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Concept for adaptive wall elements with switchable U- and g-value

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Abstract

This contribution will present a concept for (translucent) wall elements with switchable U- and g-values. The basic concept of the element consists of an insulation panel (preferably realized by a translucent and light-guiding foam grid or in the future by transparent vacuum glazing) which is arranged inside a glazed closed cavity so that thermally driven convection around the element can either be enabled or suppressed. Supression of convection is realized by a rollable second insulation inside the cavity which can reflect incident solar radiation: If the secondary insulation is fully retracted resulting in high U and g-value and daylight being guided inside the building. By successively rolling down the insulation, convection can be suppressed and the g-value can be varied from almost unchanged to almost zero. In the case of the secondary insulation being rolled fully down, the U-value of the element is also minimal. This state is favourable in a cold winter night or during hot daytime hours in summer. The high translucence, low-U-value case is favourable in conditions where solar gains and good insulation are favourable and the translucent high-U-value case is favourable for example in a summer night to cool the building.

In addition to the concept of the wall element, the need for appropriate building control strategies is discussed allowing to make optimal use of the element's potential to save energy for lighting, cooling and heating. Demonstrators for various design generations are presented. Furthermore, the potential to include further functionalities such as thermal- or electrical energy harvesting from the element's outer surface is addressed as well.

1 Introduction

With the exception of external shading elements, the vast majority of building envelopes is rather static than adaptive. The use of shading elements is usually limited to the transparent fraction of the building envelope where they are used to control unwanted solar gains and glare phenomena and in certain cases also to enhance the inhabitants' feeling of privacy. Opaque parts of the building envelope are usually not adaptive at all. Over the last decades, heat transmission through the building envelope has been greatly reduced by the introduction of insulating glass units and various types of thermal insulations for the opaque parts. While reduced heat transmission through the building envelope is clearly desirable under permanently cold or hot conditions, it can also aggravate heat trapping effects in buildings exposed to large temperature variations or in buildings with strong thermal loads even in a cold environment [1].

While transparent parts of the building skin are essential for visual contact from the building to the outside world, their performance with respect to light transmission into the building is rather poor due to a very inhomogeneous distribution of light inside the room and due to glare issues. This often leads to the paradoxical situation that daylight needs to be kept out of the building while at the same time artificial lighting is switched on. Translucent building elements provide much better daylight distribution in the building interior since light is distributed deeper into the building.. However, they don't provide visual contact to the outside world and furthermore, they also need to be combined with shading in order to avoid aggravated heating of the building by solar gains during the cooling season. For this reason, translucent elements play only a minor role in most present-day building skins.

In this paper, we present a concept for a wall element that comes with adaptive thermal and light transmission properties and thus may enable novel buildings skins that can provide a viable alternative to both opaque and transparent building components. For parts of the building envelope that require visual contact to the outside, a transparent variant of the element seems also feasible by the use of vacuum glass units instead of translucent insulation materials.

2 Wall element – basic principles for adaptivity

Our concept for the adaptive wall element consists of a cavity with a depth of about 20 cm and with single glazing on the exterior and interior face. In this cavity, a static translucent insulation panel and a rollable foil insulation are positioned in the way sketched in figure 1. This approach combines two concepts for switchable insulation that have been described earlier [2,3,4] in a synergistic way. At the same time, also adaptive g-values can be achieved.

