Trombe Curtain Wall Façade

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Abstract

In times of energy use awareness, decarbonisation, and resource efficiency, the performance of well-known façade components must be pushed beyond current limits through innovative designs and new combinations in construction. This paper presents an unconventional redesign of a double skin façade (DSF), based on Trombe wall principles, to enlarge solar gains in heating seasons and avoid overheating issues in summertime. The DSF variant is equipped with a thermal storage mass in the DSF cavity and interior insulation. The thermal mass, in this case concrete, is of a dark colour for high solar absorption, whereas the shading device is highly reflective. In contrast to traditional Trombe wall systems, this TCW is not supposed to actively heat interior space or transfer thermal energy. Instead, the TCW aims to regulate heat flux within the façade level by the management of solar thermal energy fluxes. The potential to reduce buildings' heat losses through solar energy use is shown and compared to a traditional external thermal insulation composite system (ETICS) with an appropriate insulation thickness for renovation purposes in Switzerland. The U-Value is therefore considerably lower, 0.25 instead of 0.41 for the TCW. Due to the innovative design and fully transient operation, a highly detailed and flexible simulation tool is needed to analyse and assess the façade performance. The decision to simulate the novel system was made for Modelica-Dymola, with its object-oriented, equation-based simulation language. The simulations of both TCW and ETICS show potential for heat loss reduction due to solar energy storage on every orientation. However, the TCW shows a high solar energy usage due to its 'natural' overheating tendency. Furthermore, heat losses are significantly lower than the U-Value predicts and, in some cases, even lower than the ETICS heat losses. In addition, due to its lower use of material and lower weight, the system can be used as a curtain wall system instead of traditional DSFs, which have higher heat losses in winter and higher solar gains in summer.

Keywords

Passive façade, Low-Tec, energy efficiency, adaptive façade, performance gap, adaptive g-Value

DOI 10.7480/jfde.2019.1.2619

1 INTRODUCTION

In recent decades, there has been a constant rise in awareness of energy. According to the International Energy Agency (2013), the largest energy consumer is the building sector, which is responsible for one-third of global energy consumption and carbon dioxide emissions. If energy efficiency is not improved, the energy demand is expected to rise by 50% by 2050. However, the EU Energy Roadmap 2050 (European Commission, 2012) states that the buildings that will be in use in 2050 are being designed and built now. To achieve those energy goals, higher energy efficiency in new and existing buildings plays a key role. In addition, Zero Energy Buildings (ZEB) should become the standard for new buildings.

Achieving high energy efficiency in buildings is a complex process with various influences. The role of its envelope, as a physical separator between controlled and uncontrolled environments, is an important factor. A façade controls the energy and mass transfer between indoors and outdoors, making it one of the most promising solutions for the improvement of energy consumption in buildings. Therefore, improved façades will lead to lower energy demand for cooling and heating. Furthermore, the façade can support HVAC systems and reduce their size. Undoubtedly, more efficient HVAC installations also contribute to a building's energy savings. However, the façade still makes the highest demands on HVAC energy. As Perino & Serra (2015) emphasise, new and more revolutionary concepts and technologies to achieve a ZEB or nearly ZEB standard need to be developed.

Various research efforts in the area of energy efficient and / or adaptive façades are in progress. While some focus on the limits of available simulation tools (Loonen, 2010), others explore the potential of smart materials, such as a Phase Change Material (PCM) filled double glazing unit (Goia, Zinzi, Carnielo, & Serra, 2015) or other smart windows (Casini, 2015) for improving the energy efficiency of buildings. Furthermore, kinematic (Schleicher et al., 2011; Suralkar, 2011) solutions are being researched. However, the possibilities of active or passive solar energy use within façades are also under exploration. For this topic, a review of Quesada Rousse, Dutil, Badache, & Hallé (2012) gives a good overview of opaque solar façades, which have significant potential to reduce heating loads.

