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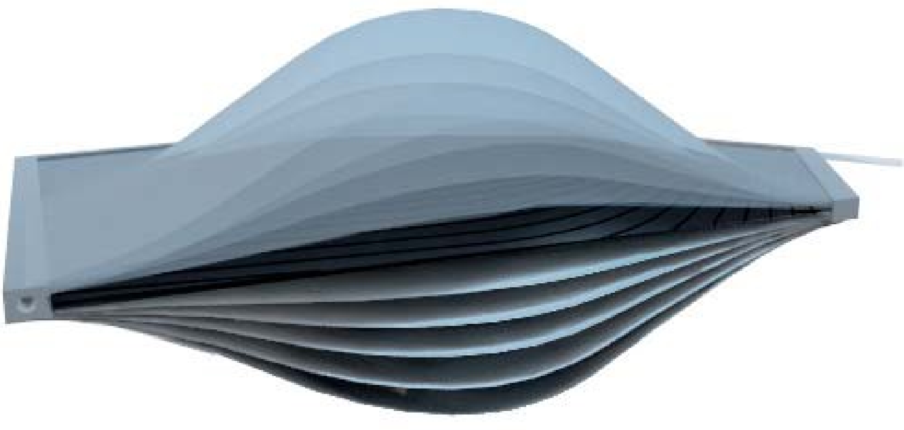

USING ADVANCED CLIMATE SKINS AS SOLAR THERMAL SYSTEMS

- A study of utilizing ETFE cushion façade systems for solar thermal collection-

Master of Science Thesis in the Master's Programme Architecture and Engineering

MOA CARLSSON

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover:
Visualisation of ETFE Cushion Solar Thermal Collector

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ABSTRACT

Solar thermal collectors are widely used for space heating and hot water production. Their benefits include a high thermal efficiency and a relatively cost effective and simple construction technique. The downside is ridged, heavy and fragile constructions and lack of possibilities for esthetical and architectural considerations. In recent years Ethylene Tetrafluoroethylene (ETFE) film has been an increasingly common material in climate skins, either as inflated cushions or membranes. The properties of ETFE cushions would be beneficial as the infrared transparent insulation layer which is required in solar thermal collectors.

This report is the result of an investigation of the potential of utilising the technique of ETFE-cushions in combination with the technique behind flat plate solar thermal collectors to create a single building climate skin which incorporates the function of a solar thermal collector without adding heavy, fragile or aesthetically disturbing elements. Calculations are carried out and shows a maximal efficiency in the given circumstances for a cushion with 14 layers of ETFE film. The efficiency of this configuration is found to be 33 %, slightly lower than a conventional flat plate collector, but with benefits such as light weight and durability.

Key words: ETFE, Solar thermal collector, climate skin, infra-red transparent insulation

Avancerade klimatskal som termiska solfångare
-en studie i utvecklande av ETFE-fasadsystem för utnyttjande av termisk solenergi-
Examensarbete inom Master of Architecture and Engineering

Institutionen för bygg- och miljöteknik
Chalmers tekniska högskola

SAMMANFATTNING

Termiska solfångare används idag i stor utsträckning för uppvärmning och varmvattenproduktion. Fördelarna inkluderar en hög termisk effektivitet och låga produktionskostnader. Nackdelarna är tunga, stela och sköra konstruktioner med små möjligheter till estetiska och arkitektoniska anpassningar.

Under de senaste åren har Ethylene Tetrafluoroethylene-film (ETFE-film) blivit ett vanligt material i klimatskal, antingen i form av uppblåsta kuddar, eller utsteckt till membran. Egenskaperna hos ETFE-kuddar är fördelaktiga för infraröd-transparenta isoleringslager som vilket är en nödvändig komponent i en termisk solfångare.

Denna rapport är resultatet av en undersökning kring potentialen för att använda tekniken bakom ETFE-kuddar i kombination men tekniken bakom plana solfångare för att skapa ett klimatskal som integrerar termiska solfångare utan tillägg i form av tunga, sköra eller estetiskt störande element.

Beräkningar har utförts och visar en maximal effektiviet I de givna förutsättningarna för en kudde med 14 lager ETFE-film. Effetiviteten för denna konfiguration beräknas till 33 %, något lägre en för konventionella plana solfångare, men med fördelar som låg vikt och lång hållbarhet.

Nyckelord: ETFE, termiska solfångare, klimatskal, infrarödtransparent isolering

Contents

1. BACKGROUND

This master thesis proposes the idea of developing solar thermal collectors in the form of inflated cushions of Ethylene Tetrafluoroethylene (ETFE) film. The main focus is on the function of the ETFE layers as the infrared transparent insulation of the collector.

The infrared transparent insulation in conventional solar thermal collectors is made by one or several sheets of glass. ETFE-film is a plastic material which has several advantages in comparison, such as being light weight, flexible, durable, and having low requirements for maintenance, while still having the required high IR-transparency and, as cushions, good insulation properties. ETFE is also self-cleansing and cost efficient. This motivates studies of configurations of solar thermal collectors with ETFE film.

Since the 1980's, when ETFE was developed, it has been increasingly popular as a climate skin, in the form of inflated cushions covering steel structures. The collector configuration developed in this thesis could possibly be integrated as part of the climate skin in that building typology.

A principle solar thermal collector will be developed and described in the thesis. The thesis also proposes a system design as well as a building design where the cushions are integrated.

The proposed building is a dance hall located in Gävle. It will have a building climate skin consisting of ETFE cushions, which will also produce heating and hot water. This building will serve as a basis for calculations of collector efficiency.

Solar thermal collectors

Solar thermal collectors are today widely used as a way to harvest solar energy, transforming solar radiation into heat for space heating and domestic hot water production. While photovoltaics is a popular and useful technology for creating electricity, for the purpose of heating, solar thermal collectors are far more efficient. The commonly used thermal collectors today are about 4 times more effective than photovoltaics when comparing area used by the systems and the output in kWh. In Sweden about 24% of the total energy consumption is used to heat buildings, (Energimyndigheten 2013, 14). 58% of this energy is distributed by district heating. The remaining part, about 36 TWh/year, in areas where no district heating is available, consists of mixed energy sources, i.e electricity, oil, biomass fuel and gas. (Energimarknadsinspektionen, 2012, 12) In these cases a solar thermal system could be both more economical and more ecologically sustainable.

There is a wide variety of solar thermal collectors on the market, including flat plate collectors, evacuated tube collectors and concentrating collectors among others. Most of these are made from ridged, heavy and fragile plates of glass and metal, which limits their flexibility in architectural applications, and also contributes to high investment costs.

2. METHOD

The design proposal will be based on the technology behind conventional solar thermal collectors in combination with the technology behind ETFE cushions systems in building climate skins.

An overall design of the dance hall space is carried out to serve as a basis for calculating heat consumption and geometries for the application. The location of the dance hall will provide meteorological data for calculations.

The technology behind existing solar thermal collectors will be investigated to identify desired material- and geometrical properties as well as guidance for system design. Existing ETFE cushions are studied as a reference for cushion and building skin design and details, as well as to provide information about material properties to be used in calculations.

From this, a system design proposal will be derived, where properties such as absorber material and number of cushion film layers to be left as variables to be determined in the analysis.

As a comparison the cushion performance will be determined for a different climate, to investigate how climate properties effect the optimization of the cushion design.

Verified equations for flat collectors are studied and modified in order to adapt to the proposed cushion design and its efficiency.

DELIMITATIONS

Structure and architecture will be developed only to a level which is required for the cushion design.

Calculations will be carried out to determine the efficiency for a single collector, and not for a collector system.

Absorber materials considered will be limited to materials used in solar thermal collectors today.

Thermal losses are calculated for a flat plate absorber area.

Thermal losses in heat exchangers or storage tanks will not be considered.

Energy consumption for pumps to keep cushion inflation and water flow will not be considered.

Transport fluid will be set to water and inflow temperature will be assumed to be constant throughout the year.

3. SOLAR THERMAL COLLECTORS

General

A solar thermal collector can be described as a device which absorbs incoming solar radiant energy and converts it to thermal energy, which is then transferred to a transport medium, usually air, water or oil. The transport medium carries the heat, via a heat exchanger, either directly to the end use, such as hot water or space heating, or to a well-insulated buffer tank, where it is stored until it is used.

When radiant energy is absorbed by the collector, the absorbing surfce must be insulated to keep the heat from going directly back to the surrounding. For the collector to be effective this insulation needs to be highly transparent to infrared radiation, to allow solar beams through, and simultaneously having a low enough thermal transmittance. In conventional solar thermal collectors this is usually done by one or more layers of glass, with air or vacuum between.

The glass however makes the collectors heavy and rigid and also requires increased maintenance since the infrared transparency is reduced when the glass is weathered.

Conventional collectors can be divided into two groups; concentrating and non-concentrating (stationary).

Concentration solar collectors usually have either a parabolic or a compound parabolic reflective surface placed behind its receiver, or an optic lens in front of the receiver. These are used to concentrate the sunbeams to a smaller area, which will then receive a higher radiation flux. This smaller area will move as the angle between the collector and the sun changes, and the receiver is therefore mounted on a mobile device, which is tracking the suns movements DeWinter, F (1990).

When heating the transport medium to temperatures approximately 50 degrees Celsius or more above the ambient temperature, concentrating collectors are usually more effective, while stationary collectors are more efficient when lower temperatures are desired.

Stationary collectors do not require a tracking device, and are therefore cheaper to produce and maintain. They have an absorbing area which is the same as the area for interception DeWinter, F (1990).

When integrating solar thermal collectors to a building climate skin, mobile tracking devises would require more maintenance and thereby reduce the lifespan of the collector, and thus also the building skin.

The required temperature for domestic hot water and space heating on the design is approximately 60 degrees Celsius, and can effectively be produced by a flat plate collector. For these reasons the design of the collector cushion is based on the principles behind flat plate stationary collectors.

