# Design and Experimental Proof-of-concept of a Façade-integrated Solar Thermal Venetian Blind with Heat Pipes

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**Abstract**

*Solar thermal venetian blinds (STVB) pursue the goal of reducing the primary energy demand of buildings with highly transparent façades during operation. They can provide solar control and daylighting functions and at the same time function as a solar thermal collector. A technical overview of STVB based on a design parameter space, which can be used as guideline for the design of STVB, is presented. It is then applied to develop a first actual-size test sample of STVB. The design principle, based on heat pipes and a switchable thermal coupling for heat transfer between the slats and a header tube, allows the STVB to be tiltable and retractable. The key characteristics of the built STVB test sample are: (1) integrated in a double skin façade element; (2) conventional absorber sheet with diagonally mounted heat pipe; (3) switchable thermal coupling with mechanism using springs and solenoids; (4) a multi-port header tube. Outdoor measurements have been carried out and are discussed, demonstrating the technical feasibility of the concept. In the end, design choices for architects and planners for the STVB system and possible installation processes are presented, and recommendations for further developments are assessed.*

**Keywords**

*Multifunctional façade, solar control, double skin façade, BIST, design parameter space, heat pipes*

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# 1 INTRODUCTION

Many contemporary buildings employ large proportions of glazing in their façades, due to the opportunities that glass offers for daylighting and visual contact with the outside, combined with aesthetic considerations that aim for maximum transparency as proclaimed by modernism (Murray, 2013). At the same time, the drive for green and sustainable buildings with reduced primary energy demand is a current topic of discussion (Mays, 2019). As transparent façade areas cannot be used to install opaque energy-harvesting systems, such as building-integrated solar thermal collectors (BIST) or building-integrated photovoltaic systems (BIPV), new technical solutions are desirable. The solar thermal venetian blind (STVB) represents a novel BIST technology which can turn a venetian blind into an energy-harvesting building component which supplies solar thermal heat to the technical building services. At the same time, the STVB can control and lower passive solar heat gains through the façade by extracting excess heat from the façade thus lowering cooling loads. Like venetian blinds, they provide further adaptive solar control functionalities such as glare control (Kuhn, 2017). The synergy of lowering cooling loads and supplying heat to the technical building services has the potential to lower the overall energy demand of buildings equipped with STVB compared to conventional venetian blinds.

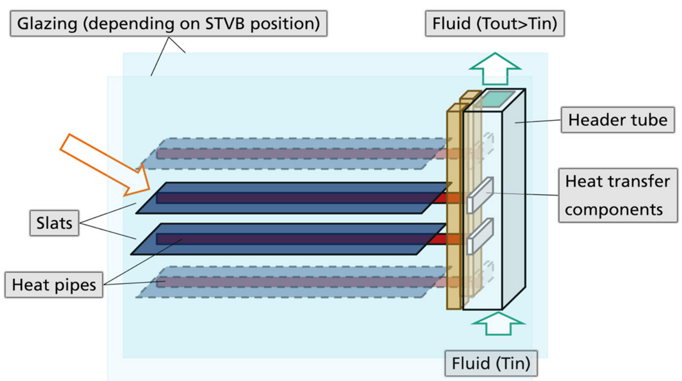



FIG. 1 Main components of a solar thermal venetian blind positioned between an outer and an inner glazing pane. The increase between fluid inlet temperature $T_{in}$ and fluid outlet temperature $T_{out}$ illustrates the harvesting of solar thermal heat. The blind mechanism for retracting and tilting the slats is not shown.

The technological approach of the studied STVB is to incorporate heat pipes or closed two-phase thermosiphons[1] into the slat and transfer the absorbed heat via a dry connection to a header tube which transports the heat to the technical building services (cf. Fig. 1). This is advantageous compared to having pipes with flowing fluid incorporated into the slats because no flexible piping is needed. Flexible pipes need space to fold when the slats are retracted and have a higher risk of leakage. The slats of the solar thermal venetian blind need to be movable like a conventional venetian blind to provide adaptive solar control functionalities, i.e. the slats can be tilted, and retracted or lowered. There are several approaches to realising this as will be discussed, one being a "switchable thermal coupling".

1 In the solar industry, the term "heat pipe" is often used for heat pipes working with capillary forces to return the fluid from the condenser to the evaporator part, as well as for two-phase thermosiphons returning the fluid by gravity. This paper refers to the term "heat pipe" as a generic term for both heat transfer devices whenever no clear declaration is needed.

## 1.1 STATE OF THE ART

Using the building envelope to harvest solar thermal heat was proposed over a century ago (US246626, 1881) and semi-transparent solar collector windows have also been previously presented (Fuschillo, 1975). To date, there are some examples of research projects and products dealing with semi-transparent BIST (Abu-Zour, Riffat, & Gillott, 2006; erfis GmbH; L. Li, Qu, & Peng, 2017; Maurer et al., 2014; Molter, Wolf, Reifer, & Auer, 2017; Palmero-Marrero & Oliveira, 2006; EP1376026B1, 2002; Siebert, 2018). A review of building-integrated solar thermal collectors including semi-transparent BIST was presented in Maurer, Cappel, and Kuhn (2017). Because all of the above-mentioned semi-transparent solutions are static, they are either limited to the parapet areas of the façade or undesirably reduce the visual contact to the exterior (i.e. transparency) and daylight availability. The latter is problematic especially on overcast days with low irradiance. Additionally, they only provide limited control of passive solar heat gains and limited glare protection, as they cannot actively adapt to changing weather conditions, e.g. the position of the sun or heating versus cooling season. Glare issues were reported for a semi-transparent BIST consisting of vacuum tubes and a perforated mirror due to partial shading resulting in dark and bright spots in the field of view of users and reflection of direct sunlight (Molter, Wolf, Reifer, & Auer, 2017). For these reasons, semi-transparent BIST have thus far rarely been used in modern architecture (Cappel et al., 2015).

To address these opposing requirements, many buildings use venetian blinds on transparent areas of the building envelope as an adaptive solar control device to reduce the energy demand for cooling and provide visual comfort (e.g. daylight availability, glare protection, visual contact to the exterior). An extensive review on solar control devices and a design method can be found in Kuhn (2017). In double-skin façades, box-type windows, and closed-cavity façades (CCF), blinds are often installed in the cavity between outer and inner glazing. One problem that can arise in this configuration is the overheating of the cavity (Gratia & Herde, 2007a; Lutz, 2012). Approaches to mitigate this overheating, such as the proper positioning of the blind (Gratia & Herde, 2007b) or integrating phase-change material into blinds (Li, Darkwa, Kokogiannakis, & Su, 2019) were studied.

Solar thermal venetian blinds, as a multifunctional combination of venetian blinds and BIST, have been described in several patents (DE 102006000668 B4, 2006; US4143640 A, 1977). However, none of these patents discusses STVB, which are both tiltable and retractable. A solar thermal venetian blind for the purpose of heating air was presented in US4002159 (1975). A master's thesis on STVB presented both simulation results as well as proposing technical solutions for a STVB design (Cruz Lopez, 2011). This study assumes that heat pipes that work on the horizontal orientation are available for the application in STVB. As will be discussed in Section 2.1, heat pipes suitable for horizontal orientation are not yet available. The study seems to disregard previous studies on BIST and on building energy performance simulations. It uses a simple calculation method for simulation of the STVB which neglects the coupling between STVB and building regarding heating and cooling loads. Furthermore, the presented technical solution for the heat transfer from the heat pipe condenser to the header tube should be investigated experimentally to prove that it functions reliably and efficiently. Theoretical studies and simulations of STVB application in the Mediterranean climate were presented in Guardo, Egusquiza, Egusquiza, and Alavedra (2015); and Velasco, Jiménez García, Guardo, Fontanals, and Egusquiza (2017) without presenting technical solutions. The effect of cooling the slats of venetian blinds in a double skin façade by embedding pipes into the slat through which water is circulated was studied in Jiang, Li, Lyu, and Yan (2019); and Shen and Li (2016) and related studies. The proposed "pipe-embedded" blind is shown to reduce overheating of the cavity and passive solar heat gains. The studies focus on static blinds which cannot be lifted and tilted, thus significantly reducing the visual contact to the exterior as well as daylight availability.

Additionally, photovoltaic venetian blinds and their effect on the thermal performance of double-skin façades have been studied (Luo et al., 2017). They act as shading device-like conventional venetian blinds but cannot remove excess heat like a solar thermal venetian blind. Due to their high absorptivity they could even increase overheating problems.

