# Bio-inspired Transparent Microfluidic Platform as Transformable Networks for Solar Modulation

**Mark E Alston**[1*], **Uta Pottgiesser**[2] ,**Ulrich Knaack**[3]

1 School of Engineering, Architecture and the Built Environment, University of Nottingham, mark.alston@nottingham.ac.uk
2 Professor of Interior Architecture – Faculty of Design Sciences, University of Antwerp
3 Professor of Design of Construction - Department of Architectural Engineering + Technology, TU Delft

## Abstract

*The glazed envelopes on buildings play a major role in operational energy consumption as they define the boundary conditions between climate and thermal comfort. Such a façade is viewed as an uncontrolled load that sets the operational performance requirements for artificial lighting and air-cooling mechanical systems. This is in contrast to nature, which has evolved materials with the ability to learn and adapt to a micro-environment through self-regulation using materials that are multifunctional, formed by chemical composition in response to solar load. Leaf vasculature formations are of particular interest to this paper. Through leaf maximisation of daylight capture, the total leaf area density and angular distribution of leaf surfaces define the tree structure.*

*This paper will define an approach to simulate nature to advance a microfluidic platform as a dynamic NIR absorber for solar modulation: a transformable network of multi-microchannel geometry matrix structures for autonomous transparent surfaces, for real time flow management of conductivity. This is realised through active volumetric flows within a capillary network of circulation fluidics within it, through it, and out of it for energy capture and storage, the cycle of which is determined through precise management of heat flow transport within a material. This advances transparent façades into an energy system for heat load modulation nested to climate and solar exposure, which is demonstrated in this paper.*

## Keywords

*microfluidic, thermal transport, absorber, solar, geometry matrix, bio-inspired*

# 1 INTRODUCTION

Transparent glass façades play a major role in operational energy consumption, as they define the boundary between climate and human comfort. This determines operational performance requirements in setting mechanical systems (air-conditioning, artificial lighting demands) in the consumption of primary energy. The conductance of opaque materials for solar modulation is well researched and advanced analytically, and such materials are well established as energy collectors. These materials outperform optic materials and there is nothing of note to add in terms of this research. Optic materials' performances, however, are energetically weak in terms of visible transmittance, and have limited solar energy modulation efficiency and high transmission temperature.  As these façades suffer from long-wave solar radiation inputs leading to the overheating of internal spaces and increased cooling demand loads, façades are viewed in terms of transmission loss. This is due to a resulting inflow heat load that is dependent on the overall solar transmittance 'g', including any solar shading. The technical challenges in providing thermal and visual comfort in buildings with large expanses of floor to ceiling glazing are significant. Large areas of glazed façades orientated to the east, west, or south (or north if in the southern hemisphere) (Hens, 2011) will experience the thermal impact of overheating due to sunlight and harsh solar glare. Energy demands in buildings bring together a range of complex relationships between the climate, individuals, and their perception of comfort.

The glazed boundary layer has been determined to date by impact energetic flows focused on high energy consumption, lighting lumens/watts, HVAC, and plug-in end-use loads. Passive systems of Low Zero Carbon (LZC) technologies have been employed as active responses to solar radiation and these measures have been determined by: ventilated, double-skin, kinematic shading system, hybrid, nanocoating thin film reflective, PCM membranes, vacuum insulation, electrochromic, and transparent insulation materials. The minimisation of operational energy building use and maximisation of generated energy in order to reduce greenhouse gas emissions is an aim of the European Directive 2010/31/EU (2010). However, this strategy requires material component elements to respond in real time to yearly, seasonal, and hourly changes in climatic and microclimatic conditions. This multiscale design approach would enable materials to react to external influences and change their thermal behaviour and functionality accordingly (Knaack, Klein, Bilow, & Auer, 2014). LZC technologies do not currently adopt such characteristics of integrated material functionality. The challenge is to progress from the static boundary conditions of steady state theory to the characterisation of non-steady states, and this is determined by thermal (energy) flow. Government targets are making considerable demands on energy reduction targets within an increasingly uncertain climate. These facts all converge on a clear need for a solution that is more compliant than the current state of the art. There is a greater need to measure and understand the nature of thermal transfer effects at the material level for real time responsive conductance measures.

Nature's use of matter and energy is a dynamic relationship that is achieved at differing scales through material diversity (species) and material connectivity (chemical compounds). Nature assembles materials at a formation level to actively manage the composition of a microenvironment that obeys the rules of minimum energy loss and minimum effective power output. Leaves are of particular interest to this research proposal, in terms of management of fluidics through absorption (photosynthesis). This research uses a leaf-like model to progress experimental absorption testing to establish proof of concept.