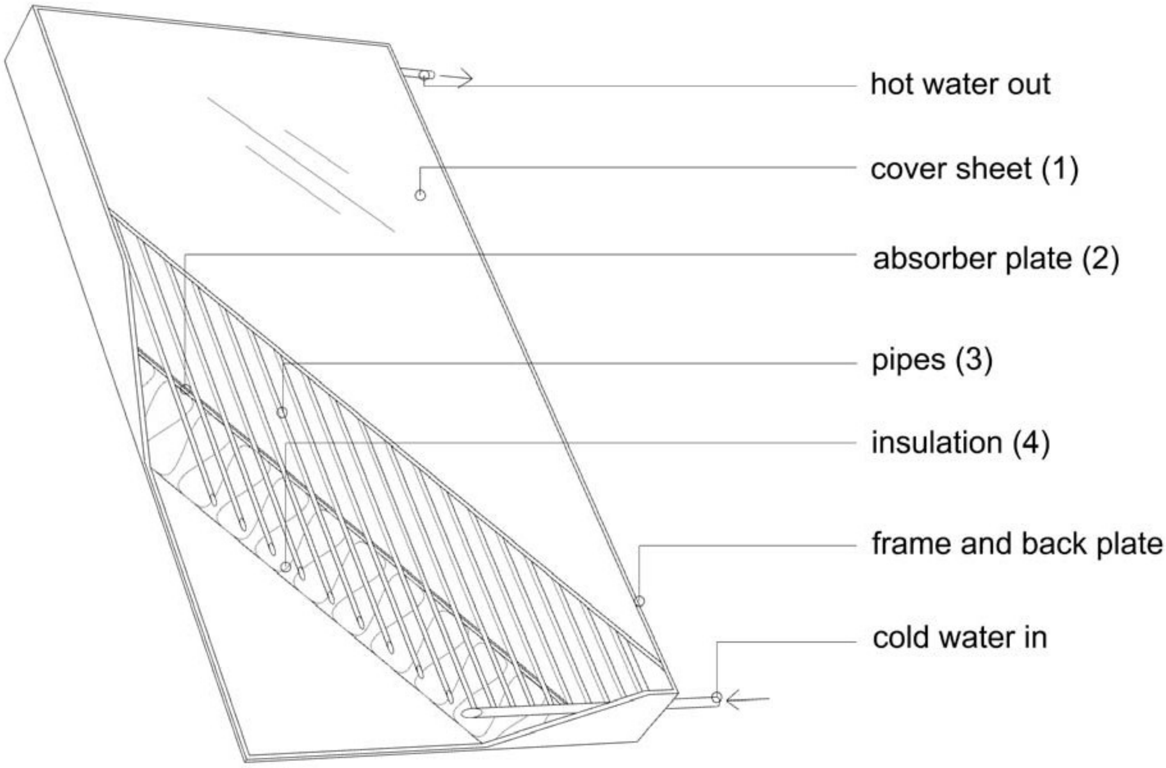

Figure 3.1 principle flat plate collector axonometric

Flat Plate Collectors

The diagram (figure 3.1) in the previous page shows the principle design of a conventional flat plate solar thermal collector. Solar beams pass through the transparent cover (1) and reaches the black surface (2). The surface absorbs a large portion of the radiation i.e transfers the radiant energy to heat energy. This energy can then be transferred to the transport fluid, which is contained in pipes (3) connected to large header tubes, and from here moved by convection to either storage or usage. The underside of the absorber plate, and the sides of the collector, are covered by insulation (4), to reduce heat losses by conduction to the sides and back. The losses outward is reduced by the transparent cover, which keeps a thin level of air in and thereby reduces conductive heat transfer. It also protects against radiation loss, since the transparent cover is permeable for short-wave radiation, but not to the long-wave thermal radiation emitted by the absorber surface. This is the same principle as the greenhouse effect. Sukhatme (2008) Mounting of stationary, flat plate collectors should be based on the geographic location. For maximum amount of radiation to be received, the plate should be facing the equator, meaning south in the northern hemisphere and north in the southern hemisphere. The tilt angle should be the same as the latitude of the location of the collector, Klein, Beckman, and Duffie (1977).

Aiming to collect as much energy as possible, with as little cost as possible means cheap production and high effectiveness, but also long effective life, by resisting damage caused by freezing, ultraviolet radiation, corrosion, clogging, dust or moisture on the glazing, and breaking of the glazing.

Ethylene Tetraflouroethylene

ETFE is a fluorine based plastic which was developed in the 1940's by DUPONT, an American chemical company. The properties making ETFE suitable for application in solar thermal collectors include a high transparency, high resistance to ultra violet radiation and self-cleansing properties, LeCuyer (2008).

When used for architectural applications the material is extruded to sheets with typically 50 μm-300 μm thicknesses. These sheets are then either stretched to a single layer membrane or inflated to cushions, usually with 2-5 sheet layers. The cushions are heat welded in the edges and then clamped together. The construction and properties of cushions used today will be further described, Robinson (2005)

ETFE Cushions in Architectural Applications

When used as a structural wall or roof, a primary structural system is needed, which supports a secondary structure with a gutter and weather flashings. Aluminium flashings are typically used to clamp the ETFE cushions to this secondary structure, Robinson (2005).

Hexagonal ETFE cushions have been constructed with a length of 11 meters across, and rhomboid cushions have been constructed with a length of 17 meter across. A large size cushion normally reduces the proportion of flashing which increases the overall heat transfer co-efficient of the system. It also contributes to decrease weight and risks of water leakage.

The cushions can be inflated by a system of a pump and hose, and normally keeps an air pressure of 200-600 kPa above atmospheric pressure.

This gives a sufficient stiffness to resist external loads such as wind and snow. The cushions can have sensors tracking weather related factors such as wind pressure and direction, temperature, snow load, humidity and dew point. This information can be used to automatically adjust the air pressure of the cushion, LeCuyer, (2008).

Pumps are used to maintain the aimed pressure in the cushion. One inflation unit can pressurize around 1000 m^2 ETFE cushions. The inflation units consists of two backward air foil blowers, which are powered by electric motors of 220 and 100 watts, where the 220 watt motor is in standby and the 100 watt motor operates about 50% of the time. When pumps are not operating the cushions can maintain their pressure for 3-6 hours, LeCuyer, (2008).

Figure 3.2 ETFE cushions in architecture (From left to right 1.The National Aquatics Centre, PTW Architects, Bejing, photo: Chris Bosse, 2. The Eden Project, Grimshaw Architects, Cornwall 2001, photo Lisa J Lai, 3. Allianz Arena, Herzog & DeMeuron, Munich 2005, photo: Ulrich Rossmann-Arup.

4. MATERIAL AND GEOMETRICAL PROPERTIES

Material Properties

ETFE is made from fluorine, hydrogen sulphate and trichloromethane, which are combined into chlorodifluoromethane. By pyrolysis, the chlorodifluoromethane is turned into tetrafluoroethylene (TFE). The tetrafluoroethylene monomer is then mixed with an ethylene monomer, and makes the ETFE copolymer. The thermal conductivity of ETFE is 0.24 W/mK. The required thickness of ETFE film to be used for cushions is approximately 100 μm. Solar transmission for one sheet is determined to approximately 0.96 at the time of installation and 0.94 after 15 years of weathering, Drobny,(2006).

Cushion Geometry

The proposed design for collector cushions is mainly based on the technique behind flat plate solar thermal collectors. The benefits of durability and low maintenance needs of the ETFE cushions are maintained by the choice of a technique without solar tracking devices or other moving parts. Figure 5.1 shows a principle design for a collector cushion.

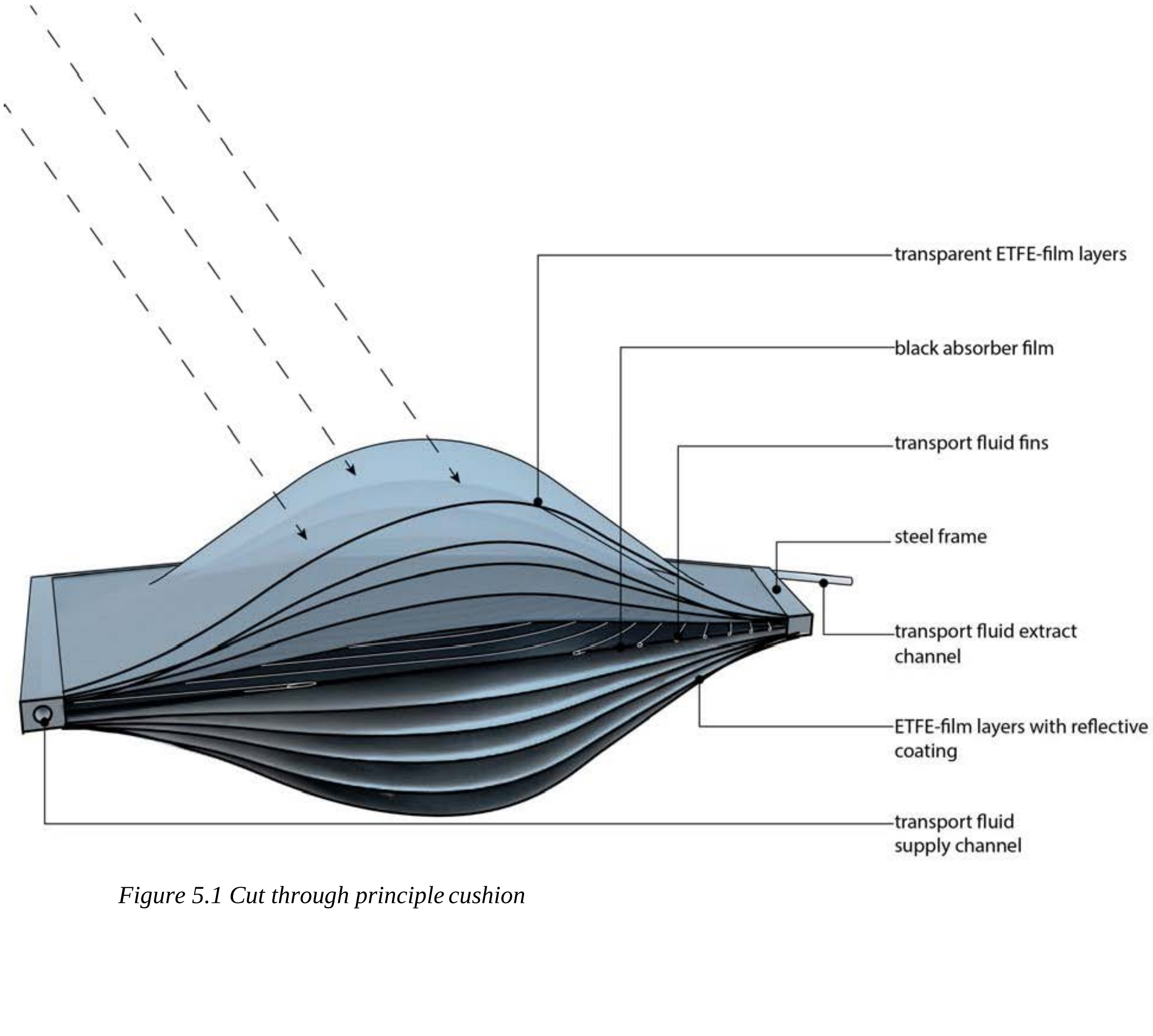

Figure 5.1 Cut through principle cushion

Construction details and waterproofing are based on standard details for ETFE facades, and include aluminium clamping, glass fibre insulation, water proofing film and a steel structure, see fig 5.2 and 5.3.

The cushions have a number of layers (to be determined in calculations) of transparent ETFE film facing the exterior. These are transparent to infrared radiation and visible light. The purpose of the multiple layers is to reduce heat transfer through convection. Together, the film layers compose the sought-after infrared transparent insulation, with the benefits of being lightweight and self-cleansing. In the centre of the cushion the absorber is located, consisting of a thin membrane. The impact of membrane material properties will be further analysed in the thesis.