There are other approaches for fully transparent BIST system, which use fluid between glass panes to remove the heat (InDeWag, 2017; Heiz, Pan, Lautenschlager, Sirtl, Kraus, & Wondraczek, 2017; Li & Tang, 2020; Stopper, 2018, 2019; Stopper, Boeing, & Gstoehl, 2013). With these approaches, ensuring glare protection is challenging and combination with solar control devices such as textile screens is necessary.

It is concluded that a detailed technical overview for designing movable (retractable and tiltable) STVB and an experimental proof of feasibility have not been published yet. Within this publication, a detailed design parameter space for development of *STVB with heat pipes* will be presented. This design parameter space can be helpful for the design of STVB as it gives a detailed overview of the technological options. It was used to guide the development of a first actual-size test sample of a façade element with integrated STVB. The technical performance of this test sample with regard to solar thermal and solar control functionality is subsequently evaluated based on results of calorimetric measurements, to prove the general feasibility of the technological approach. Later, the STVB system is discussed regarding its potential for customisation and from the context of façade construction. Finally, recommendations for further developments are assessed based on expert feedback and on the conclusions drawn from the investigated test sample. As the focus of the paper is the design and proof-of-concept, the energy savings potential by STVB in buildings is not evaluated in detail. This should be part of future studies based on building performance simulations using an experimentally validated simulation model of STVB. The paper at hand lays the foundation for further in-depth performance evaluations.

## 2 DESIGN OF SOLAR THERMAL VENETIAN BLINDS

A detailed design parameter space (DPS) is developed to give an overview of the technical design options and is then used to create a full-scale test sample of a STVB. The design parameter space is divided into different categories (such as different subassemblies of the STVB). For each category the relevant components and their different design choices, named design parameters, are listed. The design parameter space provides a detailed technological overview to engineers and researchers designing and constructing STVB with heat pipes. It can thus help to create new variants of the STVB and continue its development.

### 2.1 DESIGN PARAMETER SPACE

The STVB must simultaneously function as a building-integrated solar thermal collector and as solar control device. For the design parameter space presented here, *STVB with heat pipes* are defined as venetian blinds with horizontal, tiltable and retractable slats that incorporate a heat pipe along their lengths. The heat pipe is responsible for the heat transfer from the slat to the fluid in a header tube, thus providing solar thermal heat. The STVB is defined as the venetian blind with all elements relevant for heat transfer, including the header tube, but without the surrounding or adjacent façade element and glazing (cf. Fig. 1). As such, the STVB is then mounted as part of the façade.

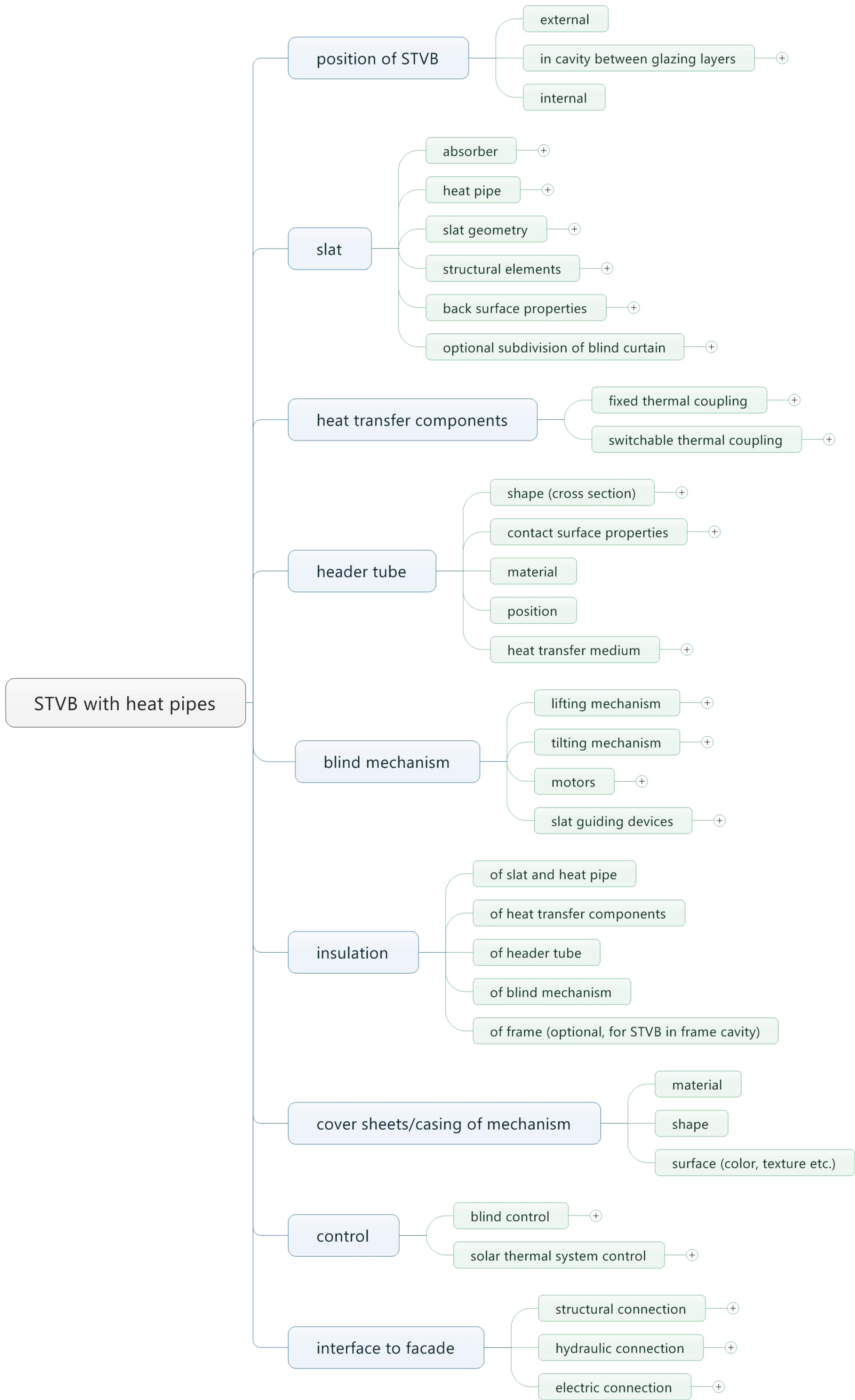



FIG. 2 First and second level of the design parameter space of solar thermal venetian blinds with heat pipes. The full design parameter space is provided as a supplementary file.

An overview of design parameters for BIST collectors and a design parameter space for solar control devices were published in Cappel, Kuhn, and Maurer (2015); and Maurer, Cappel, and Kuhn (2015); and Kuhn (2017), respectively. Following the above-mentioned definition of *STVB with heat pipes*, the STVB design parameter space was compiled to give a complete insight into all design choices that play a role when designing, engineering, and developing a solar thermal venetian blind. As a starting point, the essential functional elements of STVB were analysed. For each of these, the different technical possibilities and design choices were analysed. Each branch of the DPS in Fig. 2 thus presents a different main category. For each main category the relevant design parameters are presented, sometimes grouped into sub-categories (cf. full DPS as Supplementary File). The DPS is considered to include all relevant design parameters at the time of writing; nonetheless, new developments and technologies might alter it in the future.

When using the DPS, an option has to be chosen for each design parameter in each category. The design parameters are not linear independent, i.e. changing one parameter can influence other parameters. The DPS provides exemplary options for each design parameter but does not claim to include all possible options. The DPS is not intended to evaluate the resulting STVB variants, but rather to give a detailed overview to help the understanding of the relevant design parameters of STVB.

The first two levels of the DPS, which represent the main functional elements and main design choices of STVB, are now discussed in detail. Subsequently, examples of the application of the DPS to develop a STVB concept are shown in Section 2.2. This STVB concept has been realised as a functional actual-size test sample.

### Position of STVB

The STVB can be positioned *externally* on the façade, or inside the building (*internal*). In double skin façades, box-type windows, or closed-cavity façades, the STVB can be mounted *in a cavity between glazing layers* where conventional venetian blinds would be mounted as well.