Thermally active solar façades usually need fans or pumps to distribute the solar thermal gains for heating, cooling, or storage purposes. Passive systems instead utilise natural processes of heat transfer (conduction, convection, radiation). The most popular solar walls are Trombe walls and its variants. Trombe walls are rather simple constructions elements; they consist of an external glass layer and an internal, high absorptive thermal mass, divided by an air gap, which uses the greenhouse effect. Active or passive controllable flaps enable the natural airflow to be controlled and, therefore, the internal heat gain. Hu, He, Ji, & Zhang, (2017), Quesada et al. (2012), and Omrany, Ghaffarianhoseini, Ghaffarianhoseini, Rhaahemifar, & Tookey (2016) agree that Trombe walls (TW) have the potential to significantly reduce a building's energy consumption.

However, most TWs are often considered as massive, thick walls that allow significant thermal transfer to the room. This study introduces a new TW façade with solar thermal storage, which can be used as "lightweight" curtain wall façade element. In contrast to earlier attempts, this new TW façade renounces to "heat" interior spaces; instead, its purpose is to passively balance out thermal heat gains on the façade level. In addition, this study aims to use low-tech solutions as far as possible. Due to the low-tech principle, this feasibility study of a Trombe curtain wall element is strongly related to currently available materials and elements.

The façade is based on non-ventilated Double Skin Façade (DSF) elements with a high reflective shading device. The inner Insulated Glazing Unit (IGU) layer of traditional DSFs is replaced by a 50mm thermal mass and 75mm internal insulation. This configuration allows it to control heat fluxes trough the façade on seasonal, daily, or hourly levels. While the “natural” overheating tendency of DSFs is used to load the thermal storage in heating seasons, the high reflective shading device, in cooperation with the thermal mass, reduces overheating in cooling seasons. This enables the Trombe Curtain wall (TCW) system to actively employ an adaptive g-Value.

In this paper, the performance of the new TCW prototype is compared to a traditional external thermal insulation composite system and shows the potential of solar energy use to reduce heating demands of buildings. This is an extract of the original project “Solar Energy Balanced Façade” (SEBF), in which the façade element is partly transparent and the TCW element is used as a parapet.

2 METHODOLOGY

To investigate the thermal performance of this new TCW prototype, a detailed dynamic calculation model must be applied. Unfortunately, most Building Performance Simulation (BPS) tools are not supposed to investigate such a dynamic system in a detailed way. Therefore, the decision was made to use Modelica, an object-orientated, equation-based language that can describe physical systems in various domains.

Detailed descriptions of the various advantages of equation-based modelling with Modelica can be found in Wetter (2011). One of the features is the possibility to encapsulate physical functions into classes, which can be tested separately and reused to build up systems that are more complex. In addition, the user can concentrate on describing the physical constraints instead of describing the intended performance.

Because of its high level of detail, the study is undertaken only at a façade level.

2.1 MODELLING APPROACH

The Trombe wall system is divided into its four main elements described in the simulation model (see Fig. 1): B) external glass layer; C) air cavity with shading device; D) thermal mass; E) insulation layer.

The external glazing (Fig 1.B) is modelled as a pane with two surface nodes and a centre node, connected by two conduction elements. The mass of the glazing is concentrated at the centre node, where the solar heat gain is applied. So far, these are standard Modelica library elements with extended parameters to simplify model changes and encapsulation. The implemented optical model uses direct radiation, diffuse radiation, and the angle of incidence to calculate the Fresnel corrected reflection and transmission of the glazing.

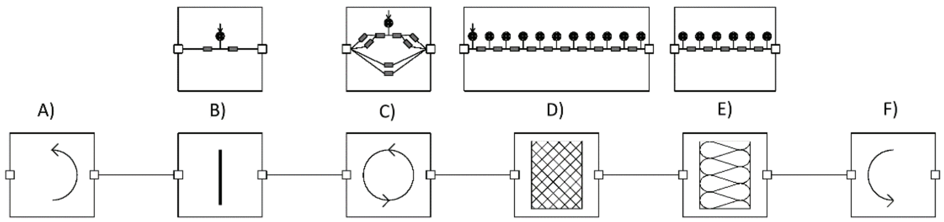

FIG. 1 Modelica model scheme for the four main components of the Trombe wall system. Bottom row, from left to right: A) external surface heat transfer, B) single glazing element, C) air cavity, D) storage mass, E) insulation, and F) interior surface transfer. Upper row: detailed scheme