This paper demonstrates this as an early assessment prototype that could be established at a larger scale for greater comprehensive performance evaluation.

This absorption approach is not used in the current state of the art for fully glazed buildings, in which directly transmitted natural light often needs to be controlled by shading or reflection in order to avoid glare problems and unfavourable distribution of light within a room. Various coatings and pigments are available for glazing to reduce the transmission of solar radiation near infrared irradiation in buildings. Reflecting metal oxide layers are most frequently used for this purpose. By reflecting solar infrared irradiation, heat gains inside the building are avoided, but incident energy is also lost when heat gains would be favourable. Furthermore, this reflective solution will be absorbed by other structures around the building and thus would contribute to urban heat island effects. Research has been undertaken to introduce fluidics into windows, using the FluidGlass technology (Stopper, Boeing, & Gstoehl, 2013) as an absorption solution rather than a reflective one. This work used a triple glazed unit with two fluidic chambers acting as absorption layers by fluid depths of 2mm. The glazing panes that formed this assembly to create the overall unit is composed of 6mm ( 3 in total ) clear glass and two low-E coated 6mm panes.

This study utilised the cavity void between glass panes by filling the void with water for conductivity absorption of solar radiation. The research demonstrated optimised results in a dyed metal particle anti-freeze fluid, demonstrating a reduction in cooling demand energy of 39%.This was achieved through the fluid volume in active flow within the two chambers absorbing solar radiation.

The introduction of anti-freeze eliminates the possibilities of freezing at low night-time temperatures. Further research highlighted a similar approach however the fluidic window generated warm water that was used for heating applications (Chow, Chunying, & Zhang, 2011). The use of water gave higher conductivity for effective window cooling designs in warm climates (Chow & Chunying, 2013).

Water flow in the experiments was set at 200 ml/min with the greater efficiency gained in higher incidence of solar radiation for working efficient conditions. However, the lack of fluidic flow management within the free-flowing volume resulted in flow turbulence and water movement uncontrolled by gravity. This also impacted on water thermal fluidic expansion through solar radiation heat transfer and glazing deflection of the water under gravity. This presents challenging issues for full volume chamber fluidics, which remain unresolved.

It was observed that the water chamber reduced the indoor temperature to 26.14°C in comparison to convection double glazed air-filled unit of 37.72°C on the summer solstice (Lopez & Gimenez-Molina, 2012). However, the difference in temperature, through natural heating buoyancy, created a temperature variation in the liquid volume. This variation in temperature heating and decay increased the thermal expansion issues and diminished control of the liquid volume for solar absorption optimisation. The volumetric weight of the liquid within the assembly is also significant when applied to floor-to-ceiling glazed façade engineering, which further reduces the effectiveness of the application. The research presents a microfluidic-based platform as a method to advance solar modulation, not through a reflective approach of current practice but through an absorption solution, as a leaf-like model. This experimental work is exploratory in nature, as it is established within a laboratory environment to make an early assessment for proof of concept. The paper presents possible methods of integration within an envelope fabric that can possibly be scaled up for advances in envelope design. However, this manuscript does not set out to demonstrate a comprehensive performance evaluation, but rather presents the next stage in which the process is scaled up for manufacturing.

This introduced method uses an IR absorbing fabrication process and characterisation method with a vascular heat transport system. Using fluidics in capillary channels as heat sinks within a material, we can modulate volumetric flows rates in the material to manipulate the material and fluid thermal transfer. Using active fluids in flow within a material will enable the removal of material thermal stresses, as a material absorbs solar radiation.

## 2 LEAF-LIKE MODEL

Leaves sync in real-time with the pattern changes of solar radiation (Feugier, Mochizuki, & Iwasa, 2005; Blonder, Violle, Bentley, & Enquist, 2011). Each leaf reacts and responds to variations in wind direction and orientation, and they adjust their surface exposure to harvest solar gain (Fig. 1).

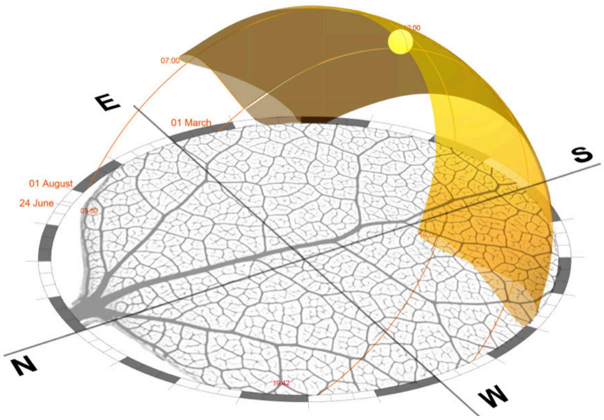

FIG. 1 Leaf Solar Model

FIG. 2 Illustrates how the network can continue to supply fluid flow even when the main central leaf fluid structure has been damaged (denoted by the central punched hole, *(Katifori, Szollosi, & Magnasco, 2010)*.

