Fluid Glass Façade Elements:
Energy Balance of an Office Space with a Fluid Glass Façade.

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Summary

High-rise buildings with a large proportion of transparent areas, where conventional external overheating protection cannot be used due to the wind loads, are often problematic from an energetic and comfort point of view. In this paper a glass façade system is examined, which controls the energy flows within the transparent building envelope. Two fluid-filled layers are implemented in a glass façade. The inner fluid layer controls the inside surface temperature and thus the room temperature, while the outer, dyeable liquid layer controls the energy transmission by absorption of the solar radiation. The inside and outside fluid layers are thermally separated.

Three standard types of glazing are adopted as benchmarks for the fluid glass: a double glazing unit (DGU) and two solar-control glazing units (SCGUs) with differing U-values. Yearly energy consumptions of a standard office space with a complete glass faced on one side are calculated in Munich and Dubai. Without coloring the fluid, the cooling demand of an office space with fluid glass façade is approximately 39% higher than with SCGU in Munich, and approximately 25% higher in Dubai. While colored fluid glass nearly halves the cooling demand compared to SCGUs. Dyeable fluid glass façades with adjustable transparency show overall energy savings of approximately 23% in Munich, and approximately 44% in Dubai. Thus, using dye to control the solar transmission is crucial for successful implementation of the fluid glass concept. Beyond this, the temperature of the inner fluid layer remains constantly close to room temperature, in summer and winter. In combination with a heat pump, a highly efficient heating and cooling system can be realized.

The current study showed the high potential of fluid glass façades for reducing the energy demand of an office space, mainly for cooling purposes.

Keywords: Solar energy, renewable energy, energy efficiency, building envelope, energy consumption, adaptive facades

1. Introduction

Since transparency is an important element of architecture, also large-scale buildings often are equipped with a high proportion of areas with transparent façades. This can lead to major problems from an energetic and comfort point of view, especially in high-rise buildings, where conventional external overheating protection cannot be used due to the wind loads. On the one hand, high solar radiation during summer can result in overheating of the building without a proper shading device. On the other hand, the large advantage of a transparent façade in winter is the solar gains. By allowing solar radiation to enter the building, heating demands can be compensated and the energy balance of the building can be improved. Therefore, glass façades need to be adjustable to different climate conditions and internal needs. One way of doing so is the dynamic transparency adjustment of the glass itself. Up to now, the issue of adjustable transparency has only been tackled with smart windows. Today adjustable transparency of windows is achieved using electrochromic materials, liquid crystals and electrophoretic or suspended-particle devices [1].

Another approach is the fluid glass façade [2] proposed in this paper. It is a glass façade system which controls the energy flows within a transparent building. Two fluid-filled layers are set into the glass façade. These two layers regulate all energy flows within the facade. The inner fluid layer keeps the inside surface temperature just below or above room temperature for heating and cooling, while the outer liquid layer controls the energy transmission by absorption of the solar radiation. The inside and outside fluid layers are thermally separated. Two basic operating modes for summer and winter are illustrated in *Fig.1*.

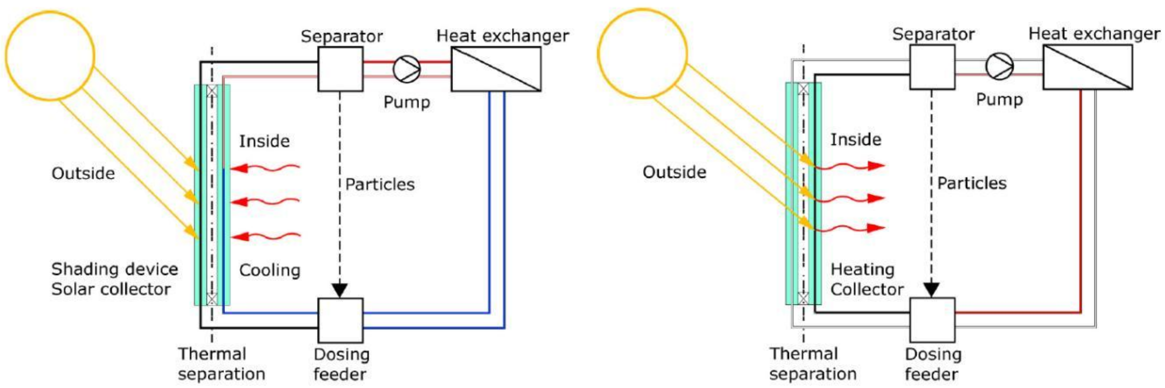

Fig. 1: Basic operating modes of the fluid glass in summer (left) and winter (right) [3].

