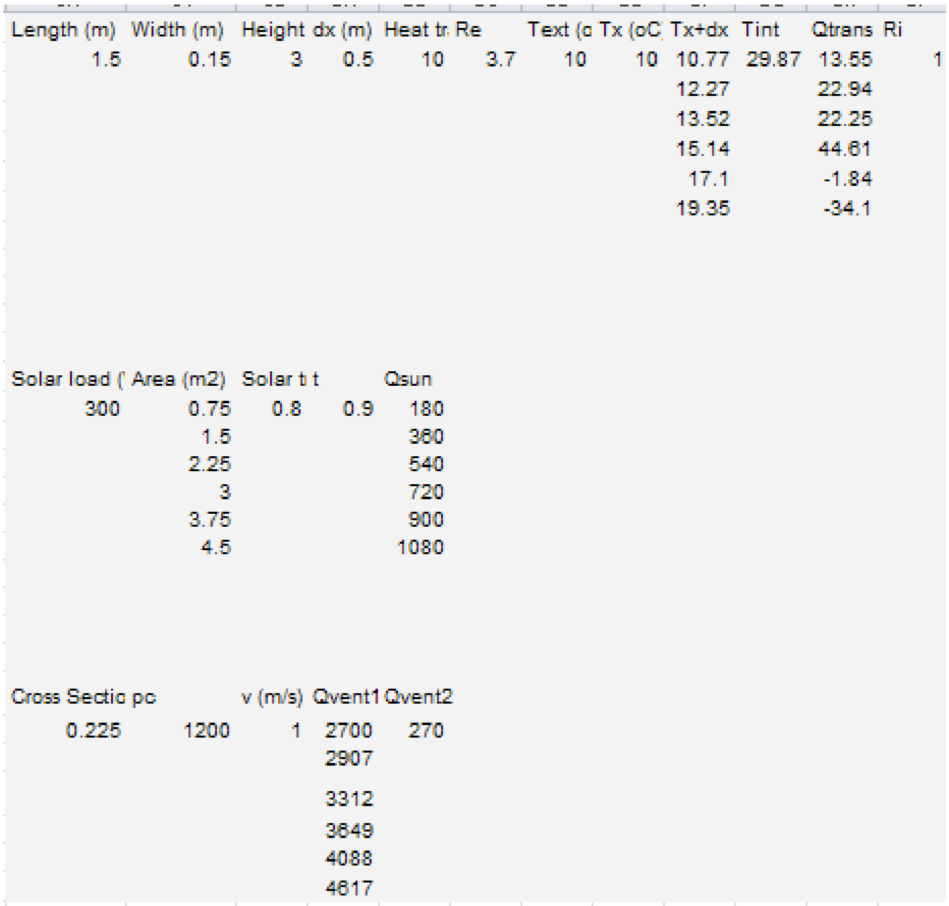
Length (m)	Width (m	Height	dx (m)	Heat tr	Re	Text (o	Tx (oC	Tx+dx	Tint	Qtrans	Ri
1.5	0.15	3	0.5	10	3.7	5	5	6.595	26.46	14.63	1
								9.623		20.63	
								12.02		6.351	
								15.05		39.38	
								18.57		-62.9	
								22.43		-71.9	
Solar load (	Area (m2	Solar t t		Qsun							
300	0.75	0.8	0.9	180							
	1.5			360							
	2.25			540							
	3			720							
	3.75			900							
	4.5			1080							
Cross Sectic	pc	v (m/s	Qvent1	Qvent2							
0.225	1200	0.5	675	135							
			890.3								
			1299								
			1623								
			2032								
			2507								



Length (m)	Width (m	Height	dx (m)	Heat tr	Re	Text (c	Tx (oC	Tx+dx	Tint	Qtrans	Ri
1.5	0.15	3	0.5	10	3.7	10	10	10.3	18.95	6.104	1
								10.88		10.59	
								11.31		11.15	
								11.86		20.85	
								12.53		5.301	
								13.3		-4.5	

Solar load (\	Area (m2	Solar t	t	Qsun
100	0.75	0.8	0.9	60
	1.5			120
	2.25			180
	3			240
	3.75			300
	4.5			360

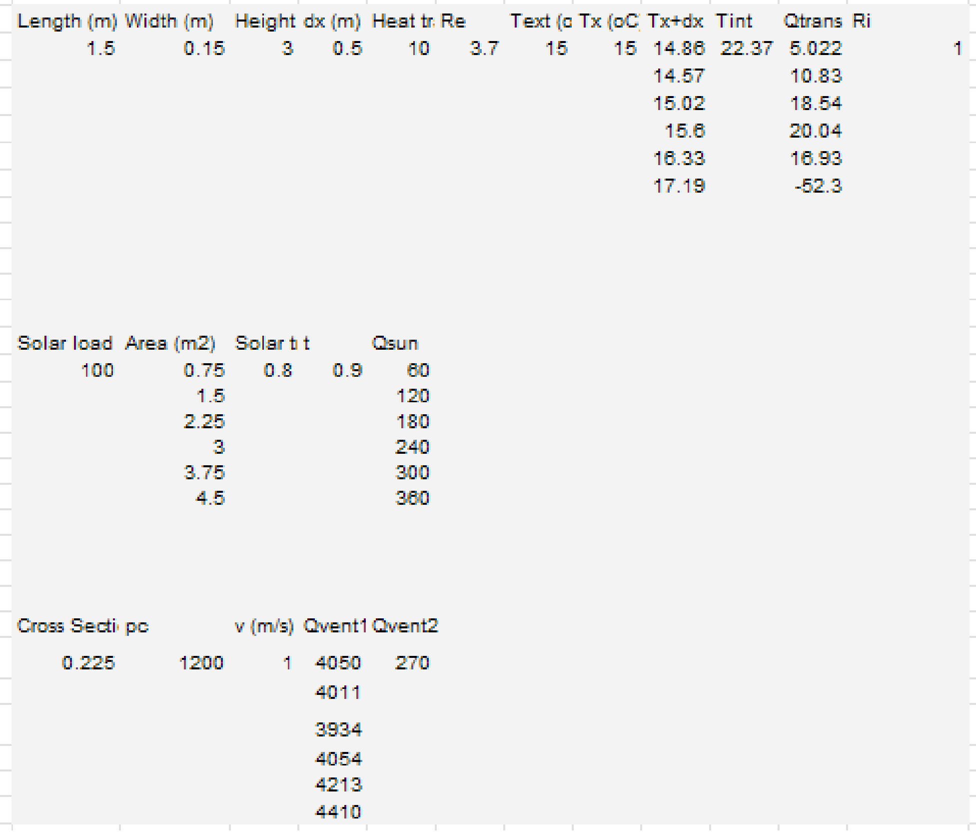
Cross Sectio	pc	v (m/s)	Qvent1	Qvent2
0.225	1200	1	2700	270
			2781	
			2938	
			3053	
			3203	
			3383	



Length (m)	Width (m)	Height	dx (m)	Heat tr	Re	Text (c	Tx (oC	Tx+dx	Tint	Qtrans	Ri
1.5	0.15	3	0.5	10	3.7	10	10	10.77	29.87	13.55	1
								12.27		22.94	
								13.52		22.25	
								15.14		44.61	
								17.1		-1.84	
								19.35		-34.1	

Solar load ('	Area (m2)	Solar t	t	Qsun
300	0.75	0.8	0.9	180
	1.5			360
	2.25			540
	3			720
	3.75			900
	4.5			1080

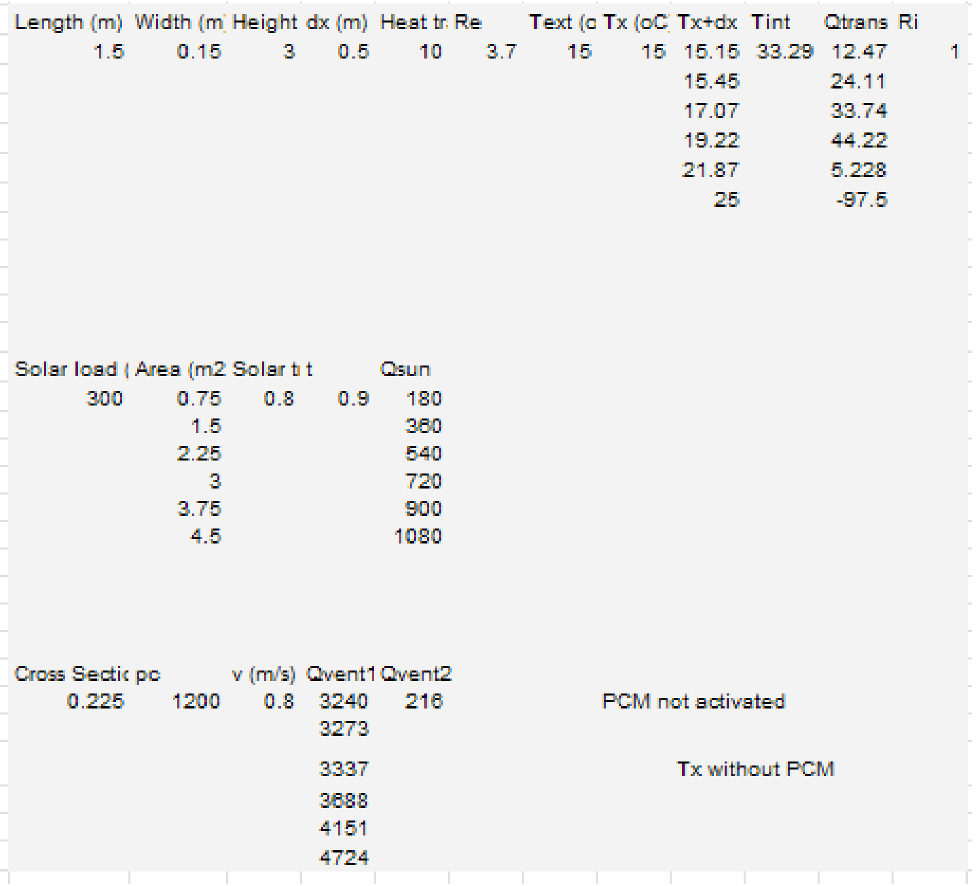
Cross Sectio	pc	v (m/s)	Qvent1	Qvent2
0.225	1200	1	2700	270
			2907	
			3312	
			3649	
			4088	
			4617	



Length (m)	Width (m)	Height	dx (m)	Heat tr	Re	Text (o	Tx (oC	Tx+dx	Tint	Qtrans	Ri
1.5	0.15	3	0.5	10	3.7	15	15	14.86	22.37	5.022	1
								14.57		10.83	
								15.02		18.54	
								15.6		20.04	
								16.33		16.93	
								17.19		-52.3	

Solar load	Area (m2)	Solar t	t	Qsun
100	0.75	0.8	0.9	60
	1.5			120
	2.25			180
	3			240
	3.75			300
	4.5			360

Cross Secti	pc	v (m/s)	Qvent1	Qvent2
0.225	1200	1	4050	270
			4011	
			3934	
			4054	
			4213	
			4410	



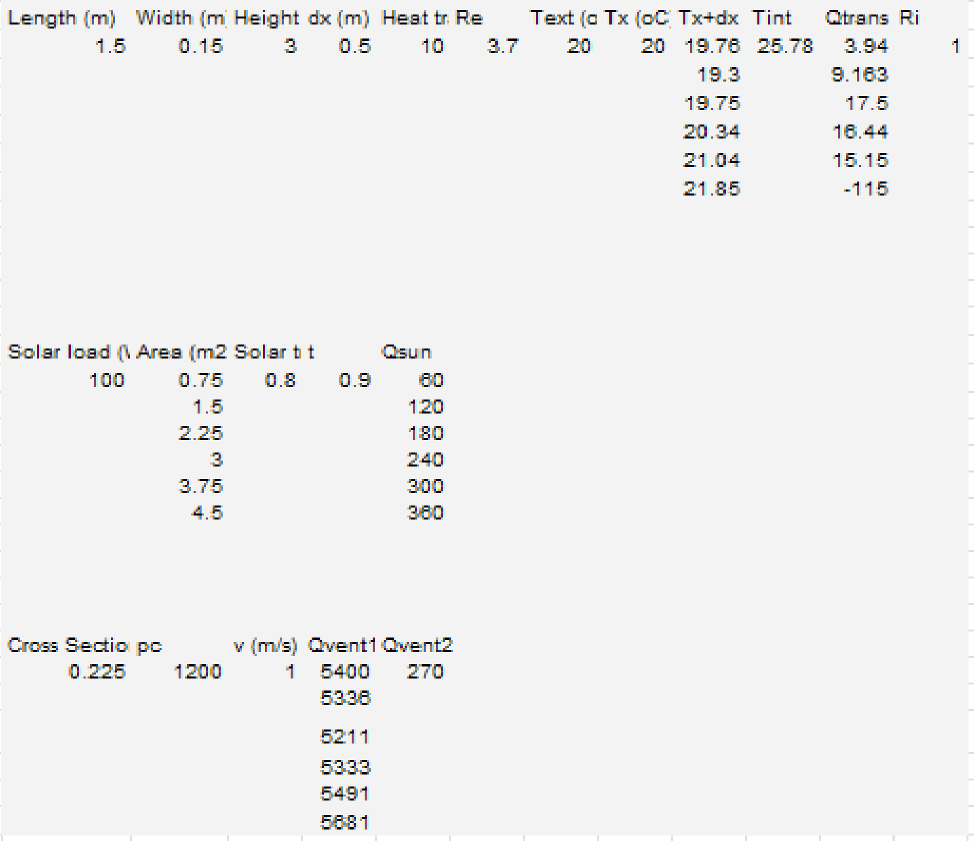
Length (m)	Width (m	Height	dx (m)	Heat tr	Re	Text (o	Tx (oC	Tx+dx	Tint	Qtrans	Ri
1.5	0.15	3	0.5	10	3.7	15	15	15.15	33.29	12.47	1
								15.45		24.11	
								17.07		33.74	
								19.22		44.22	
								21.87		5.228	
								25		-97.5	

Solar load (	Area (m2	Solar t	t	Qsun
300	0.75	0.8	0.9	180
	1.5			360
	2.25			540
	3			720
	3.75			900
	4.5			1080

Cross Sectic	pc	v (m/s)	Qvent1	Qvent2
0.225	1200	0.8	3240	216
			3273	
			3337	
			3688	
			4151	
			4724	

PCM not activated

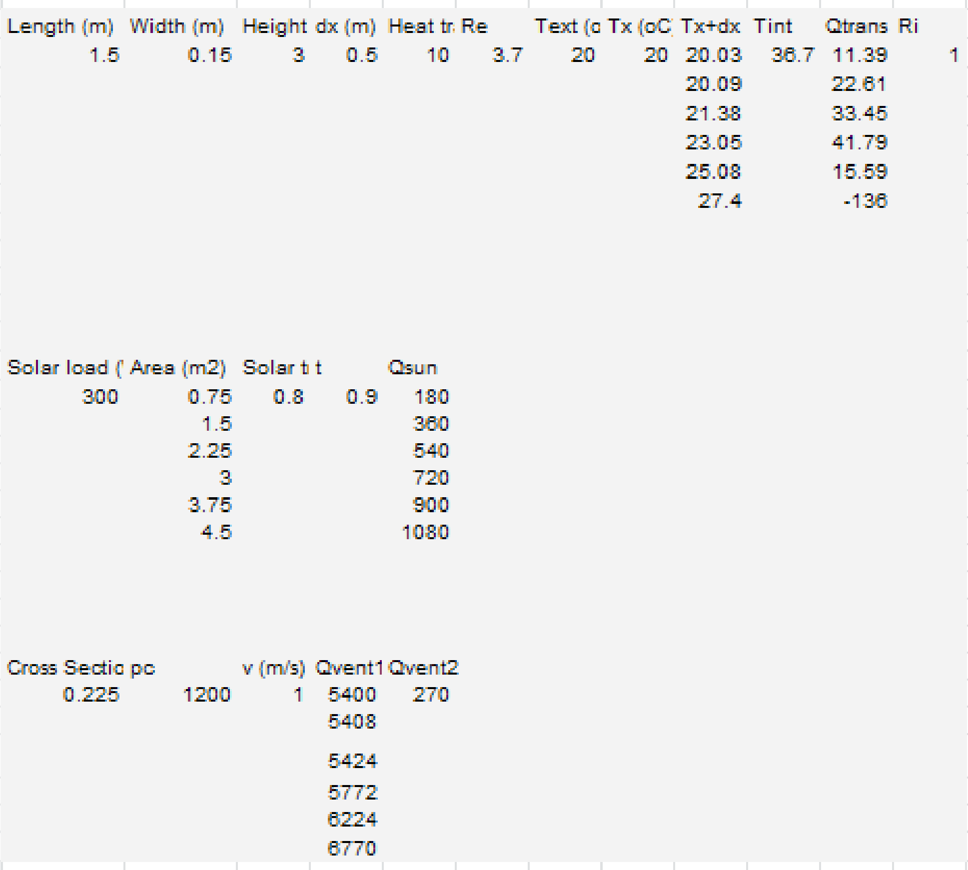
Tx without PCM



Length (m)	Width (m	Height	dx (m)	Heat tr	Re	Text (o	Tx (oC	Tx+dx	Tint	Qtrans	Ri
1.5	0.15	3	0.5	10	3.7	20	20	19.76	25.78	3.94	1
								19.3		9.163	
								19.75		17.5	
								20.34		16.44	
								21.04		15.15	
								21.85		-115	

Solar load (\	Area (m2	Solar t	t	Qsun
100	0.75	0.8	0.9	60
	1.5			120
	2.25			180
	3			240
	3.75			300
	4.5			360

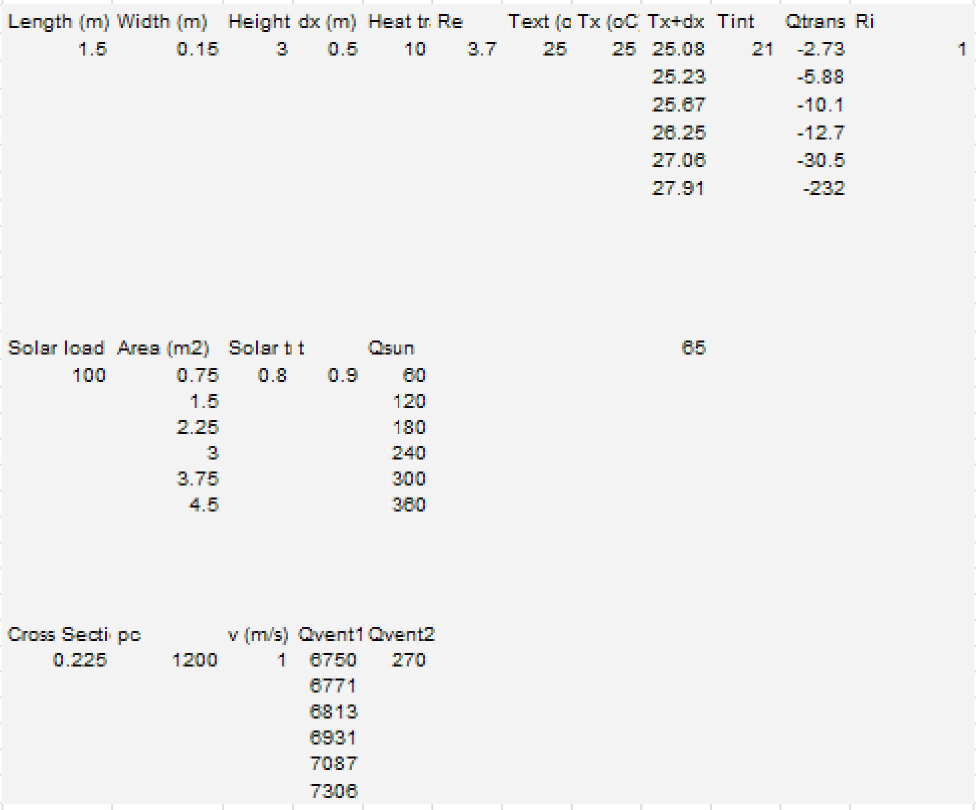
Cross Sectio	pc	v (m/s)	Qvent1	Qvent2
0.225	1200	1	5400	270
			5336	
			5211	
			5333	
			5491	
			5681	



