ADAPTIVE BUILDING ENVELOPE
Performative Water-filled ETFE Cushions

Abolfazl Ganji Kheybari [1], Jochen Lam[2]

[1]Transsolar Academy, Transsolar Energietechnik GmbH, Stuttgart, Germany
[2]Transsolar Energietechnik GmbH, Stuttgart, Germany

ABSTRACT: *Designing a multi-functional building envelope as an architectural façade, environmental interface and Solar Collector is a multi-objective exploration that should be solved through an Integrated Design Strategy. The main research question is how the thermal and optical properties of the facade component can be improved to increase comfort, reduce energy demand as well as gain more solar energy.*
This research evaluates different concepts to implement the water inside a multi-layer ETFE cushion to make a dynamic envelope component. An air cavity in the multi-layer cushion serves as an insulation layer to control the thermal conductivity; and water can absorb solar energy (Infrared: 780-2500 nm) intelligently.
Inspired by the human skin and the blood circulation responding to heat and cold stress, in a comprehensive approach, every multi-layer cushion of this envelope has a great possibility of interacting dynamically between buildings elements and the environment. Regulating the thermal (U-value and SHGC) and visual (shading fraction) properties of the components would be complimented by a controlling pneumatic system to adjust the direction and the amount of heat flow by manipulating the shape and thickness of cavities for different climatic conditions.
Finally, With regard to the simulation results of a typical office building in Dubai, Tehran and Stuttgart, this paper demonstrates the efficiency of multi-layer ETFE cushion and water-filled ETFE cushion as intelligent dynamic system to provide thermal and visual comfort as well as reduce the energy demand and harvest solar radiation.

Keywords: *Dynamic, Performance, ETFE, Computational design, Biomimicry, TRNSYS*

INTRODUCTION

Facade systems, as one of the most complex elements of building, are largely responsible for both the energy-performance and overall aesthetic qualities of a building. The multi-functionality of the elements should be solved through a multi-objective exploration with an integrated design approach. According to the urgent need to the integration of solar energy with the building concept and its impact on the building form, the building envelops are now becoming real "active skins" with a very important energetic potential (Krippner, 2016). The skins as the most important structural subsystem are the interface between architecture, solar technology and structure. Hence, they are supplementary parts of the skin and must fulfill all traditional functions, while being adapted to constructional applications and their major influence on the visual appearance. Up to now, in many of the advanced glazing systems with adjustable transparency such as the electro-chromic materials, liquid crystals and electrophoretic or suspended-particle devices (Baetens et al., 2010), the solar energy is not utilized, and in PV encapsulated glazing, high initial investment doubts the availability of those systems.

BACKGROUND

ETFE cushions have been largely used by architects since the 1980s as an alternative to glass because of their similar transparency, higher thermal insulation properties, and energy and cost-efficient assembly and production processes. (LeCuyer, 2008) ETFE Foils as a lightweight tensile structural membrane with the density of 1.75 gr/cm³ (14.6 lb/gal) (DIN53479), have the approximately 40 N/mm² (5.8 Ksi) (DIN EN ISO 527-1) of ultimate tensile strength. Regarding high tensile strength, weather resistance, UV stability, surface quality and transparency, ETFE is used almost exclusively for external architectural applications these days (Knippers, J., 2011 and Poirazis, H, 2010). Recent examples such as the 2013 Enric Ruiz Geli's Media-TIC building in Barcelona and Dolce Vita Tejo shopping-complex in Lisbon, showed the problem of glare and overheating as a big issue for sunny and hot climates. Using smoke in cushions or the idea of North-face cushions with high selective filters and low-E coatings applied to different foils are part of the available solutions. However, producing smoke by combustion reaction has some doubts in terms of sustainability.

WATER-FILLED MULTI-LAYER ETFE CUSHIONS

The driving idea of this research is developing a dynamic shading and Thermal property component to interact with the environmental conditions that allows controlling the solar transmittance to benefit from higher solar heat gains during the winter and to reduce solar heat gain during the summer while supplying enough daylight inside the room. Therefore, the middle cavity in a multi-layer ETFE cushion is using to hold the layer of water (Fig. 1). Four 0.25 mm (0.01 in) of clear ETFE foils (Nowoflon ET 6235 Z 250) with the highest transmittance (T_{sol}=89.8 %, T_{vis}=88.6 %) are supporting the variable water fluid in middle chamber and the outer cavities with higher pressure support the overall stability of the component against external wind loads and self-weight of the water.