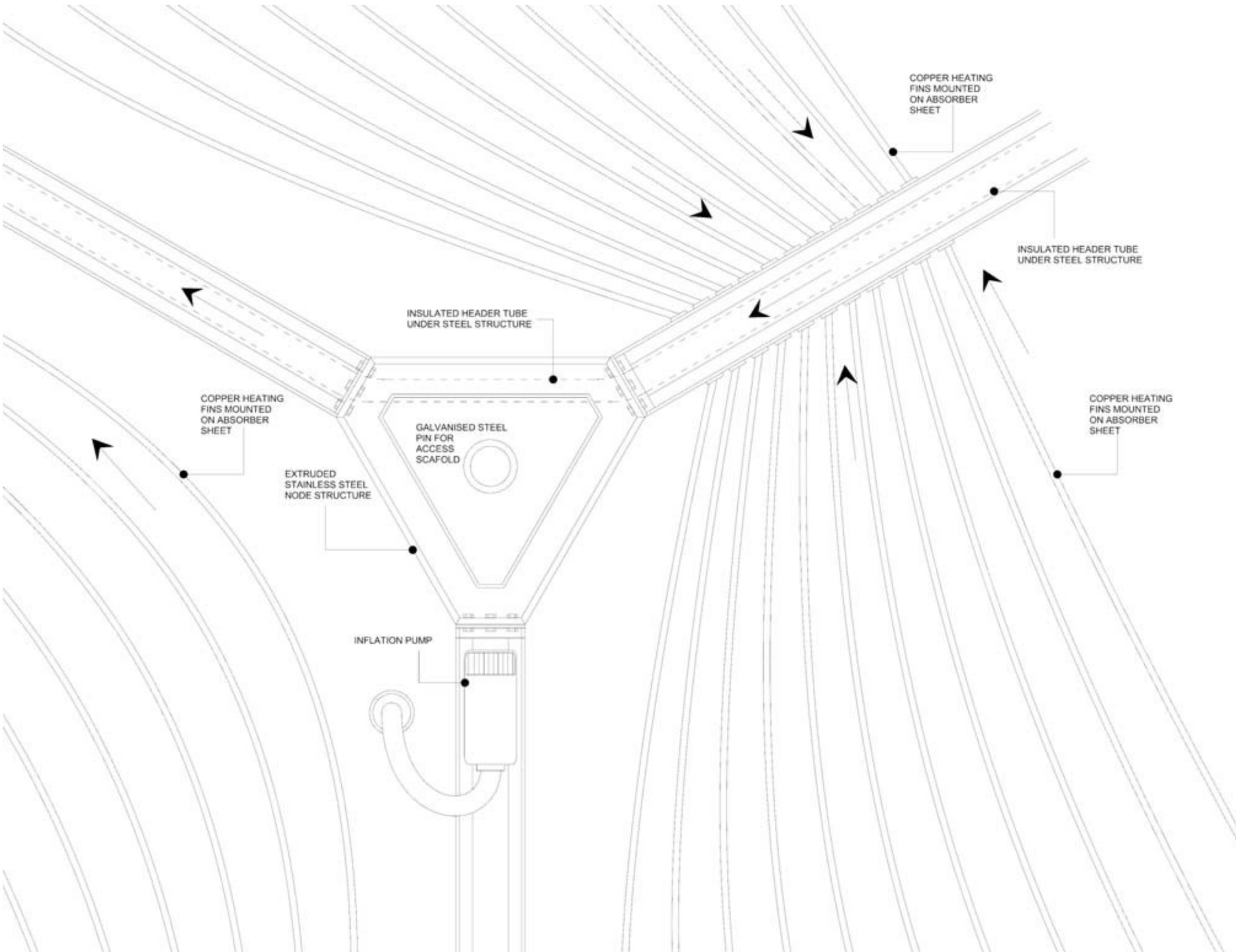

Figure 5.2 Node detail

Water for heat transport is supplied and extracted from the absorber through a water channel between the cushions and travel through the collector via channels within the membrane.

The side of the absorber facing the interior has a reflective aluminium film, reducing heat loss inwards through radiation. Further layers of ETFE film insulate the absorber from the interior through convection and conduction.

A supply air tube connects the cushion to an inflating unit that keeps a constant air pressure in the cushion but minimizes the airflow through inflated parts.

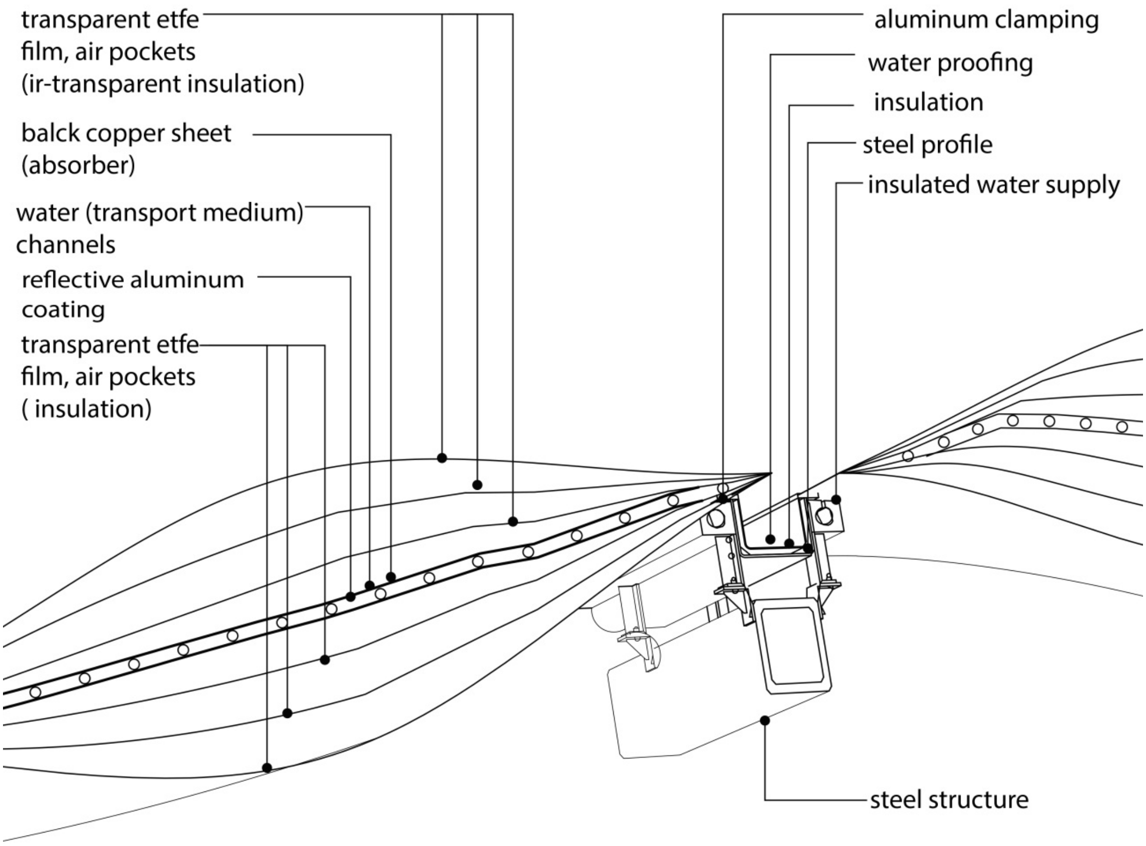

Figure 5.3 Cushion detail

The Collector in a System

As heat transfer fluid, deionized water is used. The water is kept in a storage tank, and a buffer space is included to allow different flow rates and temperatures in the system. The storage tank is connected via valves to several pumps, which each pumps a portion of water through a series of collector cushions. Each collector has a valve which senses the temperature of its exiting heat transfer fluid. This valve can switch off that circuit if beneficial, in which case the heat transfer fluid continues to the next collector cushion. Each cushion also has a separate inflation pump and a pressure sensor keeping the cushion inflated. The water temperature will gradually increase as it moves through the system. As the water exits the last cushion in its series, it reaches a heat exchanger, where the obtained heat in transferred to the hot water system. The deionized water then returns to the storage tank, from where the process is repeated. Multiple series of collector cushions will work in parallel.

The water which will be used for potable and space heating is supplied cold from the city water supply. It is pumped through the heat exchanger, and from there directed either to its end usage or to storage in a buffer tank. A secondary heating system will provide hot water when the climate does not allow sufficient hot water production by the collectors.

This process is described in a process flow diagram (figure 5.4).

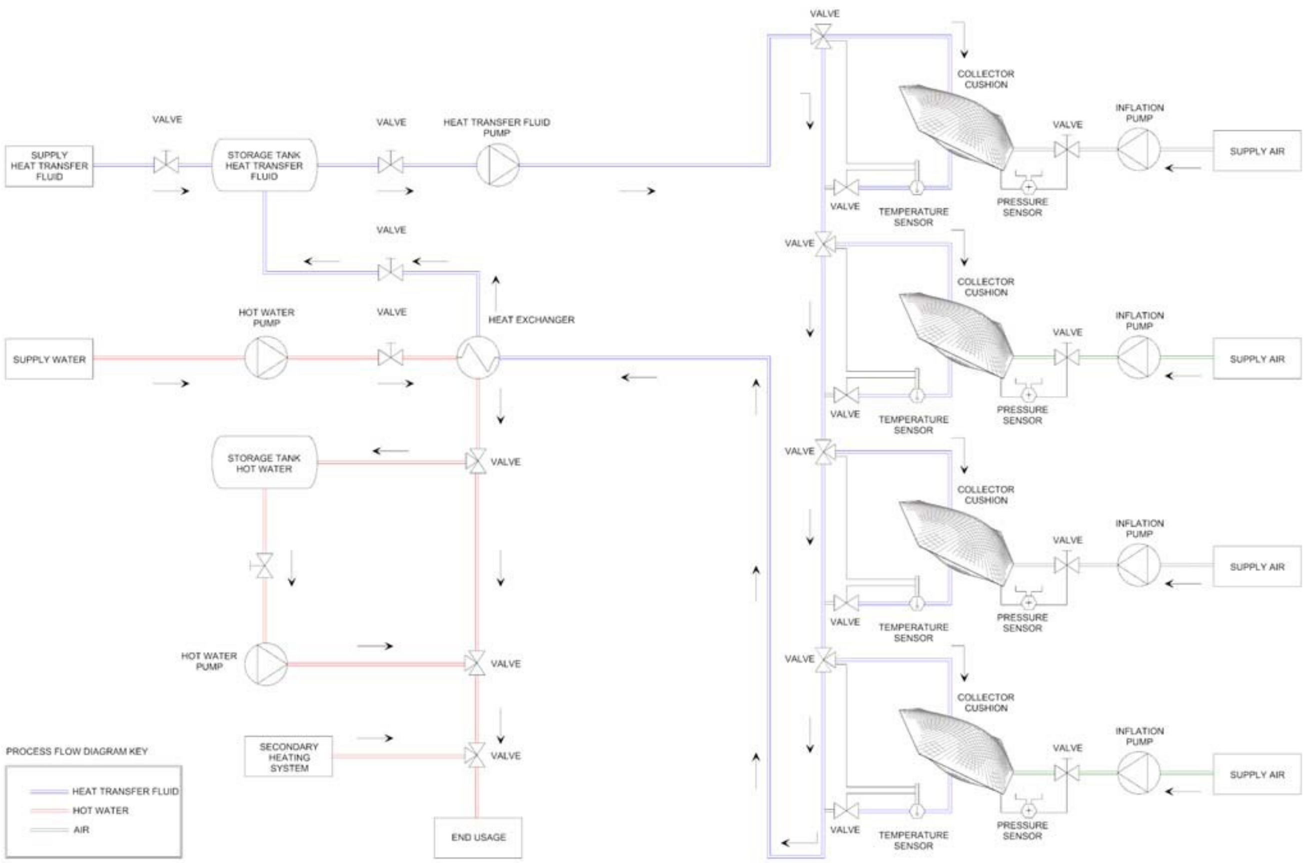

Figure 5.4 Process Flow Diagram

The series of collectors are connected to form a building climate skin as described in figure 4.6 to 4.9.