Length (m)	Width (m)	Height	dx (m)	Heat tr	Re	Text (o	Tx (oC	Tx+dx	Tint	Qtrans	Ri
1.5	0.15	3	0.5	10	3.7	20	20	20.03	36.7	11.39	1
								20.09		22.61	
								21.38		33.45	
								23.05		41.79	
								25.08		15.59	
								27.4		-136	

Solar load ('	Area (m2)	Solar t	t	Qsun
300	0.75	0.8	0.9	180
	1.5			360
	2.25			540
	3			720
	3.75			900
	4.5			1080

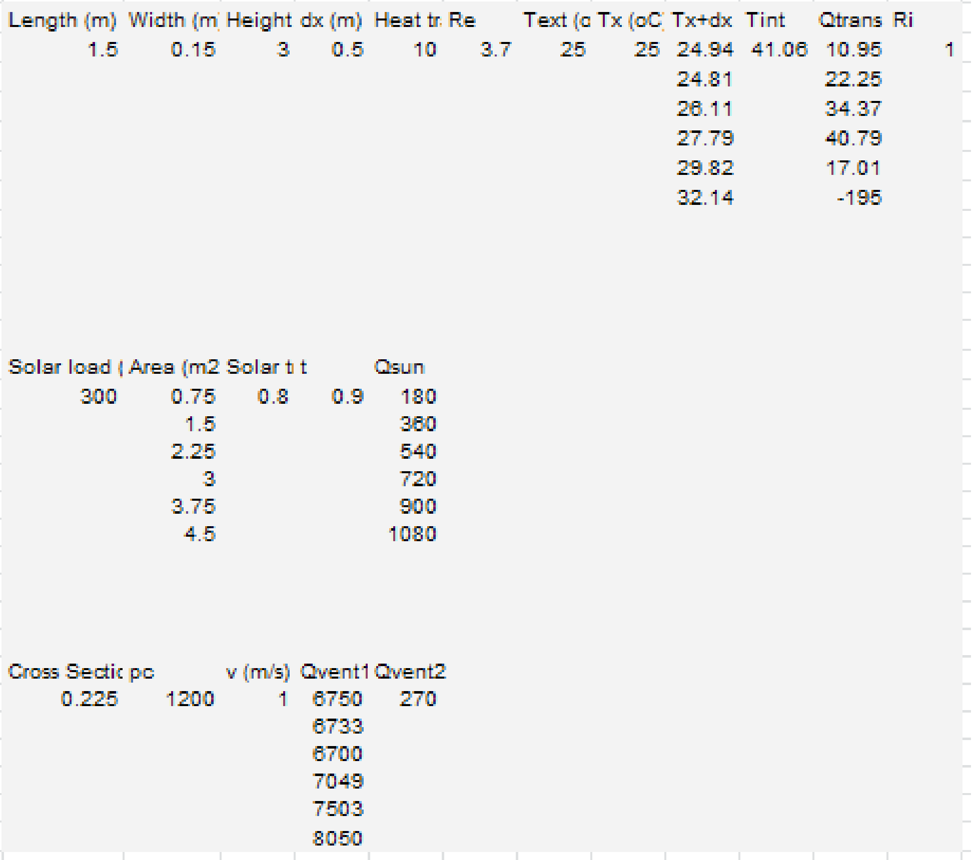
Cross Sectio	pc	v (m/s)	Qvent1	Qvent2
0.225	1200	1	5400	270
			5408	
			5424	
			5772	
			6224	
			6770	



Length (m)	Width (m)	Height	dx (m)	Heat tr	Re	Text (o	Tx (oC	Tx+dx	Tint	Qtrans	Ri
1.5	0.15	3	0.5	10	3.7	25	25	25.08	21	-2.73	1
								25.23		-5.88	
								25.67		-10.1	
								26.25		-12.7	
								27.06		-30.5	
								27.91		-232	

Solar load	Area (m2)	Solar t	t	Qsun				65
100	0.75	0.8	0.9	60				
	1.5			120				
	2.25			180				
	3			240				
	3.75			300				
	4.5			360				

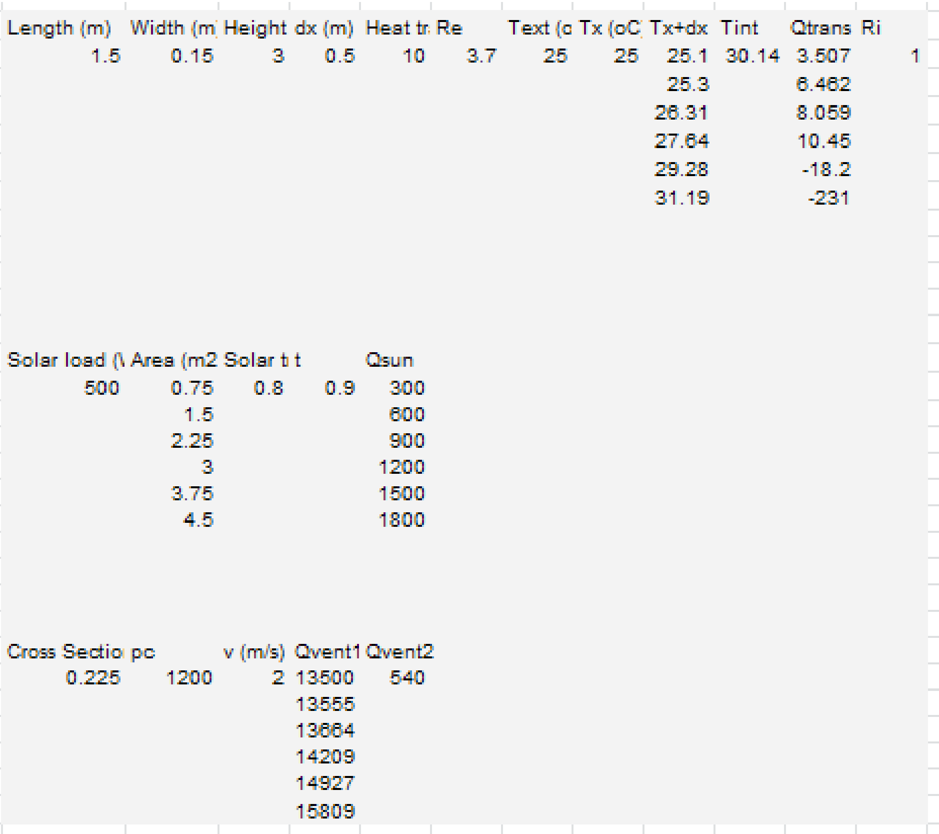
Cross Secti	pc	v (m/s)	Qvent1	Qvent2
0.225	1200	1	6750	270
			6771	
			6813	
			6931	
			7087	
			7306	



Length (m)	Width (m	Height	dx (m)	Heat tr	Re	Text (o	Tx (oC	Tx+dx	Tint	Qtrans	Ri
1.5	0.15	3	0.5	10	3.7	25	25	24.94	41.06	10.95	1
								24.81		22.25	
								26.11		34.37	
								27.79		40.79	
								29.82		17.01	
								32.14		-195	

Solar load (	Area (m2	Solar t	t	Qsun
300	0.75	0.8	0.9	180
	1.5			360
	2.25			540
	3			720
	3.75			900
	4.5			1080

Cross Sectic	pc	v (m/s)	Qvent1	Qvent2
0.225	1200	1	6750	270
			6733	
			6700	
			7049	
			7503	
			8050	



Length (m)	Width (m	Height	dx (m)	Heat tr	Re	Text (o	Tx (oC	Tx+dx	Tint	Qtrans	Ri
1.5	0.15	3	0.5	10	3.7	25	25	25.1	30.14	3.507	1
								25.3		6.462	
								26.31		8.059	
								27.64		10.45	
								29.28		-18.2	
								31.19		-231	

Solar load (\	Area (m2	Solar t	t	Qsun
500	0.75	0.8	0.9	300
	1.5			600
	2.25			900
	3			1200
	3.75			1500
	4.5			1800

Cross Sectio	pc	v (m/s)	Qvent1	Qvent2
0.225	1200	2	13500	540
			13555	
			13664	
			14209	
			14927	
			15809	

Appendix 3

Data Sheet

SP21EK

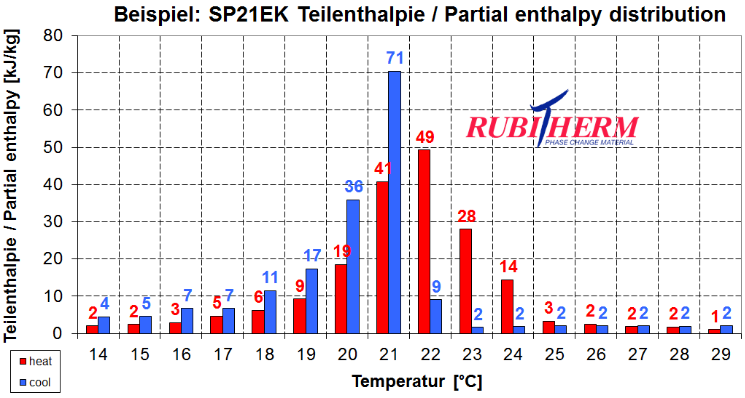
The creation of the latent heat blended material RUBITHERM® SP has led to a new and innovative class of low flammability PCM. RUBITHERM® SP consists of a unique composition of inorganic components.
RUBITHERM® SP is preferably used as macroencapsulated material. Densities of 1,0 kg/l and more can be achieved. This and all properties mentioned below make RUBITHERM® SP to the preferred PCM used in the construction industry. Both passive and active cooling can easily be realized e.g. in wall elements and air conditioners.
We look forward to discussing your particular questions, needs and interests with you.

Properties:
- stable performance throughout the phase change cycles
- high thermal storage capacity per volume
- limited supercooling (2-3K depenndig on volume and cooling rate),
- low flammability, non toxic
- different melting temperatures between -21°C und 70°C are available

The most important data:	**Typical Values**	
Melting area	**22-23** main peak: 22	**[°C]**
Congealing area	**21-19** main peak: 21	**[°C]**
Heat storage capacity ± 7,5%	**170**	**[kJ/kg]**
Combination of sensible and latent heat in a temperatur range of °C to 13 °C. 28	**47**	**[Wh/kg]***
Specific heat capacity	**2**	**[kJ/kg·K]***
Density solid at 15 °C	**1,5**	**[kg/l]**
Density liquid at 35 °C	**1,4**	**[kg/l]**
Volume expansion	**3-4**	**[%]**
Heat conductivity	**0,6**	**[W/(m·K)]**
Max. operation temperature	**45**	**[°C]**
Corrosion	**corrosive effect on metals**	

Attention

Note: The product must be initialized (melt, homogenize and cool to 0 ° C) once before use to achieve the specified properties.
Many SP-product are hygroscopic and may absorb moisture if stored improperly. This can result in a change of the physical properties given.



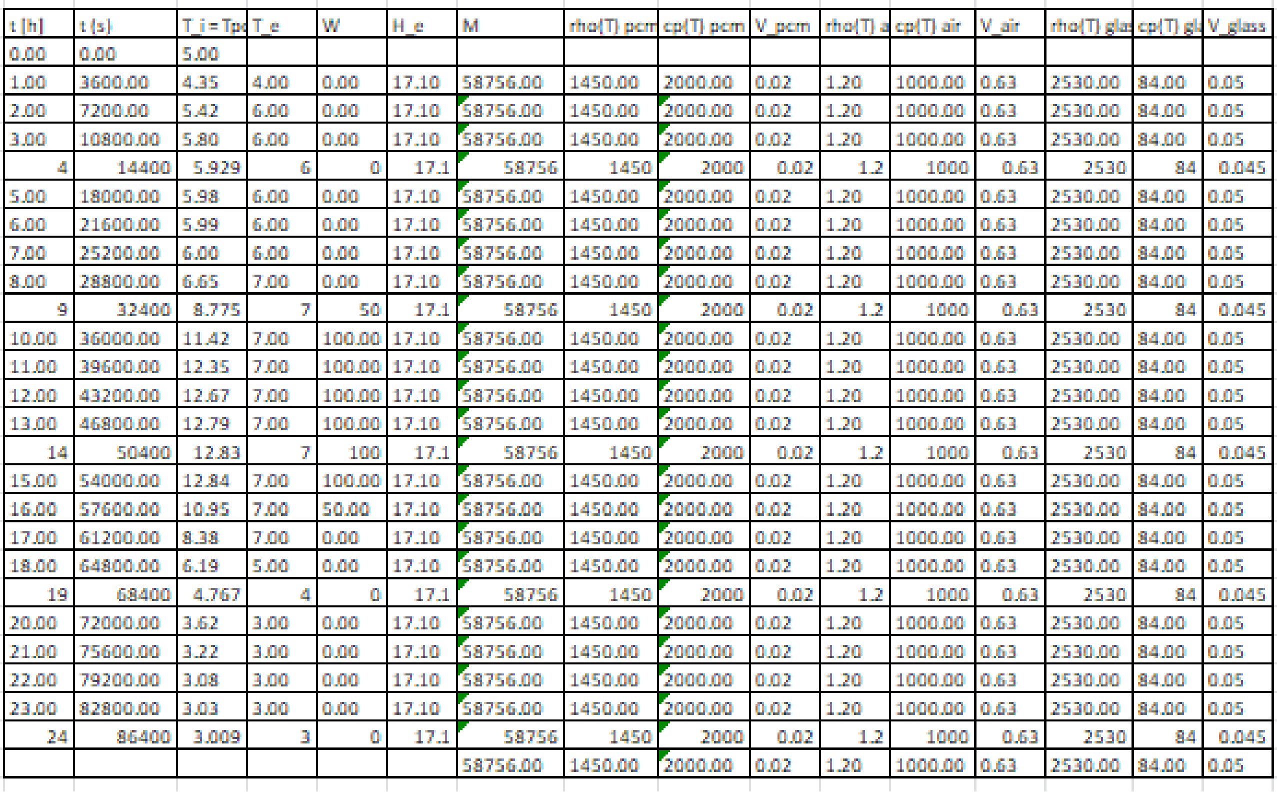
*Measured with 3-layer-calorimeter.

Rubitherm Technologies GmbH
Sperenberger Str. 5a
D-12277 Berlin
Tel: +49 30 720004-62
Fax: +49 30 720004-99
E-Mail: info@rubitherm.com
Internet: www.rubitherm.com

The product information given is a non-binding planning aid, subject to technical changes without notice. Version: 30.09.2016