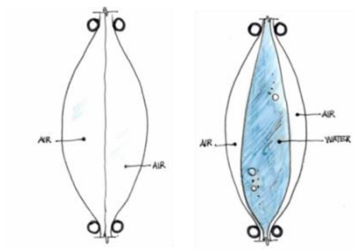

Figure 1: Multi-layer ETFE cushion with water as envelope component

ETFE cushions are usually inflated at 250-400 Pa (0.036-0.058 psi) with a small pump and topped up intermittently (Robinson-Gayle 2001). In some cases for supporting the membrane structure for extra load of snow or wind, increasing the pressure up to 800 Pa (0.12 psi) is possible. (Monticelli, C., 2013) Since the hydrostatic pressure of the water in the water bladder would make larger deformation of foils, higher air pressure and the secondary support with tensile fibers or kind of cable net is necessary. This paper suggested some of the possible solutions in feasibility studies section. In terms of increasing the thermal resistance, a reflective coating on the foils is suggested to achieve higher performance. A reflective film coating on third layer works better because the solar radiation blocked due to the reflection and absorption of layer could be got the heat in water fluid. In analogy with glass glazing systems, ETFE foil has some advantages in several aspects:

- The energy required for its production is over ten times less per square meter of coverage than that of glass.
- ETFE cushions provide greater luminosity: the cushions allow an equal range of light frequency transmission and greater total visible light transmission (Robinson- Gayle 2001).
- Based on the water absorption and solar transmittance of the ETFE foil within infrared, the combination of these two elements can increase the heat gain potential of the transparent collector system and avoid overheating due to the greenhouse effect inside the room.
- Due to use of pneumatic controlling systems, cushions are more flexible in terms of shaping different geometries as an adaptive fluid lens based on the dynamic optical and thermal properties of component.

Consequently, this paper is focusing on the multi-layer ETFE Cushion, as a solution for transparent façade element, to make an active skin to supply the comfortable indoor space and generate heat.

CONCEPTUAL CONTROL SYSTEM: WATER AS BLOOD

Blood circulation and its velocity changes during the cold and hot stresses is controlled by a feedback system in the hypothalamus; the temperature-regulating center of the brain. When cold, the hairs are raised by small muscles to trap a layer of air near the skin goose bumps or fluffing in birds. Decreasing the convection the trapped air as an insulator helps to keep heat in. blood is also kept away from the surface by vasoconstriction. In hot, the blood vessels leading to the skin capillaries dilate, known as vasodilation. This allows lots of blood to flow near the surface and heat is lost through the skin by convection and radiation. All these mechanisms are parts of a normal behavior in warm-blooded animals to control their body temperature (M Lauster, 2009).

Inspired by the blood circulation responding to heat and cold stress, in a comprehensive approach, every multi-layer cushion of this envelope has a great possibility of interacting dynamically to the environment. the cushion as the live responsive skin is able to imitate birds' fluffing in cold winter to gain heat and keep it inside the vital organs and lose more heat by radiation or convection transferring outer surface like mammals' behavior in hot summer. Thermal and visual properties of the components can be regulated by a controlling system that adjusts to the direction and the amount of heat flow, based on the variable climatic conditions. In addition to activating the glazing with circulating water in water bladder to behave dynamically for daylighting and solar heat gaining; in order to increasing the responsivity of the system, the building's body is also activated as part of the hydronic system. The thermal mass in slabs, walls and foundations are enlivened to connect thermally with occupants and ambient air and soil. Accordingly, the dynamic solar envelope in synergy with building active systems is capable of transferring the amount of heat from the building core to the surface or vice versa. (Fig. 2).

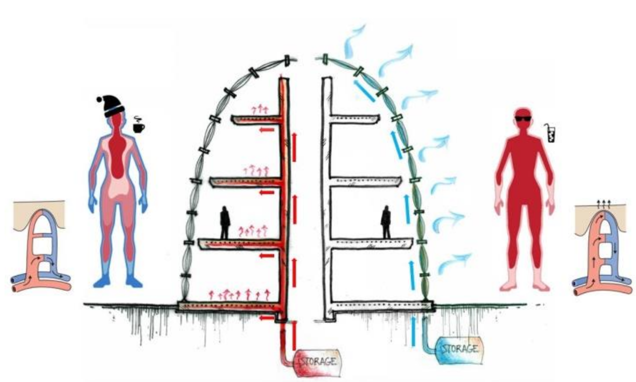

Figure 2 : Conceptual control system: the idea of building's "Blood Circulation", and integrated multi-functional façade components