### Slat

*The absorber*, i.e. the top surface of the slat, and the heat pipe have a large influence on solar thermal performance, solar control functions (e.g. passive solar gains and daylighting), and aesthetic appearance. The absorber can range from grey, that is diffusely reflecting, or light guiding as known from conventional slats, to dark blue and highly absorbing with low emissivity as known from solar thermal collectors (called spectrally selective coating). In addition, more sophisticated coatings with high absorption and yet a broader range of colours (Bläsi et al., 2017) or spectrally selective coating with IR absorption and diffuse reflection in the visual range (Lang, 2007) can be used. Absorber thickness and material influence the heat transfer to the heat pipe as well as slat weight and stability. The bulk material of the absorber sheet should ideally be the same as the heat pipe material to handle thermal expansion. In fact, the combination of an aluminium absorber with a copper heat pipe, though common in solar thermal collectors, could lead to aesthetically undesirable deformations and waviness of the absorber sheet due to different thermal expansion coefficients.

The *heat pipes* are responsible for the heat transfer from absorber to header tube. Most commercially available heat pipes for the application in solar thermal collectors have a cylindrical cross section.

The maximum amount of power they can transfer, called operating limit, depends to some degree on a sufficiently large diameter and on its angle of inclination. The operating limit of the chosen heat pipe has to be higher than the maximum amount of absorbed solar radiation, while maintaining a low thermal resistance. The thermal performance is known to decrease with decreasing diameter (Jack & Rockendorf, 2013). This is a limiting factor in achieving thin slats for STVB. Other cross-sectional shapes, such as oval or rectangular, could better suit the application in STVB but are much less common. Moreover, due to the horizontal slats, the heat pipes have to function at small angles of inclination. To be more precise, the operating limit of the selected heat pipe has to be sufficiently high for all possible tilt angles of the slat. Two technological approaches can be used for heat pipes to achieve this good thermal performance at or near horizontal orientation of the heat pipe: mesh or sintered heat pipes using capillary forces to return the fluid from the condenser to the evaporator part (Reay, Kew, & McGlen, 2014) or "overfilling" of closed two-phase thermosiphons (Bezrodny & Podgoretskii, 1994; Morawietz, Paul, & Schnabel, 2018). The topic of heat pipes in horizontal orientation for the application in solar thermal collectors is still the subject of ongoing research. Special attention has to be paid to the case of the condenser being lower than the evaporator, i.e. for negative operating angles. This could happen due to the orientation of an individual slat, of the STVB element, or the mounting in the façade. In this case the heat pipe would have to work against gravity to return the condensed fluid back to the evaporator part and the resulting operating limit is lower. Besides the important topic of the operating limit, the maximum and minimum ambient and operating temperatures have to meet the application in a STVB, i.e. typically, the heat pipe would have to withstand freezing temperatures for its application in the façade as well as high temperatures above 100°C for its application in a solar thermal collector. The outer material of the heat pipe needs to be compatible with the other components of the slat and based on availability.

*Slat geometry* such as cross-sectional shape, edges, etc. can be chosen, taking into consideration the absorber and heat pipe properties as well as the requirements of architectural design and solar control properties. One important characteristic is the slat thickness in packed position. The packed slats will be an opaque area of the façade, which should be minimised for highly transparent façades and/or needs to coincide with opaque areas of the façade such as floor slabs. Furthermore, the projected slat thickness of the lowered blind as seen from an observer inside the room is important as it influences the visual contact to the exterior. *Structural elements* of the slat have to be designed carefully to deal with the increased mass of the slat due to heat pipe, absorber and other components. *Back surface properties* need to be considered as they influence daylighting, could cause glare if not chosen well, and influence the overall appearance of the blind curtain. Finally, different slat types can be chosen for parts of the blind curtain, e.g. using light redirecting slats for the top part and STVB slats below, leading to an *optional subdivision of blind curtain*.

### Heat Transfer Components

The *heat transfer components* include all elements and mechanisms involved in the heat transfer between heat pipe condenser and header tube. Two main approaches were identified. *Fixed thermal coupling* means that the connection between heat pipe and header tube is fixed except for the movement necessary for the slat. An example can be found in Cruz Lopez (2011), where the heat is transferred via overlapping of fin-type heat sinks mounted onto the heat pipe condenser and header tube without direct contact or only a sliding contact between the elements. *Switchable thermal coupling* is a concept that was filed for a patent and in which the thermal and mechanical contact between heat pipe condenser and header tube can be switched (Haeringer, Abderrahman, Vongsingha, Camarena Covarrubias et al., 2017). In the closed position the heat is transferred via conduction, while in the open position the slats can be moved freely. For the switchable thermal coupling, a mechanism including actuators is necessary to switch from closed to open position and back. To ensure a good heat transfer across the switchable thermal contact, the contact pressing force of the mechanism has to be sufficiently high (Bahrami, Yovanovich, & Culham, 2004). Additionally, the heat transfer from heat pipe to header tube can be enhanced using elements such as an adapter around the heat pipe condenser, special condenser geometries and/or heat transfer films. As this heat transfer is crucial for the solar thermal performance and the control of passive solar heat gains, detailed simulations or experiments are recommended when comparing different concepts (Haeringer, Abderrahman, Vongsingha, Camarena Covarrubias et al., 2017).

### Header Tube

The *header tube* needs to transfer the heat into a *heat transfer medium* such as water or solar fluid (a water-glycol mixture), which then transports the heat to the technical building services. The heat transfer to the header tube is influenced both by the design of the *heat transfer components* as well as the *contact surface properties* of the header tube The heat transfer into the fluid is mainly influenced by the *shape (cross section)* and *material* of the header tube. For example, multi-port pipes or fins inside the header tube can be used to create a large contact area and high heat transfer coefficients between fluid and header tube (Schiebler, Giovannetti, Schaffrath, & Jack, 2018). Mechanical strength, with regard to the pressing force of a switchable thermal coupling and against deformation due to the inner fluid pressure of the system, is important and influenced mainly by the cross-sectional geometry. Another parameter is the *position:* The header tube would typically be at the side of the element, but the orientation relative to the heat pipe condenser can be chosen (Haeringer, Abderrahman, Vongsingha, Camarena Covarrubias et al., 2017).

### Blind Mechanism

To move the slats, a *blind mechanism* has to be designed. The main components include the *lifting mechanism* and the *tilting mechanism* responsible for retracting and lowering the blind curtain and changing the slat tilt angle with the help of *motors*. Furthermore, *slat guiding devices* can be used such as guiding rails or guiding ropes. Regarding costs, it is preferable to use conventional components (motors, gears, lifting tapes etc.) which use a single motor for lifting and tilting. However, the increased weight of the blind curtain and potentially higher temperatures need to be taken into consideration. Additionally, the alignment between the slats and the header tube is critical for the *heat transfer components*, especially for the *switchable thermal coupling*. Therefore, elongation of the elements connecting the motors and bottom bar or slats, caused by the suspended load, has to be considered. Conventional lifting tapes and tilting cords are based on textile material. To improve their strength and reduce the elasticity modulus, these textile elements can be fibre-reinforced or replaced by metal elements (e.g. steel). Plastic tape reels, conventionally used for tilting and lifting of venetian blinds with one motor, can typically carry up to 5 kg of weight each. With heavier STVB slats a larger number of tape reels must be used to carry the additional weight, or they have to be replaced by a more robust alternative. Commercially available all-metal blinds use a system of scissor chains for tilting and a chain mechanism for lifting (Griesser AG, n.d.; Griesser AG, 1979; Schenker Storen, n.d.) achieving a precise, reliable positioning of heavy slats but requiring regular maintenance.

### Insulation

*Insulation* can and should be applied in various locations to increase solar thermal yield and lower passive solar heat gains by lowering heat losses. Additionally, *cover sheets* can be used to hide elements such as the blind mechanism and the mechanism of switchable thermal coupling for aesthetic reasons. The design of the STVB allows architectural design freedom such as using a shadow box technique or glass fritting when positioning the STVB between two glazing layers. Cover sheets and many other elements allow for individual architectural designs.

### Control

In operation, different *control* strategies can be applied. The *blind control* could be manual or automated. Due to the multifunctionality, it is highly advisable to employ an automated control strategy that considers both passive solar gains, solar thermal energy harvesting and user comfort. Automated controls could prioritise, for example, user comfort (e.g. thermal comfort, glare control or daylighting) or solar thermal yield, and allow overriding by the user. The extent of overriding by the user might have to be limited, to not compromise the overall performance of the system especially regarding solar thermal yields. Advanced control strategies with optimisation routines could be adapted to balance the different demands and provide a robust system (Katsifaraki, Bueno, & Kuhn, 2017).