This single leaf unit acts within a transformable daylight capture system: the tree canopy— through distribution of the leaf surfaces for daylight capture. This is determined by canopy volume, total leaf area density, and the angular distribution of leaf surfaces, to form the tree structure.

This approach to solar orientation and absorption of light energy by biochemical processes are responsive measures and a dynamic system of solar radiation.

Leaves use embedded microfluidic channels as a means to harvest solar energy through fluidic volume filled networks . This formation of capillaries is determined through precise control of channels' geometries set within a material determined by a rule-based hierarchical pattern for the transportation of active liquids. This approach of a leaf-like model could advance materials that are thermally functional to act as a NIR stop band through an absorption approach.

These networks of micro-channels are called vascularisation patterns. This is a highly refined energy reaction system for enhanced material properties of chemical energy flow.

Vasculature patterns are linked to material scale, leaf size, and species in the formation of the channel network (Dengler & Kang, 2001). These closed loop exothermic networks are subject to flow resistance and flow rate, thus enabling significant regulatory roles with tolerances given to damage and water stress conditions (Fig. 2).

The leaf fluid network structure (illustrated by the yellow colour, Fig. 3) exhibits a diminishing order of vein size, as all classes of veins contract in size distally from the main fluidic (central) stem vasculature channel  (Turing, 1952). This distribution network is defined by hierarchical scaling that conforms to rules of minimum energy loss, minimum effective fluidic power flow rates, and minimum pressure drop, determined through pressure equalisation by diminishing flow pressure variation across the network. This can be simulated through resistance circuit theory (Oh, Lee, Ahn, & Furlani, 2010), by the regulation of fluidics that is achieved by unified flow rate regulation and thermal dynamics of the fluid within the capillaries.

An experimental device was fabricated to assess and validate the concept within a laboratory environment. Sensors and actuators connected to the device gave active measures in regulating flow rate and absorptivity in setting steady state energy capture and storage. A thermal transport system was determined by energy load – unload processes to maintain a steady state liquid temperature for solar modulation.

## 2.1 EXPERIMENTAL MULTI MICROCHANNEL DEVICE

A plant closed loop vasculature can be analysed through simulation to generate optimum succession sequencing of a multi microchannel network, such as a leaf-like model. A device demonstrated this iterative approach to obtain a flow parabolic profile for a fully developed flow rate, to advance a multiple channels' network defined by hydrodynamic control of fluids. This optimisation work of capillary succession of channels achieved an accuracy of 1 micron in the capillary geometry formation.

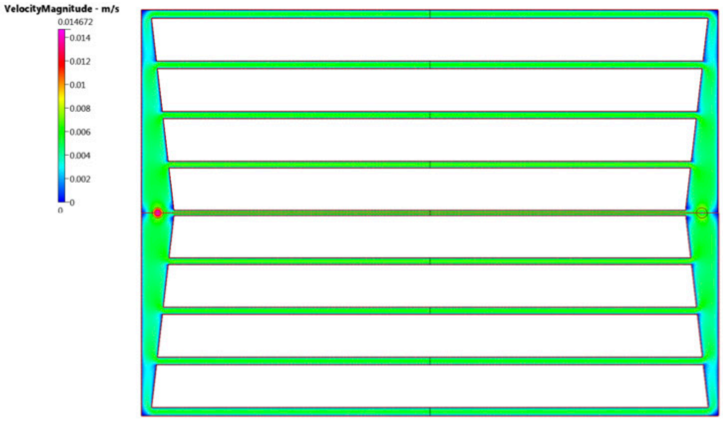

FIG. 3  CFD illustrates a unified flow rate to enhance uniform absorption of solar radiation at high temperature.

The device demonstrated this functionality by IR absorption that is dependent on solar radiation at high temperature (Alston & Barber, 2016). CFD illustrates the optimisation of flow rate within the multi microchannel network to achieve unified planar extensional flow across a planar device (Fig. 3).

NIR absorption is characterised by heat flow determined through the temperature difference between input and extract liquid, coming from the flow circuit (Alston, 2017). The fluid in this network circuit increases in temperature in a non-linear way as a result of solar radiation hitting the surface of the polymer (Fig. 4).