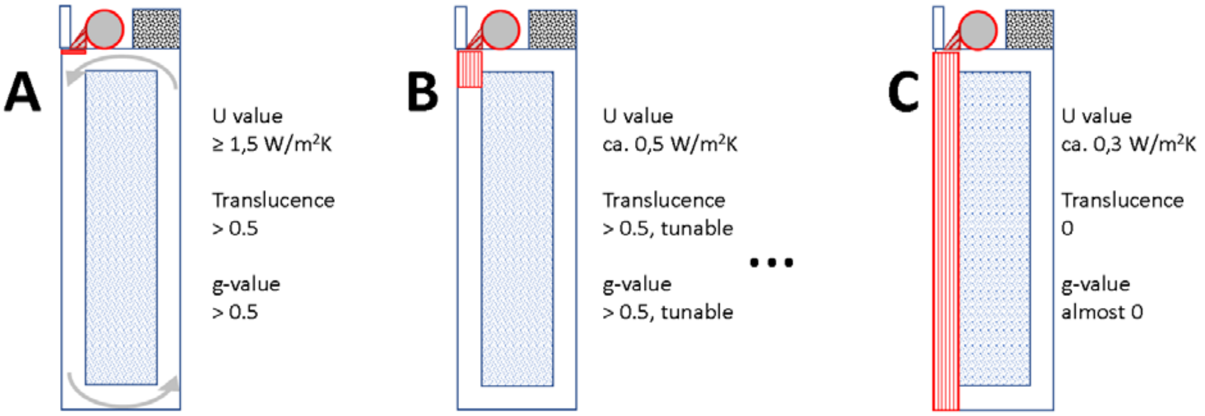

Figure 1: Basic concept and key switching states of the adaptive wall-element described in this paper. While a roll of spontaneous convection can run around the element in state A, this convection is blocked by the rollable insulation in state B and C.

2.1 Switching insulation by convection control

In an otherwise empty cavity, a convection roll can form around the insulation panel positioned in the cavity as shown in figure 1a. It was shown both theoretically and experimentally that this convection process sets on spontaneously for temperature differences in the range of a few K [2]. The U-value of the cavity element with convection active is around 1.5 W/Km^2.

If the convection is disrupted by blocking one of the gaps between the insulation panel and the cavity walls, the U-value of the element will essentially decrease to the U-value of the insulation panel ameliorated by the thermal resistances created by two vertical air gaps around it. In case of the element described in figure 1, this blocking can be achieved by partially rolling down the rollable foil insulation. In this stage, most of the translucence is unchanged and the g-value even slightly increased. By further scrolling down the foil insulation, the translucence and the g-value of the element can be changed to almost 0. At the same time, also the U-value of the element is further reduced by the combined insulation effect of the panel and the foil insulation (figure 1c).

2.2 Material and constructive details

While the general concept of the element described in figure 1 is rather straightforward, it comes with several challenges that need to be answered when actually building the element.

The first challenge concerns thermal expansion effects inside the element itself. From the experience with closed double glazing systems, it is well known that thermal expansion and contraction of the enclosed gas volume becomes almost impossible for interpane distances beyond 7 cm. In order to reach a thermal insulation effect in the range of those stipulated by building codes such as EnEV for opaque walls, insulation thicknesses of more than 7 cm are needed for most insulation materials. As space for the air gaps is required as well, the space available for insulation would be reduced even further to roughly 3 cm which even for standard vacuum insulation panels won't be enough to reach such values. Overcoming this problem is possible by packaging a mechanically stable open porous insulation material into a transparent bag under about 500 hPa underpressure. In this case, the gas pressure inside the insulation panel is always lower than inside the rest of the cavity and thus the volume of the gas inside the insulation panel is determined by the panel volume and does not contribute to the pressure-volume product of the gas in the free interpane space (see figure 2). This essentially enables almost arbitrarily thick insulation panels.

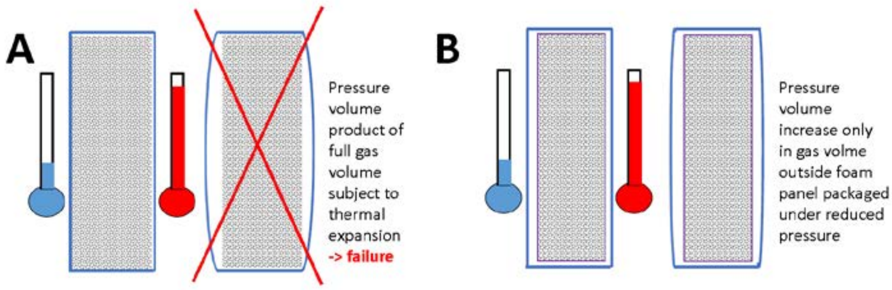

Figure 2: Reduction of thermal expansion problems in a closed wall element by underpressure housing of main insulation package