The *solar thermal system control* includes control of mass flow and fluid inlet temperature or target outlet temperature. This greatly depends on the intended use of the solar thermal heat and the building service system. In general, applications requiring lower fluid temperatures are preferable, such as low temperature radiant heating or as a source for heat-pumps. With lower fluid temperatures, the solar thermal efficiency is higher (due to reduced losses to the ambient) and passive solar heat gains are lower (due to reduced secondary heat gains). At times when the heat demand of the building is significantly lower than the heat provided by the STVB, stagnation can occur (e.g. in summer, as in a conventional solar thermal system). The design of the STVB, overall façade system, and the integration into the building service system therefore has to ensure that the control of passive solar heat gains and prevention of overheating is guaranteed during stagnation or that stagnation is prevented.

### Interface to the Facade

Taking the *position of the STVB* into account, the *interface to the facades* has to be defined including the *structural, hydraulic,* and *electric connections*. Considerations for the interfaces during the installation process are presented in Section 4.2.

## 2.2 DESIGN AND CONSTRUCTION OF A FIRST SOLAR THERMAL VENETIAN BLIND TEST SAMPLE

The presented design parameter space was used to develop a detailed concept of a STVB, which then was realised as actual-size test sample. This publication discusses the design parameter categories *position of the STVB* and *slat*, as they are relevant to architectural appearance. The design considerations are done for the most part on a qualitative level for the design and realisation of the first STVB test sample but can be extended to quantitative comparison using detailed simulation models or extensive testing. Criteria to evaluate solar control functionality including visual comfort and daylighting of solar control devices were presented in Kuhn (2017). The general evaluation criteria for building-integrated solar thermal systems *functionality, aesthetics, ecology, economy,* and *feasibility* were presented in Maurer, Cappel, and Kuhn (2015). The main technical evaluation criteria used for the design process of the STVB test sample are *solar thermal yield* and *solar control functionality*, especially *passive solar heat gain control* (g-value). The main aim of the presented STVB concept is maximising solar thermal yield.

## 2.2.1 Position of the Solar Thermal Venetian Blind

Mounting the STVB *in a cavity between glazing layers* as in double-skin façades (DSF) (or box-type windows or closed-cavity façades) protects it from wind, dust, and human contact (Knaack, Bilow, Klein, & Auer, 2014), leading to longer life expectancy, reduced maintenance, and the capacity to function in strong winds. A higher solar thermal yield can be achieved, when compared to *external* or *internal* mounting, as fewer heat losses to the surroundings via convection and radiation occur, especially for non-ventilated DSF (e.g. closed-cavity façades CCF). Mounting the STVB within the cavity between two glazing layers resembles the situation of a conventional flat plate collector, where a front glass pane covers the absorber and the back is insulated. The test sample was therefore constructed as a double-skin element façade, identified as a suitable façade type for STVB.

## 2.2.2 Slat Design

The slats have a significant influence on solar thermal performance, aesthetic appearance, and structural stability. The slat developed for the STVB test sample is shown with its individual components in Fig. 3. Conventional copper-based collector absorber sheets with spectrally selective coating (i.e. high absorptivity in solar range, low emissivity in the IR range) were used aiming to maximise solar thermal yield. The influence on the passive solar heat gain is not clear without in-depth analysis due to two opposing effects:

- higher absorptivity leads to higher secondary heat gains, due to increased temperatures of the absorber
- lower reflectivity leads to a lower effective transmission of solar radiation through the STVB layer into the building (i.e. less radiation is reflected from the slat into the building, especially for small slat tilt angles)

For the designed STVB, commercially available cylindrical mesh heat pipes with 8 mm diameter and copper as the outer material were chosen. Alcohol as working fluid is used to withstand temperatures below 0°C. The selected heat pipe works at an almost horizontal orientation, but the thermal performance increases with increasing operating angle (if angles near 0° are considered). For this reason, the heat pipe is mounted diagonally behind the absorber sheet. A geometric analysis of the heat pipe inclination in correlation with the slat dimensions and slat tilt angle was carried out in TABLE 1. The slats dimensions are length $l = 1020\ mm$, width $w = 93.8\ mm$ , and thickness $t = 10.6\ mm$ with a vertical slat distance of $d = 83.4\ mm$. The absorber area per slat is $A_{abs,slat} =$ ($1004 \cdot 72\ mm^2$) = $0.072\ m^2$. The absorber and heat pipe were assembled using laser-welding, which is established for solar collectors and is less visible than, for example, ultra-sonic welding (Cappel et al., 2015). The bond from laser welding is nonetheless slightly visible on the front surface of the absorber sheet in Fig. 3.

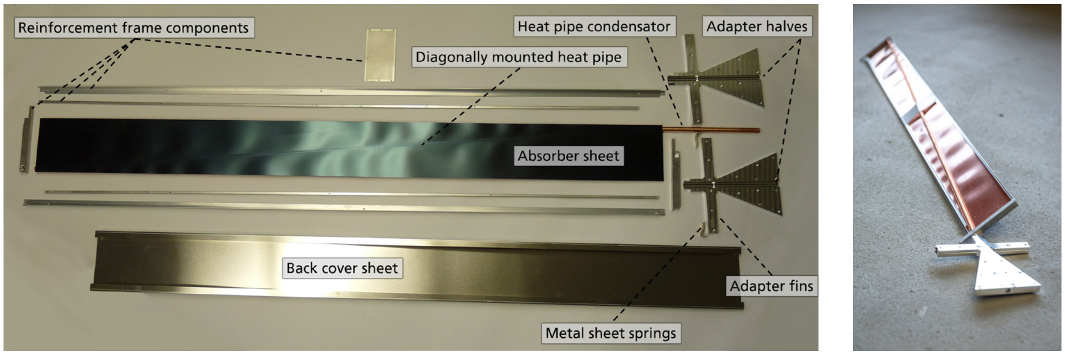



FIG. 3 Left: Slat components. Right: Back surface of a slat with diagonally mounted heat pipe and triangular adapter in the foreground (back cover sheet removed).

TABLE 1 Heat pipe inclinations in correlation with slat dimension and slat tilt angle.

| SLAT SIZE | SLAT TILTING ANGLE β | HEAT PIPE INCLINATION |
|---|---|---|
| 1020 x 94 mm | 5° | 0.4° |
| | 10° | 0.8° |
| | 45° | 3.1° |
| | 82° (closed) | 4.3° |

The slat geometry was chosen to be flat as the heat pipe is mounted diagonally along the length of the absorber sheet. Curved absorber sheets would require a curved heat pipe. This is technically feasible but results in a more costly manufacturing process. Taking into account the slat thickness $t$ and vertical slat distance $d$, 12% of the visual contact to the exterior is blocked in the horizontal viewing direction for slats in a horizontal position. Reducing the slat thickness would improve the visual contact to the exterior and reduce the opaque area for the retracted slats.

As both the heat pipe and absorber sheet itself are structurally weak, reinforcement is needed to deal with the weight of the heat pipe, absorber sheet, and adapter, which is used for heat transfer to the header tube. For the test sample, a reinforcement frame assembled out of commercially available aluminium profiles was designed to support the perimeter of the absorber sheet. The aim was to achieve structural strength while keeping a low overall slat weight. The reinforcement frame elements on the short, lateral edges are slightly thicker than the rest of the slat. They act as spacers between the slats, when they are in a packed position, to protect the absorber coating from damage. The back and sides of the slats are covered using a thin aluminium back cover sheet resulting in a plain slat appearance. In mass production, an aluminium frame profile that supports the absorber and heat pipe, and functions as back cover sheet, could be manufactured cost-effectively via extrusion moulding. The absorber and heat pipe could then be inserted easily in a simple assembly process.

For the first test sample, no subdivision of the blind curtain was employed for simplicity and cost reasons. In a more advanced STVB, the upper part of the blind curtain could use light-redirecting slats to provide daylight to the depth of the room.

## 2.2.3 Overall Concept of the Test Sample

The overall design of the test sample, an actual-size double skin façade element with integrated solar thermal venetian blind, is shown in Fig. 5. The heat transfer from heat pipe condenser to the header tube is achieved using an adapter and a switchable thermal coupling mechanism as shown in Fig. 4. The adapter is mechanically fixed to the heat pipe condenser to increase the contact surface area to the header tube (cf. Fig. 3). The switchable thermal coupling mechanism employs springs and solenoids. The springs press each adapter against the header tube to achieve the heat transfer, while the solenoids open the coupling when blind movement is necessary (cf. Fig. 4 and Fig. 5). The pressing force between each adapter and the header tube is approximately 10-15 N. The development of a first switchable thermal coupling as *heat transfer component* was presented in Haeringer, Abderrahman, Vongsingha, Camarena Covarrubias et al. (2017). A video demonstrates the movement of the switchable thermal coupling and the ability of the test sample to tilt and retract the slats (Fraunhofer ISE, 2018). The *header tube* is based on a multi-port profile, which has a large contact surface with the fluid for heat transfer, while its structural strength minimises deformation due to internal fluid pressure (see Fig. 4). Deformations would lead to a reduced contact between the adapter and the header tube. The *blind mechanism* employs rigid steel ropes for lifting, and steel scissor chains to connect the slats for tilting. Using steel was necessary to achieve the high precision in positioning the slat and adapter perpendicular to the header tube surface.