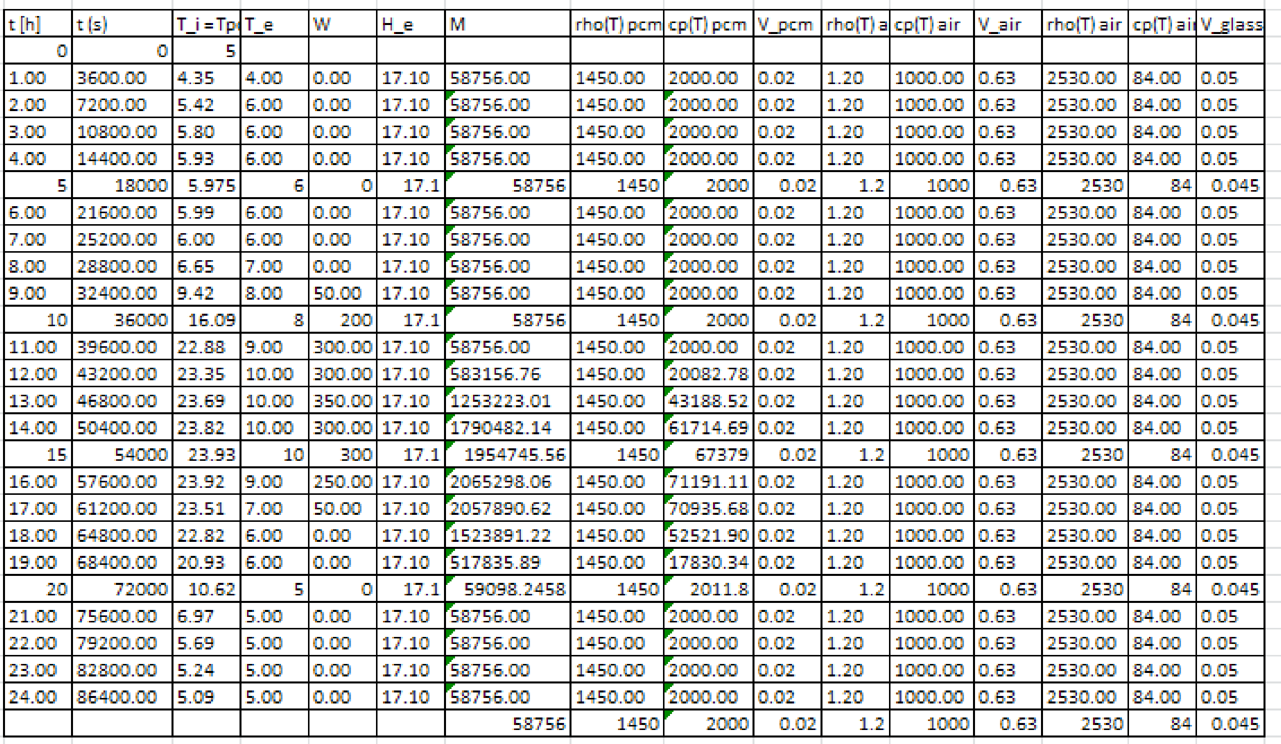
Appendix 3
PCM 0.02 m³

Winter cloudy day



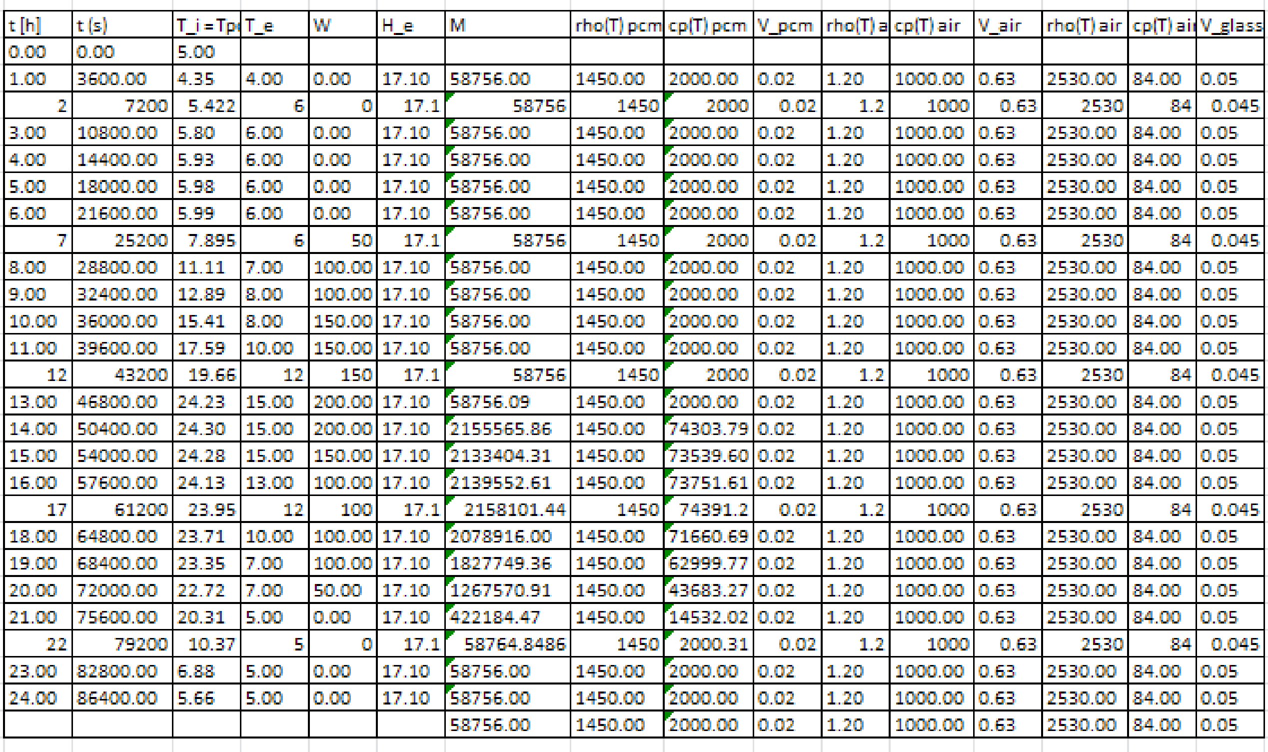
t [h]	t (s)	T_i = Tp	T_e	W	H_e	M	rho(T) pcm	cp(T) pcm	V_pcm	rho(T) a	cp(T) air	V_air	rho(T) glas	cp(T) gl	V_glass
0.00	0.00	5.00													
1.00	3600.00	4.35	4.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
2.00	7200.00	5.42	6.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
3.00	10800.00	5.80	6.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
4	14400	5.929	6	0	17.1	58756	1450	2000	0.02	1.2	1000	0.63	2530	84	0.045
5.00	18000.00	5.98	6.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
6.00	21600.00	5.99	6.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
7.00	25200.00	6.00	6.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
8.00	28800.00	6.65	7.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
9	32400	8.775	7	50	17.1	58756	1450	2000	0.02	1.2	1000	0.63	2530	84	0.045
10.00	36000.00	11.42	7.00	100.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
11.00	39600.00	12.35	7.00	100.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
12.00	43200.00	12.67	7.00	100.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
13.00	46800.00	12.79	7.00	100.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
14	50400	12.83	7	100	17.1	58756	1450	2000	0.02	1.2	1000	0.63	2530	84	0.045
15.00	54000.00	12.84	7.00	100.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
16.00	57600.00	10.95	7.00	50.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
17.00	61200.00	8.38	7.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
18.00	64800.00	6.19	5.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
19	68400	4.767	4	0	17.1	58756	1450	2000	0.02	1.2	1000	0.63	2530	84	0.045
20.00	72000.00	3.62	3.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
21.00	75600.00	3.22	3.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
22.00	79200.00	3.08	3.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
23.00	82800.00	3.03	3.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
24	86400	3.009	3	0	17.1	58756	1450	2000	0.02	1.2	1000	0.63	2530	84	0.045
						58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05

Winter sunny day



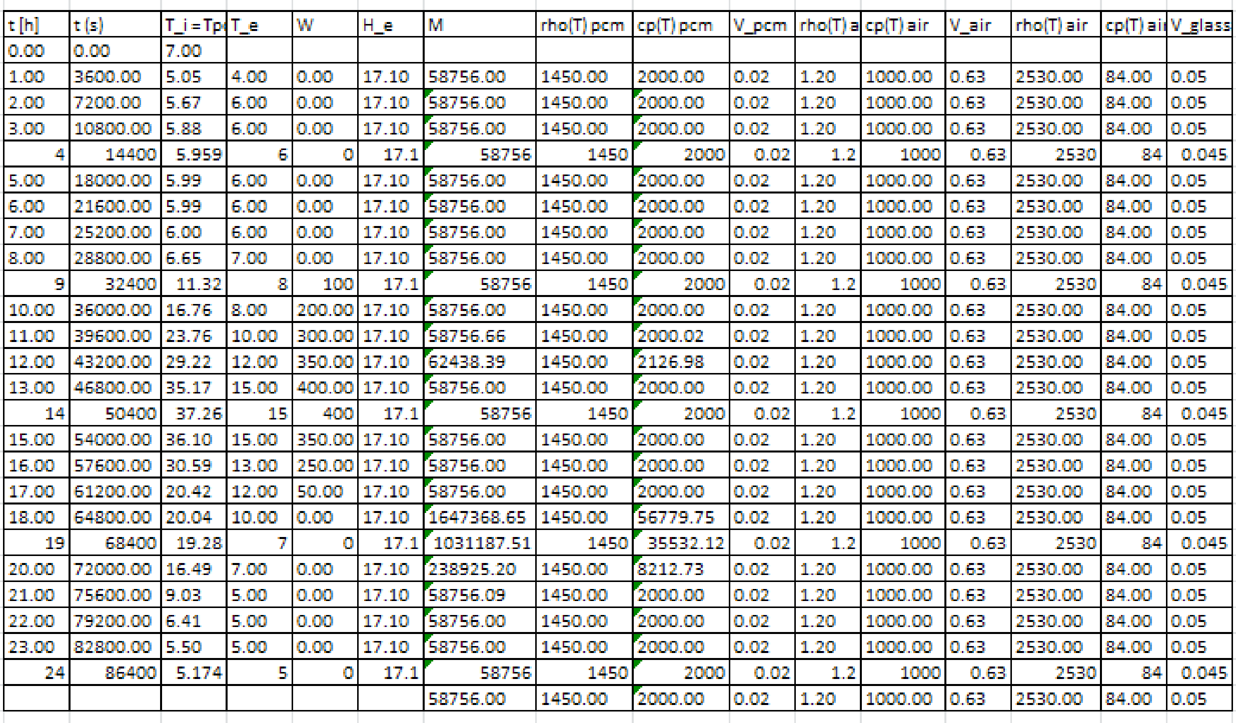
t [h]	t (s)	T_i = Tp	T_e	W	H_e	M	rho(T) pcm	cp(T) pcm	V_pcm	rho(T) a	cp(T) air	V_air	rho(T) air	cp(T) ai	V_glass
0	0	5													
1.00	3600.00	4.35	4.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
2.00	7200.00	5.42	6.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
3.00	10800.00	5.80	6.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
4.00	14400.00	5.93	6.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
5	18000	5.975	6	0	17.1	58756	1450	2000	0.02	1.2	1000	0.63	2530	84	0.045
6.00	21600.00	5.99	6.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
7.00	25200.00	6.00	6.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
8.00	28800.00	6.65	7.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
9.00	32400.00	9.42	8.00	50.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
10	36000	16.09	8	200	17.1	58756	1450	2000	0.02	1.2	1000	0.63	2530	84	0.045
11.00	39600.00	22.88	9.00	300.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
12.00	43200.00	23.35	10.00	300.00	17.10	583156.76	1450.00	20082.78	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
13.00	46800.00	23.69	10.00	350.00	17.10	1253223.01	1450.00	43188.52	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
14.00	50400.00	23.82	10.00	300.00	17.10	1790482.14	1450.00	61714.69	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
15	54000	23.93	10	300	17.1	1954745.56	1450	67379	0.02	1.2	1000	0.63	2530	84	0.045
16.00	57600.00	23.92	9.00	250.00	17.10	2065298.06	1450.00	71191.11	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
17.00	61200.00	23.51	7.00	50.00	17.10	2057890.62	1450.00	70935.68	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
18.00	64800.00	22.82	6.00	0.00	17.10	1523891.22	1450.00	52521.90	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
19.00	68400.00	20.93	6.00	0.00	17.10	517835.89	1450.00	17830.34	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
20	72000	10.62	5	0	17.1	59098.2458	1450	2011.8	0.02	1.2	1000	0.63	2530	84	0.045
21.00	75600.00	6.97	5.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
22.00	79200.00	5.69	5.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
23.00	82800.00	5.24	5.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
24.00	86400.00	5.09	5.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
						58756	1450	2000	0.02	1.2	1000	0.63	2530	84	0.045

Spring/autumn cloudy day



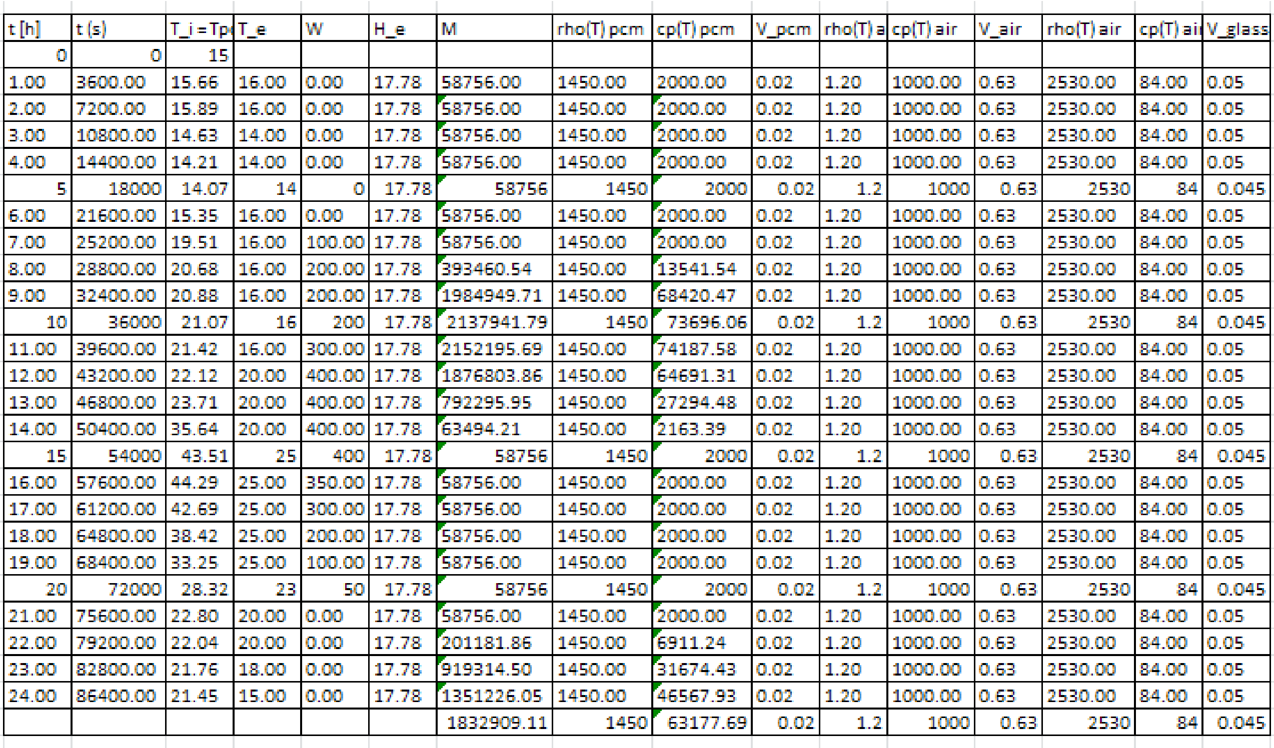
t [h]	t (s)	T_i = Tp	T_e	W	H_e	M	rho(T) pcm	cp(T) pcm	V_pcm	rho(T) a	cp(T) air	V_air	rho(T) air	cp(T) ai	V_glass
0.00	0.00	5.00													
1.00	3600.00	4.35	4.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
2	7200	5.422	6	0	17.1	58756	1450	2000	0.02	1.2	1000	0.63	2530	84	0.045
3.00	10800.00	5.80	6.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
4.00	14400.00	5.93	6.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
5.00	18000.00	5.98	6.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
6.00	21600.00	5.99	6.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
7	25200	7.895	6	50	17.1	58756	1450	2000	0.02	1.2	1000	0.63	2530	84	0.045
8.00	28800.00	11.11	7.00	100.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
9.00	32400.00	12.89	8.00	100.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
10.00	36000.00	15.41	8.00	150.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
11.00	39600.00	17.59	10.00	150.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
12	43200	19.66	12	150	17.1	58756	1450	2000	0.02	1.2	1000	0.63	2530	84	0.045
13.00	46800.00	24.23	15.00	200.00	17.10	58756.09	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
14.00	50400.00	24.30	15.00	200.00	17.10	2155565.86	1450.00	74303.79	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
15.00	54000.00	24.28	15.00	150.00	17.10	2133404.31	1450.00	73539.60	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
16.00	57600.00	24.13	13.00	100.00	17.10	2139552.61	1450.00	73751.61	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
17	61200	23.95	12	100	17.1	2158101.44	1450	74391.2	0.02	1.2	1000	0.63	2530	84	0.045
18.00	64800.00	23.71	10.00	100.00	17.10	2078916.00	1450.00	71660.69	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
19.00	68400.00	23.35	7.00	100.00	17.10	1827749.36	1450.00	62999.77	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
20.00	72000.00	22.72	7.00	50.00	17.10	1267570.91	1450.00	43683.27	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
21.00	75600.00	20.31	5.00	0.00	17.10	422184.47	1450.00	14532.02	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
22	79200	10.37	5	0	17.1	58764.8486	1450	2000.31	0.02	1.2	1000	0.63	2530	84	0.045
23.00	82800.00	6.88	5.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
24.00	86400.00	5.66	5.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
						58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05

Spring/autumn sunny day



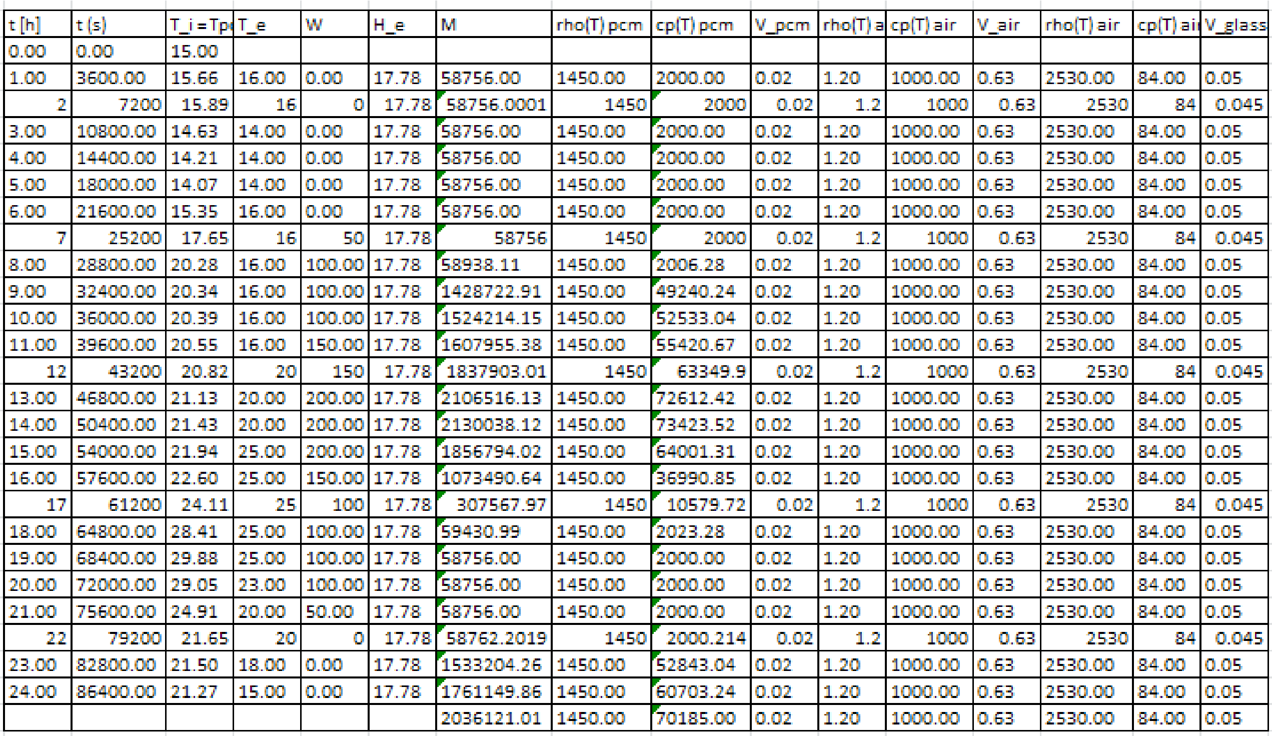
t [h]	t (s)	T_i = Tp	T_e	W	H_e	M	rho(T) pcm	cp(T) pcm	V_pcm	rho(T) a	cp(T) air	V_air	rho(T) air	cp(T) ai	V_glass
0.00	0.00	7.00													
1.00	3600.00	5.05	4.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
2.00	7200.00	5.67	6.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
3.00	10800.00	5.88	6.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
4	14400	5.959	6	0	17.1	58756	1450	2000	0.02	1.2	1000	0.63	2530	84	0.045
5.00	18000.00	5.99	6.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
6.00	21600.00	5.99	6.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
7.00	25200.00	6.00	6.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
8.00	28800.00	6.65	7.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
9	32400	11.32	8	100	17.1	58756	1450	2000	0.02	1.2	1000	0.63	2530	84	0.045
10.00	36000.00	16.76	8.00	200.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
11.00	39600.00	23.76	10.00	300.00	17.10	58756.66	1450.00	2000.02	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
12.00	43200.00	29.22	12.00	350.00	17.10	62438.39	1450.00	2126.98	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
13.00	46800.00	35.17	15.00	400.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
14	50400	37.26	15	400	17.1	58756	1450	2000	0.02	1.2	1000	0.63	2530	84	0.045
15.00	54000.00	36.10	15.00	350.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
16.00	57600.00	30.59	13.00	250.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
17.00	61200.00	20.42	12.00	50.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
18.00	64800.00	20.04	10.00	0.00	17.10	1647368.65	1450.00	56779.75	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
19	68400	19.28	7	0	17.1	1031187.51	1450	35532.12	0.02	1.2	1000	0.63	2530	84	0.045
20.00	72000.00	16.49	7.00	0.00	17.10	238925.20	1450.00	8212.73	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
21.00	75600.00	9.03	5.00	0.00	17.10	58756.09	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
22.00	79200.00	6.41	5.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
23.00	82800.00	5.50	5.00	0.00	17.10	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
24	86400	5.174	5	0	17.1	58756	1450	2000	0.02	1.2	1000	0.63	2530	84	0.045
						58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05