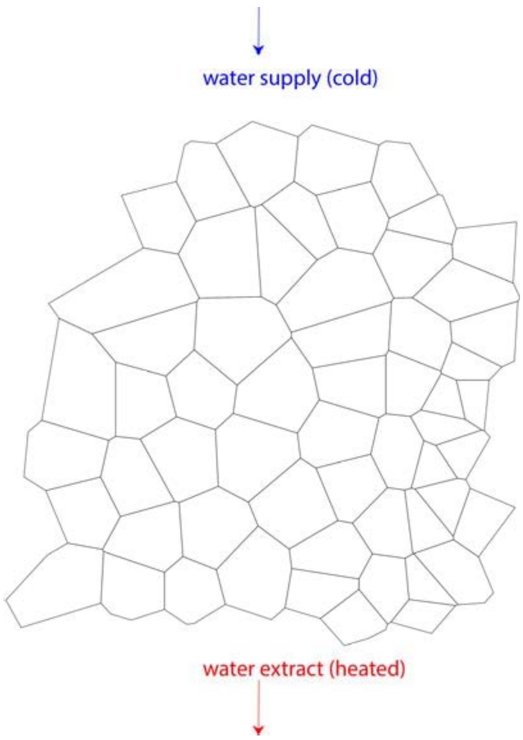

Figure 4.6 cushion grid for part of climate skin

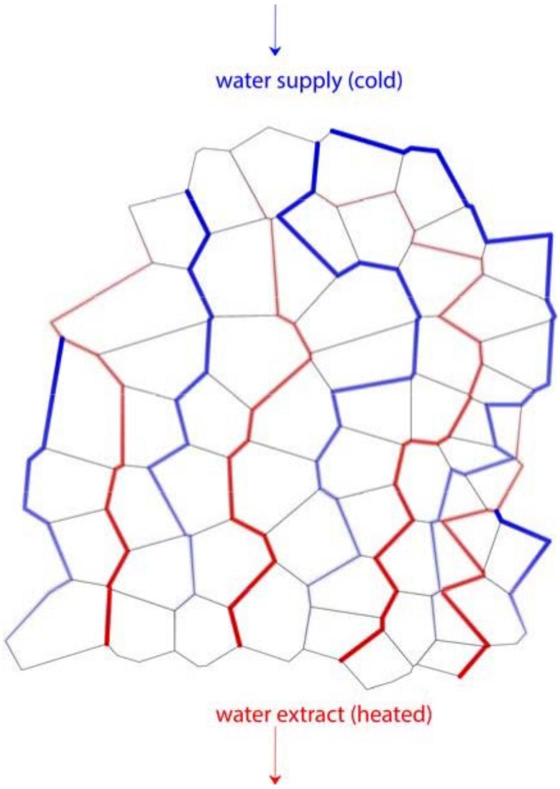

Figure 4.7 cold and hot water veins in grid (blue=cold water, red=hot water)

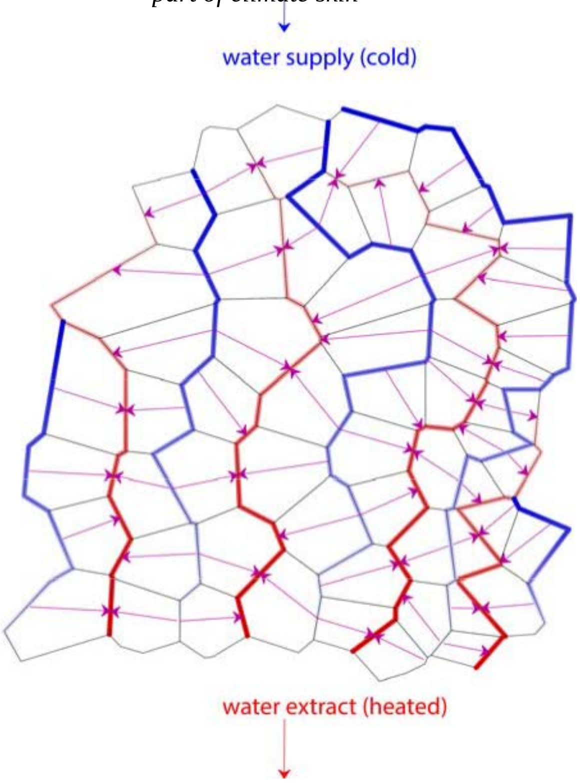

Figure 4.8 water flow direction within cushions (flow from cold vein to hot vein)

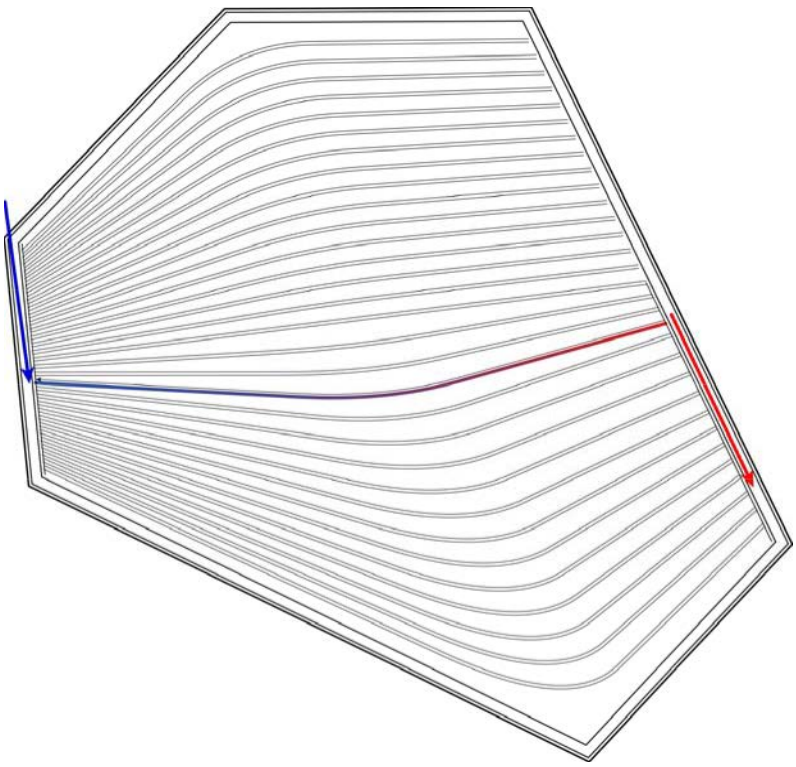

Figure 5.9 zoom in on water flow within one cushion channel, from cold vein to hot vein

5. BUILDING WITHETFE

For the purpose of design and calculations of the solar thermal cushions, a dance hall with an ETFE cushion building skin has been designed. (See picture figure 7.1)

The proposed building is designed as a tensile structure, with three steel arches stretching a cushion system. The cushions are combined in a voronoi grid, where each voronoi cell creates a cushion that functions as an individual solar thermal collector.

The steel arches meets in three points on the interior building floor. In these points hot water storage tanks and heat exchangers are installed. Water and air supply is contained in an insulated channel along the structural arches and the seams of the voronoi cells.

Geographical and geometrical data to be used for calculation of collector cushion efficiency has been collected for the proposed building.

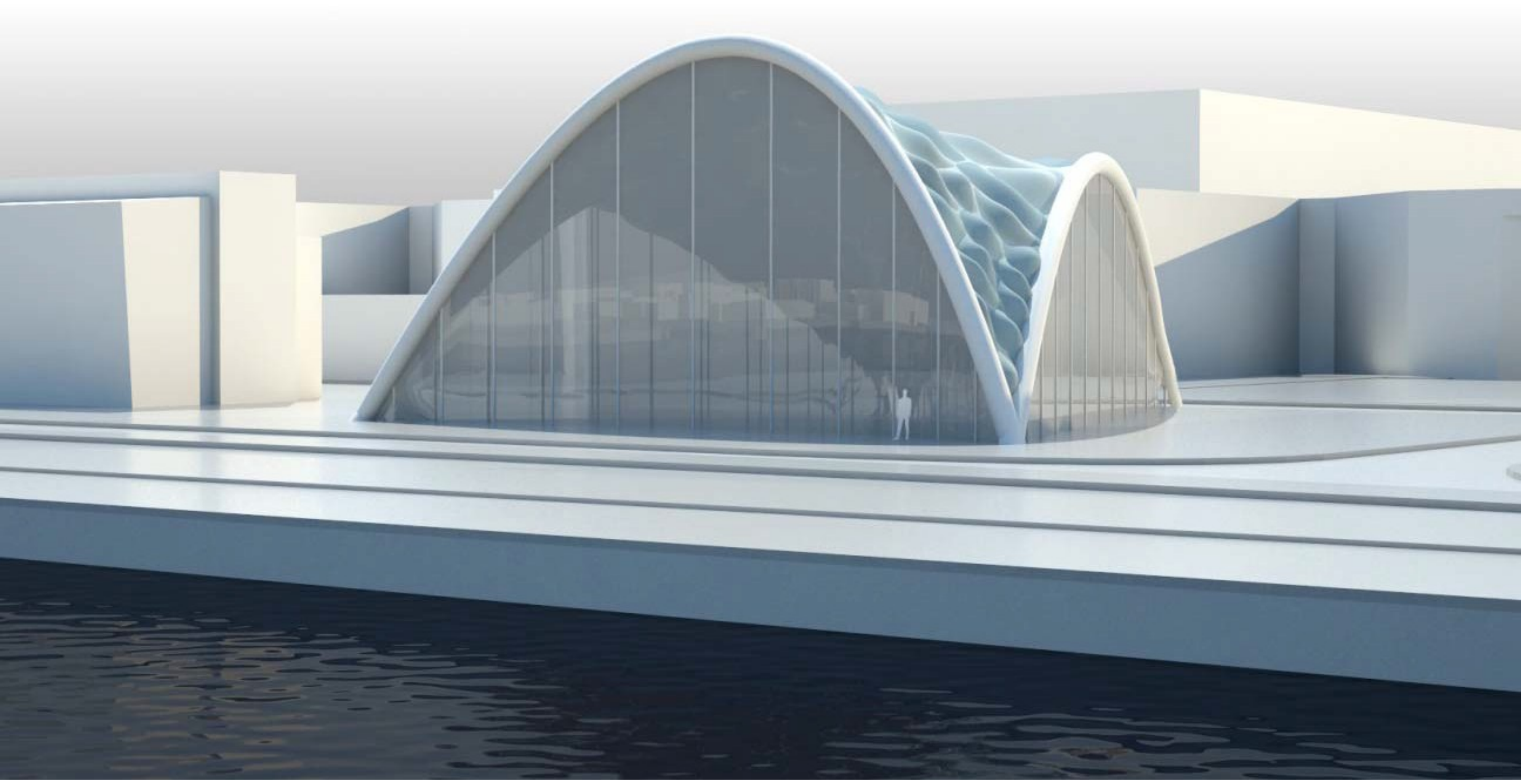

Figure 5.1 Image of building proposed building, with solar cushions as climate skin on roof and south facing wall.

Geographical Data and Function

The proposed building is located in Gävle, Sweden, at 60.6747° N, 17.1417° E.

The proposed building functions as a dance hall, including a large dance floor and changing rooms with showers, see layout in figure 7.3. Space heating is required, as well as hot water for changing rooms. The high activity level of the building occupants means that temperature of the hall can be set slightly lower than common indoor temperatures.

