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Fluidglass - Façade Elements for Active Solar Control for High-Rise Buildings

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ABSTRACT

High-rise buildings of modern architecture are usually built with transparent facades. This often leads to problems with the energy control inside the building. During summer solar radiation leads to overheating of the building and in winter time the low U-Value of the glazing results in high heat losses through the façade. In order to achieve a sufficient comfort level, large amounts of energy are needed. A new facade type, called fluidglass, is under development for future high-rise buildings as well as to retrofit existing buildings. This new facade allows increasing the energy efficiency of the building as well as the comfort of people inside. The system works as a shading device, a solar collector for heating and domestic hot water and as a cooling device.

Core of the system is a fluidized glass facade that controls the heat flux as well as the solar radiation through the facade. Two fluid-filled layers are set into the glass facade. These fluid layers regulate the energy flow within the facade by being adjustable in transmittance. The outer layer is used to control the absorption of the solar radiation and the inner layer is used for the control of the inner room temperature. Both layers are thermally separated by an insulation glass system. The radiative energy transmission as well as the shading of the room can be regulated by pigmenting the fluid. For cooling and heating purposes the inner layer of the overall facade is used for heat exchange. Therefore, only small temperature differences between room and supply temperature are required leading to high efficiency of A/C and heat pumping equipment.

The aim of this paper is to show the concept, a simulation model and a first prototype of fluidglass. The first simulation shows the impact of the fluid layer thickness onto the transmission rate. The results are that the fluid layer thickness has almost no influence on the transmission rate through the window, for a fluid layer thicknesses larger 1 mm. Secondly, an ideal fluid was simulated, which only lets the visible spectrum of the light pass through the fluid. Shading in several steps was simulated which represents the addition of ideal particles. The absorption rate of the fluid was varied in this way between 10-90%. The results show that the effect of shading and heat protection works, but the solar gains of the thermal collector are relatively small compared to a usual opaque thermal collector.

The concept of the façade system could be proven with a prototype. It is expected that architects and engineers will receive a new standardized product, which helps to increase the efficiency of their buildings significantly in a few years of time.

Keywords: Adaptive façade, solar thermal collector, solar energy, shading device

1. INTRODUCTION

In modern architecture transparent facades are an essential component to design large-scale buildings. Especially high-rise buildings have disadvantages from an energetic and comfort point of view. The principle of the solar irradiative flux through a windowpane is shown in figure 1. When solar radiation strikes a windowpane the solar radiation splits in reflection, absorption and transmission. One part of the radiation is reflected backwards from the surface of the windowpane. One portion of the thermal radiation is absorbed by the glass and increases the glass temperature and one portion, the largest part, mainly the short-wave thermal radiation is directly transmitted into the room. The room temperature starts to rise. During summer time, solar radiation will lead to overheating of a building. In the winter time, the low thermal resistance of the building envelope results in high heat losses through the transparent facade and in low surface temperatures which decrease thermal comfort.

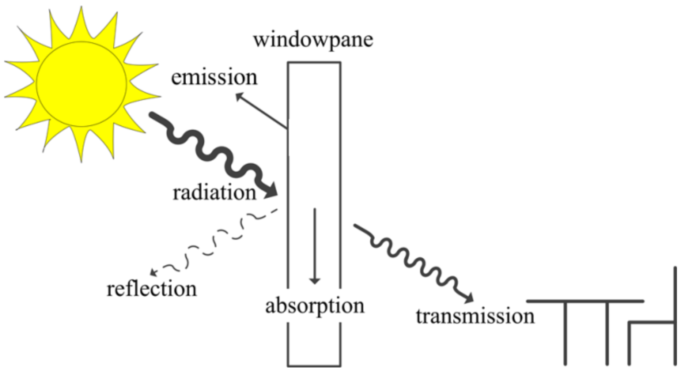

Figure 1: Radiation through a windowpane

One approach to increase the thermal performance of buildings is the current development of so called smart windows (e.g. electro chromatic coatings). The basic idea is that by adjusting the transparency of the building the solar gains are optimized in order to reduce heating demand and cooling load. But as Green et al. 1997 showed in his patent, electro chromic coatings have problems with unsteady shading for big windowpanes, because of the small conductivity which limits the switching speed for big cells. Furthermore discoloration of electro chromatic coatings is a widely occurring problem. Therefore, fixed and movable shading devices traditionally cover the function of blocking the sun. Such shading devices, like venetian blinds have the drawback that they are not allowed for use in buildings which have more than six floors because of the wind forces. Also, the absorbed solar energy is lost when venetian blinds are used. Typically they cannot be used as solar thermal collector.