Summer cloudy day



t [h]	t (s)	T_i = Tp	T_e	W	H_e	M	rho(T) pcm	cp(T) pcm	V_pcm	rho(T) a	cp(T) air	V_air	rho(T) air	cp(T) ai	V_glass
0	0	15													
1.00	3600.00	15.66	16.00	0.00	17.78	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
2.00	7200.00	15.89	16.00	0.00	17.78	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
3.00	10800.00	14.63	14.00	0.00	17.78	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
4.00	14400.00	14.21	14.00	0.00	17.78	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
5	18000	14.07	14	0	17.78	58756	1450	2000	0.02	1.2	1000	0.63	2530	84	0.045
6.00	21600.00	15.35	16.00	0.00	17.78	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
7.00	25200.00	19.51	16.00	100.00	17.78	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
8.00	28800.00	20.68	16.00	200.00	17.78	393460.54	1450.00	13541.54	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
9.00	32400.00	20.88	16.00	200.00	17.78	1984949.71	1450.00	68420.47	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
10	36000	21.07	16	200	17.78	2137941.79	1450	73696.06	0.02	1.2	1000	0.63	2530	84	0.045
11.00	39600.00	21.42	16.00	300.00	17.78	2152195.69	1450.00	74187.58	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
12.00	43200.00	22.12	20.00	400.00	17.78	1876803.86	1450.00	64691.31	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
13.00	46800.00	23.71	20.00	400.00	17.78	792295.95	1450.00	27294.48	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
14.00	50400.00	35.64	20.00	400.00	17.78	63494.21	1450.00	2163.39	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
15	54000	43.51	25	400	17.78	58756	1450	2000	0.02	1.2	1000	0.63	2530	84	0.045
16.00	57600.00	44.29	25.00	350.00	17.78	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
17.00	61200.00	42.69	25.00	300.00	17.78	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
18.00	64800.00	38.42	25.00	200.00	17.78	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
19.00	68400.00	33.25	25.00	100.00	17.78	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
20	72000	28.32	23	50	17.78	58756	1450	2000	0.02	1.2	1000	0.63	2530	84	0.045
21.00	75600.00	22.80	20.00	0.00	17.78	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
22.00	79200.00	22.04	20.00	0.00	17.78	201181.86	1450.00	6911.24	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
23.00	82800.00	21.76	18.00	0.00	17.78	919314.50	1450.00	31674.43	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
24.00	86400.00	21.45	15.00	0.00	17.78	1351226.05	1450.00	46567.93	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
						1832909.11	1450	63177.69	0.02	1.2	1000	0.63	2530	84	0.045

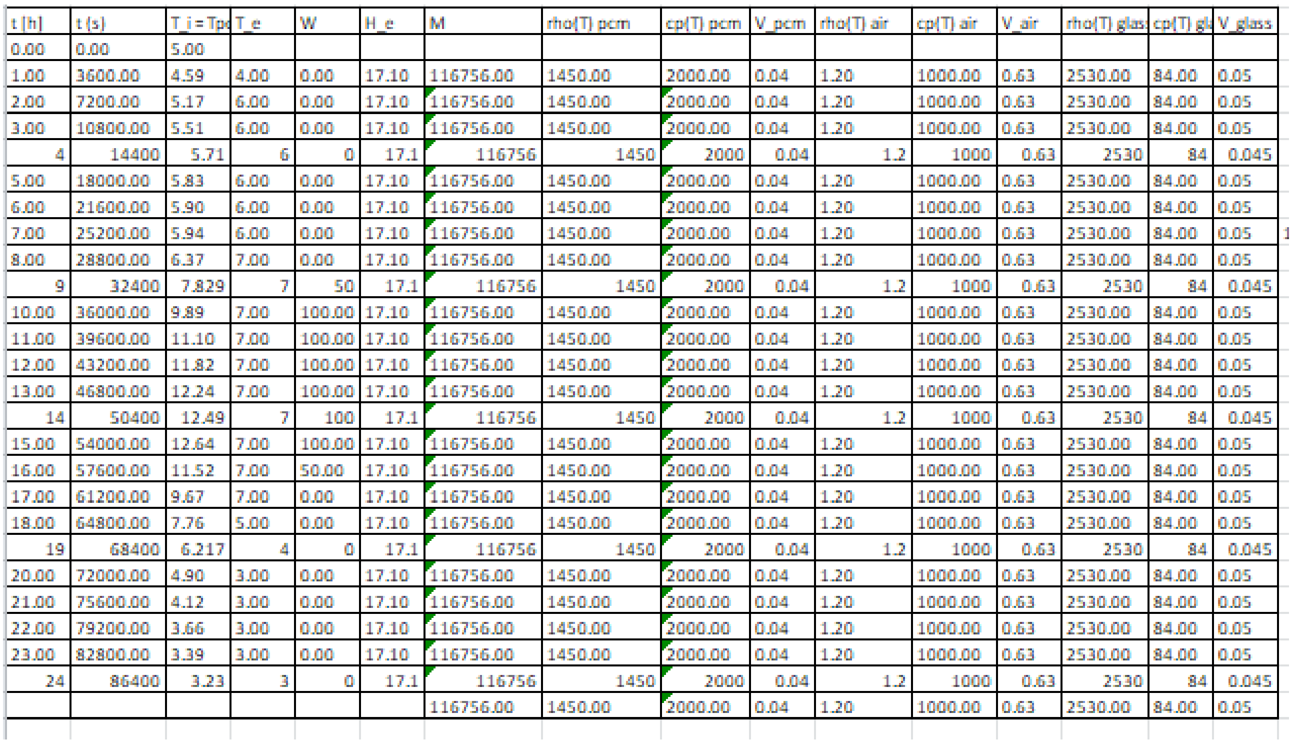
Summer sunny day



t [h]	t (s)	T_i = Tp	T_e	W	H_e	M	rho(T) pcm	cp(T) pcm	V_pcm	rho(T) a	cp(T) air	V_air	rho(T) air	cp(T) ai	V_glass
0.00	0.00	15.00													
1.00	3600.00	15.66	16.00	0.00	17.78	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
2	7200	15.89	16	0	17.78	58756.0001	1450	2000	0.02	1.2	1000	0.63	2530	84	0.045
3.00	10800.00	14.63	14.00	0.00	17.78	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
4.00	14400.00	14.21	14.00	0.00	17.78	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
5.00	18000.00	14.07	14.00	0.00	17.78	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
6.00	21600.00	15.35	16.00	0.00	17.78	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
7	25200	17.65	16	50	17.78	58756	1450	2000	0.02	1.2	1000	0.63	2530	84	0.045
8.00	28800.00	20.28	16.00	100.00	17.78	58938.11	1450.00	2006.28	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
9.00	32400.00	20.34	16.00	100.00	17.78	1428722.91	1450.00	49240.24	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
10.00	36000.00	20.39	16.00	100.00	17.78	1524214.15	1450.00	52533.04	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
11.00	39600.00	20.55	16.00	150.00	17.78	1607955.38	1450.00	55420.67	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
12	43200	20.82	20	150	17.78	1837903.01	1450	63349.9	0.02	1.2	1000	0.63	2530	84	0.045
13.00	46800.00	21.13	20.00	200.00	17.78	2106516.13	1450.00	72612.42	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
14.00	50400.00	21.43	20.00	200.00	17.78	2130038.12	1450.00	73423.52	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
15.00	54000.00	21.94	25.00	200.00	17.78	1856794.02	1450.00	64001.31	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
16.00	57600.00	22.60	25.00	150.00	17.78	1073490.64	1450.00	36990.85	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
17	61200	24.11	25	100	17.78	307567.97	1450	10579.72	0.02	1.2	1000	0.63	2530	84	0.045
18.00	64800.00	28.41	25.00	100.00	17.78	59430.99	1450.00	2023.28	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
19.00	68400.00	29.88	25.00	100.00	17.78	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
20.00	72000.00	29.05	23.00	100.00	17.78	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
21.00	75600.00	24.91	20.00	50.00	17.78	58756.00	1450.00	2000.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
22	79200	21.65	20	0	17.78	58762.2019	1450	2000.214	0.02	1.2	1000	0.63	2530	84	0.045
23.00	82800.00	21.50	18.00	0.00	17.78	1533204.26	1450.00	52843.04	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
24.00	86400.00	21.27	15.00	0.00	17.78	1761149.86	1450.00	60703.24	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05
						2036121.01	1450.00	70185.00	0.02	1.20	1000.00	0.63	2530.00	84.00	0.05

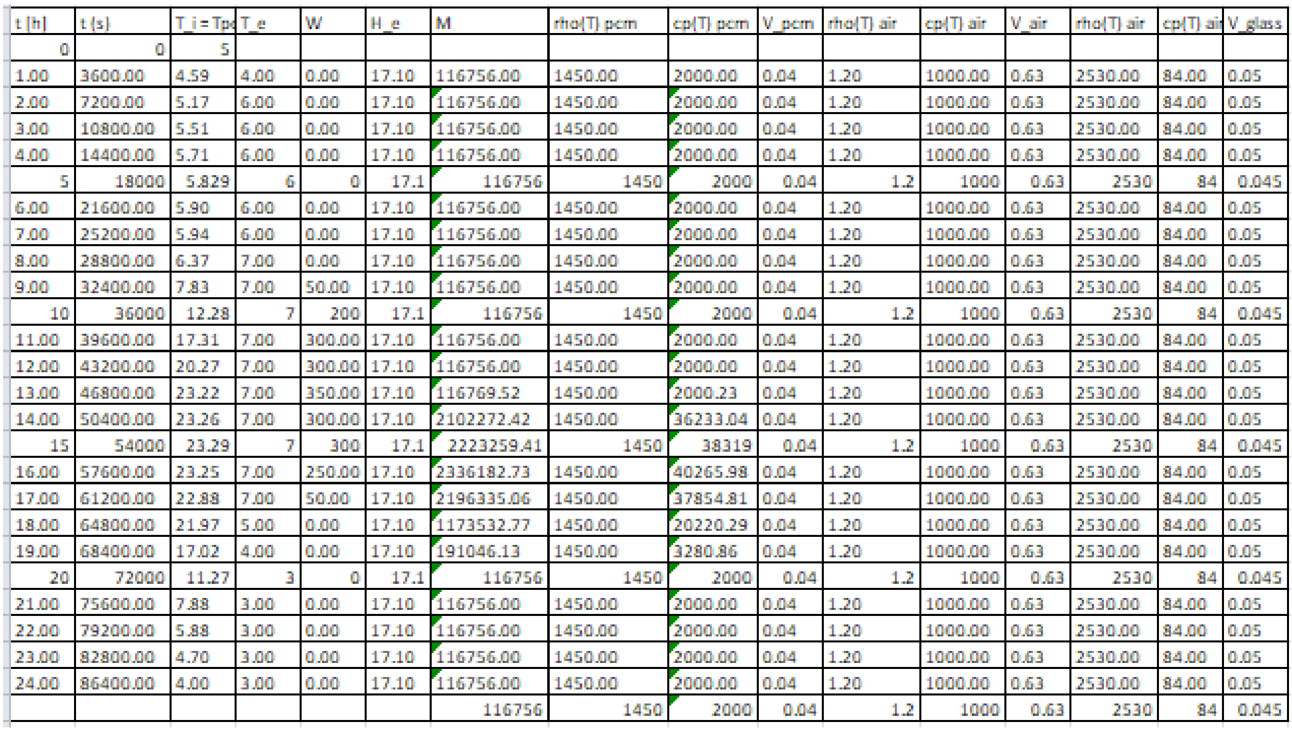
PCM 0.04 m^3

Winter cloudy day



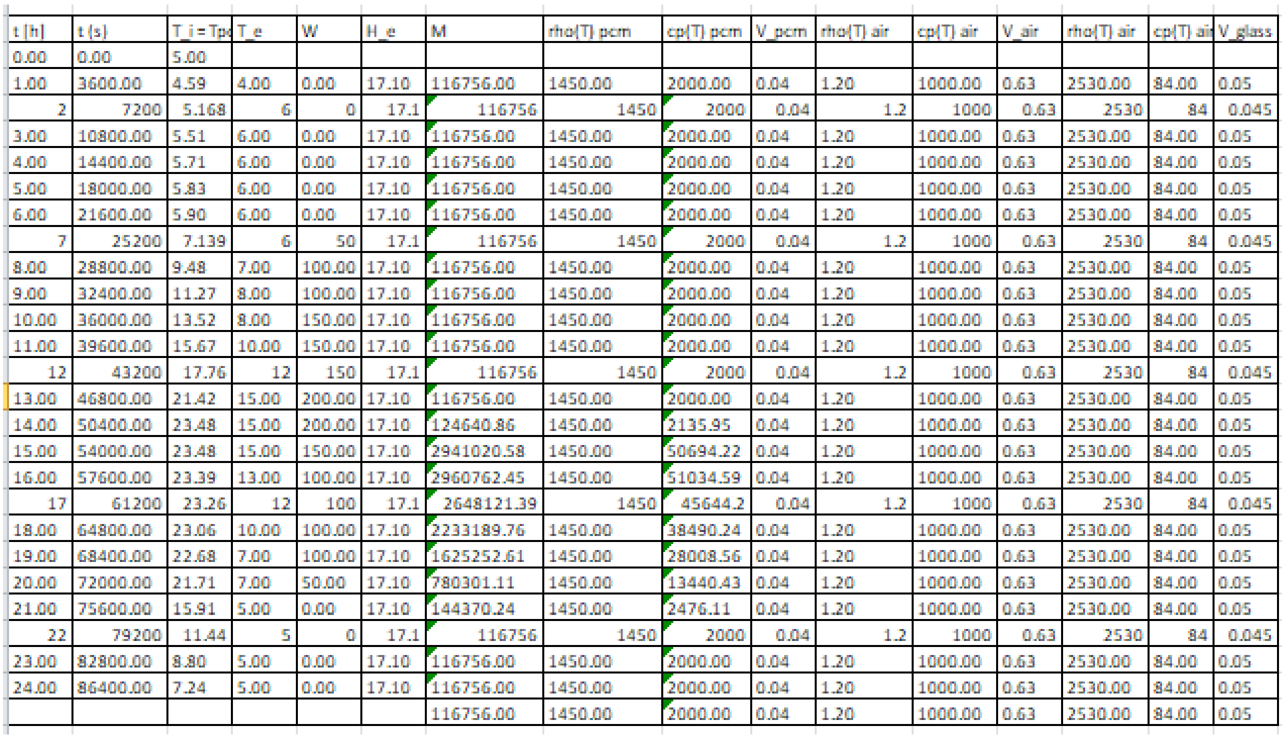
t [h]	t (s)	T_i = Tp	T_e	W	H_e	M	rho(T) pcm	cp(T) pcm	V_pcm	rho(T) air	cp(T) air	V_air	rho(T) glas	cp(T) gl	V_glass
0.00	0.00	5.00													
1.00	3600.00	4.59	4.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
2.00	7200.00	5.17	6.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
3.00	10800.00	5.51	6.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
4	14400	5.71	6	0	17.1	116756	1450	2000	0.04	1.2	1000	0.63	2530	84	0.045
5.00	18000.00	5.83	6.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
6.00	21600.00	5.90	6.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
7.00	25200.00	5.94	6.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
8.00	28800.00	6.37	7.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
9	32400	7.829	7	50	17.1	116756	1450	2000	0.04	1.2	1000	0.63	2530	84	0.045
10.00	36000.00	9.89	7.00	100.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
11.00	39600.00	11.10	7.00	100.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
12.00	43200.00	11.82	7.00	100.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
13.00	46800.00	12.24	7.00	100.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
14	50400	12.49	7	100	17.1	116756	1450	2000	0.04	1.2	1000	0.63	2530	84	0.045
15.00	54000.00	12.64	7.00	100.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
16.00	57600.00	11.52	7.00	50.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
17.00	61200.00	9.67	7.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
18.00	64800.00	7.76	5.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
19	68400	6.217	4	0	17.1	116756	1450	2000	0.04	1.2	1000	0.63	2530	84	0.045
20.00	72000.00	4.90	3.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
21.00	75600.00	4.12	3.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
22.00	79200.00	3.66	3.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
23.00	82800.00	3.39	3.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
24	86400	3.23	3	0	17.1	116756	1450	2000	0.04	1.2	1000	0.63	2530	84	0.045
						116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05

Winter sunny day



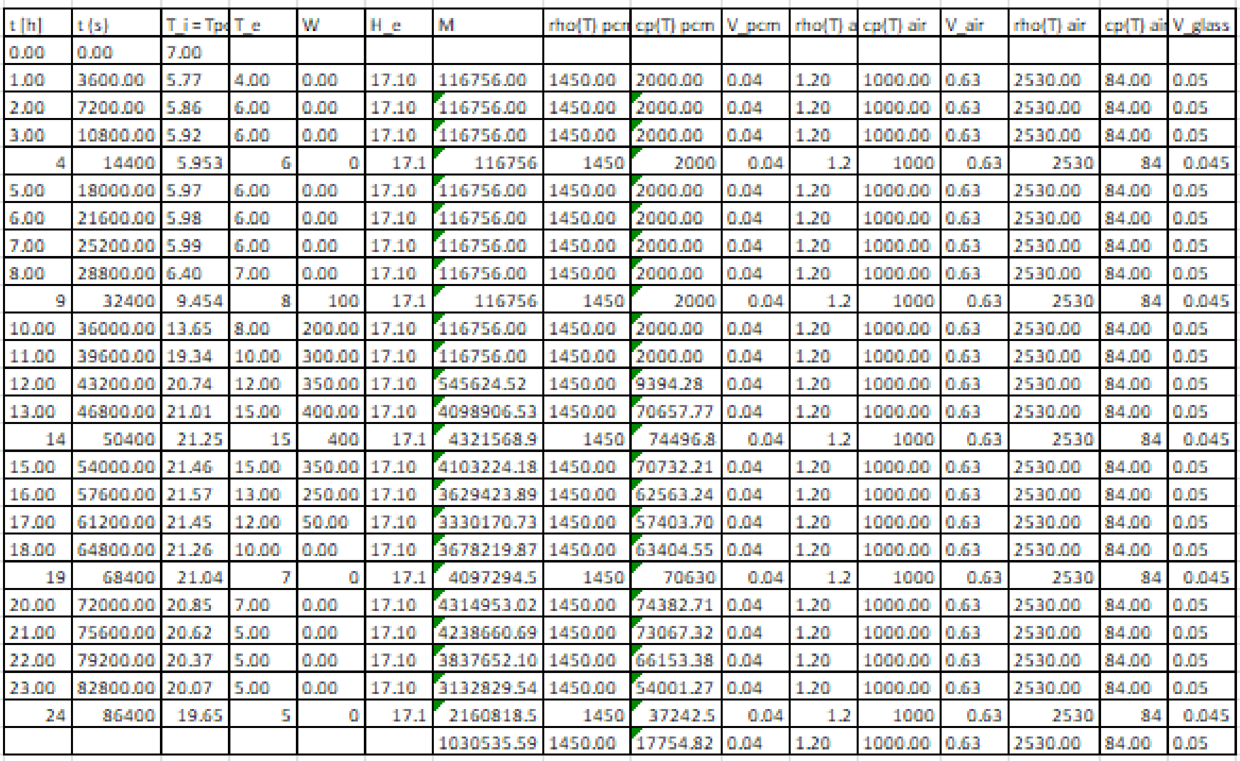
t [h]	t (s)	T_i = Tp	T_e	W	H_e	M	rho(T) pcm	cp(T) pcm	V_pcm	rho(T) air	cp(T) air	V_air	rho(T) air	cp(T) ai	V_glass
0	0	5													
1.00	3600.00	4.59	4.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
2.00	7200.00	5.17	6.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
3.00	10800.00	5.51	6.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
4.00	14400.00	5.71	6.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
5	18000	5.829	6	0	17.1	116756	1450	2000	0.04	1.2	1000	0.63	2530	84	0.045
6.00	21600.00	5.90	6.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
7.00	25200.00	5.94	6.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
8.00	28800.00	6.37	7.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
9.00	32400.00	7.83	7.00	50.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
10	36000	12.28	7	200	17.1	116756	1450	2000	0.04	1.2	1000	0.63	2530	84	0.045
11.00	39600.00	17.31	7.00	300.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
12.00	43200.00	20.27	7.00	300.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
13.00	46800.00	23.22	7.00	350.00	17.10	116769.52	1450.00	2000.23	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
14.00	50400.00	23.26	7.00	300.00	17.10	2102272.42	1450.00	36233.04	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
15	54000	23.29	7	300	17.1	2223259.41	1450	38319	0.04	1.2	1000	0.63	2530	84	0.045
16.00	57600.00	23.25	7.00	250.00	17.10	2336182.73	1450.00	40265.98	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
17.00	61200.00	22.88	7.00	50.00	17.10	2196335.06	1450.00	37854.81	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
18.00	64800.00	21.97	5.00	0.00	17.10	1173532.77	1450.00	20220.29	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
19.00	68400.00	17.02	4.00	0.00	17.10	191046.13	1450.00	3280.86	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
20	72000	11.27	3	0	17.1	116756	1450	2000	0.04	1.2	1000	0.63	2530	84	0.045
21.00	75600.00	7.88	3.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
22.00	79200.00	5.88	3.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
23.00	82800.00	4.70	3.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
24.00	86400.00	4.00	3.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
						116756	1450	2000	0.04	1.2	1000	0.63	2530	84	0.045