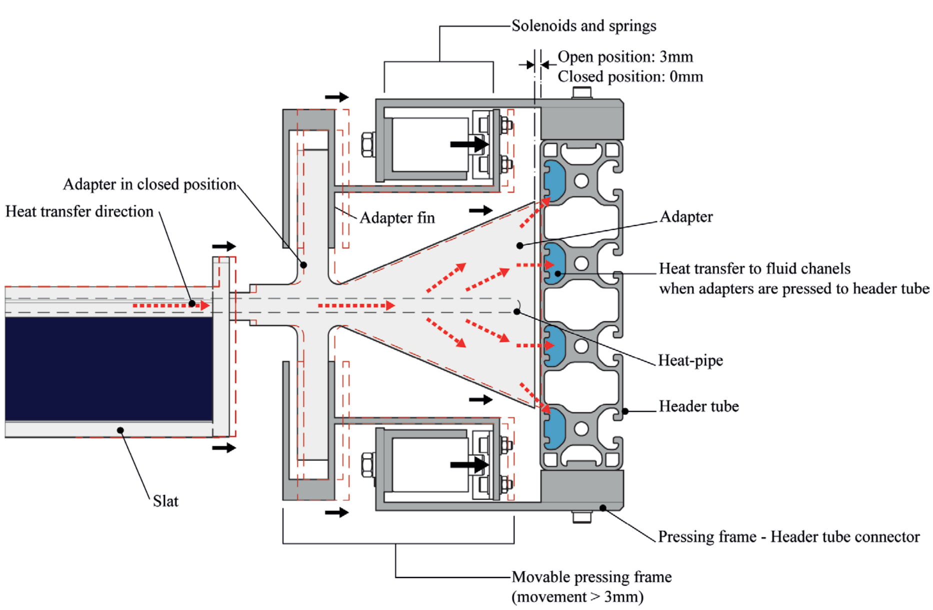



FIG. 4 Schematic horizontal cross-section of the switchable thermal coupling mechanism used as heat transfer component in the STVB test sample. Red arrows indicate the heat flow from slat through heat pipe and adapter to the fluid in the header tube. Black arrows indicate the movement of the switchable thermal coupling mechanism from open to closed position. The dashed red lines indicate the position of slat, adapter, and movable pressing frame when the switchable thermal coupling is closed.

The outside of the façade element is fully glazed and the overall active slat absorber area is $A_{abs,tot}$ = 37·$A_{abs,slat}$ ≈ 2.67 m$^2$, out of the overall gross façade element area $A_{gross}$ = 5.0 $m^2$. The exterior glazing layer is 8mm low-iron single-pane toughened safety glass with a solar transmission of $t_e$ = 0.89. The interior glazing has an area of 2.9 m$^2$, i.e. about 60% of the façade element is transparent from the inside. It is a conventional insulating double-glazed unit with single low-e coating and argon filling with $t_e$ = 0.52, solar heat gain coefficient $g$ = 0.60 and $U$ = 1.1 $W/(m^2K)$. Plain steel sheets cover the remaining area of the back surface of the façade element. The cavity between the exterior and interior glazing layer is 31 cm in depth and has no ventilation openings (but it is not hermetically sealed). Slats, header tube, and mechanism of the STVB are all placed in this cavity. A detailed description of the overall test sample has already been published in Haeringer et al. (2018); and Haeringer, Denz, Vongsingha, Delgado, and Maurer (2019).

FIG. 5 Left: Test sample of double skin façade element (1.4 m x 3.6 m) with integrated solar thermal venetian blind seen from the exterior side. Right: Switchable thermal coupling mechanism with springs and solenoids mounted in the test sample, upper part covered with cover sheets.

# 3 EXPERIMENTAL PROOF OF CONCEPT

The STVB test sample that was developed based on the presented design parameter space has been characterised using calorimetric measurements on an outdoor test facility for solar active building envelope elements. Based on these results, the technical performance of the test sample has been evaluated with regard to solar thermal performance and solar control functionality. The overall goal was to prove the technical feasibility of the chosen STVB concept, i.e. to show the simultaneous functioning as solar control device and as solar thermal collector.

## 3.1 METHODOLOGY

The experiments were carried out at an outdoor test facility for real-size building envelope elements (Haeringer, Denz, Kuhn, & Maurer, 2019; Maurer, Amann et al., 2015). The measurements report the energy flux through the façade element as well as renewable energy performance, specifically the solar thermal yield. Thus, solar heat gain coefficients ($g$) and solar thermal efficiency $\eta$ can be calculated. The measurement of the energy flux through the element relies on a "cooled plate method" as discussed in detail for indoor laboratory conditions in Kuhn (2014).

The operation parameters varied during the measurements as shown in TABLE 2 are:

- blind curtain extension $BE$, with $BE$ = 1 for fully lowered blind and $BE$ = 0 for fully retracted blind
- slat tilt angle $\beta$, with $\beta$ = 82° representing fully closed slats
- collector fluid inlet temperature $T_{f,in}$, covering the whole working temperature range

The solar irradiances $G_h$ (total hemispherical irradiance on the collector plane), $E_d$ (horizontal diffuse irradiance), and ambient temperature $T_{amb}$ vary naturally. The sample was placed in the vertical position with the façade azimuth angle tracking the sun, i.e. the sample receives the irradiance with changing solar altitude angles $\theta$ and constant zero azimuth angle. The collector fluid mass flow was set to $\dot{m} \cong 0.02\ kg/(m^2/s) \cdot A_{abs,tot} = 0.054\ kg/s$ following the standard test conditions of (ISO 9806, 2017), but using the absorber area $A_{abs,tot}$ instead of the gross collector area $A_{gross}$. For all measurements the interior temperature was set to $T_{int} = 22°C$ to approximately match $T_{amb}$.

TABLE 2 Design of experiments for calorimetric measurements of STVB test sample.

| DESCRIPTION | | $BE$ | β [°] | $T_{f,in}$ [°C] |
|---|---|---|---|---|
| **Slats lowered & closed** | with low fluid temp. | 1 | 82 | 21 |
| | with medium fluid temp. | 1 | 82 | 55 |
| | with high fluid temp. | 1 | 82 | 90 |
| **Slats lowered & 45°** | with low fluid temp. | 1 | 45 | 21 |
| **Slats lowered & opened** | with low fluid temp. | 1 | 10 | 21 |
| **Slats halfdown & closed** | with low fluid temp. | 0.5 | 82 | 21 |
| | with medium fluid temp. | 0.5 | 82 | 55 |
| **Slats halfdown & 45°** | with low fluid temp. | 0.5 | 45 | 21 |
| | with medium fluid temp. | 0.5 | 45 | 55 |
| **Slats halfdown & opened** | with low fluid temp. | 0.5 | 10 | 21 |

The main measurement results are solar thermal yield $\dot{Q}_{use}$ and the local solar energy fluxes $q_{SHG,i}$ to the building interior for each individual measurement situation. The instantaneous hemispherical solar thermal efficiency $\eta = \dot{Q}_{use}/(G_h \cdot A_{ref})$ at the present operation and boundary conditions is calculated using the overall absorber $A_{abs,tot} \approx 2.67\ m^2$ as reference area $A_{ref}$ (cf. Fig. 6). In contrast to conventional opaque collectors, the STVB can offer partial transparency, and thus visual contact to the exterior, while harvesting solar thermal energy. To take into account this multifunctionality of the STVB, the total projected area of the slats on the front glass pane $A_{proj} = l \cdot (t \cos \beta + w \sin \beta) \cdot 37 \cdot BE$ can be used as reference area $A_{ref}$ as shown in Fig. 6. This is the opaque area in the normal viewing direction (neglecting the blind pack). This area reaches its maximum at $A_{proj,max} = 3.15\ m^2 \cdot BE$ for slat tilt angles $\beta \geq 56°$ where the transparent area in normal viewing direction dissapears. For $BE = 1$ this is the total venetian blind area. Achieving a similar ratio of transparency in normal viewing direction for an opaque solar thermal collector would result in an absorber with area $A_{proj}$.