THERMAL AND OPTICAL PROPERTIES OF WATER AND ETFE FOIL

According to precedent studies (Wagner, W., 2002), thermal properties of ordinary water such as Molecular weight, conductivity, viscosity and specific heat coefficient are defined for different temperatures 0 to 50 °C (32 to 122 °F). Also, thermal conductivity of ETFE is defined as 0.24 W/m.k (1.67 Btu·in/(hr·ft^2 ·°F)) (Teflon Tefzel™ products' datasheet, 2016).

In terms pf optical properties, regarding to the Beer Lambert law, based on the α (Absorption Coefficient (cm^{-1})) of pure water (Pope, 1997 and Palmer, 1974) and l (thickness (cm)) the absorption and transmission of water layer is calculated for 1 to 15 cm (0.39 to 5.91 in). The resultant optical property is figured in combined diagram (Fig. 3) to show the heat gaining potential of different layers of water, based on the potential solar radiation on the earth surface (ASTM E-490 AM0 Standard Spectra) and the optical properties of pure water and 0.25 mm (0.01 in) of clear ETFE foil (Nowoflon ET 6235 Z 250).

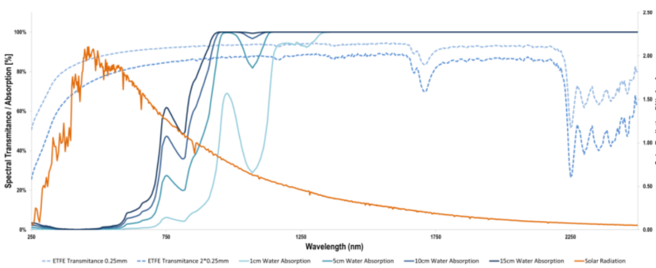

Figure 3: Total solar Irradiation and the potential of solar envelope to gain heat: Based on the absorption coefficient of water with different thickness and ETFE foil transmission

Referring to the figure 3, it is noticeable that depending to the thickness of water, the light absorption of water layer in visible part of spectrum (380–700nm) is negligible (0.07% to 11.41%) but the solar absorption (250-2500nm) is significant (30.33% to 48.18%) in infrared part. For example all the solar radiation with the wavelengths larger than 1125nm are absorbed by 15 cm (5.91 in) of water layer, while 5cm (1.97 in) of water layer only absorbs the solar radiation with wavelengths larger than 1230nm.

Table 1: the potential of solar envelope to gain heat and its effect on T_{vis}, based on the absorption coefficient of water with different thickness

Water Thickness	Absorbed Energy	Solar Heat Absorption	T_{vis}
cm	W/m^2	250-2500 nm	380–700 nm
1	407.956	30.33 %	99.03 %
5	543.046	40.38 %	95.49 %
10	607.308	45.16 %	91.74 %
15	647.966	48.18 %	88.59 %
Total Solar Energy	1344.873		

Regarding to different solar heat absorption and visible light transmission (T_{vis}) values corresponding to the thickness of water (Table 1), the optical behavior of water layer in combination with ETFE foil makes a potentially high-performance selective layer with high solar heat gain absorption and high visible light transmission. Regulating the thermal (U-value and SHGC) and optical (shading factor) properties of the envelope is possible by a controlling pneumatic system. By manipulating the shape and thickness of chambers for different weather conditions, depending on system can dynamically react to the location and the time of the day and adjust the direction and the amount of heat flow. In addition, it is possible to control the color of the water makes increase the absorption inside the fluid and reduced the energy transmission to the indoor space from 0.165 to 0.015 (Gstoehl, D. et al., 2011).

METHOD

SUMMER AND WINTER SCENARIOS WITH SIMPLIFIED CONFIGURATIONS

Similar to any dynamic systems with active components, the controlling function is as important as the function of each component. At some climate with high temperatures, when the solar irradiation is relatively high, unwanted interior solar heat gains can cause overheating in airtight modern buildings. In summer scenario, according to the solar absorption potential of water bladder, by gaining solar radiation inside water flow and allowing the visible light to transmit through the envelope, the system can effectively avoid the problem of overheating and consequently decrease cooling and electrical loads due to supplying sufficient daylight (Fig. 4 Right). Referring to the results of this paper, in these climates, using a reflective film or proper controlling system to add color to the water is effective to supply the comfortable indoor space and improve the efficiency of the system. Consequently, the gained heat by active water fluid on the critical windows can be consumed for heating space in other parts of the building (e.g. north faced window) that are not directly exposed to the solar irradiation.

