ADAPTIVE BUILDING ENVELOPE: Performative Water-filled ETFE Cushions

Designing a multi-functional building envelope as an architectural facade, environmental interface and Solar Collector is a multi-objective exploration that should be solved through an Integrated Design Strategy.

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maximize the impact
of sustainable building design

Deliver justice for impacted people
Upon receiving my Bachelor’s degree in Civil Engineering, I graduated with a Master’s degree in Architectural Technology; with a focus on multidisciplinary approaches in the design process of the building envelope. In this new landscape, the design process of multifunctional elements is focused on the combination of form finding, material selection and assessment of the environmental behaviors.
While celebrated as a precious source of inspiration in traditional architecture, the lack of multidisciplinary approach in Iran restricts any modern interpretation of these solutions toward a new design. Most of the scholars and architects in Iran only operate computers for the purpose of drafting or rendering. Yet, computational design shifts the boundaries of disciplinary roles and opens up the possibility for the emergence of a performance-oriented design. In this approach, the design can be considered as a process of multi-objective exploration that is driven by some desired performances (aesthetic, structural and environmental). In Iran, those of us who consider the practice of design with new digital tools as a collaboration of architects and engineers remain on the fringes.
Before starting my Ph.D. studies in Iran, I researched vernacular architecture as solutions for climatic design and passive strategies. In contrast to modern strategies, the traditional architecture offered simple yet holistic solutions to complex problems. In some of the Iranian vernacular architecture, the harsh climate and inhospitable environment is most effectively tempered by the use of gentle tectonic ornamentations such as Palekones (Mashrabiyes), Orosi windows, Wind Catchers, and so on.
Passive Design Strategies:
- Natural Daylighting: Up to 3660 hours
- Passive Heating
- Direct Solar Gain
- High Thermal Mass + night Flushed
- Trombe Wall and Water Walls
- Passive Cooling
- Shading for Solar Heat Gain
- Natural Ventilation
- Humidification and Direct Evaporating Cooling
- Earth Cooling (Conductive Cooling)

Thermal Comfort Range: 18°C - 21°C (Iran Meteorological Organization)
Adaptive Comfort Curve (Dr. Sh. Heydari)

Source Weather wal. Tehran-Mehrad 40760C (ITMY)
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 the 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).

Multifunctional: Designing a building envelope as an architectural façade, thermal barrier and load bearing structural

Adaptive: Interacting dynamically with the environment. Water as building’s blood. Transfer the amount of heat energy from the building core to the surface or vice versa.

Transsolar, academy
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 envelope 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.

### Concept
**Multifunctional Adaptive Facade**

### Adaptive Envelope Functions:
1. **Transparent Solar Heat Collector**
2. **Dynamic Shading and Daytime Heat Rejection**
3. **Nighttime Heat Rejection to the Sky**
4. **Supply Useful Daylight**
5. **Shading Without Shades (Refraction Effect)**
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 are 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°C - 50°C) (32°F - 122°F) as a new gap gas in LBNL Window Gap library.
Complex Fenestration Modeling
Simplification and Defining Water as Shading Material and Gap Gas

1. Defining optical properties of ETFE foil and coating films
2. Defining solar absorption of water layer as homogeneous diffusing shade
3. Defining thermal properties of water layer as gap gas
4. Assembling the glazing systems and generating BSDF & .idf
5. Generating BSDFs based on the dielectric material and cushion geometry
6. Defining refraction effect of water layer as xml as shading
7. Generating combined BSDFs as .dat
8. Comparing the layer's temperature results (NFRC)

In the new coming version of TRNSYS18, it is possible to apply the BSDF data per a complex fenestration system generated by LBNL Window and combine as different configurations per a detailed window per any dynamic thermal simulation. This new feature provides one detailed window containing all optical and thermal information per layers and gaps, which is possible to calculate the absorbed solar radiation and temperature per each layer and gap specifically.
Referring to the figure, it is noticeable that depending on the thickness of water, the light absorption of water layer in the 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 wavelengths larger than 1125nm are absorbed by 15 cm (5.91 in) of water layer, while 5 cm (1.97 in) of water layer only absorbs the solar radiation with wavelengths larger than 1230nm.
Winter Conditions: Increasing the thickness of water layer, the amount of absorbed solar radiation would be a supplement source of energy for heating. During the cold night, the exterior air layer plays the role of Night Insulation.
Summer Scenario: According to the absorption coefficient \( \varepsilon \) of water, this selective layer can gain 30-48\% of solar radiation and allow more than 99.88\% of the visible light spectrum to transmit through the envelope and supply sufficient daylight. Consequently, the intelligent behaviour of water layer in a combination with ETFE foil makes a high-performance selective layer with high Solar Heat Gain Coefficient and high Visible Light Transmission. This function can avoid the problem of overheating during a summer day and decrease cooling and electrical loads effectively.