For the air gap model, two models are combined: a) air gap without shading and b) air gap with shading. Both possible heat fluxes are completely modelled by one (or two) convective and radiative (standard) conduction elements based on the ISO 15099 formulation (Section 8.3.2.2 and 8.4.3.1). The shading device is modelled in the same manner as the single glazing, two conductors, one mass, and heat gain elements. Due to the small thickness (1mm) and high conductivity (λ=160W/mK) of aluminium, this is regarded as a valid simplification. All conduction elements in the air gap were connected to the shading control by a shading area factor (0…1). In case of activation or deactivation of the shading device, a critical damping element smoothens the transition from open to closed, or vice versa. The optical model is also connected to the shading area factor to calculate transmission, reflection, and solar heat gain on the shading mass.

The wall is divided into 10 equidistant conductors and 11 masses, nine of which represent 1/10th of the total thickness with the final two representing 1/20th of the total thickness as surface elements. The solar heat gain is applied to the outer surface mass, depending on the surface's characteristics. The insulation layer is a simplified wall model in which only five conductors are used instead of 10. This also applies to the masses, four of which represent 1/5th and two represent 1/10th of the surface.

Internal and external surface heat exchange is modelled according to EN 15099 with a radiation temperature equal to air temperature. The definition of those basic elements allows the main components to be reconnected to a comparison model of a standard insulated wall system (see Section 2.3).

2.2 ELEMENT DESCRIPTION

For the investigations shown in this paper, the results are based on elements of 2.5m^2, with 1m width and 2.5m height. To compare the results, two elements are considered: the Trombe curtain wall element and a standard insulated wall for renovation purposes (SIA 380/1, 2009).

The Trombe curtain wall (TCW) element consists of:

- 6mm external glazing
- 150mm air gap (shading mounted centrally)
- Shading device (1mm aluminium)
- 50mm of concrete
- 75mm insulation
- U-Value: 0.44 / 0.41 W/(m2K) (without and with shading)

The second wall, a usual external thermal insulation composite system (ETICS);

- 15mm plaster
- 150mm insulation
- 150mm concrete
- U-Value 0.25 W/(m^{2}K)

2.3 MATERIAL PROPERTIES

Each material used is considered in terms of "common" values from practice, according to related literature (see Table 1). This is not to distort the results of the comparison with standard façades. The adjustment of material properties and therefore the improvement of the façade performance are topics for further investigations.

MATERIAL	ρ [-]	τ [-]	λ [W/(mK)]]	ρ [kg/m^3]	c_p [J/(kgK)]	ε [-]	d [mm]
Glass (orthogonal)	0.08	0.82	1.0	2700	750	0.84	6
Insulation	0.5	0	0.04	80	600	0.9	75
Concrete	0.8	0	2.1	2400	1000	0.9	150 / 50
Plaster	0.5	0	0.87	1600	1000	0.9	15
Shading device	0.85	0	160	2800	880	0.9	1

TABLE 1 Material properties

2.4 BOUNDARY CONDITIONS

Internal air temperature is set to 22 °C, and influences of occupancy, which lead to temperature variations, are not considered here. The climatic outdoor conditions are given by a standard design year for Zürich (CH) on an hourly basis from METEONORM. All parameters, such as temperature, wind speed, façade irradiation, and sun position, are interpolated linearly from hourly values.

2.5 SHADING CONTROL

The TCW makes use of solar gains in cold periods and prevents overheating during warmer periods, for which a customised shading control is responsible.