Fluidglass is a smart, multifunctional glazing system applicable to facades and windows. This system replaces the shading device, solar collector, insulation as well as cooling and heating system of the building. The basic idea consists of two fluid-filled layers which are set onto a standard triple glazing. The standard triple glazing consists of three windowpanes to form two chambers which are filled with inert gas for a better insulation. The additional two fluid layers of fluidglass regulate all energy flows within the building envelope. The outer layer controls the energy transmission by absorbing the solar radiation and the inner fluid layer keeps the glass surface temperature just below or above room temperature for heating and cooling. Both fluid channels are thermally separated by the insulating glass.

In order to allow shading, the outer fluid channel can be enriched with particles. These particles absorb the solar radiation. The absorption rate depends on the particle concentration of the fluid. When low solar transmission is needed, the particles can be separated from the liquid and if required added again. The façade becomes a thermal collector, since the fluid can be circulated and used to exchange heat with the building HVAC system. The thermal energy which is absorbed is therefore not lost but can be transported wherever needed, using the fluid from the window pane (i.e. domestic hot water production, thermal storage, moving heat from the south façade to the north façade, where heat might be needed).

During summer time the fluidglass element can cool the adjacent rooms by flowing cool water through it, while in winter time fluidglass can replace the heating device. Two different operating modes for summer and winter time are illustrated in figure 2.

In summer time, clear water below room temperature is circulating inside the inner layer, thus cooling the room. In winter mode, the outer fluid layer will be clear. Solar radiation enters the room to reduce the heating demand of the building. The inner layer works then as a heating device. Warm water (around room temperature) is circulating through the inside layer and the room is heated. Only small temperature differences between room and supply temperature are needed because the whole facade area can be used as heat exchanger. This also leads to a high efficiency of A/C and heat pumping equipment.

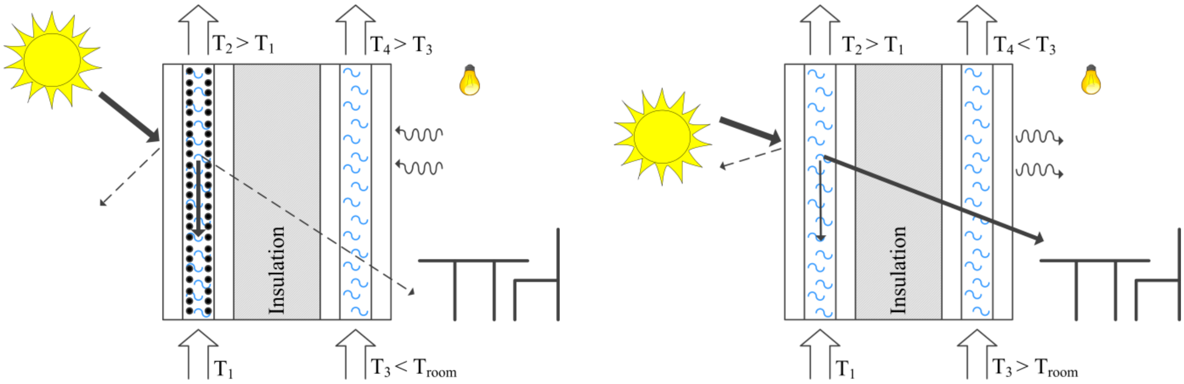

Figure 2: Basic operating modes of the fluidglass in summer (left) and winter (right)

The principle of a facade with fluid layers was already reported in some patents (Woods et al. 1973, Seemann 1983, Holzer 1988, Schwarz 1998, and Hernandez et al. 2008). But until now, no such system with particles for shading has been entirely realized.

The transmittance as a function of radiation wavelength is shown in figure 3. Several curves are shown for various system setups: The first one is an air gap between two windowpanes. The curve shows that the UV range of the solar radiation is blocked and the IR-radiation is reduced. When water is added to replace the air between the two windowpanes, it cuts off more of the wavelengths from IR range. But it reduces the reflection in the visible range leading to a higher visual performance of the window. Therefore, fluidglass reduces the thermal load on the building even when the pigmentation is not active. For an ideal fluidglass the target is to only let visible solar radiation pass (grey dashed line). According to the concentration of pigments, the transmission of visible solar radiation can be controlled.