The absorption of solar radiation within the façade can be controlled by coloring or decoloring the fluid [3]. In summer mode, the outer fluid layer will be dyed to increase the absorption – it protects against overheating. The solar energy will be absorbed in the fluid and can be transported by fluid circulation where needed. In winter mode, the outer fluid layer will be clear to allow solar radiation entering the insulated perimeter to reduce the heating demand of the building.

This system works as a shading device, solar collector, cooling ceiling, floor heating system, and insulating façade of a building within a thickness of a few centimetres, and it replaces equivalent common systems. The transparent façade can help to increase the energy efficiency of buildings in every climate zone and enables the use of renewable solar energy throughout the whole façade area.

2. Materials and Methods

A basic physical model of the façade system was developed [3]. The software EES from F-Chart Software was used to calculate the absorbed solar radiation for all layers in the first step and to solve a static energy balance in the second step. To validate the models, a prototype was built and tested. The prototype features two fluid layers separated by a thermal barrier of a commercial triple-glazed insulation unit. It consists of three layers of 6mm thick glass with gaps of 16mm each. The glazing gap is filled with the inert gas krypton. Low-E coatings are on the inside surface of the outer pane and on the outside surface of the inner pane of the insulation glazing unit. On both sides of the insulation glazing unit, a 6mm thick glass is placed to form the chambers for fluid 1 (outside) and fluid 2 (inside). The fluid chamber width is 2mm, resulting in a total thickness of the glazing system of 66mm. The complete glazing system is illustrated in *Fig*. 2. The clear glass is PLANILUX® (zone 2, 6, 10) and the coated glass is PLANITHERM® ONE II (zone 4 and 8), both from Saint-Gobain Glass.

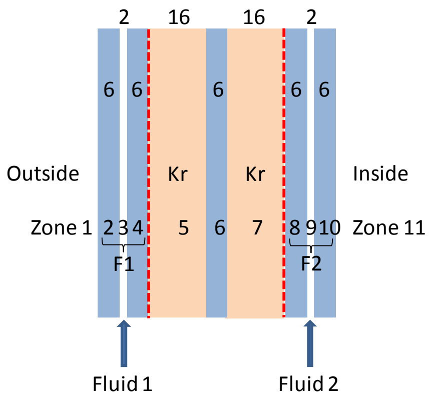

Fig.2: Glazing system consisting of two fluid chambers separated by an insulation glass unit [3].

An inlet and outlet system has been developed to achieve a uniform flow within the two fluid chambers [3]. The fluid enters and leaves the chambers perpendicularly to the flow directions. Streamlined nozzles inside the fluid chambers support the uniform flow. The façade element is operated such that the pressure in the fluid chamber is always below the ambient pressure. This operation mode is chosen to minimize the glass thickness, since stress resulting from the pressure difference between water and surrounding air can be supported by small columns between the windows. The prototype was tested in the solar test facility at the Technische Universität München, Institute for Energy Economics and Application Technology [4]. Both the optical and thermal simulation models were validated and further developed in [5] and [6], respectively.

Based on these fundamentals, static calculations of the yearly energy consumption of an office space are made on an hourly basis. In accordance to the room types of the VDI 6020, the dimensions of the room are 3.0 x 3.5 x 5.0 meters (height x width x depth) [7]. The user profile is set for single offices based on the DIN V 18599 [8]. The office space is calculated with a theoretical glazing share of 100% within the façade area. The three interior walls, the floor and the ceiling are set adiabatically in relation to the surrounding rooms. The static energy balance calculations take into account, the direct and indirect solar radiation, the heat transfer through the outer shell and the internal loads. The energy demands for heating, cooling, artificial lighting and the operation of the pump for the fluid circulation within the fluid glass façade are calculated as effective energy. Energy demand for fluid circulation is based on the assumption that the temperature increase within the fluid chamber is restricted to 5K. The south-west orientation was chosen to simulate the worst case for overheating in Munich and Dubai. The calculations neglect the frame components of the glazing, the thermal mass of the building, the ventilation heat loss and the thermal entry through the artificial lighting.