First, the shading control must decide whether it is a heating or cooling period. Therefore, the mean value of external air temperature over 24 hours is used as deciding factor. If the mean outside temperature is below 12 °C, which is more or less the heating limit temperature in Switzerland, the 'heat gain' mode is activated. Consequently, the 'avoid heat gain' mode is enabled for mean temperatures above 12°C. For mean outside temperatures higher than 15°C, the system enlarges night time heat losses.

To prevent heat losses, the shading is activated at night time (global radiation < 25 W/m^2) with a mean outside temperature below 15°C as an additional thermal resistance. During daytime with solar irradiation >25 W/m^2 and mean outside temperatures below 12 °C, the high absorptive thermal storage accumulates solar energy.

To avoid solar gains, the high reflective shading device is activated on days with mean outside temperatures above 12°C. In addition, during nights with mean outside temperatures above 15°C, the shading device is disabled to enlarge heat losses and 'pre-cool' the thermal storage.

This TCW control strategy is determined to react to seasonal needs. At the moment, this is undoubtedly a simplified approach to prove the feasibility of the system for the Central European climate. Further investigation to define the right set points and, perhaps, additional input parameters is in progress.

3 RESULTS

In this chapter, the simulation results are presented. To begin with, the systems are simulated in a detailed transient manner without solar gains in order to compare it to the U-Value calculation. Based on those "no-sun" results, the solar energy potential for each façade system in the four main orientations is presented. Finally, the orientation-dependent transient results are compared directly.

3.1 NON-SOLAR RESULTS

Based on Chapters 2.2 and 2.3, the U-Value of the TCW system is 64% higher. The transient simulation, without solar gains, shows similar results to the simplified calculation (see Table 2). However, the shading control system within the TCW façade receives the same data and therefore provides the same control output as when solar gains occur. The relatively higher heat losses in summer months (June to September) is due to the night-cooling mode and therefore the discharged thermal storage. Furthermore, the shading device is closed during "sunny" hours and reduces daily heat gains due to higher outside temperatures.

	JAN	FEB	MAR	APR	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Massive	-9.2	-8.0	-7.6	-5.6	-3.9	-2.1	-1.6	-1.7	-3.2	-5.0	-7.3
Trombe	-15.0	-13.0	-12.4	-9.4	-6.6	-3.9	-3.1	-3.2	-5.7	-8.5	-11.9
%	163%	163%	163%	167%	171%	185%	194%	192%	179%	170%	164%

TABLE 2 Heat flux through façade elements per month, without solar influences in [kWh] per element

The U-Value prediction is confirmed and an overheating of the DSF is, due to the lack of solar irradiation, not observed.

3.2 SOLAR ENERGY POTENTIAL FOR THE ETICS

The solar potential is strongly dependent on orientation (available solar irradiation) and solar absorption. In this study, the solar absorption coefficient of the massive wall system is assumed to be

0.5, which is relatively high for painted surfaces and low for bricks. However, it is an average value to demonstrate the solar potential and to provide a comparison with the Trombe wall system.

As shown in Fig. 2, the solar irradiance has an influence on all façade orientations. For the four main directions (North = 0°, East = 90°, South = 180°, and West = 270°), a reduction of at least 2% and increases up to 135% in the monthly energy losses are observed, where a reduction of 100% means that no energy losses occur and values over 100% mean that gains occur. For the heating demand, the winter months (December to February) are considered. Within this time range, North, East, and West façades show a reduction of less than 10%. The South facing wall, shows a significant reduction of 9% to 17%. For the summer period, East, South, and West can turn into zero or even plus energy façades.