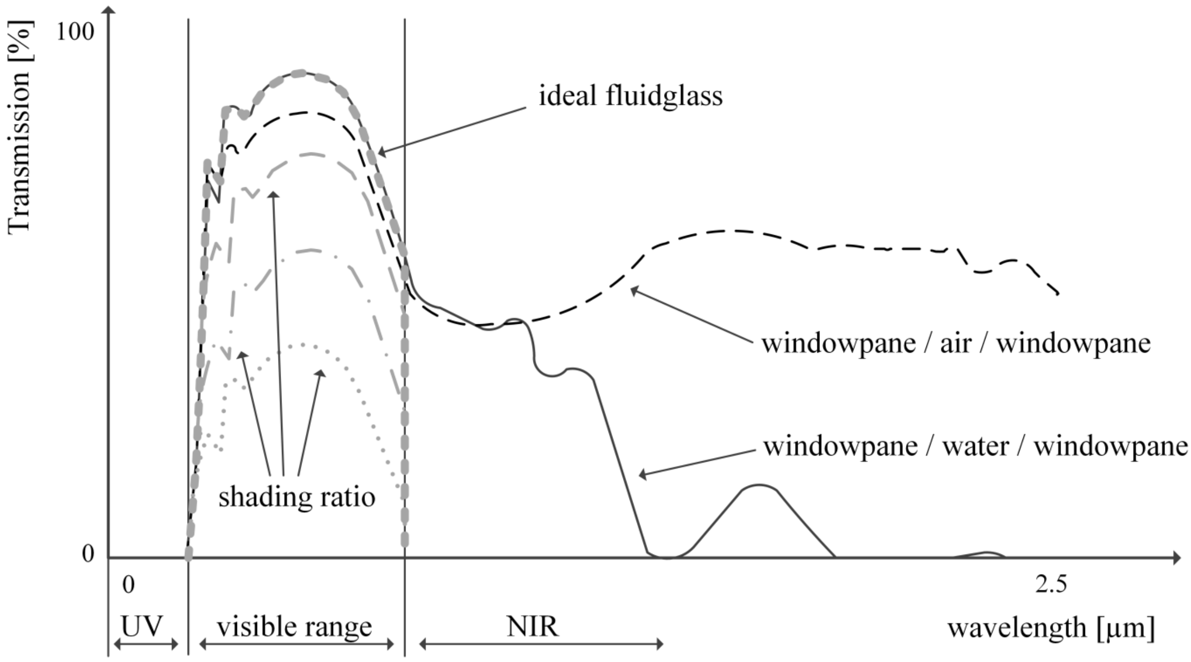

Figure 3: Transmission rate of windowpanes, filled with air, filled with water and for the ideal fluidglass with several shading values.

2. SIMULATION MODEL

A basic physics based model of the façade has been developed (Gstoehl et. al. 2011, Garzia 2013) in order to determine the potential of fluidglass. The theoretical setup of fluidglass is shown in figure 4. A commercial triple – glazed insulation glass unit is used as thermal separation (zones 4 to 8). Zone 5 and 7 contain the inert gas Krypton. Two additional glass panes are needed to form the fluid channels (chamber 1 and 2). Overall 5 window panes are represented by the simulation model (zone 2, 4, 6, 8 and 10). Low- emissivity (low-e) coatings are on the inside surface of the outer pane and on the outside surface of the inner pane of the insulation glass unit (dashed lines). The clear glass is PLANILUX (zone 2, 6, 10) and the coated glass is PLANITHERM ONE 2 (zone 4 and 8), both from Saint-Gobain Glass.

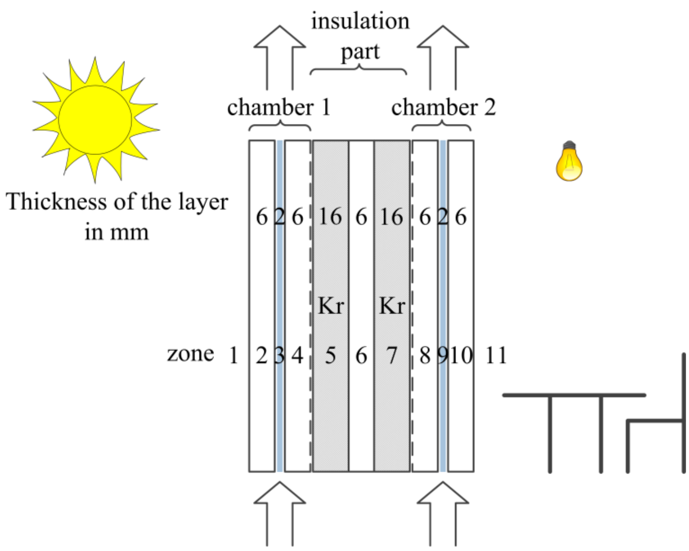

Figure 4: Glazing system consisting of two fluid chambers separated by an insulation glass unit in the middle

The absorbed solar radiation for all layers of the glazing system is determined using the equations shown below. Reflection is considered at every interface between the zones. Glass and liquid layers are considered as a semitransparent medium.