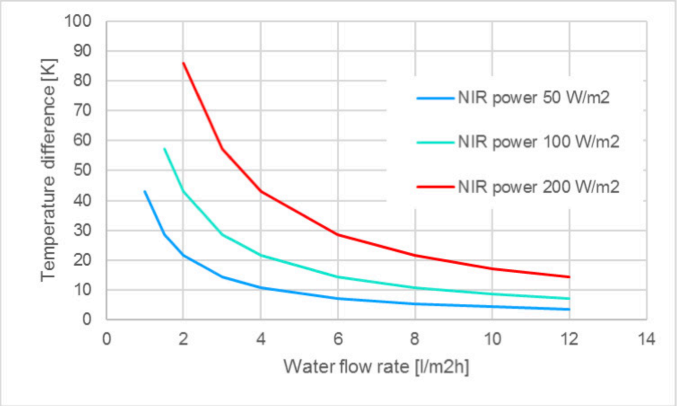

FIG. 4 Temperature gain in K for absorption rates as a function of flow rate *(Nestle, Pulbere, & Alston, 2018)*

Fig. 4 illustrates the temperature difference between fluidic feed-in to the network and the extract temperature of the fluid coming from the microchannel flow circuit. The NIR power (W/m2) determines the thermal profile of liquid temperature rise (delta t) by passage through the microfluidic network. By changing the flow rate, we change the temperature increase of the fluid in steady state flows. This contribution proposes that a microfluidic-based platform will advance NIR control by low transition temperature polymer using an absorption fluid approach. The geometry of the channels is determined by systematic resistance networking of multi micro-channel succession, inspired from biology, specifically a bifurcated leaf formation. The input and extract microchannels (manifolds) play a primary role for feed-in fluidics for the network's longitudinal channels. Simulation (CFD) have been undertaken to focus on successive channel widths, and to develop a hierarchy that emulates leaf vascular principles as a closed loop network. Flow input and export channels to accommodate and distribute incoming fluidic flow into the network define this optimised sequence of channel widths. Successive channel widths will increase in relation to increasing flow path length that is determined roughly by the square root of flow to channel path length. The optimised channel sequence in the polymer device was set at longitudinal channels at an equal spacing pattern formation of 15.575mm, with channel widths of:

R0-2.0mm, R1-2.3mm, R3-2.6mm, R4-2.8mm, and the outermost channel R4-3.0mm.

This channel geometry sequence is a hierarchical pattern defined by setting the value of resistance that is emulated by all channels. This was determined by the central channel R0 (target channel) to evaluate all others. This is a leaf-like absorption model which reflects the control of fluidics within capillary channels for unified flows across a network at low-pressure drop. This method follows the leaf vein formations by the principle of all veins diminishing in size distally from the fluidic input supply. This approach does not use or try to emulate leaf photosynthesis chemical solution fluidics due to formulation fluid complexity. Analysis of leaf-like model advances laminar non-turbulence flows at low flow rate for heat transfer. To optimize heat transfer by volumetric fluidic flow through uniform distribution across the network, the external face of the device, as a scale up, would comprise: 6mm Low-E coated glass Planitherm One to act as a weather facing material and fire protection to form the initial solar control layer. Bonding of this pane to the polymer-based material allowed direct lateral heat flow transfer into a liquid, which was observed by experimental testing as indicated in Fig. 4 results. The synthetic polymer material overall depth is 10mm (formed by two panes). Channel depth within a network composite material (2mm) reduces the associated weight that is currently associated with volume chamber fluidic windows. Thermal functionality is determined through optimum lateral heat transport flow with a minimum amount of fluid volume in network channels at a low flow rate of 1ml/min. Results indicated that water temperature rise occurred through the passage of a fluid within the network by absorbed solar heat gain from a heated polymer surface.

Experimental results demonstrated that input distilled water temperature at 10 $^0$C was heated to an output temperature of 14$^0$C by the polymer heating up through the passage within the capillary network. The solar load applied to the device was 1000 W/m$^2$. This energy gain was distributed within the device through the top polymer pane absorbing 210W/m$^2$, the fluid absorbing 707W/m$^{2,}$ and the lower polymer pane 83W/m$^2$. If this device was to be scaled up to a façade area of 10m$^2$, 200 litres of water would be obtained at this temperature. Increased solar loading would amplify water temperature rise in the network and associated water output storage temperatures. In principle, polymer microfluidics act as IR stop bands through absorption that is modulated by fluidics to manage the thermal stress that would occur if heat storage was not removed within the material. This is achieved by a reactive response to changing solar intensity environments that is managed by flow rate ml/min and temperature rise, delta t, measurements.