In accordance with DIN 12521 the room temperatures are set between 20°C and 26°C during usage times from 7am to 6pm. In between the upper and the lower temperature limit, the ambient temperature is adopted. Outside of working hours, the minimum room temperature is set to 18°C. The guidelines for cooling are either an outside temperature of greater than 20°C, or an external temperature of 18°C with a solar radiation on the facade of greater than 350W/m². By exceeding these parameters, the cooling system is switched on. Room heating starts with an outside temperature of below 10°C, based on the passive house standard value [9]. The maximum temperature of the outer liquid layer is set to 40°C. From this temperature, the fluid is circulated and the heat flux is removed to keep the fluid temperature at a constant level. The optical model relies on measured data of dyed liquid with three coloring concentrations. For the current investigation, interpolated values were used in the optical model to calculate the liquid layer. For the investigated fluid glass assembly, the visual transmission coefficient (τ_{vis}) can thus be adjusted from 0.505 to 0.000 and the solar transmission coefficient (τ_{sol}) from 0.253 to 0.021, according to DIN EN 410 [10]. The coloring degree of the fluid is chosen so that at least 500 Lux is guaranteed as average illuminance at the usage area of the room, according to DIN EN 12464 [11] The average illuminance level was derived from a daylight simulation with Relux [12].

Three standard types of glazing are adopted as benchmarks for the fluid glass: on the one hand, a double glazing unit (DGU) based on the specifications from the German building typology for high-rise buildings from 1981 to 1985 [13], and on the other hand, two solar-control glazing units (SCGUs) with different heat transfer coefficients (U-values). The glazing assembly of the fluid glass corresponds to the assembly shown in *Fig. 2*. Two fluid glass scenarios are considered: one with adjustable transparency (dyed) and one with constant properties of a clear fluid. The parameters of the tested glazing scenarios are shown in *Table 1*.

Table 1: Parameters of investigated glazing scenarios.

No.	Titel	g-value	τ_{sol}	τ_{vis}	U-value [W/m²K]
1	Double glazing unit (DGU)	0.75	0.68	0.80	2.6
2	Solar-control glazing unit 0.7 (SCGU 0.7)	0.26	0.22	0.54	0.7
3	Solar-control glazing unit 0.4 (SCGU 0.4)	0.25	0.22	0.53	0.4
4	Fluid glass with dyed fluid (fluid glass dyed)	0.34 – 0.06	0.25 – 0.02	0.50 – 0.00	0.44
5	Fluid glass without dyed fluid (fluid glass clear)	0.34	0.25	0.50	0.44

3. Results and Discussion

The simulations show large energy savings potential for glazing with improved U-values–fluid glass, as well as SCGUs with a U-value of 0.7 or 0.4W/m²K–compared to the DGU with a U-Value of 2.6W/m²K, both for heating and cooling demands as illustrated in *Fig. 3*. The lighting demand is lowest for the DGU and increases for the SCGUs and the fluid glass following the coefficient τ_{vis}.

In Munich, the heating demand decreases by 46% for glazing with a U-value of 0.4W/m²K compared to glazing units with a U-Value of 0.7W/m²K. The cooling demand is strongly connected to the g-value of the glass. Without coloring of the fluid, the fluid glass has a 39% higher cooling demand than the SCGU 0.4. While colored fluid glass nearly halves the cooling demand compared to the SCGU 0.4. Colored fluid glass shows an overall saving in the energy demand of approximately 23% compared to the SCGU 0.4.

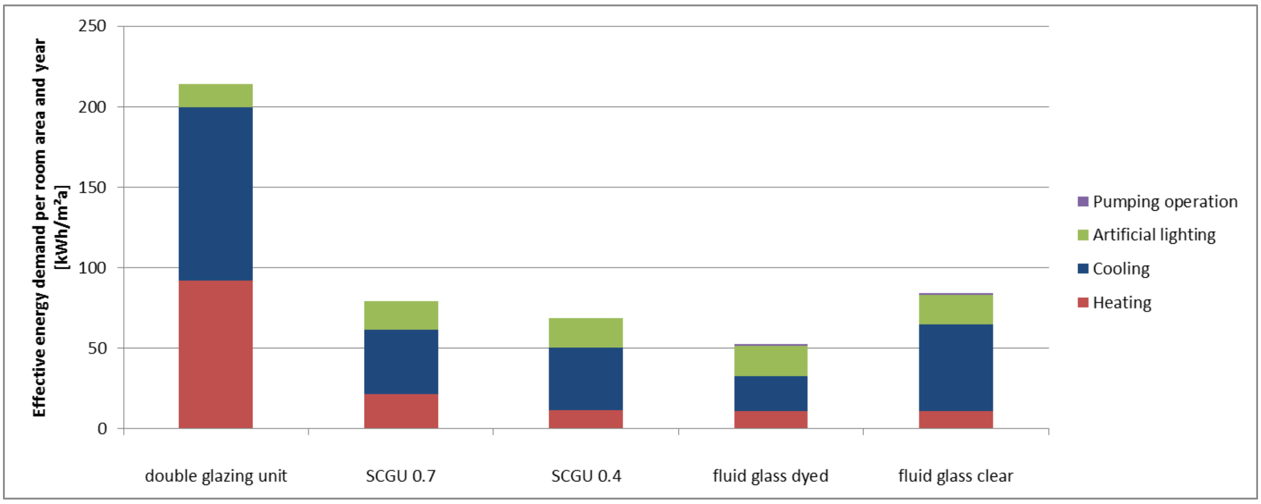

Fig. 3: Munich south-west orientation: Yearly effective energy demand for the five scenarios listed in Table 1.