The flow of cold water in the cavity facing the interior can be operated during the hot day as radiative cooling panel to improve the thermal comfort perception because of the impact of low temperature surface. Beside the effect of large glazing areas as heating and cooling surface; In general, a surface area of the glazed facade closer to the temperature of other components of the building (floor, ceiling, interior walls) also reduces the imbalance of long wave radiation in the space and raises the thermal comfort of the user (Ritter, 2015).

Using two different underground water tanks, the system performance can be improved. The heated water passing through the water bladder during day is stored in the first tank with high conduction to the soil temperature or geothermal heat exchangers to reject the excessive heat. Moreover, during a summer night, increasing in thermal conductivity of the system by deflating the external air cavity and circulating the heated water to the exterior cavity makes it possible to radiate the excessive heat to cold sky. In these mechanisms chilled water stores in the second fully isolated tank for cooling purpose for the next day (Figure 4 Left). In this paper, the Qrej kWh [kWh/a] is defined as a representing parameter for cooling potential of the system during summer day. This is the amount of solar heat, which is absorbed by the water bladder (as sunshade) and rejected to the earth or radiated to the cold sky overnight.

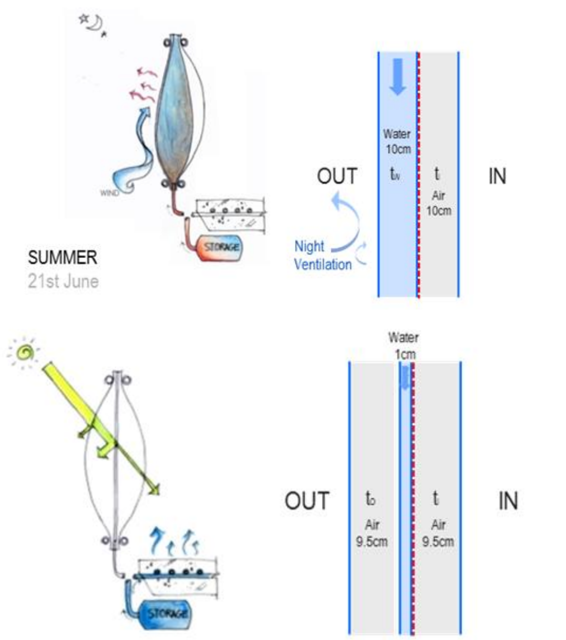

Figure 4: The Schematic of the basic operation of envelope components: dynamic thermal and optical properties, Up: Summer night configuration (SN), Down: Summer day configuration (SD)

While the sufficient amount of visible light is transmitted to the space, during a winter day, collected heat can be used to support space heating as heat source for a radiant heating slab system or to provide hot water indirectly (Fig. 5 Right). Increasing the absorbed solar radiation, low mass flow rate within water bladder makes the outlet temperature higher; thus the higher heat gain can be stored in second underground tank for heating during the cold night while the exterior air layer plays the role of Night Insulation (Fig. 5 Left). The Qcollect_kWh [kWh/a] is defined as a representing parameter for heating potential of the system. This is the amount of useful solar heat gained during winter day in water bladder for different configurations. This amount of energy is simulated based on the average temperature of 35°C (95 °F), which can be used for heating space during wintertime.

In these scenarios, the Mass Flow Rate is controlled by the function of water temperature. During a winter day, the outlet temperature of circulated water raises to 35°C (95 °F) for heating purpose using hydronic active slab system and producing pre-heated water for Domestic Hot Water. While during the summer, the cold water is circulated for cooling purpose (15°C) (59 °F) with higher mass flow rate and the collector is just working for pre-heated Domestic Hot Water.

