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Thermal Performance of Solar Facade Concepts Applying Selective and Transparent Insulation Functions: Preliminary Experimental Study

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***Abstract*— Recent scientific progress in the field of building science and building engineering deals with current challenges and future directions in buildings, sustainability and creation of healthy built environment. One of the major factors contributing to this issue is application of new advanced materials, concepts and technologies. Such approach can contribute to the development of new building materials and innovative building envelope concepts. Solar façade principles are adequate for relevant utilizing of solar energy technologies when designing sustainable energy sources in buildings. This study focuses on an experimental analysis of a proposed non-ventilated solar facade concept to integrate the need for this sustainable energy design approach for buildings. A new solar façade prototype based on transparent insulation material and a selective absorber is tested experimentally and contrasted with conventional insulation and a non-selective type of absorber, respectively. The presented study focuses on an experimental non-ventilated solar type of façade exposed to solar radiation both in the laboratory and in outdoor tests. Based on solar wall principles, the key intention is to monitor temperature response within proposed components at small scale level. Due to the high solar absorbance level of the façade, high- and low-emissivity contributions were primarily studied. All the implemented materials were contrasted from the thermal aspects point of view. Temperature response is monitored by means of a solar simulator whilst outdoor testing employs real solar radiation exposure. The main objective of this analysis resides on i. Monitoring of temperature response within proposed components; ii. Analyzing the thermal benefits of optical properties involved in components; iii. Measurements of a comparative nature with solar radiation incidence; iv. Experimental confrontation between laboratory and outdoor testing. The resultant temperature growth within proposed concepts was specifically analyzed. The maximum level of the measured temperatures in proposed concepts is more than 100°C, thus the solar radiation received and transferred into the thermal energy has appreciable extent. The results of the solar-based experiments show with small-scale experimental prototypes that high potential of solar energy may be involved when designing sustainable energy sources in buildings.**

Keywords*—Solar wall; Solar façade; Selective absorber; Transparent insulation material; Thermal performance; Solar simulator; Outdoor test

I. INTRODUCTION

Solar wall concepts are highly relevant as means of utilizing solar energy when designing sustainable energy sources for buildings to integrate the need for this sustainable energy design approach for buildings. In addition, the application of multi-functional and adaptive building envelopes has recently been put forward as a promising alternative within this strive for higher levels of sustainability in the built environment [1]. The development of advanced solar façade concepts with integration of progressive materials is becoming an increasingly complex issue. The key factor aims to implement a high degree of adaptiveness that can be achieved by means of self- adaption (progressive materials) or active control (smart systems). This is based on our recent knowledge in the field of solar energy [2] [3] and can be considered as a key point for progressive façade design approach supported by energy efficient management [4] and contemporary architecture aspects [5]. Basic attribute of the proposed concept origins principally in the use of renewable energy sources (e.g. solar radiation) exploitation of the potential of passive energy storage concepts in decreasing of energy demand in buildings. A new solar façade concept based on transparent insulation and a selective absorber is proposed at small-scale level, tested and contrasted experimentally with conventional insulation and a non-selective type of absorber, respectively. Short-term monitoring on simple based elements to demonstrate dynamic response of selective absorbers with the interaction of transparent insulation material is an initial step for understanding overall interactions influencing the heat transfer. It is important that the timescales of the time transient conditions to which a solar façade responds may vary from a few minutes or hours to diurnal and seasonal through to several years. This study deals with diurnal timescale and focuses on an experimental non-ventilated solar type of façade exposed to solar radiation both in the laboratory and in outdoor tests.

II. METHODOLOGICAL APPROACH

The key aspect of this contribution resides in investigating the thermodynamic time transient diurnal heat transfer applied in a proposed small-scale solar façade concept that is to be potentially implemented in future full-scale testing modes. Laboratory and outdoor, small-scale tests were conducted to analyze the thermal performance of the proposed components based on the solar wall principle.

The main objective of this study relies on monitoring of thermal performance and temperature response during solar simulator and real outdoor tests. The temperature response was monitored with the application of a solar simulator at the BCEE labs at Concordia University. Material parameters and the data obtained from outdoor testing were obtained at the AdMaS research Centre at Brno University of Technology.