Flow rate sensors and temperature sensors, thermocouples, are established practices within the automotive and aerospace industries, and measure the above parameters. These sensors were used in the experimental device set-up, to actively modulate temperature by fluidics to regulate high temperature thermal issues. This contribution, however, does not address the visible part of the electromagnetic spectrum. Static solar shading or translucent materials would have to be incorporated within the façade design to avoid unwanted glare. The encouraging proof of concept determined a polymer acting as an infrared IR stop-band block at high temperatures through a material ability to lower its phase transition temperature. The functionality of the device is defined by heat flow transport within a composite polymer for enhanced thermal conductance. Application to the real world of the experimental device would need to consider others factors that cannot be replicated within a laboratory setting, which depends on building scale and geometry orientation connected to fluidic management.

## 3 SYNCHRONIZING MODULAR SOLAR GEOMETRY

Current transparent façade technology considers a glass building to be one surface, notwithstanding that this one surface is comprised of a number of assembly components, frames, mullions, waterproofing gaskets, and drainage channels. The entire glass envelope in a capillary composite glass material could not be treated as one entity, as the vascular network will have a significant resistance to flow. Pumping pressures need to be controlled for solar modulation, as this function would be outweighed by the pumping energy demands within the network. If the façade was broken into segments per floor level to work collectively to form the emergent façade, this would enhance fluidic flow regulation that is contained within a floor layer, (Fig. 5).

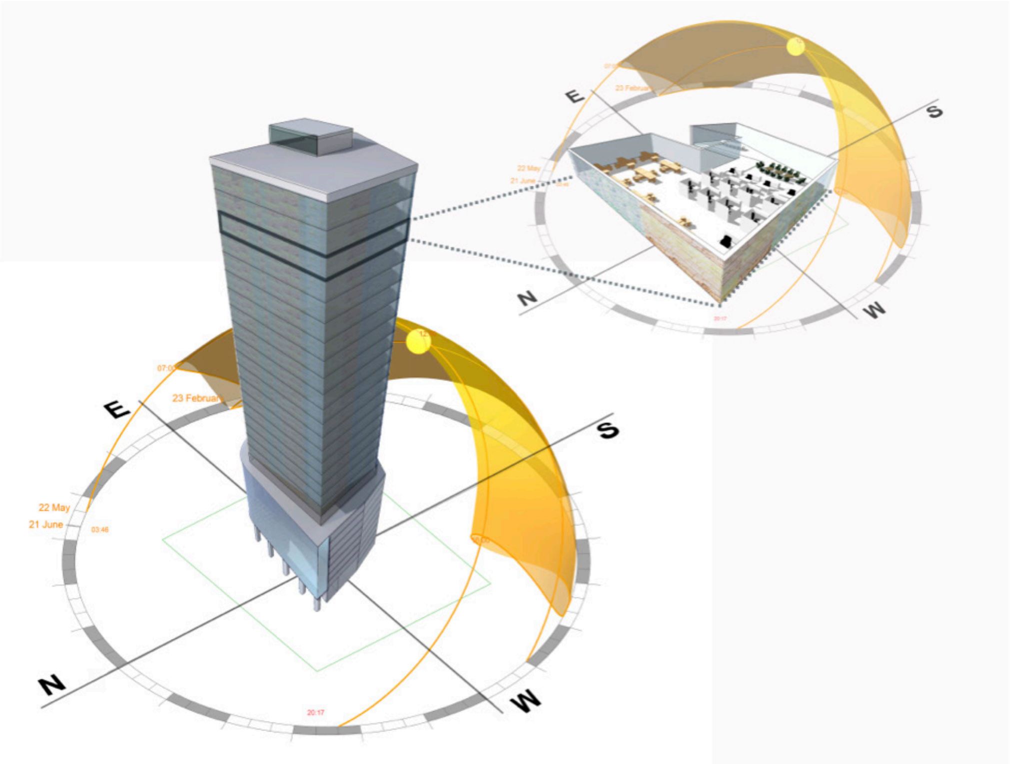

FIG. 5 Building Level Layering Approach

Each level acts as a photoactive layer to create the planar surface. This layer-by-layer approach, using gravitational pull to influence and manage fluidic flow, will reduce energy power demand, by avoiding the pumping of fluids through continuous vertical surfaces over multiple floors. This approach contains the fluid to a zonal (floor) level to manage energy load shift in segments for re-circulation. This load shift moves the active fluids in a flowing circuit into thermal storage tanks. By using the structural floor zone, the reservoir feed in and extract flows will be determined through fluidic temperature rise in relationship to time, T. Extract reservoirs, at the structural floor zone, will remove fluid at higher temperature (Fig.6), from the network for energy download heat exchange. This energy removal cycle is determined by heat transport flow within the network system that is regulated by hydrodynamic and thermal sensors in connection to a defined material datum temperature. By modulating volumetric flow rate ml/min in the networks, we are able to manipulate heat gain at fluid / polymer interfaces, using energy transfer (thermal storage, and electrical – energy conversion from Peltier devices) to monitor temperature. This process would advance energy syncing to user energy demands for consumption profiling to each and every floor (Fig. 6).