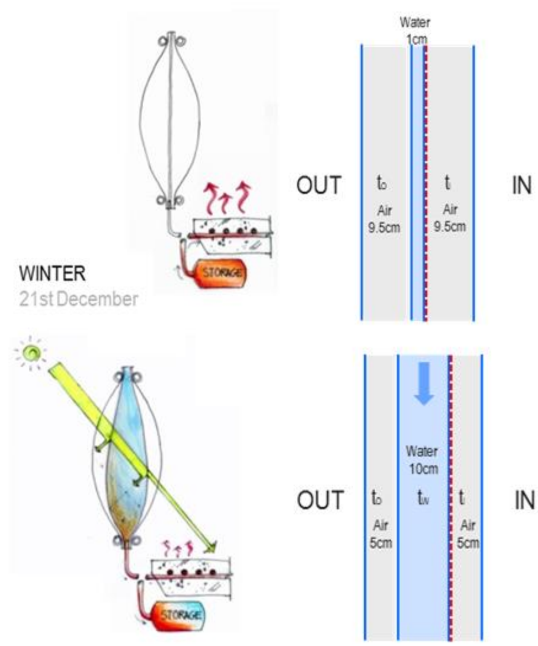

Figure 5: The performative envelope components dynamic thermal properties: Up: Winter night configuration (WN), Down: Winter day configuration (WD)

MODELING

In this paper, some of the potentials of water filled ETFE cushion are evaluated for a south oriented window for three different climate conditions in Dubai, Tehran and Stuttgart. The geometry of a standard office room (located in a middle story and surrounded by other office rooms) is modeled for daylight and thermal simulation, based on the technical standard of VDI 2078:2012-03 for 2 people (17.50 m² (188.37 ft^2), 5.0 m (16.4 ft) length, 3.5 m (11.48 ft) width and 3.0 m (9.84 ft) height). The south oriented window is 3.3 m (10.83 ft) by 2.8 m (9.19 ft) with 9.24 m² (99.46 ft^2) area. In this model, the U-value of 0.191 W/m²K (0.03 Btu /(hr·ft^2 ·°F))is assumed for external wall (Fig. 6).

In order to evaluating the potential of the system for different configurations through thermal simulation complex model of ETFE cushion is simplified into parallel layers. However, for daylight simulation, double curved geometry of ETFE cushion is modeled through form-finding procedure based on the air and hydrostatic pressure in Rhino Grasshopper with the help of RhinoMembrane and Kangaroo[1]. This geometry is used later to generate the Bidirectional scattering distribution function

[1] A grasshopper component developed by Daniel Piker as a physics engine

(BSDF) matrices to take into account the effect of water bladder geometry on light distribution.

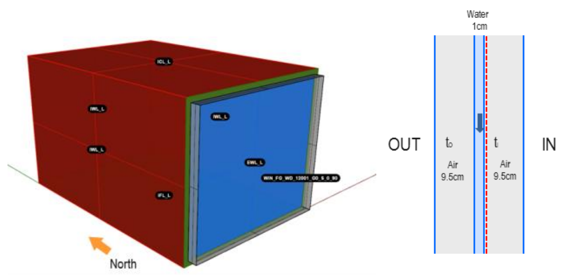

Figure 6: The geometry of a standard office room and definition of simplified glazing system main configuration with 1 cm water

LBNL WINDOW 7.4 AND RADIANCE

The simplified models for different configurations are set up in LBNL Windows 7.4. for evaluating the thermal and optical behaviors. In order to, the optical properties of 0.25 mm (0.01 in) of clear ETFE foils (Nowoflon ET 6235 Z 250) with 0.898 solar and 0.886 visible lights Transmissivity is defined in Optics 6 and exported to LBNL Window as a glazing and as a Glass Radiance material with BRTDfunc for the daylight simulation with Daysim via Honeybee. The optical properties of water are defined by assigning a dielectric material in Radiance with Refraction Index of 1.33 (Segelstein, D., 2011). The thermal conductivity of water are also defined as some polynomial curves based on different temperatures (0-50 °C) (32-122 °F) as a new gap gas in LBNL Window Gap library.

TRNSBSDF AND TRNSYS18 (DYNAMIC THERMAL SIMULATION)

In new coming version of TRNSYS18, it is possible to apply the BSDF data for a complex fenestration system generated by LBNL Window and combine as different configurations of a detailed window for any dynamic thermal simulation. This new features provide one detailed window containing all optical and thermal information of layers and gaps, which is possible to calculate the absorbed solar radiation and temperature for each layer and gap specifically.