For optical and thermal analysis, samples were prepared and spectral optical properties were measured (Table I.). The main difference between all tested samples was in their absorber part and the form of applied thermal insulation, for both the transparent and conventional type. A spectrally selective absorber and thermal insulation of the transparent type were used as a proposed base. Table II. shows all the measured materials applied for this study. Two types of absorbers were tested in combination with transparent insulation. One standard conventional sample of expanded polystyrene was used as a reference (Table III.).

TABLE I. SOLAR ABSORBER MATERIALS

Sample	Solar Absorber Types				
	Material	***Surf. shade***	***Color***	***ε_λ 0.3 – 2.5 μm***	***α_λ 0.3 – 2.5 μm***
S1	Standard synthetic paint	mat	black	0.94	0.96
S2	Spectrally selective material - TiNOx-Nano	mat	black	0.06	0.90

TABLE II. MEASURED MATERIALS

Sample	Material Parameters		
	Material	***Thickness [mm]***	***Bulk density [kg/m^3]***
M1	Gypsum board	12.5	653.70
M2	Transparent insulation	40.2	33.32
M3	Expanded polystyrene	38.2	14.11
M4	Float glass	6.0	1331.69
nvAG	non-ventilated air gap	12.0	-

TABLE III. MEASURED COMPOSITIONS

Composition	Composition Parameters			
	Composition (from exterior side)	***Equivalent thermal conductivity at 20°C [W/(m*K)]***	***Equivalent thermal resist. at 20°C [(m^2*K)/W]***	***Thickness [mm]***
A	M4 + M2 + nvAG+ S2 + 2x M1	0.088	0.862	84.4
B	M3 + nvAG + 2x M1	0.065	1.116	76.8
C	M4 + M2 + nvAG + S1 + 2x M1	0.126	0.620	84.4

III. SOLAR SIMULATOR TESTING

The Solar Simulator measurement apparatus at the Environmental Chamber Lab at Concordia University [26] was utilized for testing. A 0.762 m x 1.219 m insulated model fitted with solar façade prototypes (Fig. 1) was built, using the TIM but with a different solar absorber type. It was tested in the solar simulator under high irradiation with an ambient room temperature that was maintained at a roughly constant 22 ºC. The irradiated proposed model transfers thermal energy, which is measured along with surface and material interface temperatures. Because the only difference between the two setups is the addition of a low emissivity type of absorber on the solar absorber side, their influence can be directly evaluated. However, heat transfer through all adjacent parts plays an important role as well. Due to the high solar absorbance level of the façade, high- and low-emissivity contributions were primarily analyzed. All of the implemented materials were contrasted from the thermal point of view.

The main objective of this analysis was based on:

- The short-term monitoring of temperature response within the proposed components,
- Analyzing the thermal benefits of the optical properties of components,
- Measurements of a comparative nature taken during exposure to solar radiation.

The main difference between the tested components lay in the modifications to their absorber surface located behind the transparent insulation (Table III.). As mentioned above, two samples (A and C) were composed with regard to optical properties analyzed behind the transparent insulation material (TIM), while one sample (B) was based on conventional insulation (expanded polystyrene), though it also was constructed in the manner used in non-ventilated façades, meaning that it included an air gap layer. Each sample contains 25 mm thick gypsum board because it is assumed to act as a simple provider of heat storage. Finally, the samples with TIM differ in the application of two materials with the analyzed optical properties. Both have almost the same solar absorbance

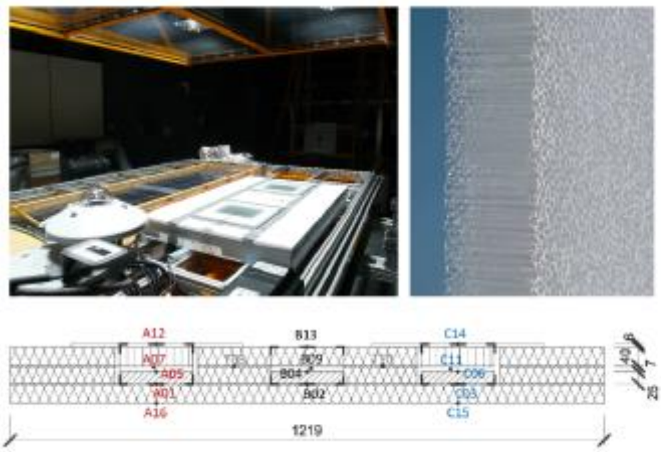

Fig. 1. Test setup exposed by solar simulator, transparent insulation material, test setup model and its sensor positioning, thermocouples (TC)

(around 0.90 and 0.96), whilst their emissivities vary widely, being 0.06 and 0.94 respectively (Table I.).