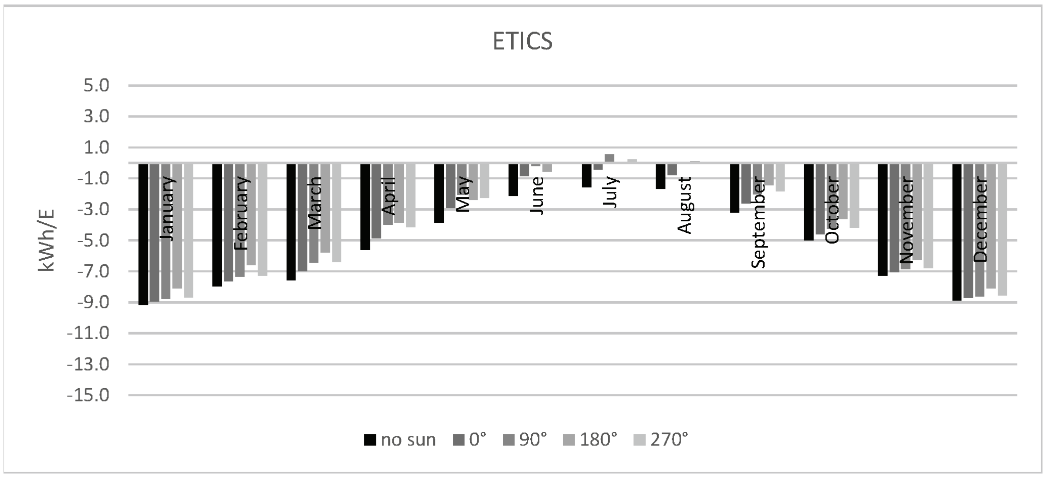

FIG. 2 Monthly energy losses of the ETICS wall element

3.3 SOLAR ENERGY POTENTIAL TCW

The TCW system is proposed to increase solar gains during heating season and to prevent overheating in cooling periods. The material properties in Section 2.2 and shading control strategy in Section 2.3 support this performance.

Fig. 3 presents the monthly energy losses for TCW under identical boundary conditions as the ETICS. The reduction in energy losses of a North facing TCW in the winter months are at least 14%, with maximum of 29%. South and West facing walls perform between 21% and 60% compared to the system without solar gains. The South facing TCW reduces heat losses in a range between 59% and 111%. This means that a South facing TCW produced solar gains in February instead of losses. Over all, the TCW presents a highly effective use of available solar energy in wintertime. This is mostly due to the exploitation of the DSFs overheating tendency.

Additionally, due to the highly reflective shading device, overheating and unwanted solar gains during the cooling period are mainly avoided. The maximum reduction in heat losses reaches 160% for the East facing TCW in July. The results in Fig. 3 support the claim that the TCW energy balance is seasonally adaptive.

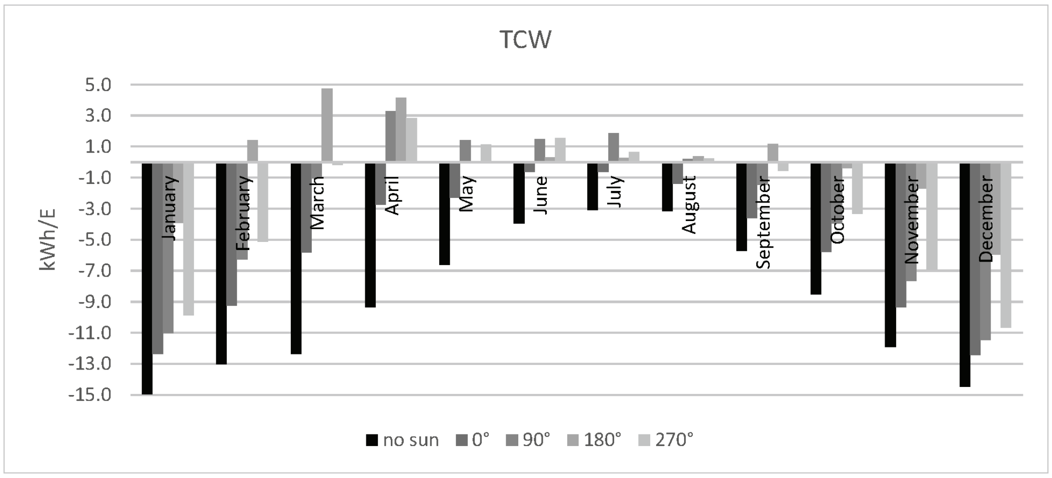

FIG. 3 Monthly energy losses of the TCW façade element

3.4 TCW AND ETICS COMPARISON

For a comprehensive performance evaluation, the transient results of TCW and ETICS are compared directly. As mentioned in Chapters 2.3 and 3.1, the TCW is supposed to lose 64% more heat than the ETICS. Whereas the ETICS is still a static construction, the TCW is seasonally adaptive.