Spring/autumn cloudy day



t [h]	t (s)	T_i = Tp	T_e	W	H_e	M	rho(T) pcm	cp(T) pcm	V_pcm	rho(T) air	cp(T) air	V_air	rho(T) air	cp(T) ai	V_glass
0.00	0.00	5.00													
1.00	3600.00	4.59	4.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
2	7200	5.168	6	0	17.1	116756	1450	2000	0.04	1.2	1000	0.63	2530	84	0.045
3.00	10800.00	5.51	6.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
4.00	14400.00	5.71	6.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
5.00	18000.00	5.83	6.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
6.00	21600.00	5.90	6.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
7	25200	7.139	6	50	17.1	116756	1450	2000	0.04	1.2	1000	0.63	2530	84	0.045
8.00	28800.00	9.48	7.00	100.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
9.00	32400.00	11.27	8.00	100.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
10.00	36000.00	13.52	8.00	150.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
11.00	39600.00	15.67	10.00	150.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
12	43200	17.76	12	150	17.1	116756	1450	2000	0.04	1.2	1000	0.63	2530	84	0.045
13.00	46800.00	21.42	15.00	200.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
14.00	50400.00	23.48	15.00	200.00	17.10	124640.86	1450.00	2135.95	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
15.00	54000.00	23.48	15.00	150.00	17.10	2941020.58	1450.00	50694.22	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
16.00	57600.00	23.39	13.00	100.00	17.10	2960762.45	1450.00	51034.59	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
17	61200	23.26	12	100	17.1	2648121.39	1450	45644.2	0.04	1.2	1000	0.63	2530	84	0.045
18.00	64800.00	23.06	10.00	100.00	17.10	2233189.76	1450.00	38490.24	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
19.00	68400.00	22.68	7.00	100.00	17.10	1625252.61	1450.00	28008.56	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
20.00	72000.00	21.71	7.00	50.00	17.10	780301.11	1450.00	13440.43	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
21.00	75600.00	15.91	5.00	0.00	17.10	144370.24	1450.00	2476.11	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
22	79200	11.44	5	0	17.1	116756	1450	2000	0.04	1.2	1000	0.63	2530	84	0.045
23.00	82800.00	8.80	5.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
24.00	86400.00	7.24	5.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
						116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05

Spring/autumn sunny day



t [h]	t (s)	T_i = Tp	T_e	W	H_e	M	rho(T) pcr	cp(T) pcm	V_pcm	rho(T) a	cp(T) air	V_air	rho(T) air	cp(T) ai	V_glass
0.00	0.00	7.00													
1.00	3600.00	5.77	4.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
2.00	7200.00	5.86	6.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
3.00	10800.00	5.92	6.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
4	14400	5.953	6	0	17.1	116756	1450	2000	0.04	1.2	1000	0.63	2530	84	0.045
5.00	18000.00	5.97	6.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
6.00	21600.00	5.98	6.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
7.00	25200.00	5.99	6.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
8.00	28800.00	6.40	7.00	0.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
9	32400	9.454	8	100	17.1	116756	1450	2000	0.04	1.2	1000	0.63	2530	84	0.045
10.00	36000.00	13.65	8.00	200.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
11.00	39600.00	19.34	10.00	300.00	17.10	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
12.00	43200.00	20.74	12.00	350.00	17.10	545624.52	1450.00	9394.28	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
13.00	46800.00	21.01	15.00	400.00	17.10	4098906.53	1450.00	70657.77	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
14	50400	21.25	15	400	17.1	4321568.9	1450	74496.8	0.04	1.2	1000	0.63	2530	84	0.045
15.00	54000.00	21.46	15.00	350.00	17.10	4103224.18	1450.00	70732.21	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
16.00	57600.00	21.57	13.00	250.00	17.10	3629423.89	1450.00	62563.24	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
17.00	61200.00	21.45	12.00	50.00	17.10	3330170.73	1450.00	57403.70	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
18.00	64800.00	21.26	10.00	0.00	17.10	3678219.87	1450.00	63404.55	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
19	68400	21.04	7	0	17.1	4097294.5	1450	70630	0.04	1.2	1000	0.63	2530	84	0.045
20.00	72000.00	20.85	7.00	0.00	17.10	4314953.02	1450.00	74382.71	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
21.00	75600.00	20.62	5.00	0.00	17.10	4238660.69	1450.00	73067.32	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
22.00	79200.00	20.37	5.00	0.00	17.10	3837652.10	1450.00	66153.38	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
23.00	82800.00	20.07	5.00	0.00	17.10	3132829.54	1450.00	54001.27	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
24	86400	19.65	5	0	17.1	2160818.5	1450	37242.5	0.04	1.2	1000	0.63	2530	84	0.045
						1030535.59	1450.00	17754.82	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05

Summer cloudy day

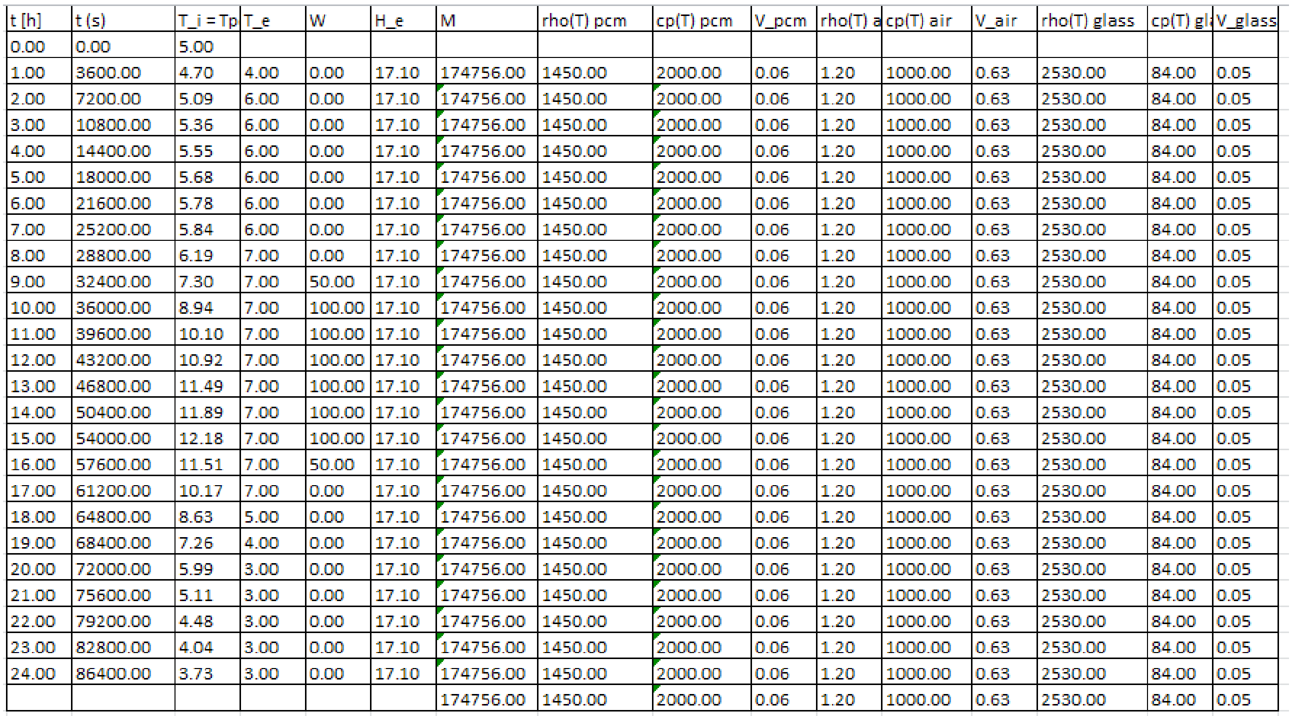
t [h]	t (s)	T_i = Tp	T_e	W	H_e	M	rho(T) pc	cp(T) pcm	V_pcm	rho(T) a	cp(T) air	V_air	rho(T) air	cp(T) ai	V_glass
0	0	15													
1.00	3600.00	15.42	16.00	0.00	17.78	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
2.00	7200.00	15.67	16.00	0.00	17.78	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
3.00	10800.00	14.96	14.00	0.00	17.78	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
4.00	14400.00	14.56	14.00	0.00	17.78	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
5	18000	14.32	14	0	17.78	116756	1450	2000	0.04	1.2	1000	0.63	2530	84	0.045
6.00	21600.00	15.03	16.00	0.00	17.78	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
7.00	25200.00	17.81	16.00	100.00	17.78	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
8.00	28800.00	21.77	16.00	200.00	17.78	117650.22	1450.00	2015.42	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
9.00	32400.00	21.90	16.00	200.00	17.78	2674677.30	1450.00	46102.09	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
10	36000	22.05	16	200	17.78	2252004.5	1450	38814.6	0.04	1.2	1000	0.63	2530	84	0.045
11.00	39600.00	22.43	16.00	300.00	17.78	1789982.74	1450.00	30848.74	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
12.00	43200.00	23.84	20.00	400.00	17.78	878978.77	1450.00	15141.77	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
13.00	46800.00	31.47	20.00	400.00	17.78	121819.98	1450.00	2087.31	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
14.00	50400.00	36.12	20.00	400.00	17.78	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
15	54000	40.93	25	400	17.78	116756	1450	2000	0.04	1.2	1000	0.63	2530	84	0.045
16.00	57600.00	42.51	25.00	350.00	17.78	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
17.00	61200.00	42.25	25.00	300.00	17.78	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
18.00	64800.00	39.72	25.00	200.00	17.78	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
19.00	68400.00	35.88	25.00	100.00	17.78	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
20	72000	31.63	23	50	17.78	116756	1450	2000	0.04	1.2	1000	0.63	2530	84	0.045
21.00	75600.00	26.72	20.00	0.00	17.78	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
22.00	79200.00	23.89	20.00	0.00	17.78	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
23.00	82800.00	21.47	18.00	0.00	17.78	120828.23	1450.00	2070.21	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
24.00	86400.00	21.35	15.00	0.00	17.78	3624496.42	1450.00	62478.28	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
						3906281.9	1450	67336.7	0.04	1.2	1000	0.63	2530	84	0.045

Summer sunny day

t [h]	t (s)	T_i = Tp	T_e	W	H_e	M	rho(T) pc	cp(T) pcm	V_pcm	rho(T) a	cp(T) air	V_air	rho(T) air	cp(T) ai	V_glass
0.00	0.00	15.00													
1.00	3600.00	15.42	16.00	0.00	17.78	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
2	7200	15.67	16	0	17.78	116756	1450	2000	0.04	1.2	1000	0.63	2530	84	0.045
3.00	10800.00	14.96	14.00	0.00	17.78	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
4.00	14400.00	14.56	14.00	0.00	17.78	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
5.00	18000.00	14.32	14.00	0.00	17.78	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
6.00	21600.00	15.03	16.00	0.00	17.78	116756.00	1450.00	2000.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
7	25200	16.63	16	50	17.78	116756	1450	2000	0.04	1.2	1000	0.63	2530	84	0.045
8.00	28800.00	18.74	16.00	100.00	17.78	116756.51	1450.00	2000.01	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
9.00	32400.00	19.62	16.00	100.00	17.78	175643.99	1450.00	3015.31	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
10.00	36000.00	19.75	16.00	100.00	17.78	974512.39	1450.00	16788.90	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
11.00	39600.00	19.98	16.00	150.00	17.78	1251713.10	1450.00	21568.23	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
12	43200	20.26	20	150	17.78	1884135.1	1450	32472.1	0.04	1.2	1000	0.63	2530	84	0.045
13.00	46800.00	20.51	20.00	200.00	17.78	2789138.93	1450.00	48075.57	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
14.00	50400.00	20.70	20.00	200.00	17.78	3563712.47	1450.00	61430.28	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
15.00	54000.00	20.95	25.00	200.00	17.78	4023032.37	1450.00	69349.59	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
16.00	57600.00	21.13	25.00	150.00	17.78	4312246.53	1450.00	74336.04	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
17	61200	21.27	25	100	17.78	4261349.8	1450	73458.5	0.04	1.2	1000	0.63	2530	84	0.045
18.00	64800.00	21.42	25.00	100.00	17.78	4068179.71	1450.00	70128.00	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
19.00	68400.00	21.58	25.00	100.00	17.78	3749231.61	1450.00	64628.89	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
20.00	72000.00	21.71	23.00	100.00	17.78	3309688.18	1450.00	57050.55	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
21.00	75600.00	21.73	20.00	50.00	17.78	2880228.84	1450.00	49646.08	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
22	79200	21.7	20	0	17.78	2800868.6	1450	48277.8	0.04	1.2	1000	0.63	2530	84	0.045
23.00	82800.00	21.62	18.00	0.00	17.78	2928962.94	1450.00	50486.33	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
24.00	86400.00	21.48	15.00	0.00	17.78	3184943.37	1450.00	54899.78	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05
						3577483.18	1450.00	61667.71	0.04	1.20	1000.00	0.63	2530.00	84.00	0.05

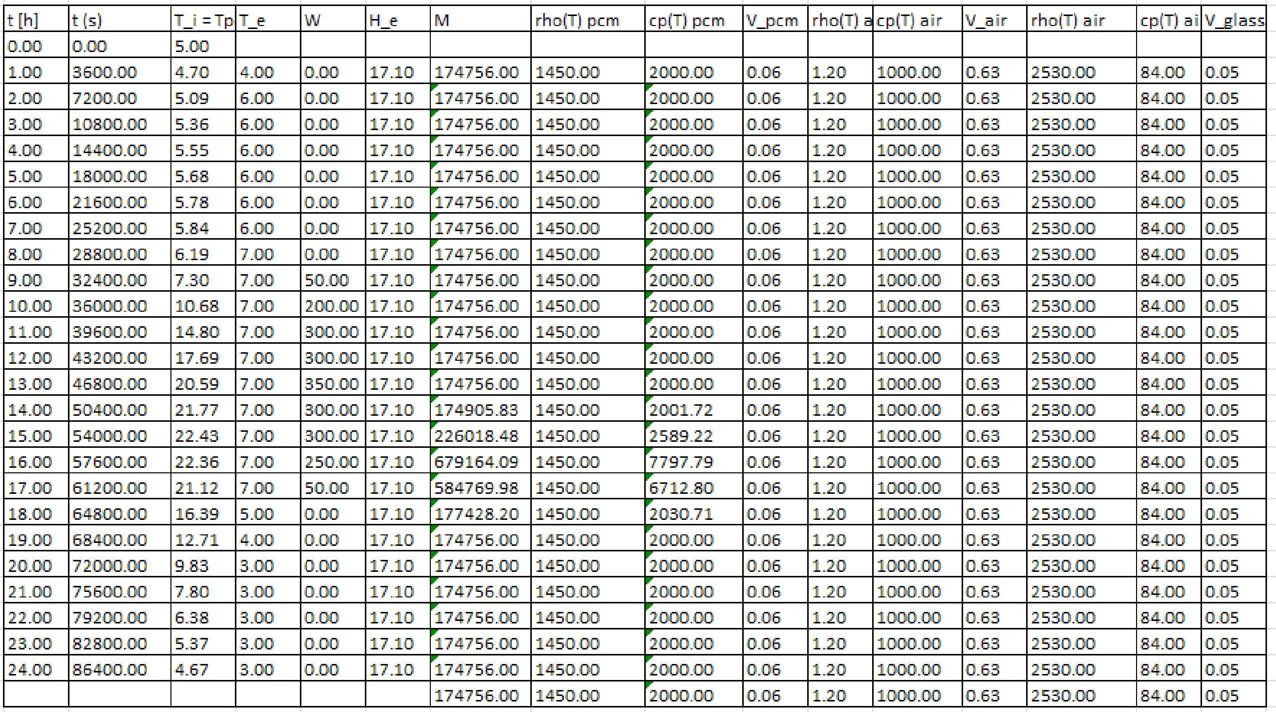
PCM 0.06 m³

Winter cloudy day



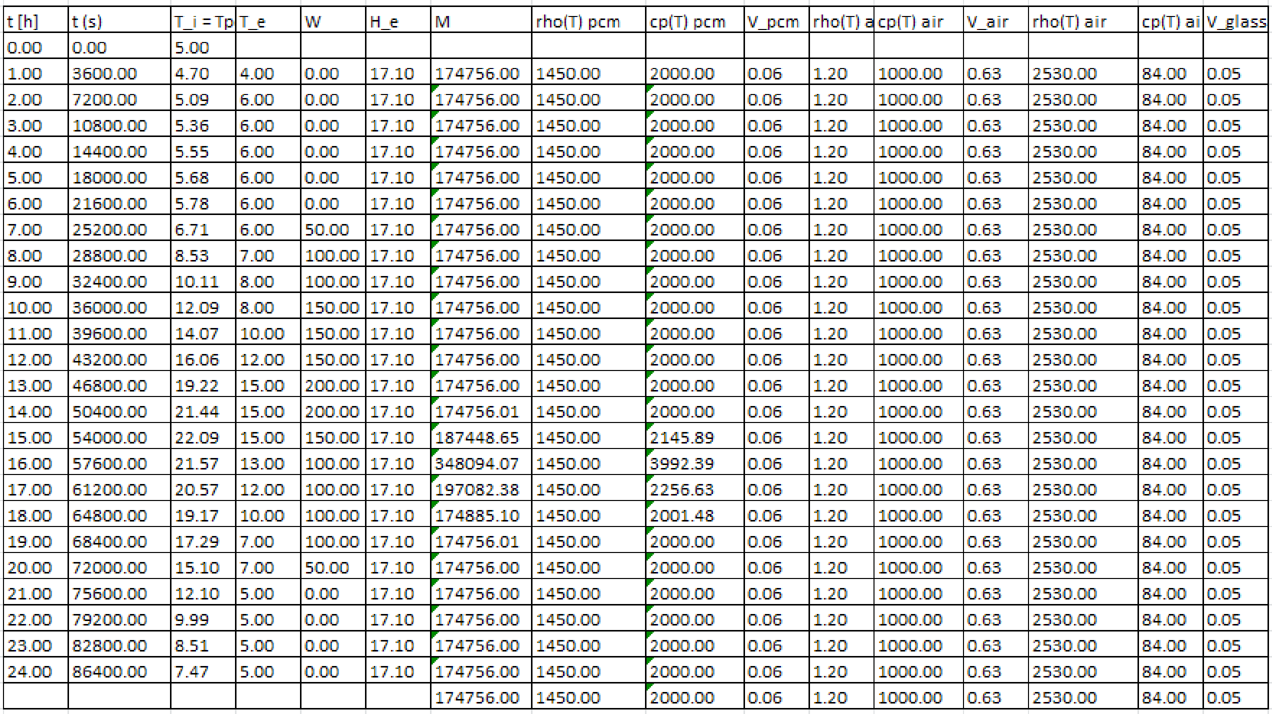
t [h]	t (s)	T_i = Tp	T_e	W	H_e	M	rho(T) pcm	cp(T) pcm	V_pcm	rho(T) a	cp(T) air	V_air	rho(T) glass	cp(T) gl	V_glass
0.00	0.00	5.00													
1.00	3600.00	4.70	4.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
2.00	7200.00	5.09	6.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
3.00	10800.00	5.36	6.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
4.00	14400.00	5.55	6.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
5.00	18000.00	5.68	6.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
6.00	21600.00	5.78	6.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
7.00	25200.00	5.84	6.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
8.00	28800.00	6.19	7.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
9.00	32400.00	7.30	7.00	50.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
10.00	36000.00	8.94	7.00	100.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
11.00	39600.00	10.10	7.00	100.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
12.00	43200.00	10.92	7.00	100.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
13.00	46800.00	11.49	7.00	100.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
14.00	50400.00	11.89	7.00	100.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
15.00	54000.00	12.18	7.00	100.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
16.00	57600.00	11.51	7.00	50.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
17.00	61200.00	10.17	7.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
18.00	64800.00	8.63	5.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
19.00	68400.00	7.26	4.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
20.00	72000.00	5.99	3.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
21.00	75600.00	5.11	3.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
22.00	79200.00	4.48	3.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
23.00	82800.00	4.04	3.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
24.00	86400.00	3.73	3.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
						174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05