Assessing the potential of the different configurations of system, three base cases are modeled with the same properties but a standard double glazing window. All the thermal properties for the external and internal walls, ceiling and floor for all the configurations and base case model are kept the same. Window wall ratio is 90% and the window property for base case model is a double glazing window (ID13002) with U-value of 1.1 W/m^{2}K (0.19 Btu/(hr·ft^2 ·°F)) and the G-value of 60% with 70% reduction due to motorized moveable external shading. In figure 7, the performances of standard base case buildings in Dubai, Tehran and Stuttgart are shown.in this figure (figure 7), the amount of annual energy demand [kWh/a] for heating, cooling and artificial light is compared with thermal comfort representing by PPS [%] (Predicted Percentage of Satisfied).

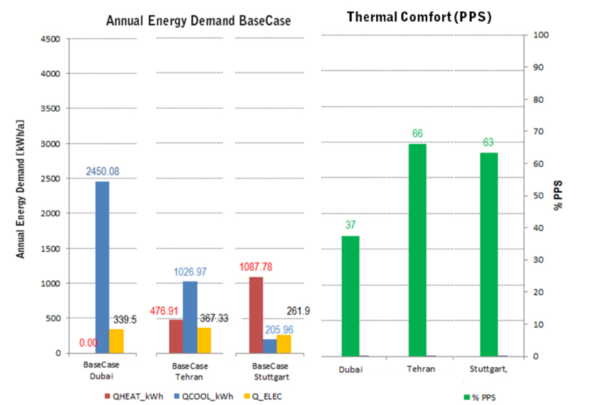

Figure 7: Annual Energy Demand [kWh/a] and Thermal Comfort, Predicted Percentage of Satisfied [PPS %] for standard base case buildings in Dubai, Tehran and Stuttgart

As shown in figure 8 for the comparison study, the thickness of water layer is assumed 1 cm (0.39 in). Zero configuration is a conventional multi-layer ETFE cushion with 4 foils and 0.25mm (0.01 in) thickness and three cavities and the main configuration (configuration 1) is a multi-layer ETFE cushion, which the middle cavity is filled with 1cm (0.39 in) of pure water. The optical properties of systems for other four configurations (configurations 2 to 5) are adjusted by applying Reflective Coatings (HeatMirror77 and HeatMirror44 for configurations 2 and 3), and dyed water with pigment (1% and 2% of concentration for configurations 4 and 5).

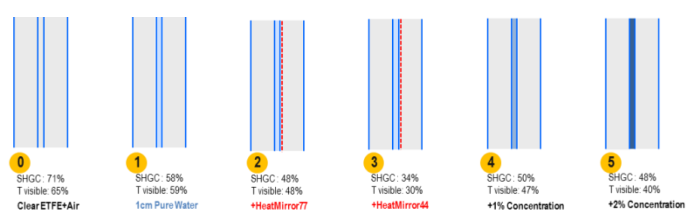

Figure 8: six different definitions of glazing system, main configuration (number 1) is a multi-layer ETFE cushion with 4 foils and 0.25mm thickness and 3 cavities which is filled with 1cm of pure water.

DAYLIGHT SIMULATION

According to the proper radiance materials for ETFE foil and water, daylight simulation for the simplified model for summer (1cm or 0.39 in water) and winter (10cm or 3.93 in water) configuration are set up in Honeybee based on the clear sky for 21st June and 21st December, Tehran. Regarding to the Illumination results (Fig. 9) for both the solstices, adding the layer of water has a negligible effect on visible light and the required Illumination level (300 Lux) for both cases is achieved. Moreover, the comparison study of six different configurations is complimented by annual daylight simulation in terms of providing useful daylight in the space. The annual daylight simulation result (sDA_300 lux) for worse configuration (configuration 3 with only 30% T_{vis}) was 67% for Tehran.