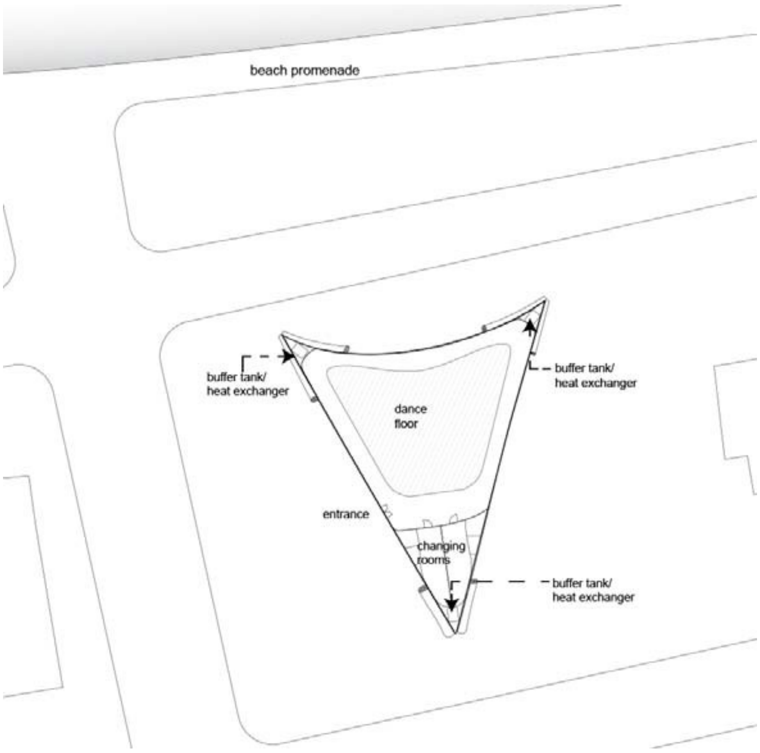

Figure 5.2 Diagrammatic plan view of proposed building

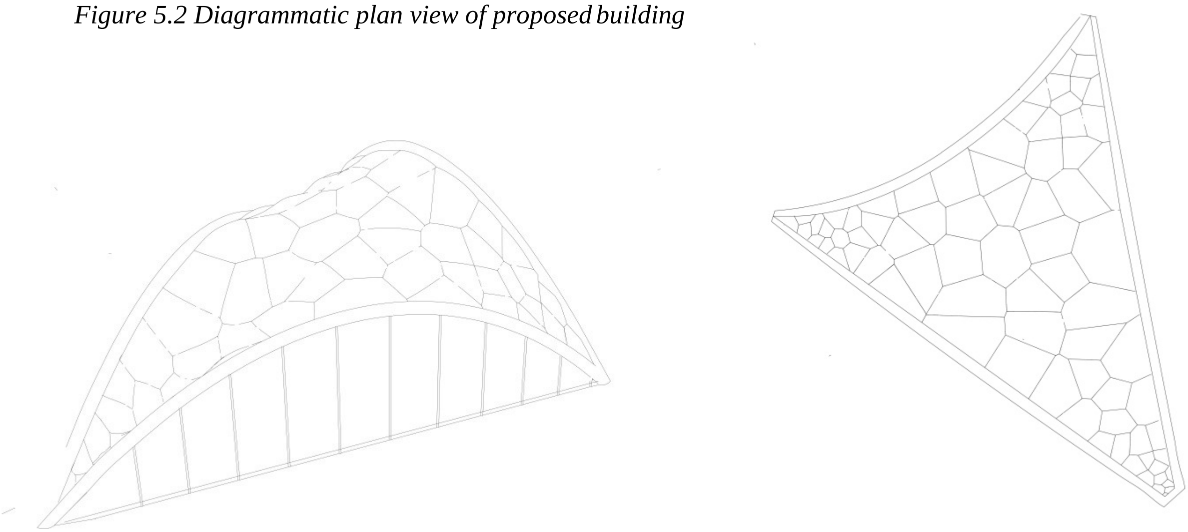

Figure 5.3 Axonometric and roof plan of proposed building; horizontal collector area 35 m^2, building volume 52 m^3.

6. ANALYSIS

Calculations

The efficiency of the proposed design is analysed to develop a functional detail solution and determine its potential as a thermal collector. The efficiency will be analysed for a typical cushion within the system, in a horizontal position.

To derive a formula to calculate the efficiency of the solar thermal cushions, the process from emitted radiation from the sun to the removed heat by the transport medium, will here be described step by step.

Solar radiation intensity, E, in W/m^2 incident to the absorber surface of the cushion varies with longitude, latitude, time of year and time of day. The actual solar radiation hitting the collector surface also depends on meteorological parameters, and is therefore used as mean values based on observations. For the specific location of the studied case, Gävle, this data can be found in figure 8.1 below, as kW/m^2, given as a mean value for each calendar month, along with mean air temperature for the same period. The data for calculations has been collected with year 2012 as a base.

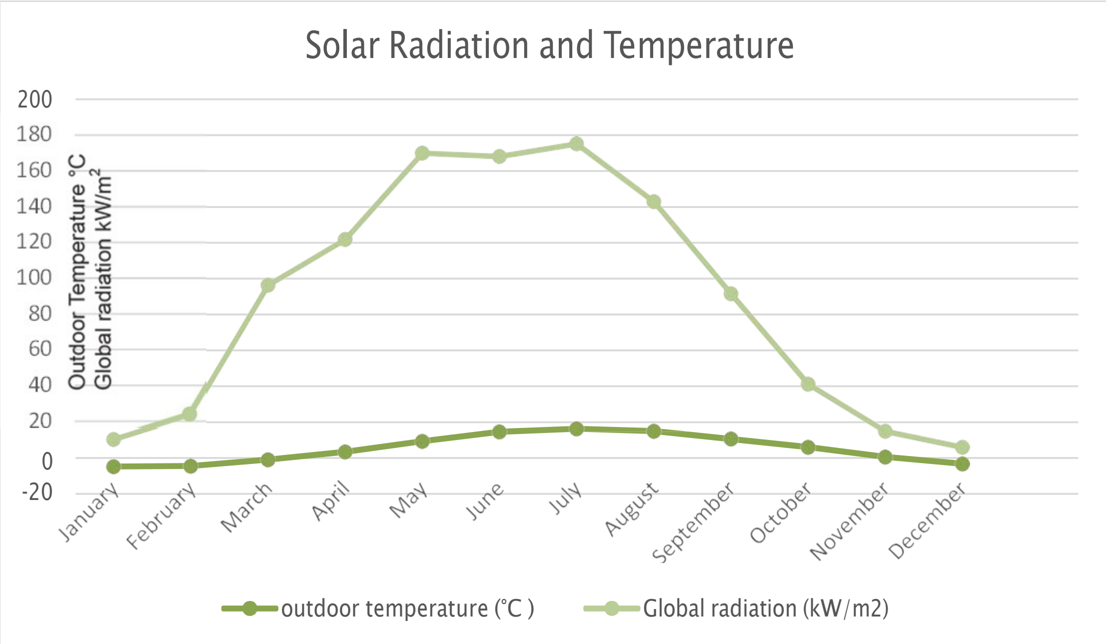

Figure 8.1 meterological data graph for Gälve 2012 (Års- och månadsstatistik, SMHI 2015-03-15)

Month	Mean Daytime Ambient Temperature c	Mean Daytime Global Irradiance W/m^2
January	-1	46,7
February	-1	120
March	3	197,7
April	8	307,3
May	14	337,2
June	19	260,3
July	20	294,1
August	20	257,4
September	15	193,8
October	9	115,6
November	5	53,8
December	2	29,6

Table 8.1 meteorological data table for Gälve 2012 (Års- och månadsstatistik, SMHI2015-03-15)

To calculate the proportion of the suns radiated energy that will be absorbed by the absorber layer, two more parameters will be taken in to account; the transmissivity of short wave radiation for the outer insulation layers, in this case one or more layers of ETFE film with air cavities in between, and the absorptivity for the material in the absorption layer.

The transmissivity (τ) of one layer of (200 µm thick) ETFE film is 96%, which is higher than the ones of glass and polycarbonates commonly used in solar thermal applications, which typically ranges from 70% to 91% as shown in the table below.

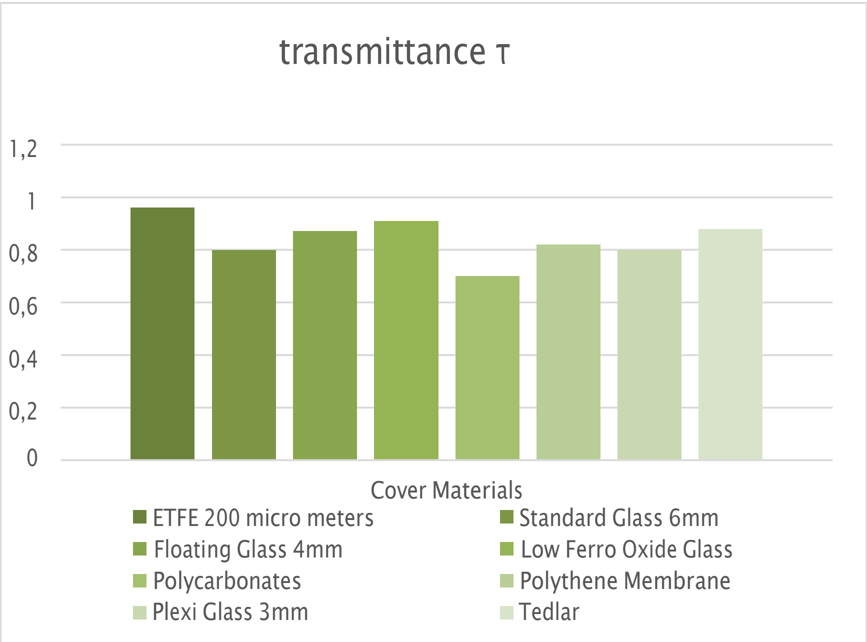

Figure 8.2 transmittance (dimensionless)

for ETFE (LeCuyer, 2008) and Common Solar Thermal Collector cover materials (Jercan, 2006)

When radiation is absorbed by the absorber layer, it is converted into heat, which can either be emitted back to the surroundings as long wave radiation or be conducted to the transport medium.

Material	α
non selective	
Pure Iron	0.44
Pure Aluminium	0.1
Gilt Copper	0.35
Oxide Steel Sheet	0.74
Black Painted Steel Sheet	0.95
Graphite	0.78
Funingina	0.96
White paint	0.15
selective	
Black Chrome on Nichel Surface	0.95
Porpsity Ceramics on Steel Surface	0.96
Black Nichel Oxide on Aluminim Surface	0.89
Copper Oxide on Copper Surface	0.9

Table 8.2 absorbtion factor for common absorber materials. Jercan,(2006)

The combined effect of transmittance and absorptivity parameters can be referred to as the optical factor, O.

$$O=\tau_1\cdot\tau_2\cdot\ldots\cdot\tau_n\cdot\alpha \qquad (1)$$

Where n is the number of layers of ETFE film. Jercan (2006)

Figure 8.5 shows the optical factor of a cushion with a varying absorber material and number of ETFE layers. The table shows the highest optical factor, 92%, for a one layer cushion with an absorber sheet of porosity ceramics on steel and the lowest optical factor, 8%, for a 5 layer cushion with a pure aluminium absorber.

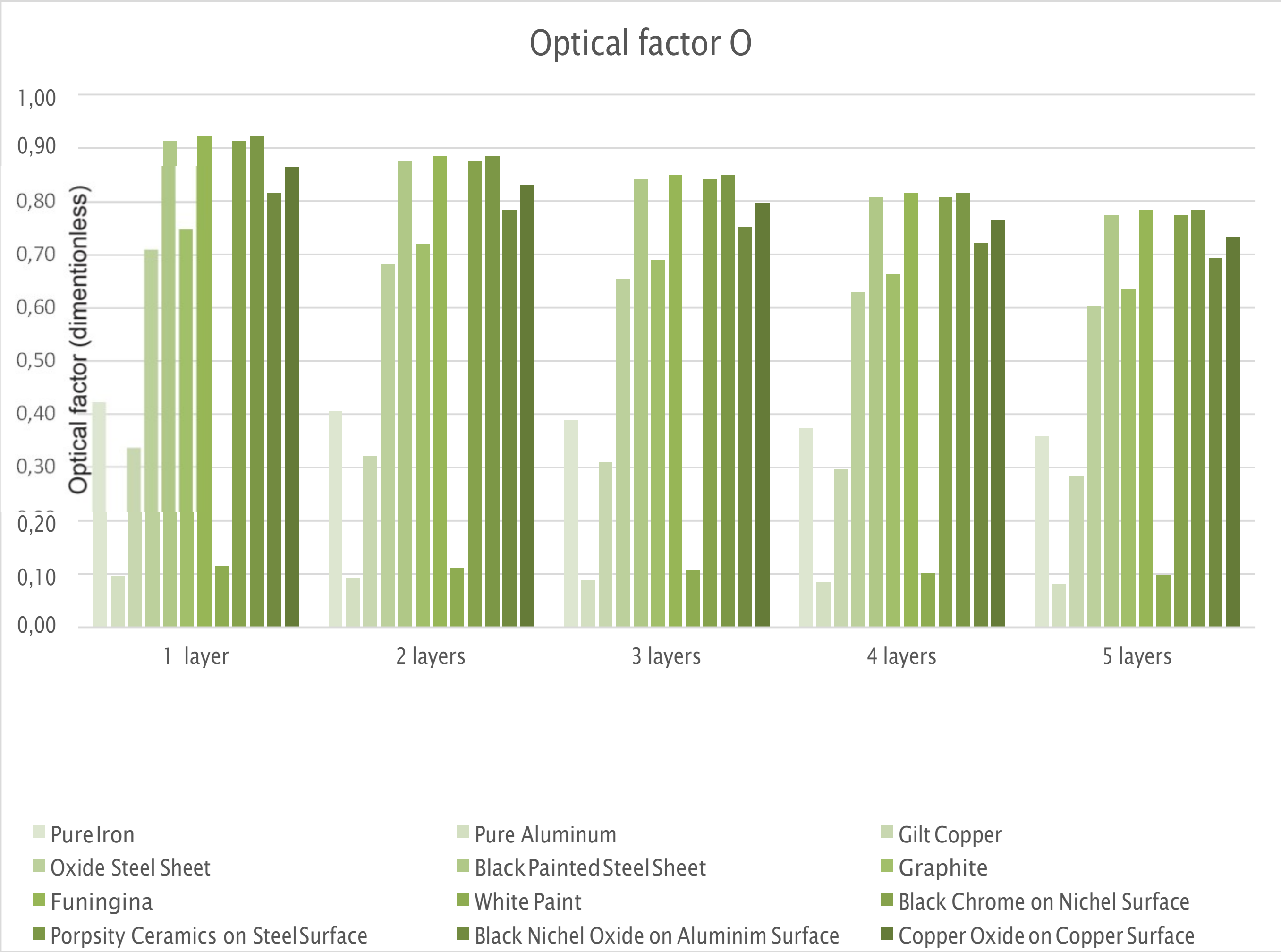

Figure 8.3 Optical factor O for cushion configurations based on α –values in table 8.2