Winter sunny day



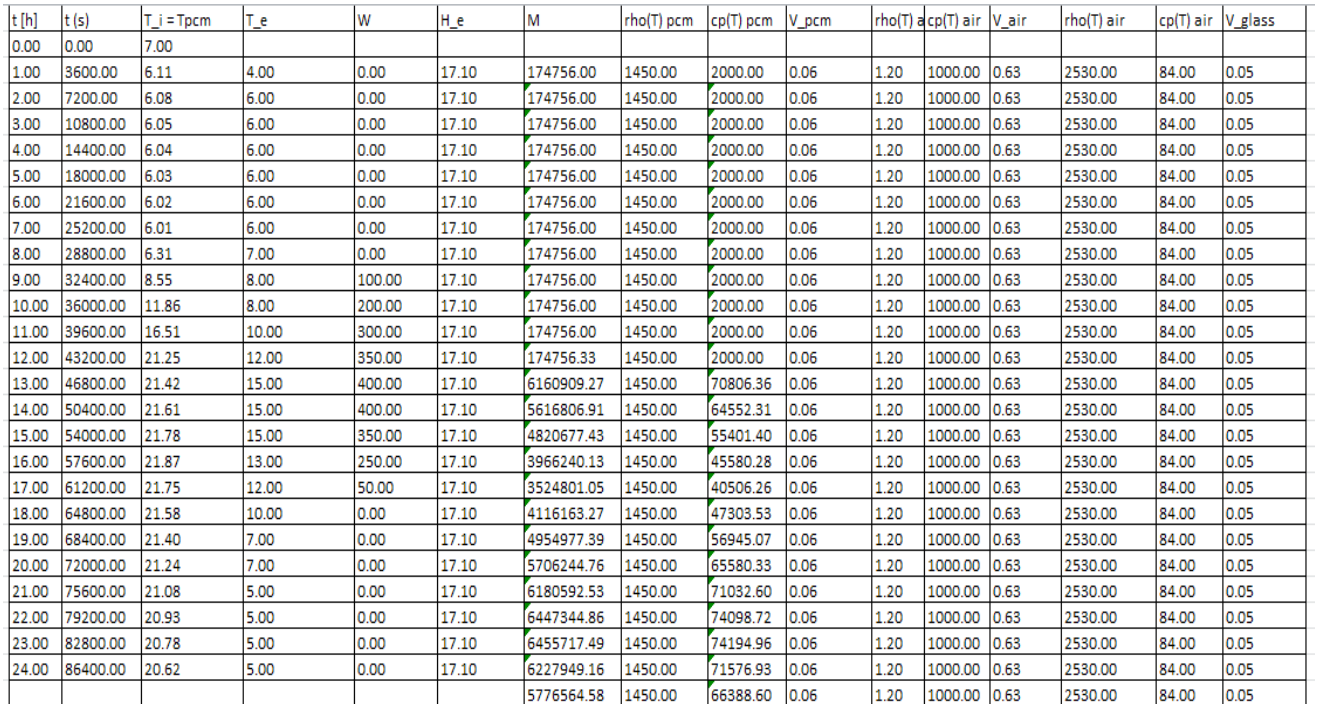
t [h]	t (s)	T_i = Tp	T_e	W	H_e	M	rho(T) pcm	cp(T) pcm	V_pcm	rho(T) a	cp(T) air	V_air	rho(T) air	cp(T) ai	V_glass
0.00	0.00	5.00													
1.00	3600.00	4.70	4.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
2.00	7200.00	5.09	6.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
3.00	10800.00	5.36	6.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
4.00	14400.00	5.55	6.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
5.00	18000.00	5.68	6.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
6.00	21600.00	5.78	6.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
7.00	25200.00	5.84	6.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
8.00	28800.00	6.19	7.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
9.00	32400.00	7.30	7.00	50.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
10.00	36000.00	10.68	7.00	200.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
11.00	39600.00	14.80	7.00	300.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
12.00	43200.00	17.69	7.00	300.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
13.00	46800.00	20.59	7.00	350.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
14.00	50400.00	21.77	7.00	300.00	17.10	174905.83	1450.00	2001.72	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
15.00	54000.00	22.43	7.00	300.00	17.10	226018.48	1450.00	2589.22	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
16.00	57600.00	22.36	7.00	250.00	17.10	679164.09	1450.00	7797.79	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
17.00	61200.00	21.12	7.00	50.00	17.10	584769.98	1450.00	6712.80	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
18.00	64800.00	16.39	5.00	0.00	17.10	177428.20	1450.00	2030.71	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
19.00	68400.00	12.71	4.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
20.00	72000.00	9.83	3.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
21.00	75600.00	7.80	3.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
22.00	79200.00	6.38	3.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
23.00	82800.00	5.37	3.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
24.00	86400.00	4.67	3.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
						174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05

Spring/autumn cloudy day



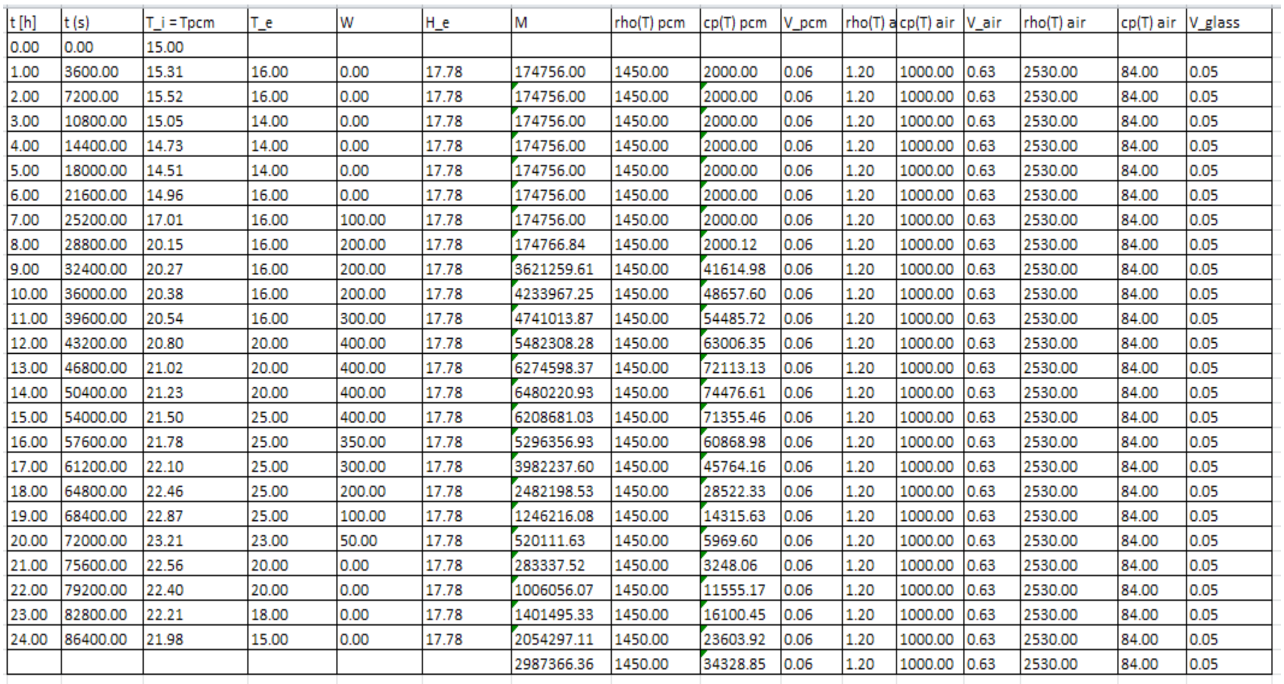
t [h]	t (s)	T_i = Tp	T_e	W	H_e	M	rho(T) pcm	cp(T) pcm	V_pcm	rho(T) a	cp(T) air	V_air	rho(T) air	cp(T) ai	V_glass
0.00	0.00	5.00													
1.00	3600.00	4.70	4.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
2.00	7200.00	5.09	6.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
3.00	10800.00	5.36	6.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
4.00	14400.00	5.55	6.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
5.00	18000.00	5.68	6.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
6.00	21600.00	5.78	6.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
7.00	25200.00	6.71	6.00	50.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
8.00	28800.00	8.53	7.00	100.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
9.00	32400.00	10.11	8.00	100.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
10.00	36000.00	12.09	8.00	150.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
11.00	39600.00	14.07	10.00	150.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
12.00	43200.00	16.06	12.00	150.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
13.00	46800.00	19.22	15.00	200.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
14.00	50400.00	21.44	15.00	200.00	17.10	174756.01	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
15.00	54000.00	22.09	15.00	150.00	17.10	187448.65	1450.00	2145.89	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
16.00	57600.00	21.57	13.00	100.00	17.10	348094.07	1450.00	3992.39	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
17.00	61200.00	20.57	12.00	100.00	17.10	197082.38	1450.00	2256.63	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
18.00	64800.00	19.17	10.00	100.00	17.10	174885.10	1450.00	2001.48	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
19.00	68400.00	17.29	7.00	100.00	17.10	174756.01	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
20.00	72000.00	15.10	7.00	50.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
21.00	75600.00	12.10	5.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
22.00	79200.00	9.99	5.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
23.00	82800.00	8.51	5.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
24.00	86400.00	7.47	5.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
						174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05

Spring/autumn sunny day



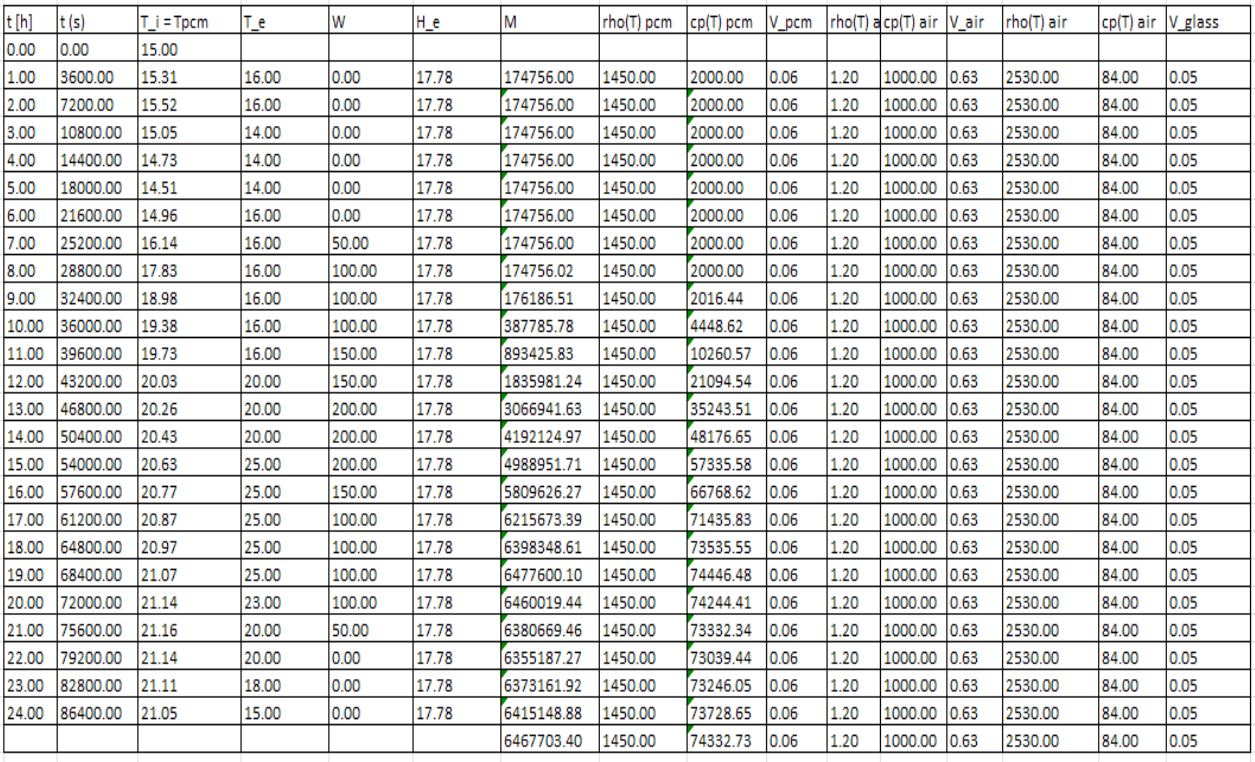
t [h]	t (s)	T_i = Tpcm	T_e	W	H_e	M	rho(T) pcm	cp(T) pcm	V_pcm	rho(T) a	cp(T) air	V_air	rho(T) air	cp(T) air	V_glass
0.00	0.00	7.00													
1.00	3600.00	6.11	4.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
2.00	7200.00	6.08	6.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
3.00	10800.00	6.05	6.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
4.00	14400.00	6.04	6.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
5.00	18000.00	6.03	6.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
6.00	21600.00	6.02	6.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
7.00	25200.00	6.01	6.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
8.00	28800.00	6.31	7.00	0.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
9.00	32400.00	8.55	8.00	100.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
10.00	36000.00	11.86	8.00	200.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
11.00	39600.00	16.51	10.00	300.00	17.10	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
12.00	43200.00	21.25	12.00	350.00	17.10	174756.33	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
13.00	46800.00	21.42	15.00	400.00	17.10	6160909.27	1450.00	70806.36	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
14.00	50400.00	21.61	15.00	400.00	17.10	5616806.91	1450.00	64552.31	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
15.00	54000.00	21.78	15.00	350.00	17.10	4820677.43	1450.00	55401.40	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
16.00	57600.00	21.87	13.00	250.00	17.10	3966240.13	1450.00	45580.28	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
17.00	61200.00	21.75	12.00	50.00	17.10	3524801.05	1450.00	40506.26	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
18.00	64800.00	21.58	10.00	0.00	17.10	4116163.27	1450.00	47303.53	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
19.00	68400.00	21.40	7.00	0.00	17.10	4954977.39	1450.00	56945.07	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
20.00	72000.00	21.24	7.00	0.00	17.10	5706244.76	1450.00	65580.33	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
21.00	75600.00	21.08	5.00	0.00	17.10	6180592.53	1450.00	71032.60	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
22.00	79200.00	20.93	5.00	0.00	17.10	6447344.86	1450.00	74098.72	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
23.00	82800.00	20.78	5.00	0.00	17.10	6455717.49	1450.00	74194.96	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
24.00	86400.00	20.62	5.00	0.00	17.10	6227949.16	1450.00	71576.93	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
						5776564.58	1450.00	66388.60	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05

Summer cloudy day



t [h]	t (s)	T_i = Tpcm	T_e	W	H_e	M	rho(T) pcm	cp(T) pcm	V_pcm	rho(T) a	cp(T) air	V_air	rho(T) air	cp(T) air	V_glass
0.00	0.00	15.00													
1.00	3600.00	15.31	16.00	0.00	17.78	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
2.00	7200.00	15.52	16.00	0.00	17.78	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
3.00	10800.00	15.05	14.00	0.00	17.78	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
4.00	14400.00	14.73	14.00	0.00	17.78	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
5.00	18000.00	14.51	14.00	0.00	17.78	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
6.00	21600.00	14.96	16.00	0.00	17.78	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
7.00	25200.00	17.01	16.00	100.00	17.78	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
8.00	28800.00	20.15	16.00	200.00	17.78	174766.84	1450.00	2000.12	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
9.00	32400.00	20.27	16.00	200.00	17.78	3621259.61	1450.00	41614.98	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
10.00	36000.00	20.38	16.00	200.00	17.78	4233967.25	1450.00	48657.60	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
11.00	39600.00	20.54	16.00	300.00	17.78	4741013.87	1450.00	54485.72	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
12.00	43200.00	20.80	20.00	400.00	17.78	5482308.28	1450.00	63006.35	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
13.00	46800.00	21.02	20.00	400.00	17.78	6274598.37	1450.00	72113.13	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
14.00	50400.00	21.23	20.00	400.00	17.78	6480220.93	1450.00	74476.61	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
15.00	54000.00	21.50	25.00	400.00	17.78	6208681.03	1450.00	71355.46	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
16.00	57600.00	21.78	25.00	350.00	17.78	5296356.93	1450.00	60868.98	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
17.00	61200.00	22.10	25.00	300.00	17.78	3982237.60	1450.00	45764.16	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
18.00	64800.00	22.46	25.00	200.00	17.78	2482198.53	1450.00	28522.33	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
19.00	68400.00	22.87	25.00	100.00	17.78	1246216.08	1450.00	14315.63	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
20.00	72000.00	23.21	23.00	50.00	17.78	520111.63	1450.00	5969.60	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
21.00	75600.00	22.56	20.00	0.00	17.78	283337.52	1450.00	3248.06	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
22.00	79200.00	22.40	20.00	0.00	17.78	1006056.07	1450.00	11555.17	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
23.00	82800.00	22.21	18.00	0.00	17.78	1401495.33	1450.00	16100.45	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
24.00	86400.00	21.98	15.00	0.00	17.78	2054297.11	1450.00	23603.92	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
						2987366.36	1450.00	34328.85	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05