For reflection at interfaces, Fresnel's law of reflection is used. It applies to beams encountering the interface of two different media, media 1 and media 2. The reflection is calculated for perpendicular polarization (2) and parallel polarization (3) which are then combined in (1).

$$\mathrm{r} = \frac{\mathrm{r}_{||} + \mathrm{r}_{\perp}}{2} \tag{1}$$

$$r_{\perp} = \frac{sin^2(\alpha_1 - \alpha_2)}{sin^2(\alpha_1 + \alpha_2)} \tag{2}$$

$$r_{||} = \frac{tan^2(\alpha_1 - \alpha_2)}{tan^2(\alpha_1 + \alpha_2)} \tag{3}$$

In order to relate the angle of the beam with the interfaces to the refractive indices, Snell`s law (4) is used.

$$\frac{n_1}{n_2} = \frac{\sin\alpha_2}{\sin\alpha_1} \tag{4}$$

where n_1 and n_2 are the refraction indices of the medium for zone 1 and 2.

For every surface of fluidglass the radiation $\ddot{q}_R$ between two zones has to be calculated.

Figure 4 shows the principle of the radiation calculation for one interface. The radiation travels always in forward and backward direction through the medium.

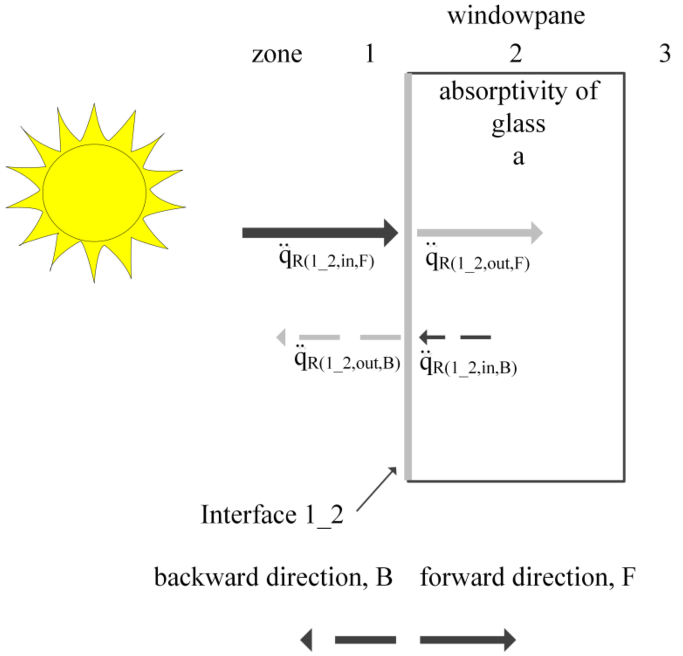

Figure 5: Radiation model (Garzia 2013)

The formulas of the radiation $\ddot{q}_R$, in forward F and backward B direction for the surface between zone 1 and zone 2 are:

$$\ddot{q}_{R(1\_2,out,F)} = \left(1 - r_{air\_glass}\right) * \ddot{q}_{R(1\_2,in,F)} + r_{air\_glass} * \ddot{q}_{R(1\_2,in,B)} \tag{5}$$

$$\ddot{q}_{R(1\_2,out,B)} = \left(1 - r_{air\_glass}\right) * \ddot{q}_{R(1\_2,in,B)} + r_{air\_glass} * \ddot{q}_{R(1\_2,in,F)} \tag{6}$$

$$\ddot{q}_{R(1\_2,in,B)} = \ddot{q}_{R(2\_3,out,B)} * (1 - a_2) \tag{7}$$

$$\ddot{q}_{R(2\_3,in,F)} = \ddot{q}_{R(1\_2,out,F)} * (1 - a_2) \tag{8}$$

Absorption is taken into account only within the glass and the liquid layers (9). The Lambert-Beer law (10) gives the intensity of the beam after travelling the path length L (13) through the material for an optical plate of thickness x and initial intensity I_o.

$$a_i = 1 - T_{ransmittance} \tag{9}$$

$$I(\lambda) = I_o * e^{-\gamma L} \tag{10}$$

$$T_{ransmittance} = \frac{I}{I_o} = e^{-\gamma L} \tag{11}$$

$$\gamma = \frac{4 * \pi * k}{\lambda} \tag{12}$$

$$L = \frac{x}{\cos \alpha} \tag{13}$$

The absorption coefficient γ (12) is a function of the wavelength λ and the extinction coefficient k. For the path length L, α means the incidence angle of the radiation in that zone.