The heat derived from the absorption plate in W can be described as

$$Q_i = O \cdot E \cdot A, \qquad (2)$$

Where A is the area of the absorber plate incident to the sun, E (W/m^2) is the radiation on the solar thermal collector from the sun, and O is the optical factor. Jercan (2006)

The absorbed energy will be transferred into heat, leading to a temperature difference between the absorber surface and the environment. The temperature difference between absorber and surrounding will lead to transport of heat from the absorber surface, which causes thermal losses. The thermal losses are proportional to the temperature difference between the absorption plate and the environment.

The rate of the heat loss, Q_{out}, depends on the overall heat transfer coefficient U_L (W/m^2K), the absorber area incident to the sun (m^2) and the cushion average temperature (°C).

$$Q_{out}=U_L \cdot A(T_c-T_a) \quad (3)$$

Where T_c is the cushion average temperature, T_a is the temperature of the surrounding atmosphere and A is the area of the absorber surface incident to the sun. Jercan (2006)

Since ETFE cushions are relatively new as building components, there is limited amounts of data is available regarding their properties. Experimentally determined heat transfer coefficients can be found for commonly used cushion configurations. This is usually limited to cushions with 2-5 layers of film, which are economically efficient when used as a climate skin. For the purpose of solar thermal collection, it is useful to study cushions with a larger number of layers and thus higher insulation values. For this reason the u-value for cushions with 1-20 layers have been determined analytically in MATLAB. The result of the calculations is close to experimental values for cushions with 2-5 layers obtained from (LeCuyer, 2008).

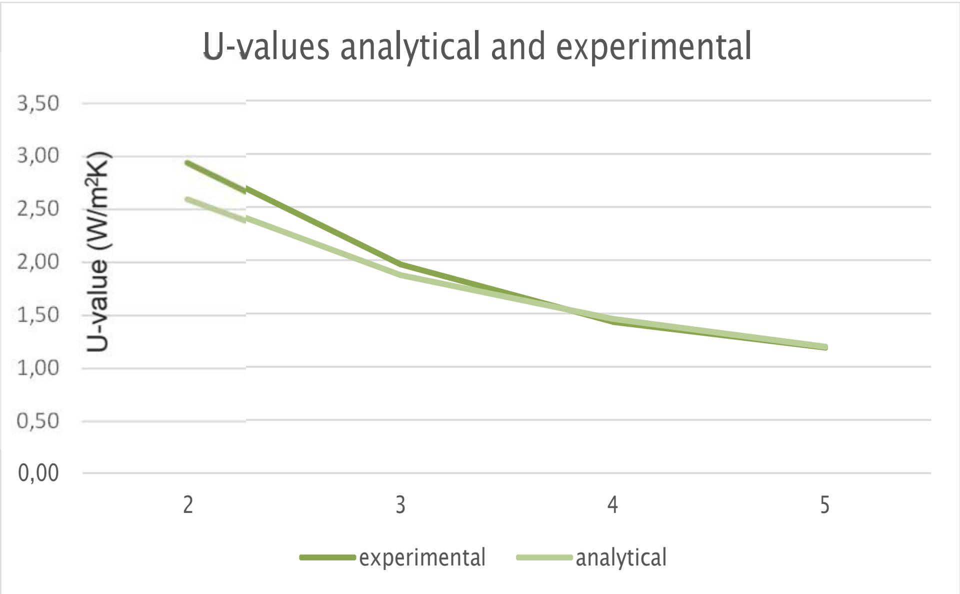

Figure 8.4 Comparison between experimentally and analytically obtained u-values

The experimentally obtained U-values are slightly higher than the analytically obtained values, likely due to product imperfections and leakages which are not considered in analytically determined values. As the number of ETFE layers increase this discrepancy reduces.

The figure below (figure 8.5) shows the overall heat transfer coefficient for an ETFE cushion with 1-20 layers, in comparison with transmittance for the same cushion:

Calculations are performed in MATLAB and codes are presented in appendix 1.

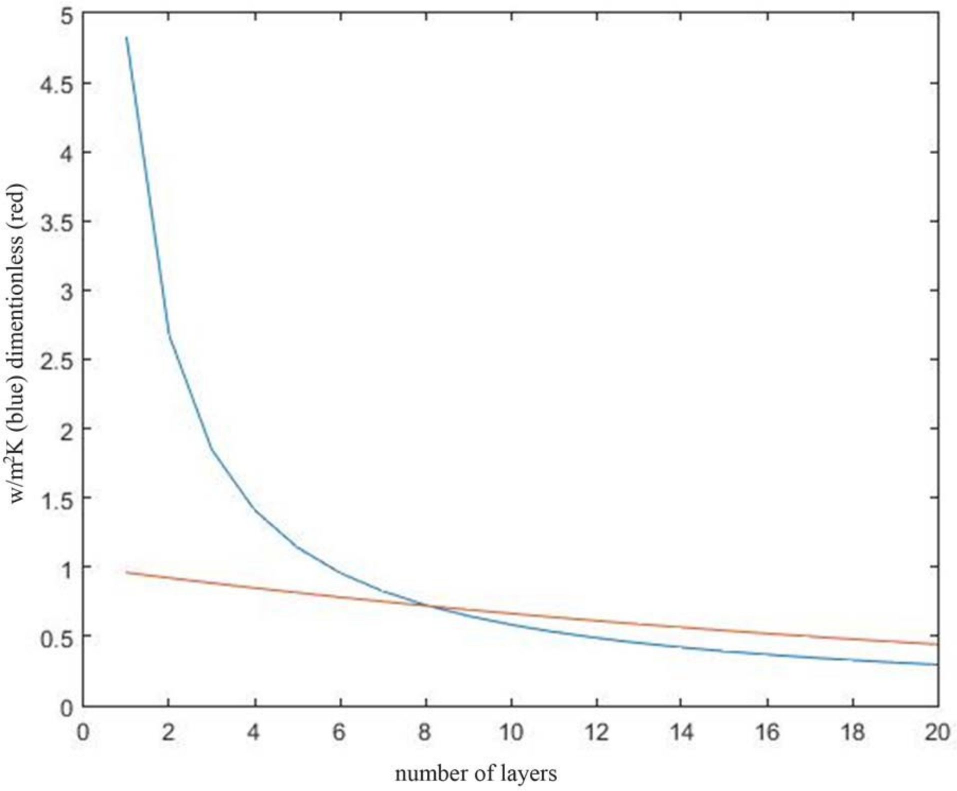

Figure 8.5 Overall heat transfer coefficient (blue) and transmittance (red) for 1-20-layer cushion

The rate of useful energy extracted, Q_u, expressed as rate of extraction under steady state conditions, is proportional to the rate of useful energy absorbed by the cushion, minus the amount lost to its surroundings. This can be written as:

$$Q_u=Q_i-Q_{out}=O\cdot E\cdot A-U_L\cdot A(T_c-T_a) \quad (4)$$

Brownson, J.R.S (2013).

However, determining the absorber average temperature T_c is difficult. Thus reason a quantity called the "the heat removal factor" has been defined, with which the inlet temperature can be divided, to then substitute the absorber average temperature.

The heat removal factor, F_R is expressed as:

$$F_R=((\dot{m}\cdot c_p)/(U_L\cdot A)) \cdot (1-\exp(-1\cdot (F'\cdot U_L\cdot A/(\dot{m}\cdot c_p)))) \qquad (5)$$

Smith, C, Weiss, T (1977)

Where $\dot{m}$ is the mass flow rate of the fluid through the absorber fins in kg/s. In this model $\dot{m}$ is set to 0.02·A, according to the ASHRAE standard for glazed flat-plate liquid-type solar thermal collectors. c_p is the specific heat capacity of water and F' is the collector efficiency factor, determined by

$$F'=1/(w\cdot U_L\cdot(1/(U_L\cdot (w-d_o)\cdot\Phi+d_o)+ 1/(\pi\cdot d_i\cdot h_f)))$$

Smith, C, Weiss, T (1977)

Where w is the average distance between fluid fins, d_o is the outer diameter of the fins, d_i is the inner diameter of the fins and h_f is the heat transfer coefficient on the inside of the absorber fins as;

$$h_f=Nu\cdot c_w/l \qquad (6)$$

where Nu is the Nusselt number for laminar flow, c_w is the specific heat capacity for water and l is the length of the fins.

Φ is calculated as

$$\Phi= \tanh((m_b\cdot (w-d_o)/2))/(m_b\cdot (w-d_o)/2) \qquad (7)$$

And

$$m_b=\sqrt{(U/(c_a*t))} \qquad (8)$$

where c_a is the heat capacity of the absorber material and t is the thickness of the absorber sheet, Brownson, J.R.S (2013).

The maximum possible useful energy gain will occur when the whole cushion is at the inlet fluid temperature. The actual useful energy gain, Q_u, is the product of the collector heat removal factor, F_R, and the maximum possible useful energy gain. This means that

$$Q_u=F_R\cdot A\cdot [E\cdot O-U_L\cdot (T_i-T_a)] \qquad (9)$$

Smith, C, Weiss, T (1977)

This equation is equivalent to the "HottelWhillier-Bliss equation", commonly used in efficiency calculations for flat plate collectors.

From the useful energy gain, the cushion efficiency, n, can be determined as

$n=Q_u/(E\cdot A)$ (10)

and the water outflow temperature T_{out} can be determined as

$T_{out}=(T_i+Q_u/(\dot{m}\cdot c_p\cdot A))$ (11)

Jercan, AS (2006)

Cushions with $1m^2$ absorber area, with a horizontal position have been analysed with these equations using MATLAB software. Cushions have been tested with 1-20 layers of ETFE-film in the given location. Figure 8.8 the variation in useful energy gain, as average for one year, for 1-20 layers of ETFE film. The highest average energy gain is obtained with a 16 layer cushion, 73,5 w/m^2.