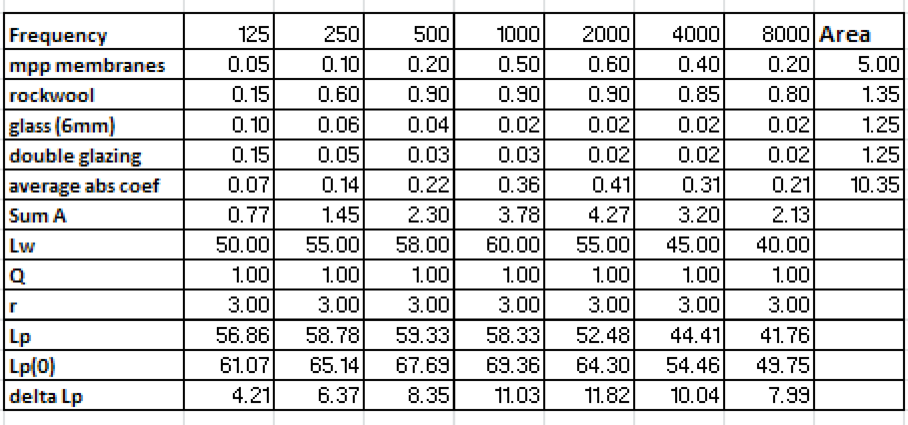
Summer sunny day



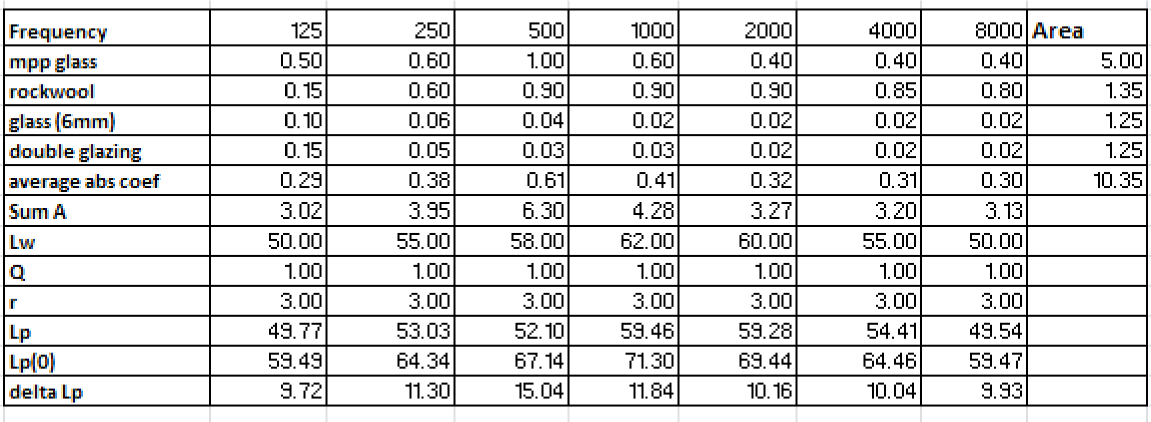
t [h]	t (s)	T_i = Tpcm	T_e	W	H_e	M	rho(T) pcm	cp(T) pcm	V_pcm	rho(T) a	cp(T) air	V_air	rho(T) air	cp(T) air	V_glass
0.00	0.00	15.00													
1.00	3600.00	15.31	16.00	0.00	17.78	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
2.00	7200.00	15.52	16.00	0.00	17.78	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
3.00	10800.00	15.05	14.00	0.00	17.78	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
4.00	14400.00	14.73	14.00	0.00	17.78	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
5.00	18000.00	14.51	14.00	0.00	17.78	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
6.00	21600.00	14.96	16.00	0.00	17.78	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
7.00	25200.00	16.14	16.00	50.00	17.78	174756.00	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
8.00	28800.00	17.83	16.00	100.00	17.78	174756.02	1450.00	2000.00	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
9.00	32400.00	18.98	16.00	100.00	17.78	176186.51	1450.00	2016.44	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
10.00	36000.00	19.38	16.00	100.00	17.78	387785.78	1450.00	4448.62	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
11.00	39600.00	19.73	16.00	150.00	17.78	893425.83	1450.00	10260.57	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
12.00	43200.00	20.03	20.00	150.00	17.78	1835981.24	1450.00	21094.54	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
13.00	46800.00	20.26	20.00	200.00	17.78	3066941.63	1450.00	35243.51	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
14.00	50400.00	20.43	20.00	200.00	17.78	4192124.97	1450.00	48176.65	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
15.00	54000.00	20.63	25.00	200.00	17.78	4988951.71	1450.00	57335.58	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
16.00	57600.00	20.77	25.00	150.00	17.78	5809626.27	1450.00	66768.62	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
17.00	61200.00	20.87	25.00	100.00	17.78	6215673.39	1450.00	71435.83	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
18.00	64800.00	20.97	25.00	100.00	17.78	6398348.61	1450.00	73535.55	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
19.00	68400.00	21.07	25.00	100.00	17.78	6477600.10	1450.00	74446.48	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
20.00	72000.00	21.14	23.00	100.00	17.78	6460019.44	1450.00	74244.41	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
21.00	75600.00	21.16	20.00	50.00	17.78	6380669.46	1450.00	73332.34	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
22.00	79200.00	21.14	20.00	0.00	17.78	6355187.27	1450.00	73039.44	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
23.00	82800.00	21.11	18.00	0.00	17.78	6373161.92	1450.00	73246.05	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
24.00	86400.00	21.05	15.00	0.00	17.78	6415148.88	1450.00	73728.65	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05
						6467703.40	1450.00	74332.73	0.06	1.20	1000.00	0.63	2530.00	84.00	0.05

Appendix 5

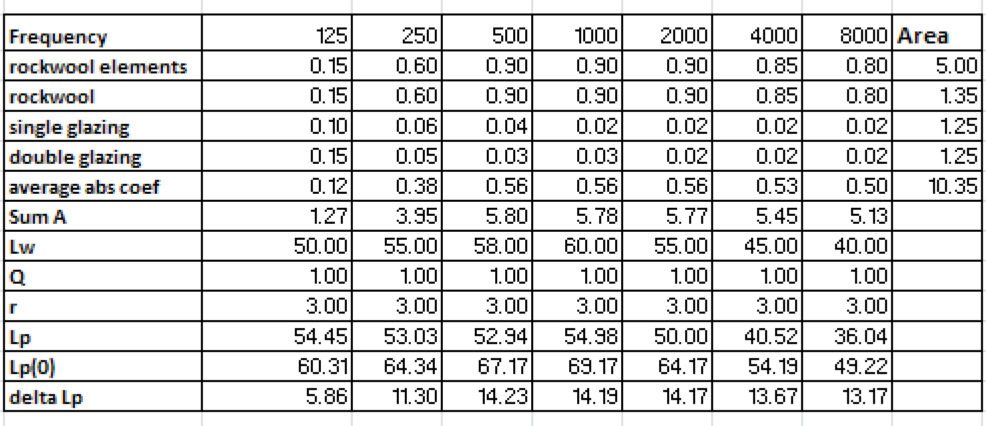
Sound pressure reduction with 5m²



Frequency	125	250	500	1000	2000	4000	8000	**Area**
mpp membranes	0.05	0.10	0.20	0.50	0.60	0.40	0.20	5.00
rockwool	0.15	0.60	0.90	0.90	0.90	0.85	0.80	1.35
glass (6mm)	0.10	0.06	0.04	0.02	0.02	0.02	0.02	1.25
double glazing	0.15	0.05	0.03	0.03	0.02	0.02	0.02	1.25
average abs coef	0.07	0.14	0.22	0.36	0.41	0.31	0.21	10.35
Sum A	0.77	1.45	2.30	3.78	4.27	3.20	2.13	
Lw	50.00	55.00	58.00	60.00	55.00	45.00	40.00	
Q	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
r	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
Lp	56.86	58.78	59.33	58.33	52.48	44.41	41.76	
Lp(0)	61.07	65.14	67.69	69.36	64.30	54.46	49.75	
delta Lp	4.21	6.37	8.35	11.03	11.82	10.04	7.99	

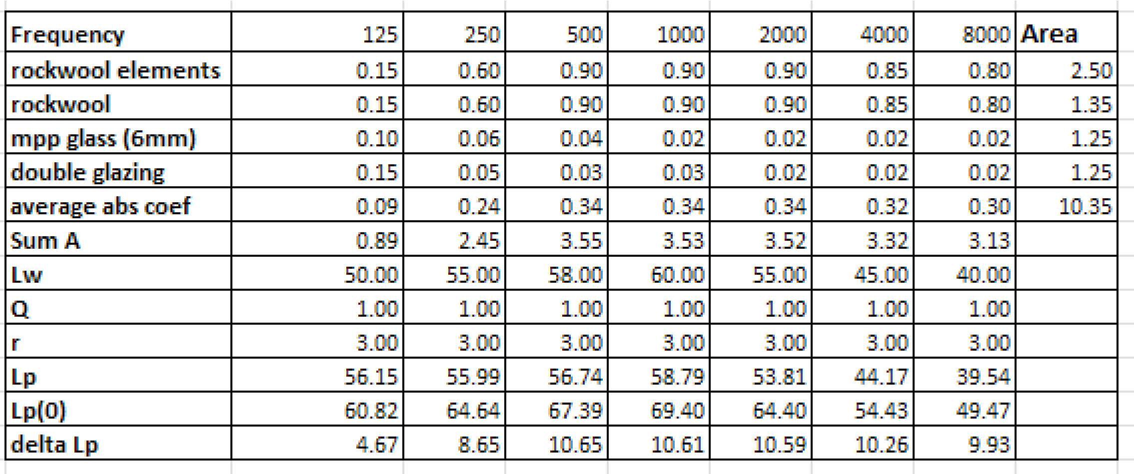


Frequency	125	250	500	1000	2000	4000	8000	**Area**
mpp glass	0.50	0.60	1.00	0.60	0.40	0.40	0.40	5.00
rockwool	0.15	0.60	0.90	0.90	0.90	0.85	0.80	1.35
glass (6mm)	0.10	0.06	0.04	0.02	0.02	0.02	0.02	1.25
double glazing	0.15	0.05	0.03	0.03	0.02	0.02	0.02	1.25
average abs coef	0.29	0.38	0.61	0.41	0.32	0.31	0.30	10.35
Sum A	3.02	3.95	6.30	4.28	3.27	3.20	3.13	
Lw	50.00	55.00	58.00	62.00	60.00	55.00	50.00	
Q	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
r	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
Lp	49.77	53.03	52.10	59.46	59.28	54.41	49.54	
Lp(0)	59.49	64.34	67.14	71.30	69.44	64.46	59.47	
delta Lp	9.72	11.30	15.04	11.84	10.16	10.04	9.93	

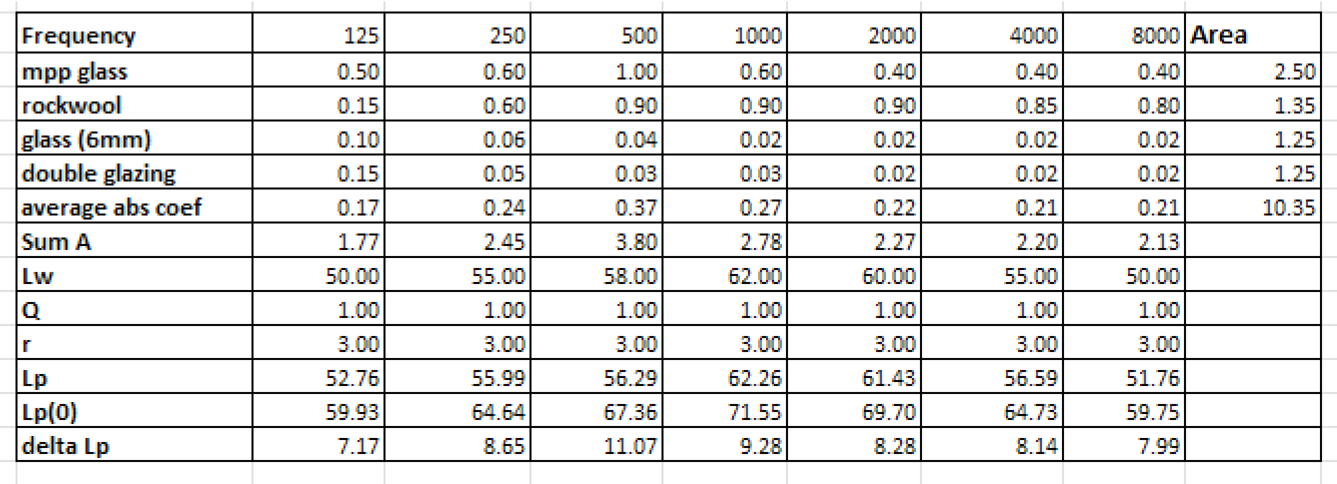


Frequency	125	250	500	1000	2000	4000	8000	**Area**
rockwool elements	0.15	0.60	0.90	0.90	0.90	0.85	0.80	5.00
rockwool	0.15	0.60	0.90	0.90	0.90	0.85	0.80	1.35
single glazing	0.10	0.06	0.04	0.02	0.02	0.02	0.02	1.25
double glazing	0.15	0.05	0.03	0.03	0.02	0.02	0.02	1.25
average abs coef	0.12	0.38	0.56	0.56	0.56	0.53	0.50	10.35
Sum A	1.27	3.95	5.80	5.78	5.77	5.45	5.13	
Lw	50.00	55.00	58.00	60.00	55.00	45.00	40.00	
Q	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
r	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
Lp	54.45	53.03	52.94	54.98	50.00	40.52	36.04	
Lp(0)	60.31	64.34	67.17	69.17	64.17	54.19	49.22	
delta Lp	5.86	11.30	14.23	14.19	14.17	13.67	13.17	

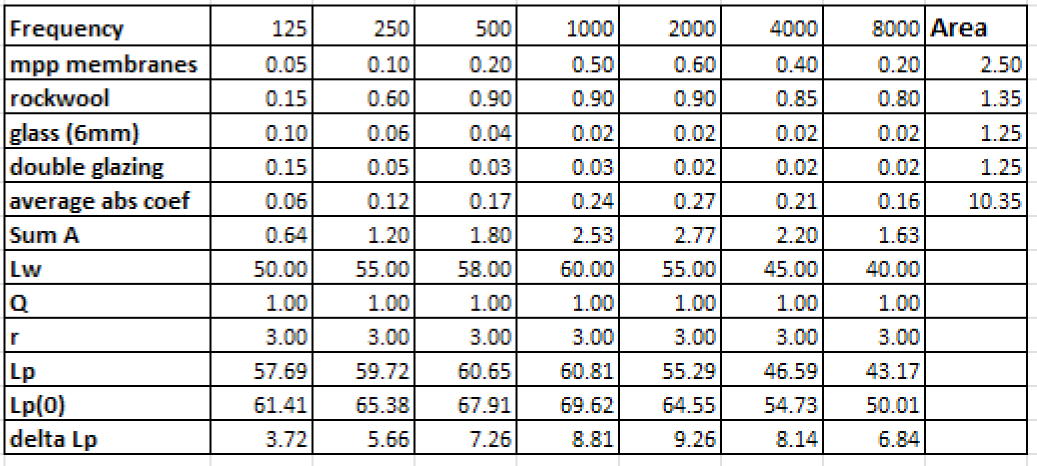
Sound pressure reduction with 2.5m^2



Frequency	125	250	500	1000	2000	4000	8000	**Area**
rockwool elements	0.15	0.60	0.90	0.90	0.90	0.85	0.80	2.50
rockwool	0.15	0.60	0.90	0.90	0.90	0.85	0.80	1.35
mpp glass (6mm)	0.10	0.06	0.04	0.02	0.02	0.02	0.02	1.25
double glazing	0.15	0.05	0.03	0.03	0.02	0.02	0.02	1.25
average abs coef	0.09	0.24	0.34	0.34	0.34	0.32	0.30	10.35
Sum A	0.89	2.45	3.55	3.53	3.52	3.32	3.13	
Lw	50.00	55.00	58.00	60.00	55.00	45.00	40.00	
Q	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
r	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
Lp	56.15	55.99	56.74	58.79	53.81	44.17	39.54	
Lp(0)	60.82	64.64	67.39	69.40	64.40	54.43	49.47	
delta Lp	4.67	8.65	10.65	10.61	10.59	10.26	9.93	

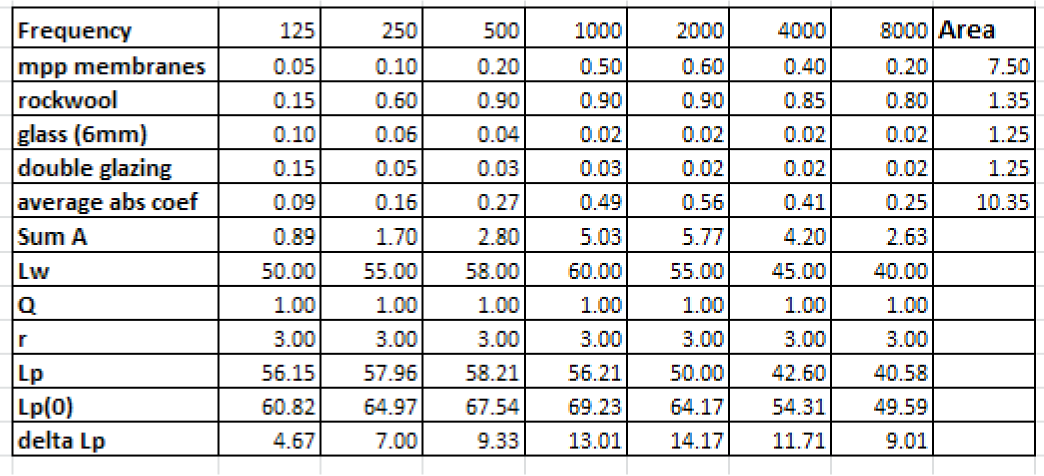


Frequency	125	250	500	1000	2000	4000	8000	**Area**
mpp glass	0.50	0.60	1.00	0.60	0.40	0.40	0.40	2.50
rockwool	0.15	0.60	0.90	0.90	0.90	0.85	0.80	1.35
glass (6mm)	0.10	0.06	0.04	0.02	0.02	0.02	0.02	1.25
double glazing	0.15	0.05	0.03	0.03	0.02	0.02	0.02	1.25
average abs coef	0.17	0.24	0.37	0.27	0.22	0.21	0.21	10.35
Sum A	1.77	2.45	3.80	2.78	2.27	2.20	2.13	
Lw	50.00	55.00	58.00	62.00	60.00	55.00	50.00	
Q	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
r	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
Lp	52.76	55.99	56.29	62.26	61.43	56.59	51.76	
Lp(0)	59.93	64.64	67.36	71.55	69.70	64.73	59.75	
delta Lp	7.17	8.65	11.07	9.28	8.28	8.14	7.99	