The second challenge is the translucence of the insulation panel. State of the art capillary plates come with thermal conductivities in the range of 80 mW/Km (but with excellent translucence and light guiding properties). Classical insulation foams such as EPS come with only minor translucence and even foams such as white Basotect® that exhibits a notable translucence in the range of a few percent at about 3 cm thickness [2] has almost no more recognizable translucence at a thickness of 10 cm. Some aerogel materials come with better translucence at thicknesses relevant for insulation and an even better performance might be reached with vacuum glazing. As the two latter options are still not fully mature and are rather expensive as well, modifying classical insulation foam to achieve higher translucence seems an interesting alternative. We have successfully implemented this approach by building polymer foam grids. The most straightforward way to build such a grid is to cut stripes with slits out of thin foam sheets and to assemble these into a grid in pretty much the same way that is used in building honeycomb structures from cardboard e.g. for packaging applications. In a first demonstrator panel (see figure 3) of 2 cm thickness, we measured a thermal conductivity of 48 mW/Km (compared to 35 mW/Km for a massive foam from the same material). For thicker foam grids, even better thermal conductivities are anticipated as the convection effect inside the more elongated cells is supressed even better.

Figure 3: Foam grid panel for high translucence and light-guiding effect

The next challenge concerns the rollable insulation. This rollable insulation mainly relies on the excellent reflectivity of metallized foils over a wide part of the electromagnetic spectrum ranging from thermal infrared to solar irradiation. Like this, it serves both as an additional thermal insulation and as a reflector for incident solar irradiation. For the present state of the art solutions [3], several layers of metallized foil have to be individually cut to measure and assembled onto a roll with complicated spacer structures guiding the individual layers of foil. We have developed this concept further to a structure in which the foil layers are separated by elastic foam beads that are arranged with an offset from layer to layer. If this assembly is rolled down, the beads serve as spacers between the different layers while for rolling the structure, only the thickness of a single compressed foam bead is needed (see figure 4). In the rolled-down state, such multilayer foil mats exhibit a thermal conductivity of 35 mW/Km and come with an especially low weight in the order of 10 g/l.

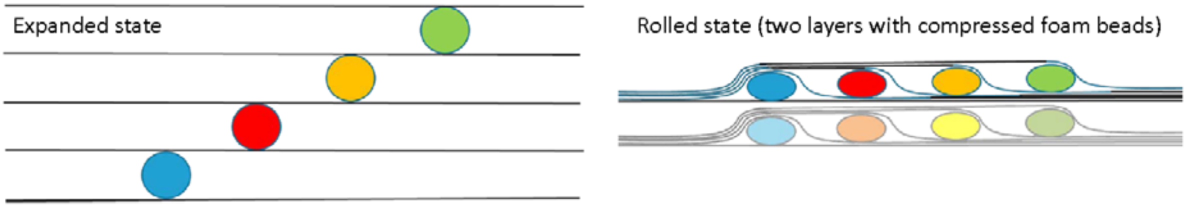

Figure 4: Top-view cross-section of the basic principle for a rollable foil insulation with elastic foam bead spacers

2.3 Possible modifications of the element

Depending on the geographic location and use of a building, there might be different priorities with respect to solar gains, daylight transmission and other energetic uses of the solar irradiation. The most straightforward way to achieve this is the integration of transparent or translucent functional elements such as Perowskite solar cells or NIR-absorbing solar thermal collectors into the exterior pane. The only requirement for such additional functional components is that they don't come with an undesired change in the visible transmission spectrum or with a significant reduction of the U-value of the exterior pane.