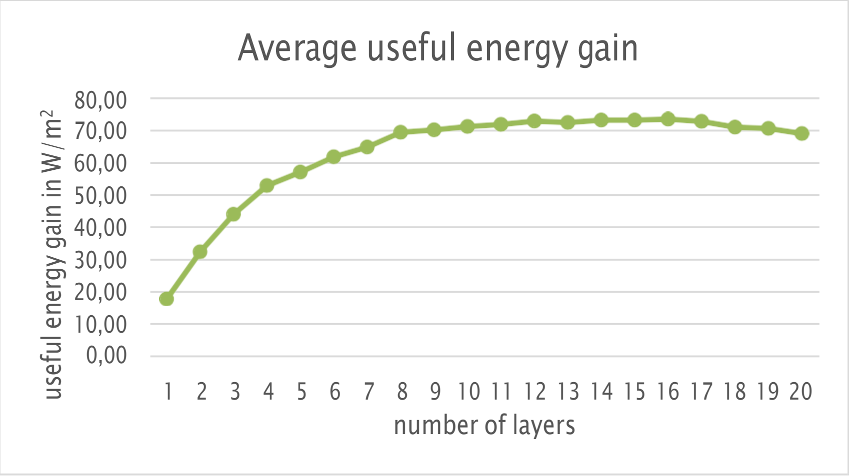

Figure 8.6 Year average useful energy gain for 1 m^2 collector area based on meteorological data for 2012

The average outflow temperature, which varies strongly with the mass flow rate, have been tested with the same number of ETFE layers. The result for a flow rate set to 0,5 g/m^{2}s is shown in diagram 8.7. The highest average temperature is reached for a 16 layer cushion, and is 47,7 °C.

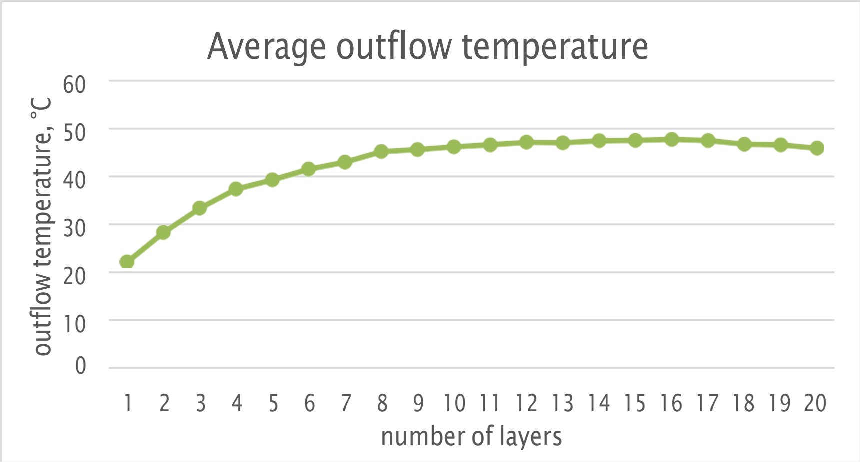

Figure 8.7 Year average outflow temperature based on meteorological data for 2012

The average efficiency has also been determined, and is presented in figure 8.8 A 16 layer cushion has the highest efficiency. MATLAB code and calculations are presented in appendix 1.

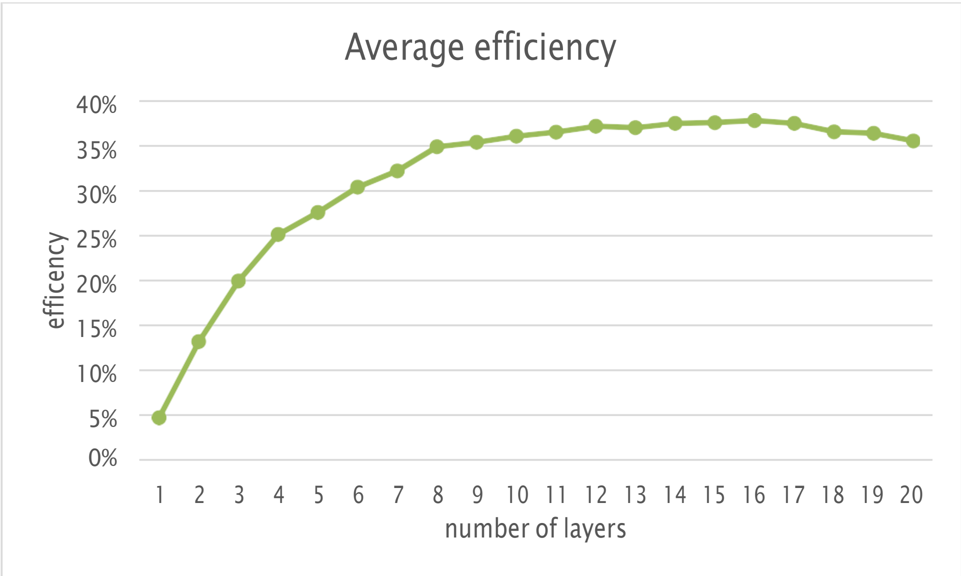

Figure 8.8 Efficiency for cushion depending n number of layers

For a 16 layer cushion, diagrams are also presented to show how useful energy gain, outflow temperature and efficiency vary over the year.

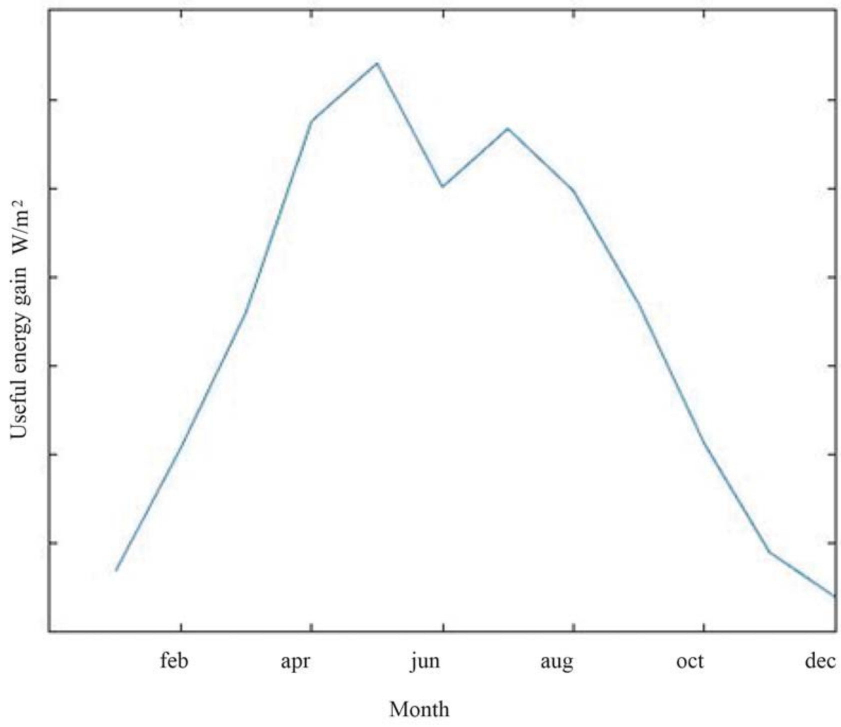

Figure 8.9 Useful energy gain W/m^2 over one year for 16 layer cushion

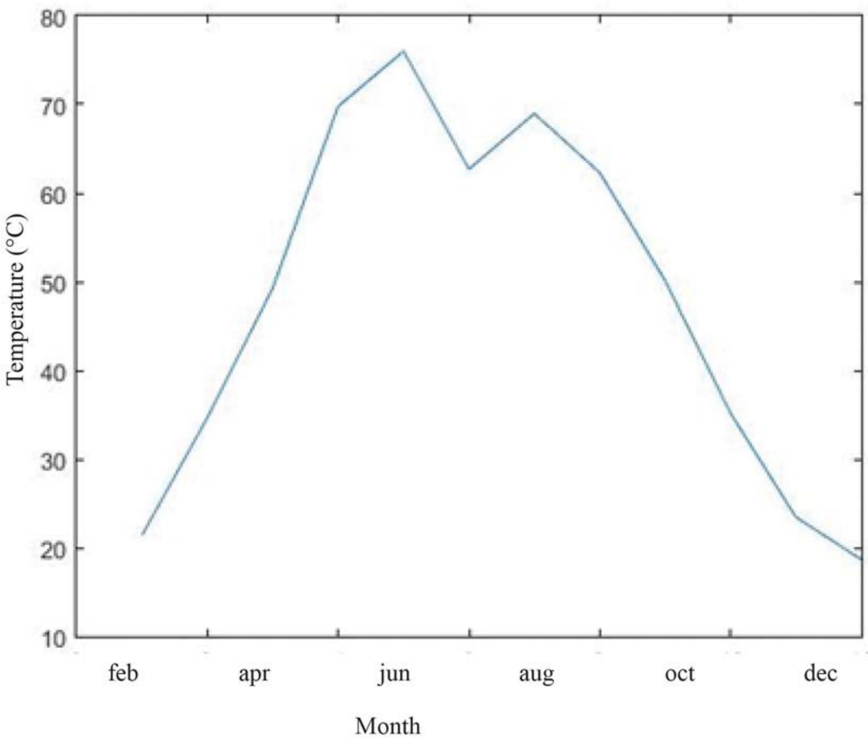

Figure 8.10 Outflow temperature °C over one year

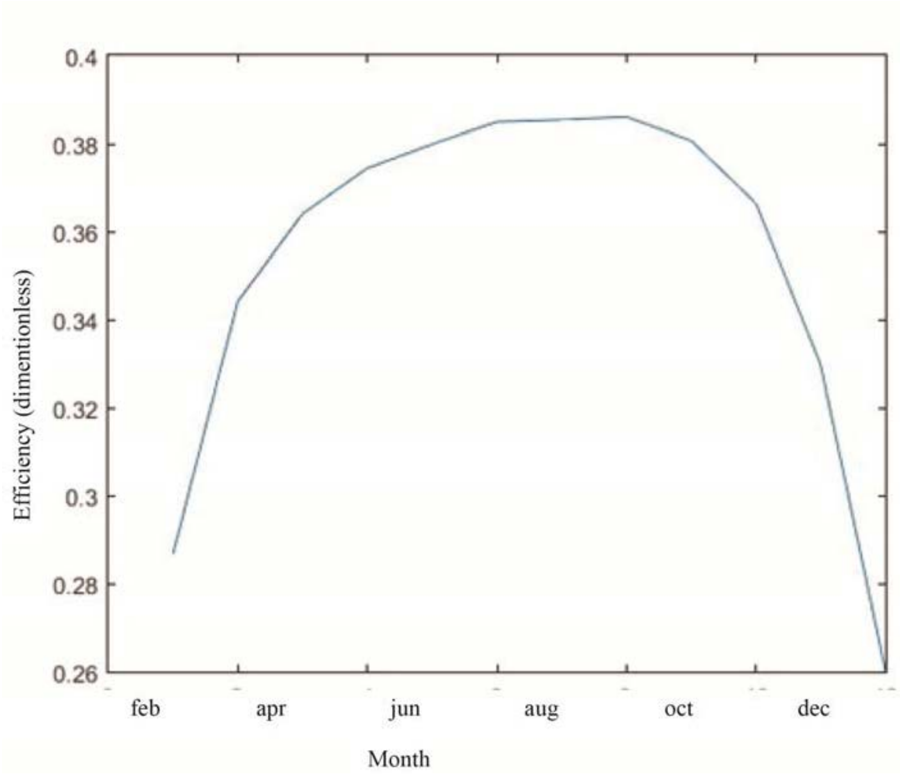

Figure 8.11 Efficiency over one year

Figures describing useful energy gain and temperatures both have a local minimum for June. This is due to metrological reasons; a low irradiance in June in the year for which data has been collected (2012).

The efficiency takes irradiance in to account, and thus it does not have a local minimum in June.

MATLAB code and calculations are presented in appendix 1.