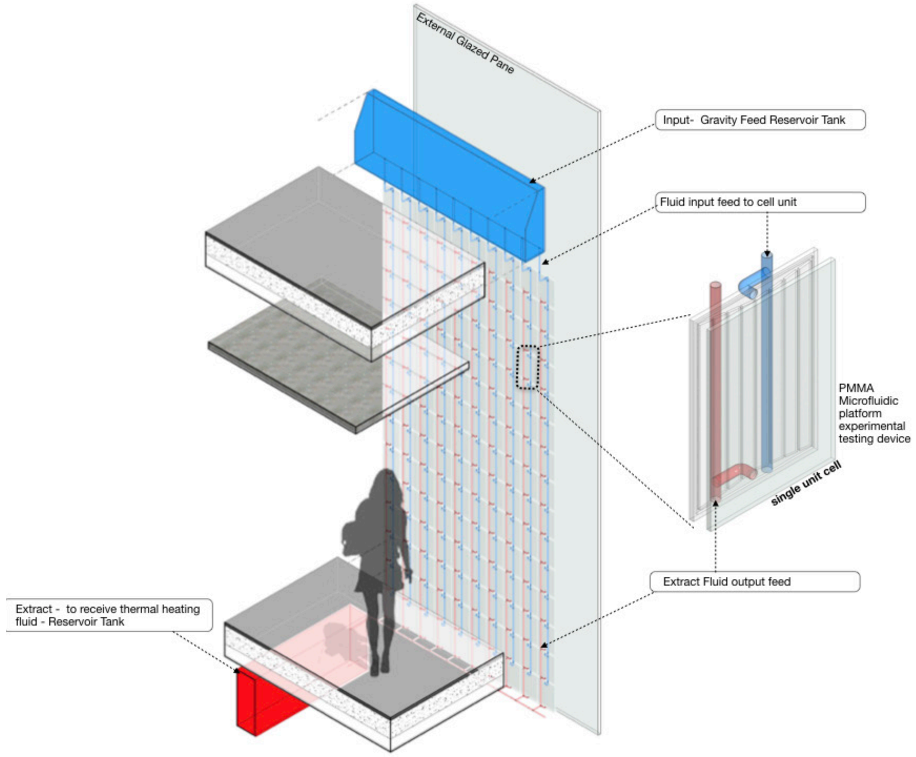

FIG. 6 Section through a building layer with a Capillary Glazed System

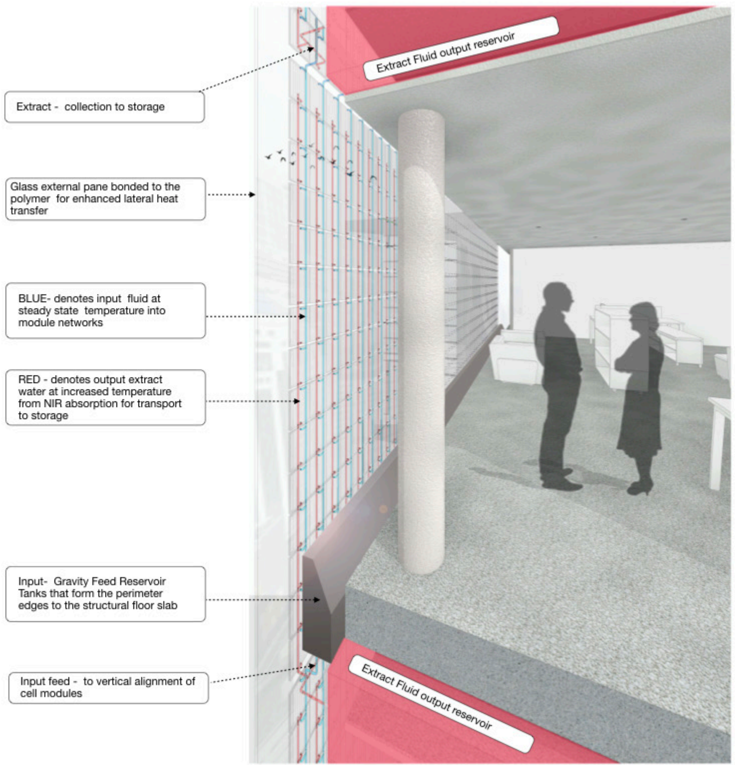

FIG. 7 Section through a building layer with a Capillary Glazed System

Fig. 6 illustrates a repeatable multi-module approach to forming a NIR filtering network to create a geometry system. As each module is independently regulated, this acts as a stop band block to boundary conditions as a performance metric of conductivity, convection, and thermal radiation. This collective approach simulates the structure of a tree by synchronizing network geometry in response to solar radiation intensity. The density of the geometry modules would increase or decrease depending on solar modulation and the requirement need for optical clarity (Fig. 7).