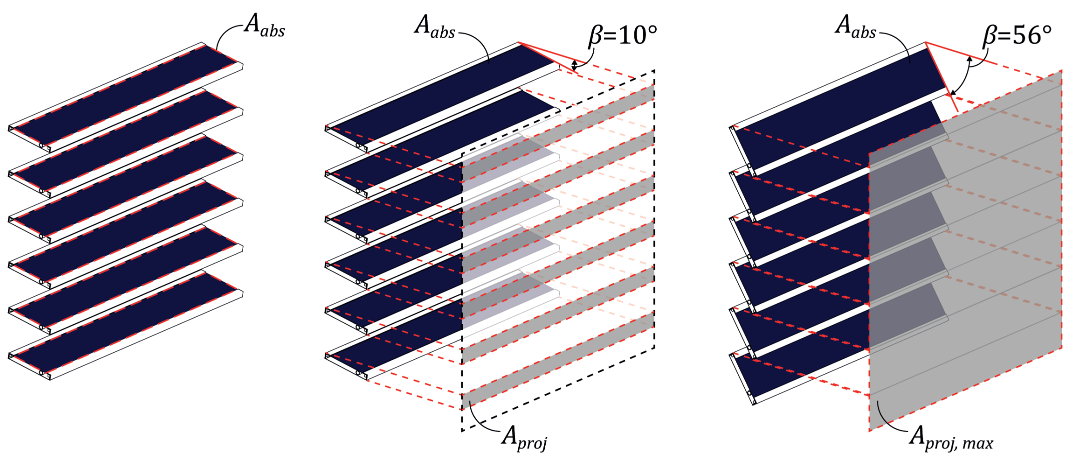



FIG. 6 Different areas that can be used as reference area $A_{ref}$ to calculate the solar thermal efficiency η. Left: Overall slat absorber area $A_{abs,tot} \approx 2.67\ m^2$. Centre: Projected slat area $A_{proj}$ for exemplary slat tilt angle of $\beta = 10°$. Right: Maximum projected slat area $A_{proj,max} = 3.15\ m^2 \cdot BE$ for slat tilt angles of $\beta \geq 56°$.

The local solar heat gain coefficient $g_i$ of the test sample (i.e. of the façade element including the STVB) is calculated with $q_{abs,i}$, $G_h$, $T_{int,i}$, $T_{amb}$ and the $U$-value (Kuhn, 2014). In this paper, only the centre-of-glazing solar heat gain coefficient $g_{cg}$ is presented. It is important to note that the solar heat gain coefficient $g$ of transparent BIST, like the STVB, varies with the collector operating conditions (Maurer & Kuhn, 2012). Semi-stationary conditions can be defined for times when efficiency and solar heat gain coefficient $g$ are stationary. This requires fairly constant irradiance and ambient temperature. Using azimuth tracking increases the time with constant irradiance to reach these conditions.

Under the condition of $T_{int} \approx T_{amb}$, the solar thermal performance of the STVB test sample, which is a BIST collector, can be evaluated like conventional solar thermal collectors according to Quasi-Dynamic Testing (QDT) as defined in ISO 9806 (2017) and setting $a_3$, $a_4$, $a_6$, $a_7$ (artificial wind source) and $a_8$ (non-concentrating collector) to zero in equation (13) of ISO 9806 (2017). As direct irradiance $G_b$ and diffuse irradiance $G_D$ on the collector plane are not directly measured by the test facility, they are calculated based on $G_h$, $E_d$, θ and a ground reflectance of 0.2 estimated for the test site. For the conversion, the isotropic sky model and the general relationship $G_h = G_b + G_d$ have been used (Duffie & Beckman, 2013). The flat plate collector model is used for the incidence angle modifier $K_b$ (θ) for closed slats with slat tilt angle $\beta = 82°$ under azimuth tracking (ISO 9806, 2013). The resulting efficiencies can be compared to efficiency curves of conventional solar thermal collectors to evaluate the technical feasibility of the STVB concept.

## 3.2 RESULTS AND DISCUSSION

The measured solar thermal yield $Q_{use}$, showed that the STVB test sample operates as a solar thermal collector for all tested cases of TABLE 2. This proves that the conversion of irradiation into heat by the absorber sheets, as well as the heat transfer via heat pipe and switchable thermal coupling to the header tube, are working. The first aspect (conversion of solar irradiation into heat) was expected because the absorber sheets are the same as those used in conventional solar thermal collectors. The second aspect (heat transfer via heat pipe and switchable thermal coupling) thus proves that the heat pipe operates properly at all slat tilt angles, and that the heat transfer across the switchable thermal coupling is working.

Stationarity of $\eta$ was found on clear days roughly between 12:00 and 17:00. On overcast days with highly varying irradiance, semi-stationary conditions were not achieved. The QDT method was applied for $BE$ = 1, $\beta$ = 82° with results in TABLE 3 and efficiency curve in Fig. 7. Efficiency curves represent the efficiency $\eta$ as a function of the so-called "reduced temperature difference", which is the temperature difference between mean fluid temperature $T_m$ and ambient temperature $T_{amb}$ divided by the irradiance $G_h$. Hence, it can be used to evaluate the solar thermal performance at different fluid temperature levels and/or irradiances. The application of the QDT approach for the STVB measurements, the resulting efficiency curve, and all comparisons to conventional solar thermal collectors are valid only for $T_{int} \approx T_{amb}$ and zero azimuth angle, as discussed. The QDT evaluation and the efficiency in semi-stationary conditions for $BE$ = 1, $\beta$ = 82° match well. Comparing the performance of half-lowered slats ($BE$ = 0.5) with fully lowered slats ($BE$ = 1) shows a lower efficiency for $BE$ = 0.5 where only 18 slats are fully exposed to the sun.

TABLE 3 Collector parameters of STVB for $T_{int} \approx T_{amb}$ obtained via QDT compared to a research flat plate collector with heat pipes - FPC-HP - (Schiebler et al., 2018) and a commercially available flat plate collector - FPC - (DIN CERTCO, 2015). Reference area $A_{abs,total}$ = 2.67 $m^2$ used for the STVB.

| | STVB<br>$BE$ = 1<br>$\beta$ = 82° | FPC-HP | FPC |
|---|---|---|---|
| $\eta_0$ [1] | 0.307±0.010 | 0.733 | 0.842 |
| $a_1$ [W/m²K] | 3.07±0.16 | 3.562 | 3.620 |
| $a_2$ [W/m²K²] | 0 | 0.017 | 0.016 |
| $a_5$ [kJ/m²K] | 138±12 | - | 6.8 |
| $b_0$ [1] | 0.12±0.11 | - | 0.13 |
| $K_d$ | 0.88±0.13 | - | - |

To learn more about the quality of the heat transfer and heat losses in the STVB test sample, the efficiency parameters in TABLE 3 are compared to a commercially available flat plate collector (DIN CERTCO, 2015) and a flat plate collector with heat pipes developed in a research project (Schiebler et al., 2018), which resembles the STVB more closely in terms of the heat transfer principle. The peak collector efficiency $\eta_0$ of the STVB test sample is much lower than $\eta_0$ of these reference collectors.

The collector heat transfer coefficient $a_1$ is comparable. The maximum reachable fluid temperature $T_m$ for given ambient temperature $T_{amb}$ and irradiance $G_h$ are considerably lower for the STVB than for the references, as can be seen from Fig. 7. It is important to note that the possibility to tilt and retract the slats offers the possibility for transparency, which is inherently not possible with conventional solar thermal collectors. Using the projected slat area $A_{proj} = 1.01\ m^2$ instead of $A_{abs,total}$ as a reference area for $\beta = 10°$ at $BE = 1$ to judge this multifunctionality would increase the calculated efficiency by a factor of 2.6. An efficency of $\eta_0 \approx 0.3$ would thus become $\eta_{0,proj} \approx 0.8$. This efficiency is comparable to a conventional solar thermal collector. Conclusively, the STVB can already provide solar thermal yields at $\eta_0$-conditions similar to a conventional collector with a comparable transparent percentage of 68%, as achieved for $\beta = 10°$, $BE = 1$ for the venetian blind area. Because the heat loss coefficient $a_1$ increases by a factor of 2.6 for the area conversion as well, the STVB efficiency drops much more quickly than a conventional collector for higher temperature differences $T_m$-$T_{amb}$.