The fraction of the absorbed radiation, $\ddot{q}_A$, was considered for forward and backward direction. The total absorbed energy $\ddot{q}_{A2}$ (7) of zone 2 is the sum of both contributions.

$$\ddot{q}_{A2} = a_2 * \left(\ddot{q}_{R(1-2,out,F)} + \ddot{q}_{R(2-3,out,B)}\right) \tag{14}$$

The total absorbed radiation is:

$$\ddot{q}_{A,total} = \sum_{i=2}^{10} \ddot{q}_{Ai} \tag{15}$$

For the current investigation the absorbed radiation is divided into three parts, see figure 4. The three parts are chamber 1 (ch1) including zones 2, 3 and 4, the window pane in the center zone 6 (the inert gas zones have no absorption) and chamber 2 including zones 8, 9 and 10.

The transmitted part, which gets inside the building is the energy flux from the last surface travelling in forward direction $\ddot{q}_{R(10\_11,out,F)}$. The reflected part which is not able to enter the fluidglass is the reflected energy flux from the first surface in backward direction $\ddot{q}_{R(1\_2,out,B)}$.

The transmission, the reflection and the absorption is calculated for the visible range and the total solar radiation spectrum in 88 wavelength steps from 0.3 to 2.5 μm. Calculations were performed according to the EN 410:2011. The EN 410 for glass in buildings considers the standard illuminant D65 for the relative spectral distribution as well as correction factors for the solar radiation**.** Mean values of the transmission ($T_{Sol,}.T_{Vis}$), absorption (A_{total}), and reflection (R_{Sol} , R_{Vis}) are calculated using these weighing factors.

3. SIMULATION

Two sets of simulations were carried out. The first simulation shows the impact of the outer fluid layer thickness onto the overall transmission rate. The second simulation shows an ideal fluid with the feature of only transmitting visible light (wavelength from 0.38 µm until 0.78 µm) while absorbing all other wavelength. In a second step the effect of changing the transmittance in the visible area was simulated which would correspond to adding particles into the fluid.

For the first simulation, the total solar radiation spectrum from 0.3 μm – 2.5 μm is simulated for the whole fluidglass glazing configuration (figure 4). For the fluid the optical constants of water were taken from M. Hale el. at (1973) and the optical constants of the glass layer were specified by the manufacturer. For this simulation the fluid layer thickness x was varied from 1 mm to 50 mm. The beam is impinging the glass perpendicular. Table 1 and figure 6 show the simulation results. Transmittance, reflectance and the total absorbance are mean values over the whole wavelength rate. As expected, the thicker the fluid layer, the more energy can be absorbed in the first chamber, but the effect is weak. The absorption in the outer fluid chamber ranges from 40% to 50% for a layer thickness of 1 to 50 mm.

Table 1: Transmittance, reflectance, and absorbance of the complete glazing system with clear water in both liquid layers for different thicknesses of the first fluid layer.

x [mm]	T_{Sol} [-]	R_{Sol} [-]	A_{total} [-]	A_{ch1} [-]	A_6 [-]	A_{ch2} [-]
1	0.2536	0.2315	0.515	0.3976	0.0578	0.0595
2	0.2533	0.2198	0.527	0.4118	0.0562	0.0589
5	0.2524	0.2081	0.540	0.4278	0.0537	0.0580
10	0.2512	0.1986	0.550	0.4417	0.0514	0.0571
50	0.2452	0.1775	0.577	0.4797	0.0442	0.0534

The transmission rate for the whole solar spectrum and for the different fluid layer thicknesses is shown in figure 6 as function of the wavelength. It can be seen, that even for a water layer thickness of 50 mm the transmittance is not getting much smaller than the transmittance of a 2 mm thick water layer. Therefore in the field a fairly narrow water-chamber will be used to reduce size and weight of the structure as well as the fluid amount. The minimum thickness will mostly be determined on manufacturability and absorptivity of the particles.