This NIR regulation, by absorption, will heat up the polymer through solar high radiation that will introduce increased thermal stresses within the material. These stresses are managed using precise hydrodynamics control of the microfluidic platform networks. The control of a fluid in volume networks, in comparison to full chamber flooding, enables greater management of thermal absorption to enhance the cooling of the polymer. With increasing solar radiation loading, the module cell geometry spatial separation will become finer and finer as the unit spacing distances reduce to form an overall coherent, maximised-density module pattern. Conversely, as solar radiation decreases, the spacing module pattern will increase to a point at which solar-energy modulation is not needed.  This will result in geometry distinctions between building surfaces in a capillary glazing approach method that will be defined by surface function response, as illustrated in Fig. 8. The geometry configuration is a radiant balance between atmosphere and thermal comfort, using module cells that are synchronised to solar radiation load, as a thermal conductance system. A repeatable cell pattern will form the surface of the façade by the deployment of multiple units. Module geometry transformations are set against a changing environmental background aligned to synchronising NIR filtering (Figs 8 & 9).

FIG. 8 Multiple parallel-aligned module cells for maximised low transition temperature

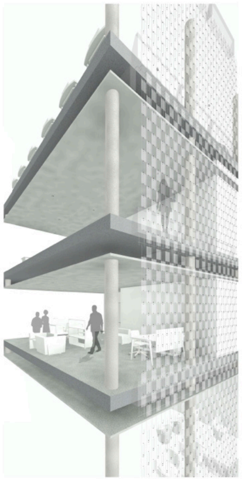

FIG. 9 Module cells with spatial separation for reduced solar radiation load

Figs 8 & 9, illustrate multiple parallel-aligned module cells as a heat seeking system that uses the optimisation parameters of visible transmittance and transition temperature for air conditioning reduction demands. It works as a collective unit that is synced to the user energy demand vector (heating, cooling) through building management monitoring. Figs. 8 & 9 show this geometry systemised solution. However, using NIR absorption glazing as a heat transport method could be optimised for enhanced areas for transparency and functional properties.

## 3.1 GEOMETRY TRANSFORMATION OF MODULE CELLS

Each module cell is individually autonomous, and would be regulated through flow control measures in relation to fluidic temperature increase within multiple network patterns. These cells are aligned vertically to block IR solar radiation at high temperatures. This gives attractive properties for each cell acting as an IR radiation stop band within a collective formation to maintain low pumping pressures and unified flow at each network entrance of multiple entrance points. These are difficult issues to resolve in maintaining equalised flow distribution for solar absorption. This method would enable operational performance cell tracking through delta t to detect solar radiation properties and the parameters for transition temperature. This approach would advance variant distribution patterns (Fig. 10) to transform transparent façades.

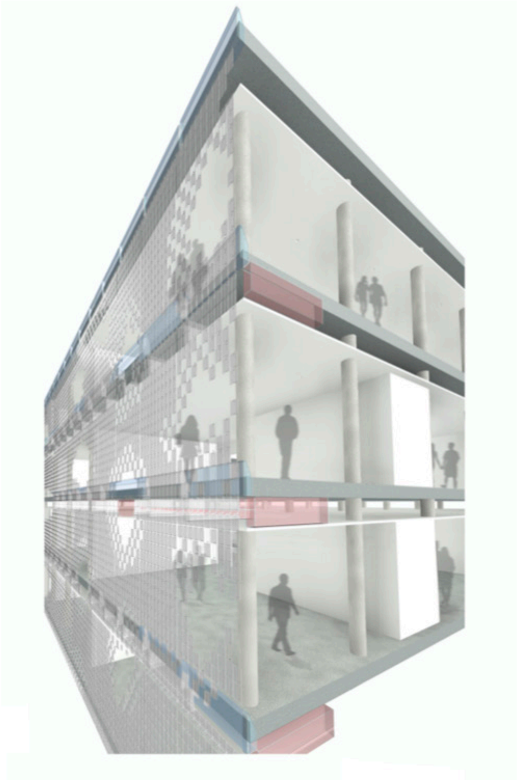

FIG. 10 Transformable module cells networks for solar modulation

This distribution system is a dynamic envelope that is nested to performance change by the hour, season, and weather conditions.