It is also useful to investigate how climate effects the ideal cushion configuration. For this reason climate data has also been collected for Sydney, Australia, 2012. Corresponding calculations were performed for efficiency with various number of layers. A comparison with cushions located in Gävle, Sweden, can be found in table 8.14 below.

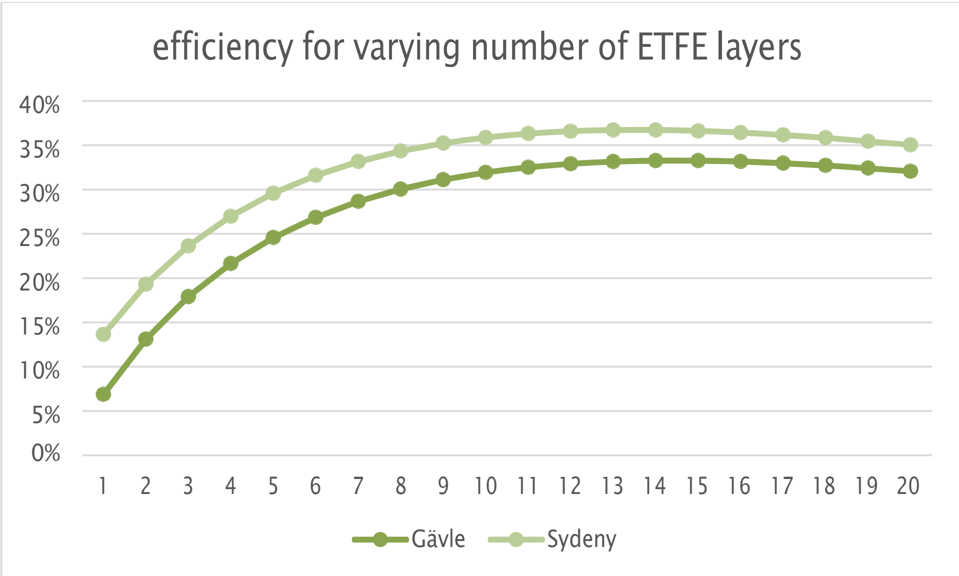

Figure 8.12 Efficiency comparison between Gävle and Sydney

For comparison, calculations were performed for the same cushion operating in a different climate; in Sydney, Australia. The collector is slightly more effective in this climate, and its optimal configuration has 2 less layers of ETFE. This is natural since the insulation is less important in a warmer climate.

7. DISCUSSION

The highest efficiency is obtained with a 14 layer cushion with an absorber of porosity ceramics on a steel sheet. This reaches a yearly average efficiency of 33.25% and an average outflow temperature of 46 °C. This can be compared to common flat plate collectors which normally has an efficiency of 40-50% for similar outflow temperatures. The lower efficiency of the collector cushion can be explained by the relation between the overall heat transfer coefficient and the transmittance. Though ETFE has a high transmittance for a single sheet, the number of layers required for insulation will reduce the efficiency of the cushion. The optimal configuration, with 14 layers of ETFE has a transmittance of 56.5%, to be compared with the transmittance of a glass cover for a flat plate collector with a transmittance of 80-91%.

The efficiency of collector cushions would closer to the efficiency of flat plate thermal collectors in warmer climates, where the optimal cushion configuration has fewer layers of ETFE and the transmittance will be higher.

However, integrating solar thermal collection in the climate skin gives a large absorber area. For the proposed building the average useful energy gain will be 2,3 kW. This equals heating water for a shower running continuously 6.3 hours per day, assuming a shower consuming 420 litres per hour heated from 12 °C to 30 °C .This could be considered sufficient for a small dance studio. The efficiency of the system is lower in the winter months (minimum 25.9% for January) and higher in the summer months (maximum 36.8% for July) since transmission losses are lower when surrounding air temperature is higher. A secondary heating system, operating only in winter months could be considered.

The system proves to be less efficient than common solar thermal collectors, and should not replace flat plate collectors when considering only efficiency. The possibilities of integrating heating system and architecture is however a possibility which could be considered when constructing ETFE- buildings, which have grown in popularity in recent years. The large absorber area will generate ahigh output. For an architectural point of view, it is interesting to imagine a building which aims to express not only its structural systems but also thetechnology behind other physical systems, especially in a time when energy efficiency and sustainable development has become highly important.

The technology behind flat plate thermal collectors was a useful base for the design, but further studies could include investigating other absorber materials than the ones used in traditional flat plate collectors.

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9. APPENDIX1

MATLAB code

```
clc
clear

%METEROLOGICAL DATA, Stockholm, PER MONTH:
%(incident solar radiation on horisontal surface w/m2,
%mean daytime temperature,degrees celcius)

jan=[46.7,-1];
feb=[120.0,-1];
mar=[197.7, 3];
apr=[307.3, 8];
may=[337.2, 14];
jun=[260.3, 19];
jul=[294.1, 20];
aug=[257.4, 20];
sep=[193.8, 15];
oct=[115.6, 9];
nov=[53.8, 5];
dec=[29.6, 2];

year=[46.7, -1; %jan
    120.0, -1; %feb
    197.7, 3; %mar
    307.3, 8; %apr
    337.2, 14; %may
    260.3, 19; %jun
    294.1, 20 %jul
    257.4, 20 %aug
    193.8, 15 %sep
    115.6, 9 %oct
    53.8, 5 %nov
    29.6, 2] %dec

%inlet temperature
Ti=15
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%
%MATERIAL DATA ETFE
%(number of film layers, thermal transmittance)
n1=[1, 5.6];
n2=[2, 2.9];
n3=[3, 1.9];
n4=[4, 1.4];
n5=[5, 1.18];
n6=[6, 0.98];
n7=[7, 0.85];
n8=[8, 0.71];
n9=[9, 0.65];
n10=[10, 0.59];
n11=[11, 0.54];
n12=[12, 0.49];
n13=[13, 0.46];
n14=[14, 0.42];
n15=[15, 0.39];
n16=[16, 0.36];
n17=[17, 0.34];
n18=[18, 0.33];
```

```
n19=[19, 0.31];
n20=[20, 0.30];

%ETFE transmissivity
tao= 0.96;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%

%CHEMICAL PROPERITES
%specific heat capacity for water
cp = 4200;
%thermal conductivity of fluid (water)
kw=0.6;
%thermal conductivity for absorber sheet copper
ca=401
%absorption factor
alpha = 0.96
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%
%VARIABLES
%area in square meters
A=1;
%month
M=jan;
% mass flow rate in kg/s, set to 0,02*area according to ashrae
standard
mdot=0.0005*A;
%cushion layers
N = input('set number of ETFE layers n1-n20');
%u-value for cushion depending on nbr of layers
U = N(1,2);
%atmosphere temperature
Ta = M(1,2);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%

%GEOMETRICAL PROPERTIES

%average distance between fins in meters, centre to centre
w=0.1;
%outer fin diameter in meters
do=0.0137;
%inner fin diametre in meters
di=0.0125;
%length of fins in meters
l=1;
%nusselt number for laminar flow
Nu=3.66;
%thickness of absorber sheet in meters
th=0.0001;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%

%calculate heat transfer coefficient on inside of fin
hf=Nu*kw/l;



%Calculate opical factor O
```

```
O=(tao^N(1,1))*alpha;

%define matrices
Qi=zeros(1,12);
Qu=zeros(1,12);
Toa=zeros(1,12);
n=zeros(1,12);

for i=1:12


% Calculate received thermal radiation Qi
Qi(1,i)=O*year(i,1)*A;

%%%%%%%%%%%%%% TO FIND HEAT REMOVAL FACTOR
%calculate mb
mb= sqrt(U/(ca*th));

%calculate fi
fi=tanh((mb*(w-do)/2))/(mb*(w-do)/2);


%calculate effectiveness
fprim= 1/(w*U*(1/(U*(w-do)*fi+do)+ 1/(pi*di*hf)));

%calculate heat removal factor
FR=((mdot*cp)/(U*A))*(1-exp(-1*(fprim*U*A/(mdot*cp))));

%useful energy gain (hottel-whiller-bliss-equation)
Qu(1,i)=FR*A*(Qi(1,i)-U*(Ti-year(i,2)));


%outflow temp
Toa(1,i)=(Ti+Qu(1,i)/(mdot*cp*A));


%efficiency
n(1,i)=Qu(1,i)/(year(i,1)*A);


end

disp ('Useful energy gain')
Qu

disp ('Actual outflow temperatrue')
Toa

disp ('cushion efficency')
n

% months=[jan;feb;mar;apr;may;jun;jul;aug;sep;oct;nov;dec]
figure(01)
plot(1:12,Qu)
figure(02)
plot(1:12,Toa)
figure(03)
```

```
plot(1:12,n)

%
% figure(plot(1:12,Qu))
%
% figure(plot(1:12,Toa))
%
% figure(plot(1:12,n))

Qutot=sum(Qu(1:12));
Toatot=sum(Toa(1:12));
ntot=sum(n(1:12));
QuA=Qutot/12
ToutA=Toatot/12
nA=ntot/12
```

MATLAB output

year =

46.7000	-1.0000
120.0000	-1.0000
197.7000	3.0000
307.3000	8.0000
337.2000	14.0000
260.3000	19.0000
294.1000	20.0000
257.4000	20.0000
193.8000	15.0000
115.6000	9.0000
53.8000	5.0000
29.6000	2.0000

Ti =

15

ca =

401

alpha =

0.9600

set number of ETFE layers n1-n20n16

Useful energy gain

Qu =

Columns 1 through 10

13.3881 41.2906 71.9653 115.0573 128.0850 100.1836 113.3242 99.3539 73.7723 42.3587

Columns 11 through 12

17.7366 7.7017

Actual outflow temperatrue

Toa =

Columns 1 through 10

21.3753 34.6622 49.2692 69.7892 75.9928 62.7065 68.9639 62.3114 50.1297 35.1708

Columns 11 through 12

23.4460 18.6675

cushion efficency

n =

Columns 1 through 10

0.2867 0.3441 0.3640 0.3744 0.3798 0.3849 0.3853 0.3860 0.3807
0.3664

Columns 11 through 12

0.3297 0.2602

QuA =

68.6848

ToutA =

47.7070

nA =

0.3535

APPENDIX 2

MATLAB code cushion u-value

```
%u-value calculation

Rso=0.04;
Rsi=0.04
Re=0.0001/0.24;  %film thickness / etfe thermal conductivity
lambdaair=0.21; %thermal conductivity cavity (unventialated
horisontal, uppward flow 10-50mm thickness)
tair=0.032; % average thickness air cavity
% n=input('set number of layers')
Rair=tair/lambdaair; %thermal resistance air cavity
tf=0.96; %optical transmittance for one film layer



%define matrix
U=zeros(1,20);
T=zeros(1,20);

for i=1:20;
Rtot=Rso+Re+Rsi+Rair*i; %thermal surface resistance + (film
resistance + cavity resistance) *number of layers
% Calculate u-value
U(1,i)=1/Rtot;
T(1,i)=tf^i;
end

disp ('U-value')
U
% disp ('optical transmittance')
T

figure(01)
plot(1:20,U)
hold on
plot(1:20,T)
```

MATLAB OUTPUT

```
>> clear
>> cushion_u_value

Rsi =

    0.0400

U-value

U =

  Columns 1 through 14
```

4.2956   2.5962   1.8603   1.4494   1.1872   1.0053   0.8718   0.7695   0.6888
0.6234   0.5693   0.5238   0.4851   0.4517

Columns 15 through 20

0.4226   0.3971   0.3744   0.3542   0.3361   0.3197

T =

Columns 1 through 14

0.9600   0.9216   0.8847   0.8493   0.8154   0.7828   0.7514   0.7214   0.6925
0.6648   0.6382   0.6127   0.5882   0.5647

Columns 15 through 20

0.5421   0.5204   0.4996   0.4796   0.4604   0.4420