The dynamic shading by different fritted pattern on ETFE foils and Diaphragm Configuration, internal refraction phenomena inside water layer and the effect of shape on more uniform distribution of light in the room are also some new interesting aspects of this study.
LOOK DEEP INTO NATURE
Green leaf optical properties, Dynamic shading device

Multiple Reflection

Chlorophyll Pigment
As shown in figure 8 for the comparison study, the thickness of the 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% w/w concentration for configurations 4 and 5).
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 of 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 (ID:13002) with U-value $1.1 \text{ W/m}^2\text{K}$ (0.19 Btu/(hr·ft$^2$·°F)) and the G-value $90\%$ 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 represented by PPS [%] (Predicted Percentage Satisfied).
As shown in Annual energy demands and annual performances diagrams (Figure 10-12), 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.
In terms of providing useful daylight in the space, the annual daylight simulation for the worst configuration (configuration 3, with 30% \( T_{\text{vis}} \)) 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 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.
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 per each climate through dynamic simulation and finding 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 13, for three different climates.

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

- Reduction in heating demand and harvesting solar heat (Tehran: 100% and Stuttgart: 55%)
- Reduction in cooling demand: (Dubai: 1140, Tehran: 137 and Stuttgart: 30 kWh/a (3889.8, 467.5, 102.4 KBTU/a)
  - Decreasing SHGC by absorbing solar radiation while it is almost transparent for visible light
  - Heat Rejection during summer night by radiation to the cold sky
- Maximizing the daylight utilization and significant reduction in electricity demand. (Dubai: 279, Tehran: 293 and Stuttgart: 128 kWh/a (952, 998.8, 436.8 KBTU/a)
- In addition to aesthetic advantages of using different colors for water which can control the absorption and shading effect
- Controlling the direct sunlight by using total internal reflection inside the water layer (work in progress)
shading without shades:
the idea of redirecting light by water layer and the effect of shape to adjust the sunlight distribution effectively.

Testing mockup, left: high angle light transmits through the empty cushion.
Right: high angle light is blocked and refracted inside the water filled multi-layer cushion.

Testing mockup, adaptive light distribution in the water filled multi-layer cushion by controlling the air pressure in outer air cavity.
Internal refraction inside the water cavity due to the tilted inner pane and blocking the incident radiation during summer time (21st June, Tehran).

Grasshopper definition and geometrical study: In order to study the proper geometry and figure out the appropriate rotating angle for different latitudes, a Grasshopper definition has been developed to calculate the angle for any desire location and period of time. Some of the results are shown in the below table (Table 1).
Based on Snell’s law, the driving idea of this research using the water layer as a shade (shading without shades) to block the specific angles of incident sunlight.

Regarding total internal refraction phenomena in water (as dielectric material with refraction index of 1.33), the sunlight radiation travelled through the water layer is blocked on the tilted pane and refracting inside the water.
Using inner cavity in multilayer ETFE cushion as an adaptive fluid lens to adjust the light distribution; the internal refraction phenomena in water cavity in a multilayer ETFE cushion and blocking the summer high angle solar radiation while allowing the winter low angle radiation.

Shading without Shader
Controlling the light distribution through water layer

- **Parallel**
  - Summer

- **Inflated**
  - Summer

- **Prismatic**
  - Winter

- **Prismatic**
  - Winter
Lighting simulation results: The idea of redirecting light by water layer needs further researches to be done to study the effect of shape to adjust the geometry and distribute sunlight effectively. The impact of some of these shapes of water layer on light transmission and distribution have been evaluated by complex fenestration system modeling method and generating the BSDF matrices through simulating daylight by use of Optic6, LBNL Windows, Daysim and Trnsys18 new features.
For a standard office room in Tehran and Stuttgart with a fully glazed south oriented façade, while the illuminance level and light distribution is in acceptable range; regarding to radiation values, decreasing the g-value of the glazing, the energy demand for cooling can be reduced potentially due to the internal refraction in water layer.
Water filled ETFE cushion façade
Performative Pattern Generation

- Supporting the ETFE foils with welded fibers
- Decreasing the hydrostatic pressure based on the Venturi effect

Supporting the hydrostatic pressure of water in lower part of cushion, higher air pressure (the maximum pressure of 2000 Pa or 0.29 psi) or the secondary support with tensile fibers or kind of cable net is necessary to avoid the foils from any plastic deformation. Supporting the ETFE foil with high performance fiberglass and carbon fibers is part of some pioneering research projects in ITKE and ICD institutes in Stuttgart (Doerstelmann, M. et al., 2015).

According to the idea of Urban Algae Folly project for EXPO Milano 2015, another solution is dividing the spans into smaller clear height up to 40cm (1.31 ft). Since the water bladder is enveloped with the outer air cavities and hydrostatic pressure due to the 40 cm (1.31 ft) height of water column is about 4000 Pa (0.58 psi), the resultant pressure exposed to the foil could be kept less than 2000 Pa (0.29 psi). Therefore, it is possible to carry the water inside the ETFE bladders.
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