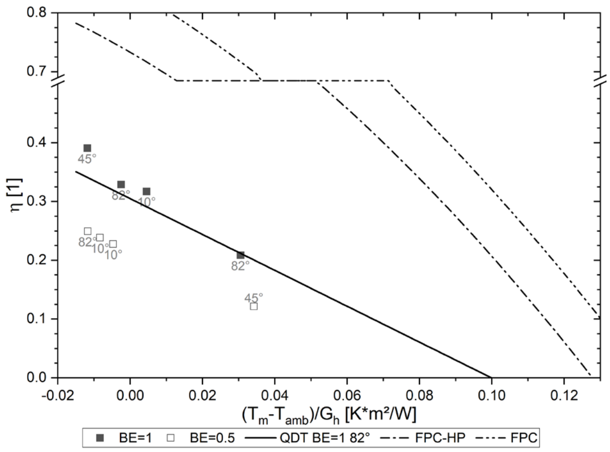



FIG. 7 Efficiency curves $\eta$ of STVB test sample for $T_{int} \approx T_{amb}$ as function of mean fluid temperature $T_m$, ambient temperature $T_{amb}$, and hemispherical irradiance $G_h$ compared to reference collectors (cf. TABLE 3). Slat tilt angles $\beta$ noted as label for each data point. Reference area $A_{abs,total} = 2.67\ m^2$ used for the STVB.

The measured solar heat gain coefficients of the test sample with closed and lowered slats ($\beta = 82°$, $BE = 1$) are in the range of $g_{cg} \approx 0.1$. The solar heat gain coefficient $g_{cg}$ increases relatively by approximately $50\%_{rel}$ with increasing fluid temperatures of the solar thermal system from $T_{f,in} = 21°C$ to 90°. Due to the overall low solar heat gain coefficient of the tested STVB façade element, this change is not considered critical to the control of passive solar heat gains. Nonetheless, operating the STVB at lower fluid temperatures would be beneficial with regard to lowering the cooling demand of a building. Considering that towards the interior only conventional double glazing is used (cf. Section 2.2.3), the measured solar heat gain coefficients are sufficiently low, even for highest fluid temperatures, and the solar control functionality is provided for all cases.

Based on the presented measurement results, it is concluded that both the solar thermal functionality and the solar control functionality of the test sample have been demonstrated successfully. Despite the need for technical improvement, especially with regard to solar thermal efficiency, this first STVB test sample therefore proves the technical feasibility of the concept of STVB with heat pipes and switchable thermal coupling. It also shows its potential due to its multifunctionality allowing transparency.

# 4 ARCHITECTURAL IMPLEMENTATION OF THE STVB SYSTEM

The concept of STVB has been evaluated regarding its applicability in architecture and façade construction. Design choices by architects, planners and building owners regarding the STVB system and their relation to the design parameter space are discussed in this section on a conceptual level. Possible installation processes are presented and recommendations for further developments of STVB are identified with the help of industry experts.

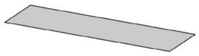
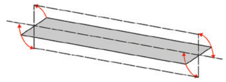
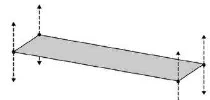
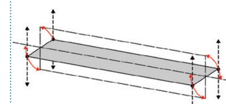
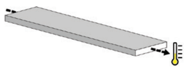
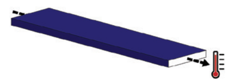
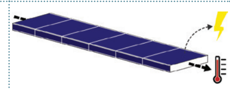
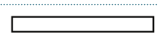
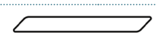
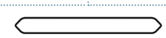
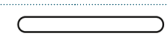
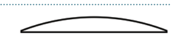
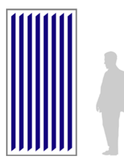
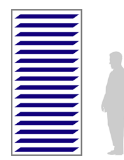
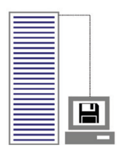
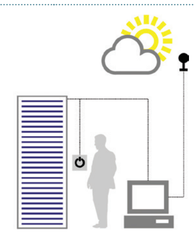
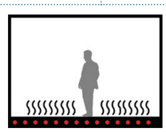
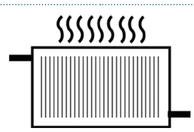
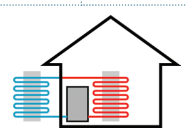
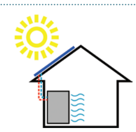
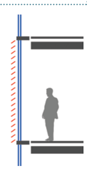
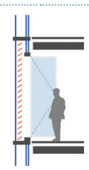
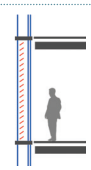
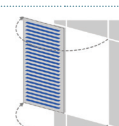
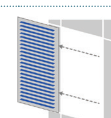
## 4.1 CUSTOMISATION OF STVB DESIGN

The functional and architectural potential of the STVB concept has been presented and reviewed at several trade fairs (BAU 2017, BAU 2019, and glasstec 2018 (Horn & Block, 2018)), and conferences (Denz, Maurer et al., 2018; Denz, Vongsingha et al., 2018; Haeringer, Abderrahman, Vongsingha, Kuhn et al., 2017). The variety of the STVB design parameter options allows for customisation of the STVB for individual building projects, e.g. concerning slat colour (*absorber*), shape (*slat geometry*), and *position* of the STVB. As the STVB can be combined with various different façade typologies, this leads to different potential adaptations of the STVB system. Changing these parameters influences the technical performance, especially solar thermal and solar control functionality. Finding a meaningful STVB concept therefore depends on the individual requirements of the building project and can require compromises, e.g. between technical performance and architectural intent.

The architect, specialist planner, or building owner can thus make different design choices. TABLE 4 provides an overview of the most important design options for the STVB system and its integration into the technical building plant. These design choices are conceptual and require experimental or theoretical validation before being applied in real buildings. The scope of the design choices in TABLE 4 is broadened compared to the DPS in Fig. 2, which explicitly focuses on technical aspects for horizontal, fully movable STVB. For example, TABLE 4 includes choices with reduced slat movement (i.e. less complexity), which could be beneficial to solving the issues with heat transfer from heat pipe to header tube and thus improving the solar thermal efficiency compared to the test sample (cf. Section 3.2). The design choice map is not as detailed as the DPS, so architects and planners can use it during conceptual and design phases when applying the STVB to an individual building project. From the design choices, the technical requirements need to be defined and solutions can be found with the help of the DPS.

Based on this overview, STVB can be seen as a slat-type solar control and solar thermal system that can be adapted to meet different architectural and constructional requirements. This customisation enables design possibilities as required for façade application of newly developed solutions (Klein, 2013). Furthermore, a reduction of the complexity can be achieved to enable application in first building projects with low risks, for example by focusing on tiltable slats, which cannot be retracted. The blind mechanism becomes simpler and the number of components is reduced. The *heat transfer components* from slat to header tube could be modified as the full movement of each slat is not required anymore. This could lead to a better heat transfer and thus a higher solar thermal efficiency. TABLE 4 therefore serves as an outlook to further development paths of the STVB and to potential adaptations of the STVB in first building projects.

TABLE 4 Design choices and options for solar thermal venetian blind systems

| DESIGN CHOICE | OPTIONS | | | | |
|---|---|---|---|---|---|
| Degree of slat movement |  Fixed |  Tiltable |  Retractable |  Tiltable & retractable | |
| Absorber surface |  No coating |  Colour coating (painted, anodized, powder coated) |  Spectrally selective coating |  PVT (combination with PV cells) | |
| Slat shape |  |  |  |  |  |
| Slat width | Large slats (>100 mm width) | Venetian blind slats (~60-100 mm width) | | | |
| Façade pattern width & slat length | Conventional (~1.35 m) | Long (>1.5 m) | | | |
| Slat orientation |  Vertical slats |  Horizontal slats | | | |
| Blind control |  Manual control |  Central control |  Fully automated control with optional overriding by user | | |
| Use of solar thermal heat |  Domestic hot water preparation |  Low-temperature radiant heating |  Space heating with radiators |  Source for heat-pump or to regenerate geothermal probes |  Solar dehumidification / Solar cooling |
| Position of STVB and façade type |  Exterior application (arbitrary façade type) |  Inside cavity of box-type window or double skin façade |  Inside cavity of closed cavity façade | | |
| Degree of STVB element movement |  Fixed element |  Window shutter type |  Sliding shutter type | | |

## 4.2 INSTALLATION PROCESS OF STVB

Due to the vast variety of façade construction typologies in the market, the installation concept of STVB should be adaptable to different façade construction and installation types. The basic installation scenarios that are investigated, under consideration of the surrounding and support components, are:

- Scenario 1: The STVB is installed on site into a façade system that provides the structure to carry and position the STVB components.
- Scenario 2: The STVB is a pre-fabricated unit supporting itself, installed in a façade system that provides supporting points only, such as brackets.