A second type of modifications is the use of alternative shading devices positioned in the gap between the exterior pane and the static translucent insulation panel. A possible candidate are stripe-like PV modules with turnable inclination which can be arranged in ways to provide full shading, shading against direct light but transmission of diffuse light and almost full irradiation. If the inclination of the lowest and the uppermost stripe can be controlled independently from the rest, these two pieces can serve as a convection control for switching the U-value.

3 Adaptive wall elements and building control software

From energetic simulations of the performance of our adaptive wall elements in buildings, we have identified the need for appropriate switching control strategies as a key challenge to really harness the energy saving potential of such elements. While there is already quite a bit of experience with energetically optimized control strategies for shading elements, there is still an unmet need for appropriate control strategies especially for adaptive elements with switchable U-values. It is rather obvious that these strategies need to comprise at least a seasonal variation or better an anticipative component as the same thermal conditions may have completely different implications for switching whether they occur on a summer morning or on a winter afternoon. Another aspect concerns the interplay between heat flows achieved by "active" temperature control methods and heat flows achieved via switchable U-value. For similar façade elements with switchable U-values, simple and advanced control strategies were developed in [4] to control the switching from for example an opaque low U-value state to a transparent high U-value state. The control was based on the mean average external temperature over 24h and a prediction of the heat flux to the interior given the exterior and room boundary conditions.

3.1 Switchable U-value: low energy need but slow

Except for the actual switching process (which consists by a displacement of a small mass), heat transfer through a wall element with adaptive U-value is completely passive, i.e. no additional energy is needed to maintain the high U-value (this is a clear difference to hydrogen-based switchable U-value systems [5] which need constant heating to maintain the high-pressure, high U-value state).

At the same time, heat conduction through a wall element is an intrinsically slow process. When switchable U-value elements are used along with active cooling technologies such as free cooling or classical air conditioning systems, one has to be aware that these cooling options are much faster but come with a higher need for energy. Like this, they should be used only early in the morning in cases where switching the walls into high U-value alone has not led to a sufficient heat transport out of the building. If active systems are started too early, they will transport away heat much faster which otherwise would have escaped slowly but with much less energy cost from the building by the action of the switchable U-value.

3.2 Anticipative control strategies for adaptive wall elements

Both solving the challenge described in section 3.1 and avoiding unwanted heat losses in winter needs anticipative control strategies for the interplay of the wall elements with the rest of the building's technical systems [6]. In addition to available intensity and orientation of daylight and present internal and external temperatures, these strategies need to take into account the weather forecast and of course technical details of the building such as its thermal mass and the time needed for heat exchange with other building components. With these informations, the right decisions can be made on

- whether and when to activate additional active cooling systems during the night in order to achieve appropriate temperatures in the morning with the lowest possible energy consumption,
- whether letting in solar irradiation for daylighting purposes or shading and artificial lighting will be energetically more effective and on
- whether cooling the building by switching to high U-value is preferable or keeping the heat in in order to compensate foreseeable unwanted heat losses during the night according to local weather forecast.

4 Conclusion

Translucent adaptive façade elements with switchable U-value and g-value open up novel opportunities for making optimal use of solar irradiation as well as of heat exchange between the building and its surroundings. Daylight is directed deeper into the building than with conventional transparent glazing thus reducing the need for artificial lighting. Overheating due to unwanted solar gains over the translucent area of the building envelope can be avoided by switching into a state in which solar radiation is transmitted instead of being reflected and by switching the U-value, heat flow through the building envelope can be increased in order to reduce the need for other, more energy-demanding types of cooling. Due to the use of spontaneous convection, no additional energy is needed for operating the element in the high U-value state.

Further functionalities can be included into the wall element especially by integrating them into the exterior pane provided that their impact onto the translucence and the heat transfer properties of the glazing does not interfere with the core functionalities of the element.

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