A. *Methodological Approach*

The measurements were carried out for three different cases and the duration of each measurement was measured until temperatures stabilized at a steady state. The resultant temperature growth within the measured samples was analyzed. The laboratory temperature was maintained at 22°C. Solar performance reached around 1000 W/m^2, where uniformity is within 5% or less, depending on the collector area. The solar simulator is equipped with special glass filters and metal halide lamps (MHG). The MHG lamp field provides a spectral distribution which is very close to that of natural sunlight. A Ventilation Unit (blower) is mounted at the bottom of the test platform, which blows grazing airflow parallel to the sample surface to simulate parallel wind conditions (up to 4m/s). In order to eliminate long wave infrared irradiation emitted by the hot lamps, an artificial sky is positioned in front of the main lamp field. The artificial sky consists of two panes of low iron glass with an antireflective coating that create a cavity within which cold air (10°C) is circulated in a closed loop and cooled by a heat exchanger. The installation of the artificial sky is necessary to simulate the radiant loss from the hot sample surface to the cold glass panes. This apparatus and the methods by which it is used comply with the specifications of EN12975:2006 and ISO9806-1:1994.

Three different cases were tested to demonstrate the thermodynamic performance of the analyzed model in terms of standardized and non-standardized procedures. Case c_1 is a non-standard mode in which the artificial sky is not used, while c_2 is a non-standardized mode featuring sky activation but no ventilation. Case c_3 sees the application of both the sky and ventilation based on an air velocity of 2m/s parallel to the sample. For the two first cases, the thermodynamic performance is analyzed in an exploratory manner at a non-standardized level of solar collector testing in order to investigate the maximum level of sample overheating, whilst the third case demonstrates the standardized procedure involving the application of both the artificial sky and ventilation.

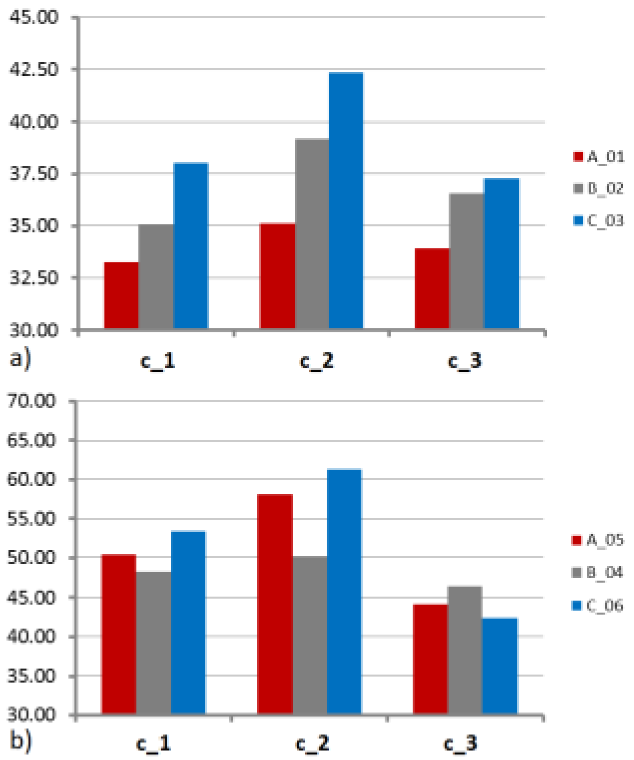

Fig. 2. *Averaged temperature values; a) Temperature of absorber surface (°C); b) Temperature behind gypsum board (°C).*

Temperatures are measured by 16 thermocouples (Type T, NBS special limits of errors, 30 AWG). Fig. 1 displays the measurement model with all sensor locations. The total temperature progression is monitored for each position in relation to the proposed components, though two material interfaces are primarily analyzed.