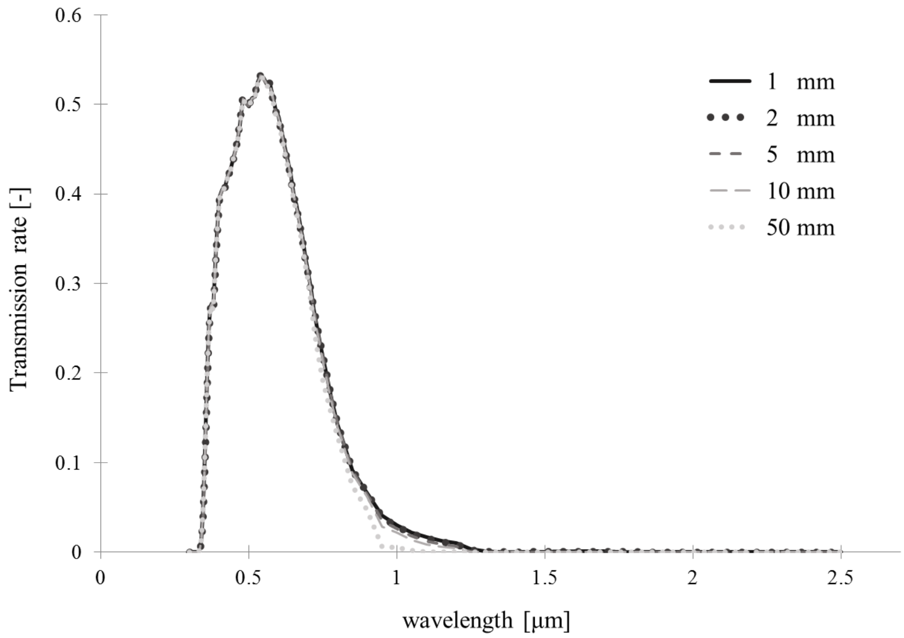

Figure 6: Transmission rate vs. wavelength, for different thicknesses of the fluid layer

For the second set of simulation an ideal fluid was considered. Only the visble radiation spectrum can pass through this fluid. In practice, this effect could be achieved with additives to the fluid or coatings on the glass. The absorption in the liquid layer was varied from 10% to 90%. This would correspond to different particle concentrations in the fluid for shading. Like in the first simulation, the complete fluidglass structure is simulated and the irradiation angle again is vertical to the glass surface. The summer case is simulated with particles only in the outer fluid layer. The fluid layer thickness was chosen as 2 mm due to manufacturability isssues and given the results of the first simulations.

Table 2 shows the simulation results. It contains the transmission and reflection for the visible spectrum (Vis) as well as for the whole solar spectrum (Sol) of the ideal fluid with particles. Zero shading rate means that there are no particles in the fluid and the optical properties correspond to water in the visible range. At a shading rate of 50% the first fluid layer will absorb 77% of the total heat flux, and even with no shading, only 23% of the incident radiation will pass through the façade, reducing the heating load of the building considerably.

Table 2: Transmittance reflectance and absorbance of an ideal fluid with ideal particles for varying absorption rates for the glazing configuration in figure 4

shading rate (outer fluid layer) [%]	T_{Vis} [-]	T_{Sol} [-]	R_{Vis} [-]	R_{Sol} [-]	A_{total} [-]	A_{ch1} [-]	A_6 [-]	A_{ch2} [-]
0	0.505	0.231	0.247	0.158	0.614	0.537	0.032	0.045
10	0.453	0.208	0.212	0.138	0.654	0.585	0.029	0.040
30	0.351	0.161	0.146	0.101	0.738	0.684	0.023	0.031
50	0.250	0.115	0.097	0.074	0.811	0.773	0.016	0.022
70	0.150	0.069	0.065	0.056	0.867	0.853	0.001	0.013
90	0.050	0.023	0.049	0.046	0.928	0.923	0.0003	0.005

Glasses with low-e coatings are used in the fluidglass façade to minimize heat losses through the façade in the winter. On the other hand solar gains in winter are reduced due to these coatings, due to the lower solar transmission. In order to determine to complete range for fluidglass the low-e coatings were removed for the next simulation. The properties of uncoated float glass were taken for all five glass panes.

Table 3 shows the simulation results of the façade element with standard glazing without low-e coatings.