In Dubai, the energy demand increases substantially compared to Munich. There is no heating demand but an enormous cooling demand during the entire year. The energy demand for lighting and pumping is very small compared to the cooling demand. Compared to the highly advanced SCGU 0.4, the cooling demand increases by approximately 25% with the fluid glass without colored fluid; however by coloring the fluid, the overall energy demand decreases by approximately 44%.

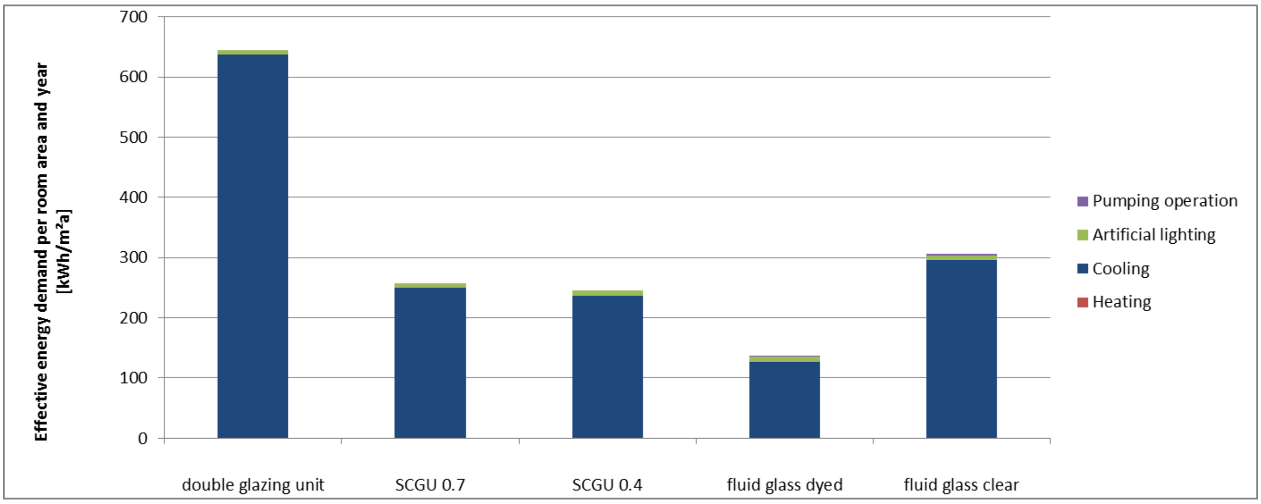

Fig. 4: Dubai south-west orientation: Yearly effective energy demand for the five scenarios listed in Table 1.

In Dubai, simulations with a higher circulation temperatures than 40°C show that there is little influence on the heat flow towards the room, and thus on the annual cooling demand. This is due to the excellent thermal insulation of the two fluid layers in combination with the mediocre collector efficiency of the fluid glass at elevated temperatures. Without circulation of the outer fluid layer a maximum fluid temperature of 61°C is reached and the cooling demand of the room increases by 3%.

By using fluid glass, there is no need for additional heat transfer layers with the unfavorable water-air heat exchange, due to the large façade area. That is a significant advantage compared to conventional air-conditioning units. This reduces the technical outlay and increases the architectural design freedom. Looking at the behavior of the fluid glass during the heating period in cold climates, a further advantage in comparison to conventional hot water heating systems can be seen: the low inlet temperatures of the inner fluid layer. A south-west oriented fluid glass façade in Munich reaches a maximum supply temperature in the inner fluid layer of 25°C, compared to a conventional hot water heating system with a supply temperature between 35°C and 90°C. Due to this relatively low temperature, a heat pump can be operated highly efficiently. Both for the heating and the cooling operation of the colored fluid glass, the temperatures of the inner fluid layer are very close to room temperature. The mean difference between room temperature and the temperature of the inner fluid layer is approximately 3.0K in Munich. In Dubai it is approximately 4.2K. Beyond energy savings, these low temperature differentials lead to a positive thermal comfort level within the room. Compared to conventional glazing, fluid glass extends the thermal comfort zone to the vicinity of the façade and thus the usable floor space of the building is increased.