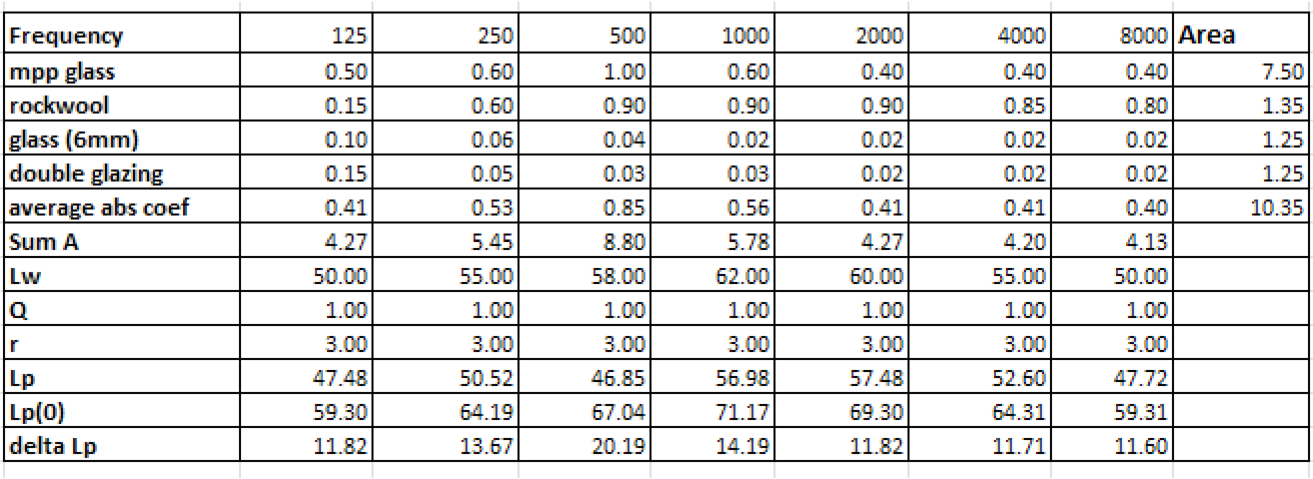


Frequency	125	250	500	1000	2000	4000	8000	**Area**
mpp membranes	0.05	0.10	0.20	0.50	0.60	0.40	0.20	2.50
rockwool	0.15	0.60	0.90	0.90	0.90	0.85	0.80	1.35
glass (6mm)	0.10	0.06	0.04	0.02	0.02	0.02	0.02	1.25
double glazing	0.15	0.05	0.03	0.03	0.02	0.02	0.02	1.25
average abs coef	0.06	0.12	0.17	0.24	0.27	0.21	0.16	10.35
Sum A	0.64	1.20	1.80	2.53	2.77	2.20	1.63	
Lw	50.00	55.00	58.00	60.00	55.00	45.00	40.00	
Q	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
r	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
Lp	57.69	59.72	60.65	60.81	55.29	46.59	43.17	
Lp(0)	61.41	65.38	67.91	69.62	64.55	54.73	50.01	
delta Lp	3.72	5.66	7.26	8.81	9.26	8.14	6.84	

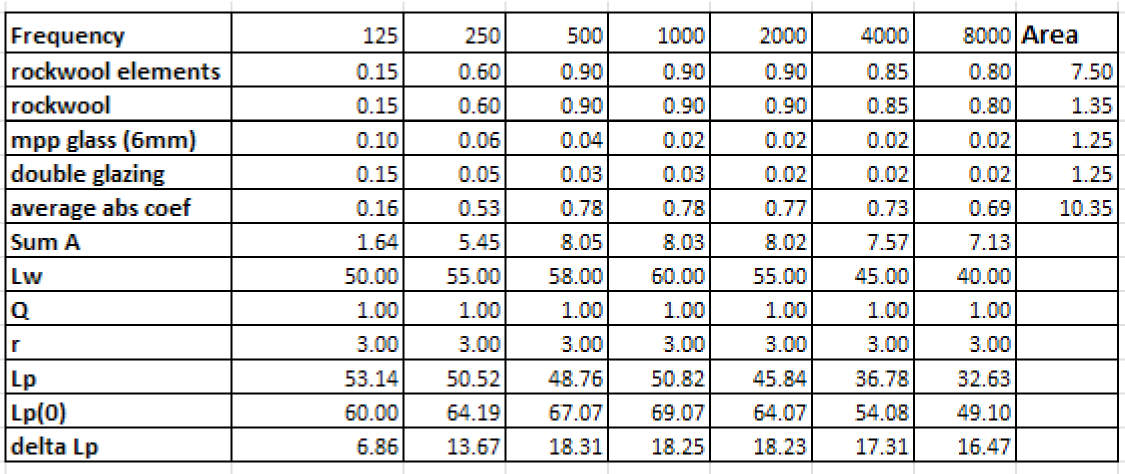
Sound pressure reduction with 7.5m^2



Frequency	125	250	500	1000	2000	4000	8000	**Area**
mpp membranes	0.05	0.10	0.20	0.50	0.60	0.40	0.20	7.50
rockwool	0.15	0.60	0.90	0.90	0.90	0.85	0.80	1.35
glass (6mm)	0.10	0.06	0.04	0.02	0.02	0.02	0.02	1.25
double glazing	0.15	0.05	0.03	0.03	0.02	0.02	0.02	1.25
average abs coef	0.09	0.16	0.27	0.49	0.56	0.41	0.25	10.35
Sum A	0.89	1.70	2.80	5.03	5.77	4.20	2.63	
Lw	50.00	55.00	58.00	60.00	55.00	45.00	40.00	
Q	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
r	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
Lp	56.15	57.96	58.21	56.21	50.00	42.60	40.58	
Lp(0)	60.82	64.97	67.54	69.23	64.17	54.31	49.59	
delta Lp	4.67	7.00	9.33	13.01	14.17	11.71	9.01	

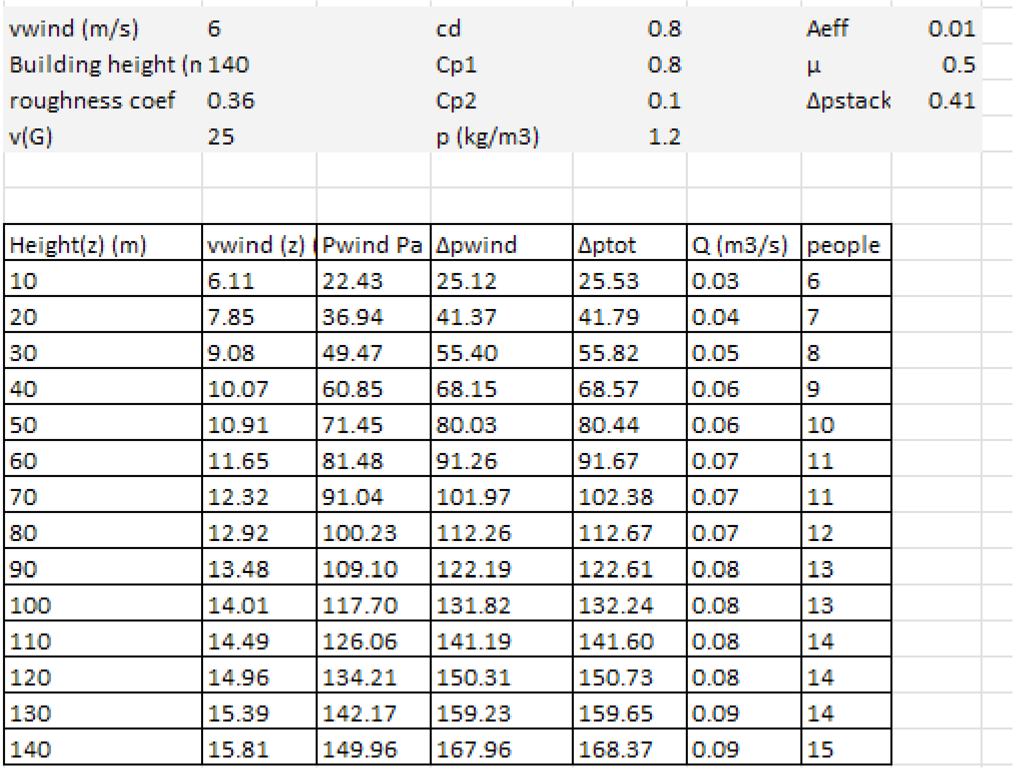


Frequency	125	250	500	1000	2000	4000	8000	**Area**
mpp glass	0.50	0.60	1.00	0.60	0.40	0.40	0.40	7.50
rockwool	0.15	0.60	0.90	0.90	0.90	0.85	0.80	1.35
glass (6mm)	0.10	0.06	0.04	0.02	0.02	0.02	0.02	1.25
double glazing	0.15	0.05	0.03	0.03	0.02	0.02	0.02	1.25
average abs coef	0.41	0.53	0.85	0.56	0.41	0.41	0.40	10.35
Sum A	4.27	5.45	8.80	5.78	4.27	4.20	4.13	
Lw	50.00	55.00	58.00	62.00	60.00	55.00	50.00	
Q	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
r	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
Lp	47.48	50.52	46.85	56.98	57.48	52.60	47.72	
Lp(0)	59.30	64.19	67.04	71.17	69.30	64.31	59.31	
delta Lp	11.82	13.67	20.19	14.19	11.82	11.71	11.60	



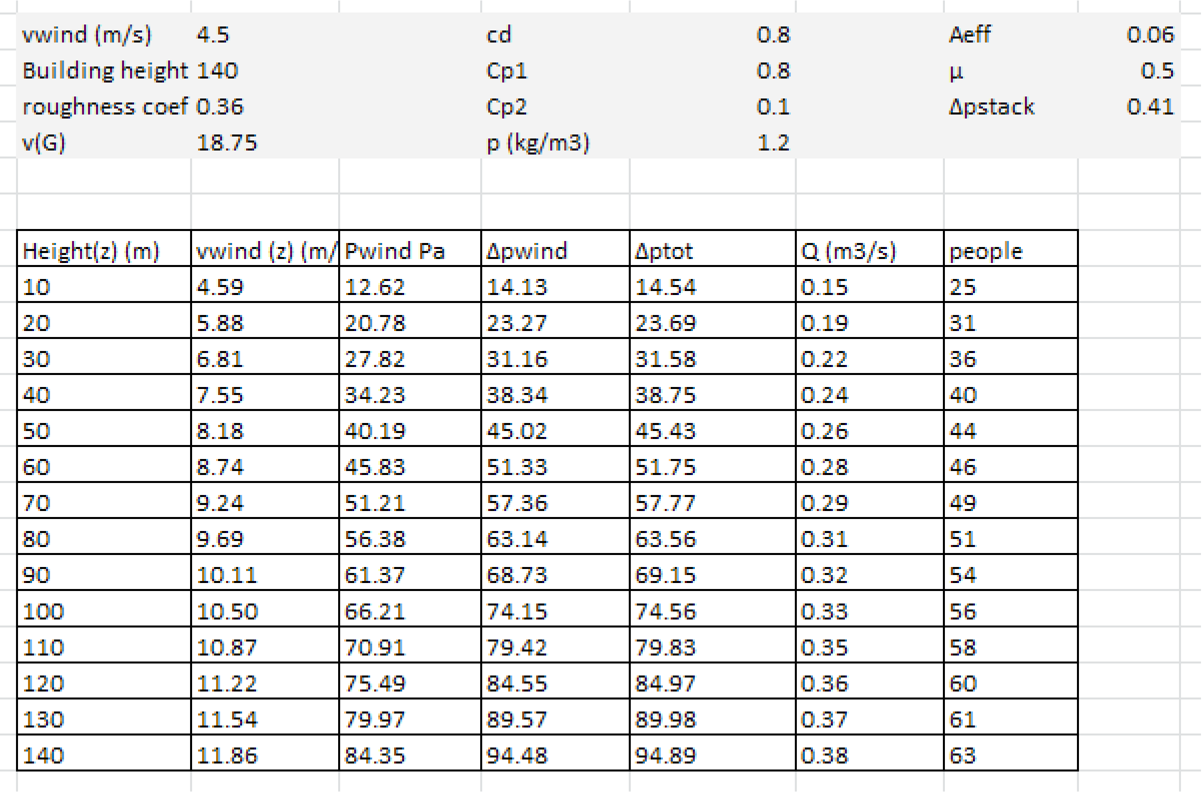
Frequency	125	250	500	1000	2000	4000	8000	**Area**
rockwool elements	0.15	0.60	0.90	0.90	0.90	0.85	0.80	7.50
rockwool	0.15	0.60	0.90	0.90	0.90	0.85	0.80	1.35
mpp glass (6mm)	0.10	0.06	0.04	0.02	0.02	0.02	0.02	1.25
double glazing	0.15	0.05	0.03	0.03	0.02	0.02	0.02	1.25
average abs coef	0.16	0.53	0.78	0.78	0.77	0.73	0.69	10.35
Sum A	1.64	5.45	8.05	8.03	8.02	7.57	7.13	
Lw	50.00	55.00	58.00	60.00	55.00	45.00	40.00	
Q	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
r	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
Lp	53.14	50.52	48.76	50.82	45.84	36.78	32.63	
Lp(0)	60.00	64.19	67.07	69.07	64.07	54.08	49.10	
delta Lp	6.86	13.67	18.31	18.25	18.23	17.31	16.47	

Appendix 6



vwind (m/s)	6	cd	0.8	Aeff	0.01
Building height (n	140	Cp1	0.8	µ	0.5
roughness coef	0.36	Cp2	0.1	Δpstack	0.41
v(G)	25	p (kg/m3)	1.2		

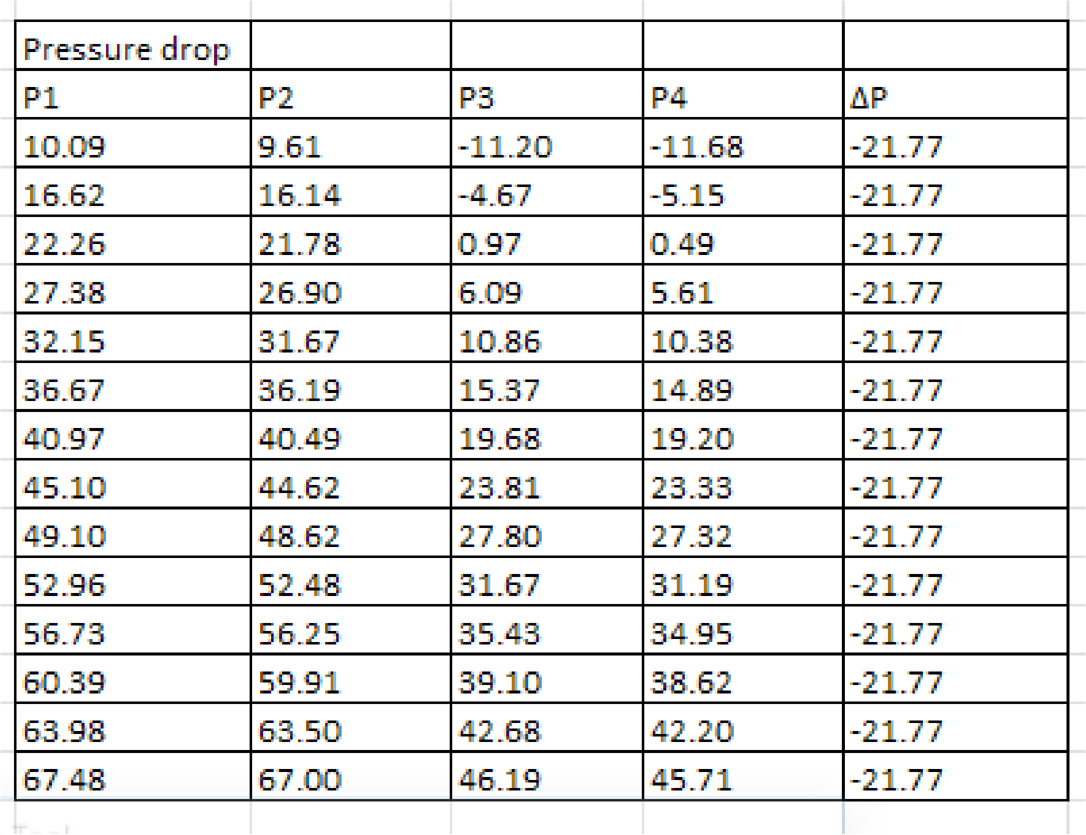
Height(z) (m)	vwind (z) (	Pwind Pa	Δpwind	Δptot	Q (m3/s)	people
10	6.11	22.43	25.12	25.53	0.03	6
20	7.85	36.94	41.37	41.79	0.04	7
30	9.08	49.47	55.40	55.82	0.05	8
40	10.07	60.85	68.15	68.57	0.06	9
50	10.91	71.45	80.03	80.44	0.06	10
60	11.65	81.48	91.26	91.67	0.07	11
70	12.32	91.04	101.97	102.38	0.07	11
80	12.92	100.23	112.26	112.67	0.07	12
90	13.48	109.10	122.19	122.61	0.08	13
100	14.01	117.70	131.82	132.24	0.08	13
110	14.49	126.06	141.19	141.60	0.08	14
120	14.96	134.21	150.31	150.73	0.08	14
130	15.39	142.17	159.23	159.65	0.09	14
140	15.81	149.96	167.96	168.37	0.09	15



vwind (m/s)	4.5	cd	0.8	Aeff	0.06
Building height	140	Cp1	0.8	µ	0.5
roughness coef	0.36	Cp2	0.1	Δpstack	0.41
v(G)	18.75	p (kg/m3)	1.2		

Height(z) (m)	vwind (z) (m/	Pwind Pa	Δpwind	Δptot	Q (m3/s)	people
10	4.59	12.62	14.13	14.54	0.15	25
20	5.88	20.78	23.27	23.69	0.19	31
30	6.81	27.82	31.16	31.58	0.22	36
40	7.55	34.23	38.34	38.75	0.24	40
50	8.18	40.19	45.02	45.43	0.26	44
60	8.74	45.83	51.33	51.75	0.28	46
70	9.24	51.21	57.36	57.77	0.29	49
80	9.69	56.38	63.14	63.56	0.31	51
90	10.11	61.37	68.73	69.15	0.32	54
100	10.50	66.21	74.15	74.56	0.33	56
110	10.87	70.91	79.42	79.83	0.35	58
120	11.22	75.49	84.55	84.97	0.36	60
130	11.54	79.97	89.57	89.98	0.37	61
140	11.86	84.35	94.48	94.89	0.38	63

Appendix 7



Pressure drop				
P1	P2	P3	P4	ΔP
10.09	9.61	-11.20	-11.68	-21.77
16.62	16.14	-4.67	-5.15	-21.77
22.26	21.78	0.97	0.49	-21.77
27.38	26.90	6.09	5.61	-21.77
32.15	31.67	10.86	10.38	-21.77
36.67	36.19	15.37	14.89	-21.77
40.97	40.49	19.68	19.20	-21.77
45.10	44.62	23.81	23.33	-21.77
49.10	48.62	27.80	27.32	-21.77
52.96	52.48	31.67	31.19	-21.77
56.73	56.25	35.43	34.95	-21.77
60.39	59.91	39.10	38.62	-21.77
63.98	63.50	42.68	42.20	-21.77
67.48	67.00	46.19	45.71	-21.77