Table 3: Transmittance, reflectance and absorbance for an ideal fluid with particles and no low-e coatings

Absorption in outer fluid layer [%]	T_{Vis} [-]	T_{Sol} [-]	R_{Vis} [-]	R_{Sol} [-]	A_{total} [-]	A_{ch1} [-]	A_6 [-]	A_{ch2} [-]
0	0.586	0.291	0.172	0.107	0.605	0.520	0.034	0.051
10	0.527	0.261	0.150	0.097	0.641	0.565	0.030	0.046
30	0.401	0.203	0.109	0.076	0.721	0.661	0.024	0.036
50	0.292	0.145	0.078	0.061	0.795	0.752	0.017	0.026
70	0.175	0.087	0.058	0.051	0.862	0.837	0.010	0.015
90	0.058	0.029	0.048	0.046	0.925	0.917	0.003	0.005

Without the low-e coating the average transmission rate for the complete solar radiation spectrum (Sol) is 25% higher when no particles are present. The reason for the small discrepancy between the two cases is that the fluid absorbs the NIR and IR radiation already. The transmission rate for the visible spectrum (Vis) without the low-e coating is 16% higher and the absorption of the first fluid layer is slightly reduced. This effect is unwanted in summer, since solar gains pass directly into the room which increases the cooling load. In this situation fluidglass offers the opportunity of reducing the solar gains by increasing the concentration of particles. In winter time on the other hand, it is expected that the higher losses with no low-e coatings will outweigh the higher solar transmission rate and from an energetical point of view the low-e coatings will be necessary. Further building simulations of the fluidglass system are required to determine the optimal configuration of fluid, glazing and coatings for certain applications.

Figure 7 shows the transmission rate for the ideal fluid and the fluidglass system with and without low-e coatings. It shows the reduction in transmittance when using low-e coatings. With no shading particles present, the effects are significant, but at high particle concentration the reduction in light transmittance can be compensated using different particle concentrations.

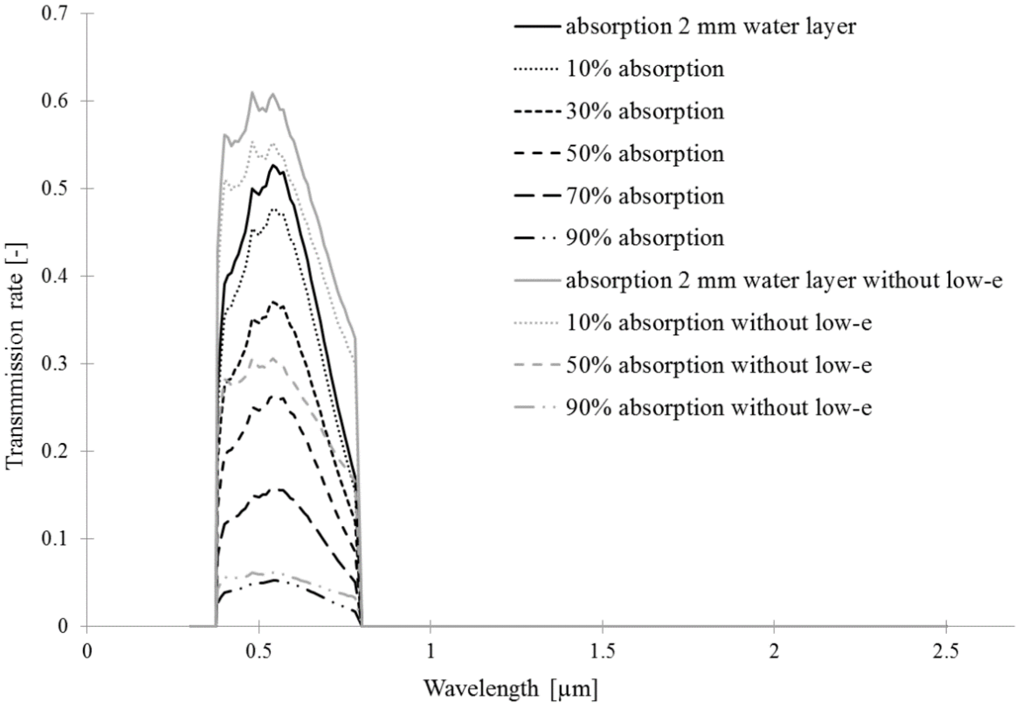

Figure 7: Ideal fluid with different absorption rates

4. PROTOTYPE SYSTEM

In order to proof the feasibility of the concept a prototype has been built. The structure of the test setup corresponds to the layout given in figure 4. The fluid channels are 2 mm thick; the total thickness of the prototype is 66 mm. The fluid enters the fluidglass through injection nozzles at the bottom and exits it at the top. The façade element is operated in a way that the pressures in the fluid chambers are always below ambient pressure. This operation is chosen to minimize the glass thickness, which in case of overpressure would need to be far thicker. In the given setup, pressure at the top of the façade element is around 0.16 bar below ambient pressure. In order to ensure a uniform distance between the glass layers that enclose the fluid channel, spacers are equally distributed.