Figs. 4 to 7 present the monthly energy balance of TCW and ETICS for the four main directions. North, East, and West facing TCWs still perform worse than ETICS in wintertime. The northern TCW's energy loss is only about 21% to 43% higher than the ETICS. For East and West directions, the TCW loses a maximum of 25% more energy than the ETICS. The southern TCW performs consistently better than the ETICS.

In Spring and Autumn, the TCW system on all orientations is more efficient than the ETICS. Even North facing façades (Fig. 4) show lower heat losses in March and April, while the East and West facing ones (Figs. 5 and 7) show lower heat losses than in the February to October period. The South facing elements, depicted in Fig. 6, demonstrate even positive energy balances in February to April.

The summer performance of the TCW shows no significant overheating problem when compared to the ETICS façade. In many cases, the energy balance is on a similar level. Only East and West façades show significantly higher heat gains up to 1.9 kWh instead of 0.6 kWh for an ETICS element (July, East, see Fig. 5).

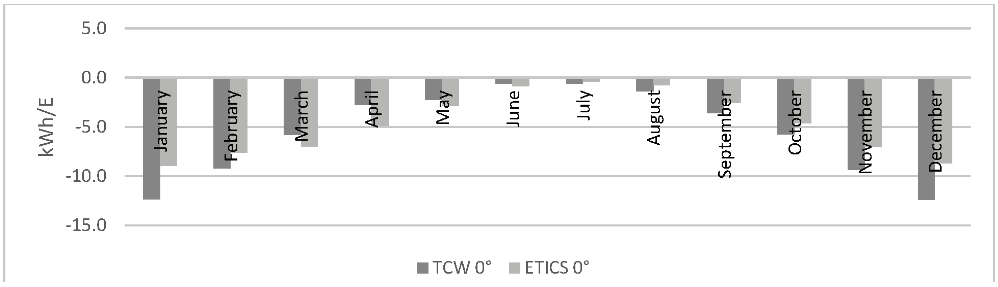

FIG. 4 Monthly energy losses of TCW and ETICS with solar gains for North orientation

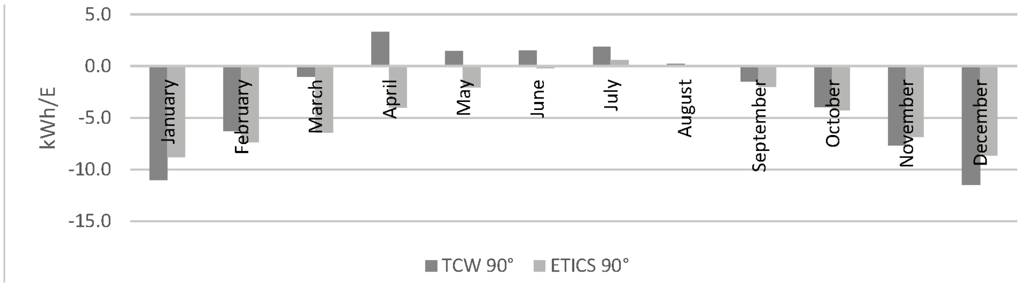

FIG. 5 Monthly energy losses of TCW and ETICS with solar gains for East orientation