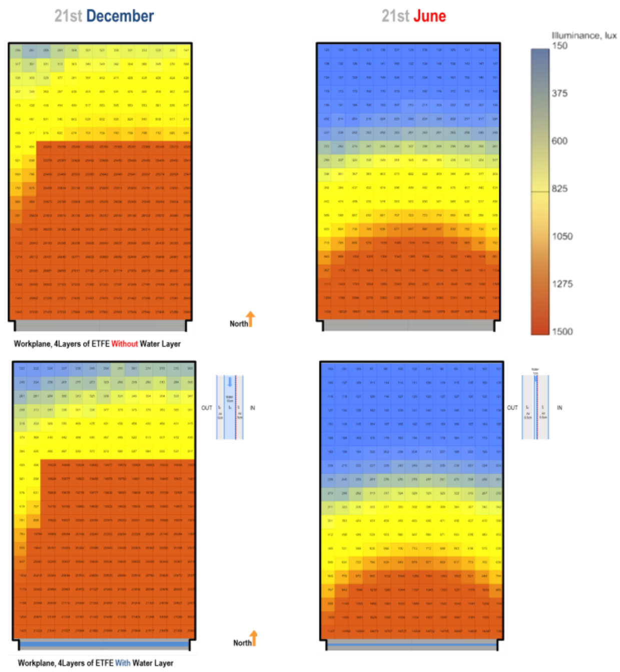

Figure 9 : Daylight distribution and the impact of layer of water on 21st June and 21st December, Iran, Tehran, Up: ETFE cushion without water, Down: ETFE cushion with water (winter: 10cm, summer: 1cm)

THERMAL SIMULATION

Evaluating the proposed idea of dynamic elements of facade in an active interaction with the environmental conditions, firstly, six different complex configurations with different shading effects have been generated by LBNL Window and combined with TrnsBSDF tool as a detailed window in TRNSYS18. Different configurations are assessed to figure out the impact of water absorption and shading effects.

CONCLUSION

In terms of providing useful daylight in the space, the annual daylight simulation for the worst configuration (configuration 3, with 30% T_{vis}) has been studied with sDA parameter. Spatial Daylight Autonomy (sDA) describes how much of a space receives sufficient daylight. Specifically, for Tehran, it describes the 67% of floor area receives at least 300 lux for at least 50% of the annual occupied hours. This performance has a great impact on reducing the electricity demand for artificial light in comparison to the base cases with automated shadings. The results also show that the increasing of shading effect due to reflective films on third layer or adding color to water can rise the efficiency of the façade component by gaining more heat in water during winter and avoiding risk of overheating in summer.

In figure 10, graphs for Annual Performance, the Qcollect_kWh [kWh/a] is the amount of useful solar heat gained during winter day in water bladder for different configurations. This amount of energy shown with dark blue bars, with average temperature of 35°C (95 °F) can be used for heating space during wintertime. Moreover, the cooling potential of the system during summer day is representing by the Qrej_kWh [kWh/a] with purple bars. This is the amount of solar heat absorbed by the water bladder and rejected to the earth or radiated to the cold sky overnight.

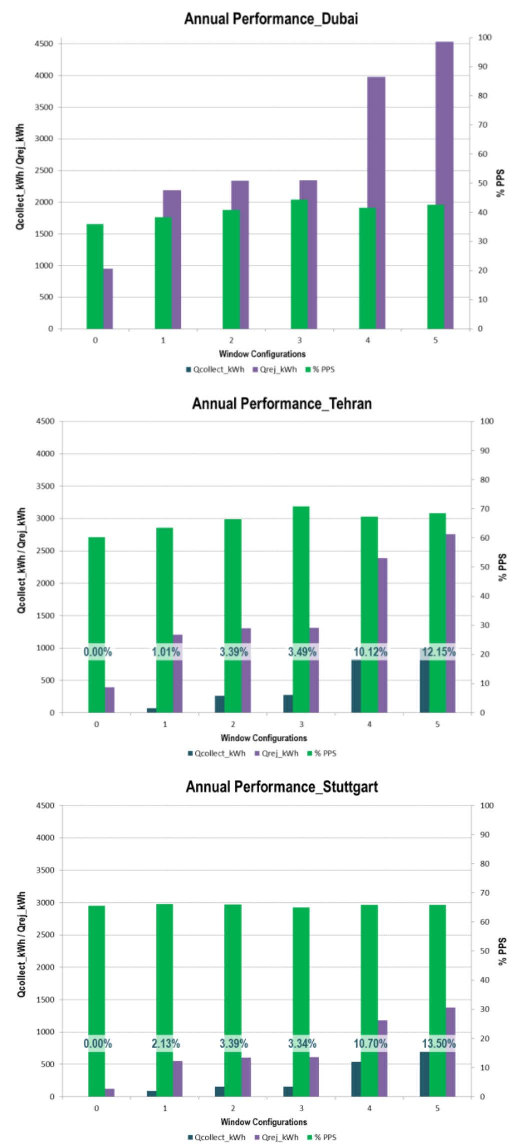

Figure 10: Annual performances of six configurations for Dubai, Tehran and Stuttgart.