Preliminary tests (Oppliger et al. 2012) were performed using a colorant to vary the absorptivity of the fluid. The complete shading is shown in figure 8. As we can see the interface of the pigmented water moves upwards in these pictures showing a total change in transmittance. Depending on the concentration of the colorant the transmission can be controlled in a continuous way.

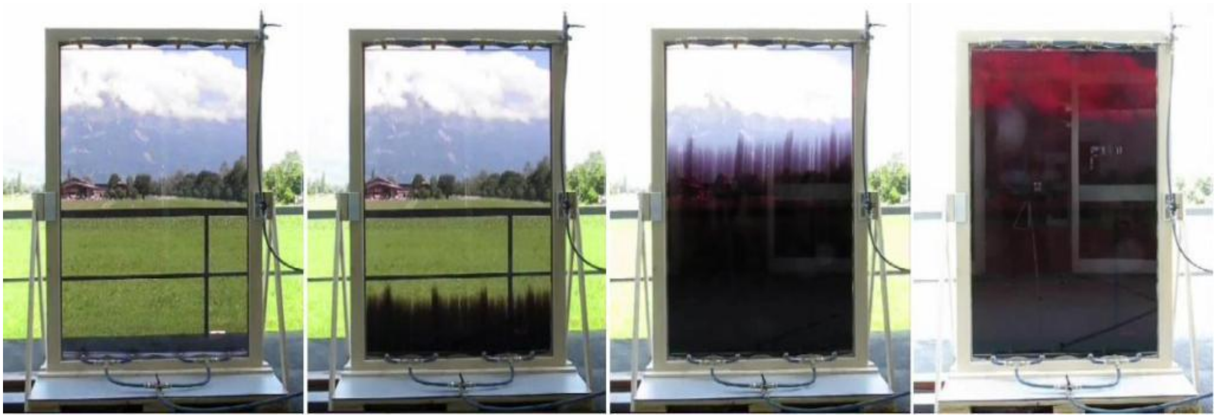

Figure 8: Preliminary tests using a colorant to vary the absorptivity, for total shading

5. CONCLUSION

Controlling all thermal energy flows through a building with one element is a highly desired function of a facade. Combining the functions of a shading device, solar collector, cooling and heating element into one system could be demonstrated with a prototype of fluidglass. One element is able to fully or partially replace several systems. In order to control the energy flows fluidglass has two fluid layers within a façade element. The outer layer is mainly used to control the solar radiation and the inner layer is maintaining the inner room temperature. Both layers are thermally separated by an insulation glass system.

The simulation results show that the thickness of the fluid layer has no significant effect on the transmission rate for the investigated fluidglass configuration. A second simulation shows an approach for an ideal fluid with particles in the outer fluid layer. The absorption in the outer layer is at a range of 50-90% for different particle concentrations. In combination with the ideal fluid the low-e coatings only have a minor effect. Further optimization of fluid and glazing are required.

A first real size prototype was successfully built to show the function of fluidglass. Currently the fluidglass system is further investigated with the goal of improving the system, finding the best fluid-particle combination, measuring system efficiency and improving reliability and durability. It is expected that architects and engineers will receive a standardized product, which increases the efficiency of the building significantly, within the next few years.

6. NOMENCLATURE

a	Absorption coefficient [-]	**Greek symbols**	
A	Absorbance [-]	α	Angle [°]
I_o	Intensity of the incident light [W/m^2]	ε	Emissivity [-]
I	Intensity of the transmitted light [W/m^2]	λ	Wavelength [m]
k	Extinction coefficient [-]	γ	Absorption coefficient [1/m]
L	Path length [m]	**Subscripts**	
n	Refraction indices [-]	A	Absorbed radiation
$\ddot{q}$	Heat flux [W/m^2]	Ch1	Chamber 1
r	Reflection [-]	Ch2	Chamber 2
R	Reflectance [-]	i	Index for zone
T	Transmittance [-]	R	Radiation
x	Thickness of a layer [m]	Sol	Solar radiation spectrum
		total	Sum of all absorption parts
		Vis	Visual radiation spectrum

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