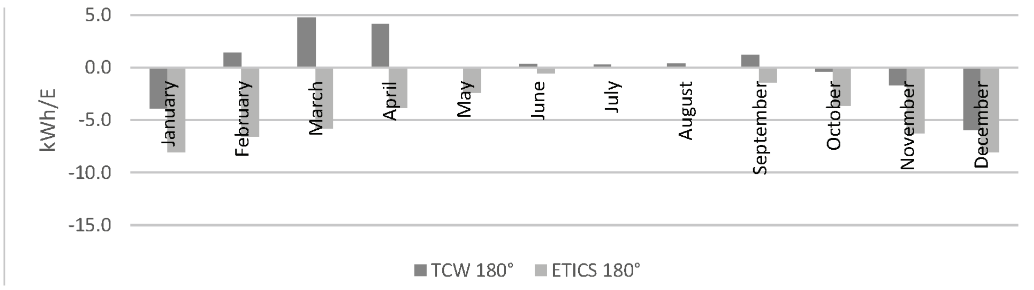

FIG. 6 Monthly energy losses of TCW and ETICS with solar gains for South orientation

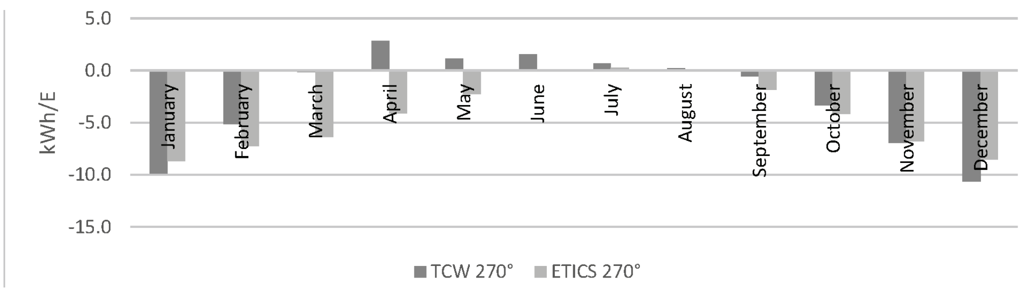

FIG. 7 Monthly energy losses of TCW and ETICS with solar gains for West orientation

4 DISCUSSION & CONCLUSIONS

Undoubtedly, the comparison between those two façade elements seems to be "unfair". On the one hand, we have twice the amount of insulation and, on the other hand, a DSF system that is predicted to overheat in summertime. Following these arguments, the TCW system's energy performance has no chance. Goia, Romeo, & Perino (2017) showed that simplified metrics (U- and g-Values) are not always suitable for determining the performance of advanced façades.

The presented results show that both systems, TCW and ETICS, can benefit from solar irradiation to reduce heat losses. In case of the ETICS, the reductions during heating seasons are constantly low, with the exception of South facing walls, whereas the TCW system presents a continuously high use of solar energy. The TCW presents higher solar gains than the ETICS, due to the utilisation of DSF's tendency to overheat to charge the thermal storage within the cavity. In summertime, both systems, TCW and ETICS, show considerably lower heat losses or even solar gains. However, the g-Value of the TCW with closed shading is below 0.02, which is hardly reachable in a dynamic environment. Furthermore, this is still one quarter of a traditional fully glazed Closed Cavity Façade (CCF) (Rudolf, 2015).

This paper has shown that even if the TCW U-Value is significantly higher, the transient energy simulation shows a high potential for solar thermal energy use to reduce energy losses of buildings at the façade level. The TCW construction tries to exploit the full potential of the used materials by using an unconventional redesign of a DSF system. In addition, the lower material usage leads to lower weight, which makes it feasible to be used as curtain wall system. However, the material properties have not yet been tuned to their limits.

To sum up, even if the system's potential is not yet fully revealed, the TCW's potential to contribute to the future energy challenges in the building sector is evident. Further investigations on shading control, material selection, optical, and radiative properties shall study additional enhancements of the system during each season.

The main SEBF project is still in progress. The first simplified laboratory tests on small-scale function models confirmed that the main simulation components are operating correctly. A 1:1 mock-up with a TCW parapet is currently being built to perform measurements and validate the simulation model. More detailed experiments to improve the SEBF / TCW system and the simulation model are planned in the future.

Acknowledgements

The authors gratefully acknowledge the funding provided by the Swiss National Science Foundation (SNF Grant No. IZCNZ0-174562) and support of the Lucerne University of Applied Sciences and Arts.

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