Scenario 1 mostly applies to window (or box-type window) units in a punctuated façade as well as stick-system façades like multi-storey ventilated double skin façades (see Fig. 8). In this scenario, the STVB is installed directly to the existing structures on site, which support the components of the STVB structurally. During the installation, the STVB requires temporary installation support elements – e.g. to hold all STVB components in place during transportation and mounting. The temporary elements are removed when the STVB is adjusted to site tolerances and fixed to the main structure in the correct position. This method would require a long installation process on site. Depending on weather and location, the installation could therefore become rather difficult.

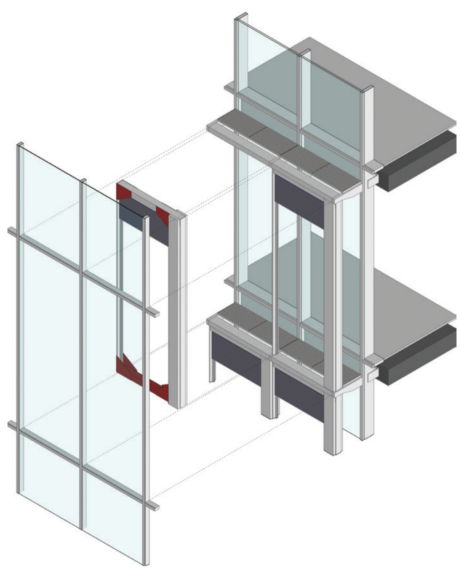


FIG. 8 STVB installation in Scenario 1 on a multi-storey ventilated double-skin façade

In Scenario 2, the STVB itself comes with a rigid frame as standalone unit to be added externally to an existing façade or as an integrated part of a unitised façade system. In this scenario, the STVB is completely assembled at the workshop before being delivered and mounted to the building. This method allows better quality control because the crucial process is done in a controlled environment thus shortening the installation process on site.

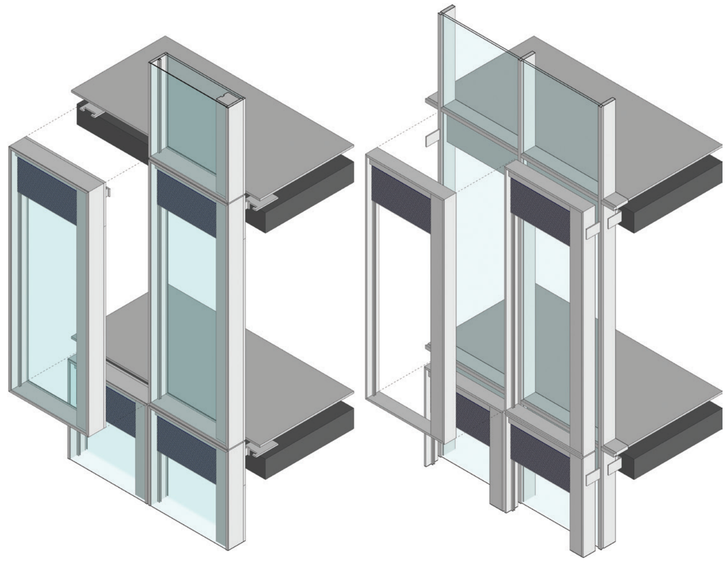


FIG. 9 STVB installation in Scenario 2 as part of double skin unitised façade (left); as an additional stand-alone element on an existing unitised or stick façade system (right)

As in any general construction process, the façade and other exterior surfaces have to be completed first, before the construction of the interior spaces, including the building service system, can start. The installation of STVB needs to be considered as part of both processes: façade construction and building service construction. After its installation as part of the façade, the STVB needs to be checked by a building service specialist who will review the inlet and outlet pipes of the solar thermal unit and carry out a leak test. After the test, the pipes need to be sealed, if the installation of building service has not yet started. Once the building envelope is fully closed and interior finishing starts, the STVB can be connected to building service piping and be put into operation.

## 4.3 RECOMMENDATIONS FOR FUTURE DEVELOPMENTS AND APPLICATIONS

Based on a detailed review of the developed STVB test sample and with input from trade fairs and conferences, a SWOT analysis was carried out underlining strengths as well as weaknesses of the STVB approach (Denz, 2019). To review the main benefits of STVB and guide the direction of further developments, feedback from external stakeholders was gathered in a lead-user workshop (Hippel, 2005). Experts with backgrounds such as façade system fabricator, sun-shading fabricator, project developer, specialist planner on climate engineering, and architects from both practice and academia were identified as lead users and took part in a workshop (Beucker, 2020). The participants discussed and evaluated the STVB test sample and its proposed benefits. Together with the lead users, relevant requirements and recommendations for future STVB developments were specified and weighted. The most important results are summarised in TABLE 5.

TABLE 5 Main requirements and recommendations for future developments of STVB as stated during the lead-user workshop.

| | |
|---|---|
| **Design requirements** | – Visually reduced and unobtrusive slat design |
| **Technical requirements** | – Reduction of mechanical complexity<br>– Reduction of the size of the heat transfer components (switchable thermal coupling mechanism and header tube)<br>– Accessibility for maintenance and cleaning |
| **Commercial requirements** | – Focus on promoting the reduction of the solar heat gain by the STVB while maintaining high visual transparency of the glazing as a unique selling point<br>– Suitable types of buildings are hospitals, hotels, restaurants, representative building of companies, offices, ministries etc.<br>– Improve the cost-benefit ratio |
| **User requirements** | – High reliability during the service life |

These results show that the main concern is the current complexity of the STVB, which presumably would result in a laborious production process, high cost, and high maintenance, or low reliability during operation. This assessment matches the review of the built STVB test sample and the SWOT analysis (Denz, 2019). Reducing the complexity as discussed in Section 4.1 could deal with these concerns and improve the cost-benefit ratio if reduced functionality is sufficient for the actual building project. In order to simplify the system, the existing components could furthermore be redesigned by applying industrial production and installation methods. For example, as suggested in Section 2.2.2, aluminium extrusion could reduce cost and time of manufacturing and assembly of the slats by reducing the amount of components.

The participants of the lead-user workshop listed the feature of STVB to reduce the thermal load within a double skin façade as well as the $g$-value, while allowing high visual transparency as one of its major strengths. Following this concept, STVB could be further developed by focusing on its application as an adaptive solar control system, which aims to control and reduce the solar heat gain coefficient $g$ rather than focusing on maximising the solar thermal yield. Optimising the STVB to reduce the solar heat gain could enable future building projects with fully glazed façades, even in corner situations, while still preventing overheating of the room in summer, as required by energy efficiency and building codes such as EnEV (2007).

# 5 CONCLUSIONS

Solar thermal venetian blinds present a novel, multi-functional, and adaptive solar control device with solar thermal functionality, fully integrated into glazed areas of the building envelope. They can simultaneously fulfil the functions of a solar thermal collector and of a solar control device as has been demonstrated experimentally with the designed test sample. The presented design parameter space for STVB gives a complete overview of possible variants of STVB with horizontal, tiltable and retractable slats that incorporate a heat pipe. Engineers and researchers can use it as guideline for future technical developments. Guided by the design parameter space, a STVB test sample with heat pipes and fully movable slats was developed. Its key design features are: (1) STVB positioned within the cavity of a double-skin façade element, (2) conventional absorber sheet with diagonally mounted cylindrical heat pipe, (3) heat transfer between heat pipe condenser and header tube via switchable thermal coupling using an adapter with an optimised shape and a mechanism using springs and self-latching solenoids, (4) a multi-port header tube. Alternative concepts with different absorber coatings, heat pipes, slat geometries, and alternative mechanisms for the switchable thermal coupling can be designed based on the design parameter space. Outdoor experiments on the STVB test sample proofed the technical performance of the studied STVB concept in terms of solar thermal efficiency η and control of passive solar heat gains (*g*-value). It was found that the solar thermal performance leaves significant room for improvement. However, when considering the multifunctionality, namely transparency, the STVB already performs comparably to conventional solar thermal collectors.

The design parameter space, various design choices, and integration into different façade systems allow architects and specialist planners to adapt the STVB to individual building projects. The installation processes for two different mounting scenarios were discussed and recommendations by industry experts for future developments were evaluated. The proposed customisation of STVB and the recommendations by the lead users will be used to guide further developments aiming at the first implementation of the STVB in a building project. Future research will investigate the effects of technical improvements and of different design variants and assess the overall energy savings potential in simulation studies using an experimentally validated model of the STVB.

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