4. Conclusion

The energy demand for cooling, heating and lighting were determined for standard office room in Munich and Dubai with a complete glass façade on one side oriented south-west. Two scenarios of fluid glass were compared to three reference scenarios. The operation of the fluid glass was performed with clear and dyed fluid in the outer liquid layer in order to control the solar energy transmission. The reference scenarios consisted of a basic double glazing unit and two advanced solar-control glazing units with low U-values of 0.7 and 0.4 W/m²K. The yearly simulation showed that thermal comfort can be achieved with fluid glass in moderate and hot climates. The room temperature is conditioned by controlling the inner surface of the glazing via a fluid chamber. The fluid glass with adjustable dyeing showed the best overall thermal behavior, resulting in the lowest energy demand in both climates. Compared to SCGUs, a reduction of energy demand up to 23% in Munich and 44% in Dubai was achieved. The reduction of the total energy demand is mainly due to the reduction of the cooling energy demand by reducing the solar gains through the transparency adjustment of the fluid. By coloring the outer liquid layer, a huge fraction of the solar radiation is absorbed in the fluid. As a result, the temperature of the liquid layer rises, but not the room temperature. Since the energy is absorbed at an elevated temperature, it can be transferred to the environment without the need of active cooling. The stagnation temperature of the fluid rises up to a maximum value of 61°C in Dubai. By circulating the fluid to the shaded side of the building, the maximum fluid temperature could be reduced to approximately 50°C.The energy savings potential of the fluid glass façades increases in hot climates with higher cooling demands. Without dye, the net energy demand for fluid glass is higher than for the solar-control glazing. Thus, using dye to control the solar transmission is crucial for successful implementation of the fluid glass concept. A clear strength of the fluid glass concept is the thermal comfort achieved by controlling the surface temperature of the glazing. Since the complete façade is available for heat exchange, only small temperature differences are required for heating and cooling purposes. In Munich, for example, the highest fluid temperature for heating purposes is 25°C, which is very low compared to conventional heating systems. In combination with a heat pump, a highly efficient heating system is obtained, resulting in low primary energy demand. The current study showed the high potential of fluid glass for reducing the energy demand, mainly for cooling. Effects of the thermally active building mass and infiltration will be considered in future investigations. Additional energy savings potential of the fluid glass concept is attributed to the optimization of the spectral absorption characteristics of the fluid and advanced thermal management capabilities, distributing the thermal energy within the whole building envelope.

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6. References

[1] BAETENS R., JELLE B. P., GUSTAVSEN A. (2010). Properties, requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: A state-of-the-art review. Solar Energy Materials & Solar Cells, Vol. 94, pp. 87-105.
[2] Patent WO 98/51973.
[3] GSTOEHL D., STOPPER J., BERTSCH S., SCHWARZ D., „Fluidised glass facade elements for an active energy transmission control", World Engineers' Convention 2011, Geneva, 2011.
[4] EIBAND W., "Modellraumprüfstand mit dynamischer Simulation klimatischer Einflussfaktoren zur Untersuchung von Raumheizsystemen", Dissertation an der Technischen Universität München, 2004.
[5] BECK H., „Experimentelle Untersuchung, Modellierung und Validierung einer Energiebilanz bei fluiddurchströmten Glasfassadenelementen zur aktiven Energietransmissionskontrolle", Bachelorarbeit an der Technischen Universität München, 2012.
[6] GARZIA F., „Modeling and simulation of fluidized glazing elements for office buildings", Masterarbeit an der Technischen Universität München, 2012.
[7] VDI 6020, Requirements on methods of calculation to thermal and energy simulations of buildings and plants Buildings, 2001.
[8] DIN V 18599-10, Energy efficiency of buildings – Calculation of the net, final and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting – Part 10: Boundary conditions of use, climatic data, 2007.
[9] LAASCH T., LAASCH E., Haustechnik Grundlagen – Planung – Ausführung, Teubner Verlag, Wiesbaden, 2005, p. 722.
[10] DIN EN 410, „Glass in building – Determination of luminous and solar characteristics of glazing", 2011
[11] DIN EN 12464-1, "Light and lighting – Lighting of work places – Part 1: Indoor work places", 2011, pp. 34
[12] Software ReluxPro Version 2012.1, Relux Informatik AG
[13] IWU Institut für Wohnen und Umwelt, „Deutsche Gebäudetypologie Systematik und Datensätze", documentation, 2005, pp. 8