Thermal comfort is also shown as green bars with Predicted Percentage of Satisfied [PPS %] parameter for Dubai, Tehran and Stuttgart. In this graphs, the values of percentage over the bars are showing the efficiency of each configuration (useful heat gain divided by total receiving solar radiation with the window surface).

After evaluating the annual performance of six mentioned configurations for three different climates, in figure 10 ,graph illustrates the annual energy demand [kWh/a] for basecases and configuration number 3, QHeat_kWh with red bars representing the heating demand, QCool_kWh with blue bars representing the cooling demand and Q_Elec representing the electricity demand for artificial light.

As shown in Annual energy demands and annual performances the performance of each configuration is highly dependent to the climate conditions. For example in a hot climate like Dubai, the system is only worked for cooling purpose. In this case, performance of configurations 1 to 3 is more or less the same; but using a reflective film is reducing the cooling demand significantly. While providing enough useful daylight for the space, configurations 4 and 5 can also reduce the cooling demand.

The full potential of the dynamic water-filled ETFE cushion and the controlling mechanism of "Building's Blood Circulation" can only be achieved after evaluating different configurations for each climate through dynamic simulation and find the most appropriate controlling strategy. However, at this stage of the research none of the combined dynamic control strategies has been assessed completely to improve the performance. The results of configuration 3 are comparing with the base cases in figure 11, for three different climates.

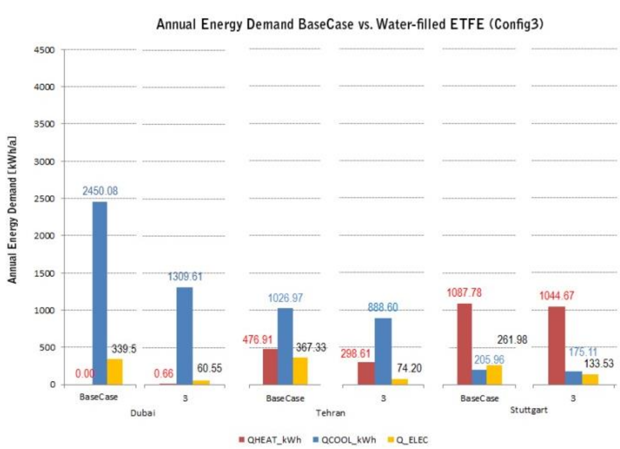

Figure 11: Annual energy demands ordinary office room (base case) in comparison to water-filled ETFE cushion configuration 3 for three different climates, Dubai, Tehran and Stuttgart

In comparison to the base cases, water-filled multilayer ETFE cushion can make a significant reduction in energy demand. Annual useful heat gain collected for configuration 3 is also noticeable. In Tehran the amount of solar heat gain with semi-transparent collector can cover 90% (Qcollect_kWh = 272.09 kWh/a (=928.4 KBTU/a), and 15% (Qcollect_kWh = 155.22 kWh/a (=529.63 KBTU/a)) of heating demand in Stuttgart. Using Configuration 5 can improve the amount of solar heat gain up to 100% and 55% of heating demand respectively for Tehran and Stuttgart.

Finally, the proposed façade component as a transparent collector allows some of the mentioned potentials for a south oriented window in different climates:

1. Reduction in heating demand and harvesting solar heat (Tehran: 100% and Stuttgart: 55%)
2. Reduction in cooling demand: (Dubai: 1140, Tehran: 137 and Stuttgart: 30 kWh/a (3889.8, 467.5, 102.4 KBTU/a)
    a. Decreasing SHGC by absorbing solar radiation while it is almost transparent for visible light
    b. Heat Rejection during summer night by radiation to the cold sky
3. Maximizing the daylight utilization and significant reduction in electricity demand. (Dubai: 279, Tehran: 293 and Stuttgart: 128 kWh/a (952, 999.8, 436.8 KBTU/a)
4. In Addition to aesthetic advantages of using different colors for water which can control the absorption and shading effect
5. Controlling the direct sunlight by using total internal reflection inside the water layer (work in progress)

ACKNOWLEDGEMENTS

This research project was done under the technical and financial support of Transsolar Academy and Transsolar Energietechnik GmbH. The authors really want to acknowledge the support of Raphael Lafargue for his generous support and Monika Lauster for her great effort to invest in cultural diversity and enhance the intercultural dialogue.