# 4 CONCLUSION

Global government targets for energy consumption reduction, and increasing uncertainty in the climate, all convey on a clear need for a solution for façades that has greater compliance to such standards. This has been determined to date through thin film reflecting metal oxide layers, electrochromic, and transparent insulation materials. These approaches also reduce the visual contact and optical benefits of view, colour, and light intensity that cannot not be underestimated for human well-being. The research demonstrates a material microfluidic platform of multiple cell geometry as a NIR absorption solution to enhance solar modulation properties, by employing the strategy of fluidics to control and manage multiple microfluidic based module cells to drive the assembly formation of a fully glazed façade as a stop band block for infrared IR solar radiation.

The regulation and management of a material is advanced through multiple networks in response to high solar radiation, by changing the synchronising geometry pattern that enhances distributed NIR filtering to create autonomous optic material surfaces for adaptive performance.

## Acknowledgements

Colleagues within BASF SE Advanced materials and system research, Germany, who are referenced within this paper. Thank you to Dr. Robert Barber for his support and advice from Scientific Research Facilities Council, UK government facility SRFC, Daresbury, UK, and to our reviewers who have given formative feedback to progress this paper.

## References

Alston, M.E. (2017). Optimal Microchannel Planar Reactor as a Switchable Infrared Absorber: (invited manuscript) MRS Advances. *Nanomaterials*. Vol. 2, 14, pp. 783-789

Alston, M.E. & Barber, R. (2016). Leaf venation as a resistor to optimize a switchable IR absorber. *Scientific Reports 6*, 31611; doi: 10.1038/srep31611.

Blonder, B.,Violle, C., Bentley, L. P., & Enquist, B. J. ( 2011). Venation networks and the origin of the leaf economics spectrum. *Ecology Letters.* 14, pp. 91–100.

Chow, T.T., Chunying, L., & Zhang, L., (2011) Thermal characteristics of water-flow double-pane window. *International Journal of Thermal Sciences,* 50: 140-148.

Chow, T.T., & Chunying, L., (2013) Liquid-filled solar glazing design for buoyant water-flow. *Building and Environment* 60: 45-55.

Dengler, D., & Kang, J. (2001). Vascular Patterning and Leaf Shape. *Plant Biology, Elsevier Science. 4*, pp. 50-56.

European Parliament Directive 2010/31/EU (2010). European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast), *Official Journal of the European Union* 53 (2010) 13.

Feugier, F.G., Mochizuki, A., & Iwasa, Y. (2005). Self organization of vascular systems in plant leaves: inter-dependent dynamics of auxin flux and carrier proteins. *Journal of Theoretical Biology* . 236, pp. 366–375.

Hens, H. (2011). *Applied Building Physics, Boundary Conditions, Building Performance and Material Properties*. Berlin: Ernst + Sohn.

Katifori, E., Szollosi, G.J., & Magnasco, M.O. (2010). Damage and Fluctuations Induce Loops in Optimal Transport Networks, *Physical Review letter,* PRL 104,04874.

Knaack, U., Klein, T., Bilow, M., & Auer, T. (2014). *Façades, Principles of construction*. Basel: Birkhäuser Verlag GmbH.

Lopez, T., Gimenez-Molina, C (2012) Influence of double glazing with circulating water chamber on a thermal energy saving in buildings, *Energy and Buildings, 56, pp.56-65*

Nestle, N., Pulbere, S., & Alston, M.E. (2018), Possible benefits of capillary flow glazing in translucent wall elements, Facade 2018 – Adaptive!, Proceedings of the COST Action TU1403 – Adaptive Facades Network Final Conference, Luzern.

Oh,K.W., Lee, K.,Ahn, B., & Furlani, E.P. (2010). Design of Pressure-driven Microfluidic Networks using Electric Circuit Analogy. *Lab on a Chip.*12, pp.515-545.

Stopper, J., Boeing, F., & Gstoehl, D., (2013) FluidGlass Façade Elements: Influences of dyeable Liquids within the Fluid Glass Façade, *Energy Forum on Solar Building Skins, Bressanone.*

Turing, A. M . (1952). The Chemical Basis of Morphogenesis, Philosophical Transaction of the Royal Society of London, Series B, *Biological Science.* 237, 641,pp 37-72 .

## COPYRIGHT NOTICE

Author(s) hold their copyright without restrictions.