B. *Measurement Results*

Although several positions were measured, the surface absorber temperatures and those located behind the gypsum boards are presented and analyzed in detail here. Fig. 2 shows

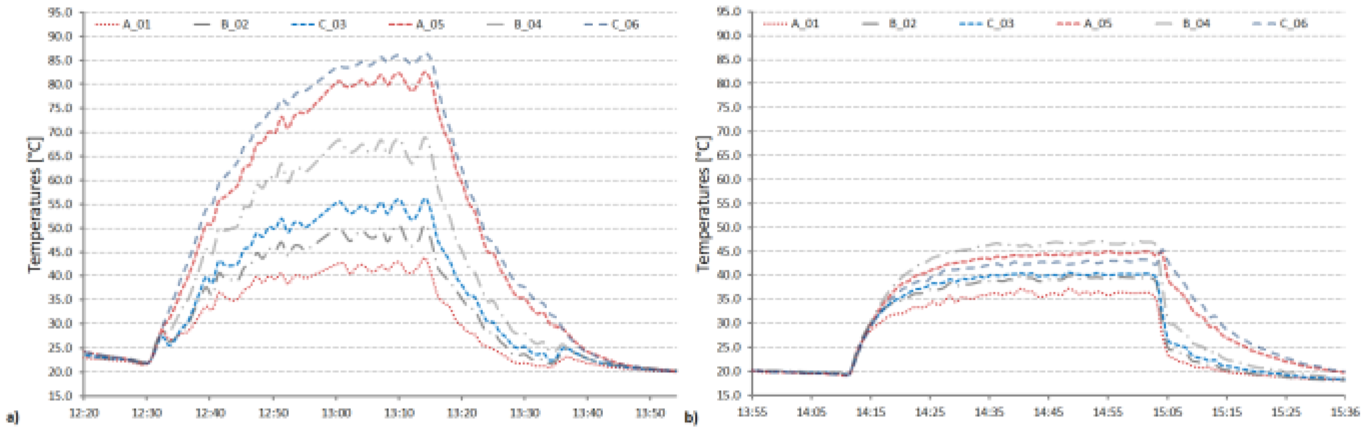

Fig. 3. Temperatures behind gypsum board and absorber surface temperatures; a) c_1 test case; b) c_3 test case.

Fig. 4. Small-scale outdoor measurements a) Test setup; Whole day b) summer and c) winter measurement

the averaged temperatures monitored during all tested cases for each component. The first two cases, c_1 and c_2, show almost the same differences between all tested samples, with the only variety occurring in the level of the maximum peak, which lies at around 80°C (Fig. 3). Looking at the surface temperatures of both absorbers, selective A and non-selective C, there is very small variety: in case c_3 it is more than +2K, whilst without fan operation it is almost -5K. The temperature response behind the absorber becomes most significant when a low-e absorber is used in comparison with a standard black painted absorber; it means a nearly +5K difference in the case of c_3; however, in the non-ventilated cases, the difference ranged from +10K to almost +15K, with the results for the conventional insulation component B lying somewhere in the middle. This aspect, as well as the highly significant temperature increase, is primarily caused by the overheating of the whole model, where heat is additionally transferred through the thermal insulation of the model. In addition, the effect of a certain level of expanded polystyrene translucency is evident, thus the use of unmodified or not plastered thermal expanded polystyrene for such experimental models is not so appropriate.

IV. Small-Scale Outdoor Testing

The proposed apparatus was additionally used to contrast measurements obtained from the solar simulator and outdoor testing, both at the small-scale level. The only difference is that one whole proposed model integrating all the elements underwent solar simulator testing, whilst in the outdoor tests both assembled concepts (not including the conventional type) were tested separately. The test scheme and experimental setup are shown in Fig. 4, both summer and winter clear sky conditions were tested respectively.

A. Methodical Approach

The measurements were carried out during real outdoor solar radiation exploitation for summer and winter case. Identical A and C samples were fabricated, placed into the test boxes and exposed to the outdoor climate. One reference case and a second comparative case were measured. Again, the only difference between both boxes was in terms of the absorber used, with non-selective black paint S1 and selective material S2 being contrasted. All of the materials are based on Table 2. Six measurement points are monitored and finally analyzed in the results section. The interpretation of all given measurement points presented in Fig.4 is: *ai* represents the air temperature of the non-ventilated air gap, *si* is the surface absorber temperature, *bl/bsel* corresponds to the material interface between the absorber and the heat accumulation layer (for this study it is gypsum board), *sd* is the temperature behind the gypsum board, *in* represents the temperature inside the box and *PYR* is the solar radiation intensity obtained by the photodiode and pyranometer sensor.

B. Measurement Results

The total temperature progression is monitored for a period of one whole clear summer and winter day. The results are presented in Fig. 5, both for a summer and the winter of the clear sky day respectively.

For summer period, not surprisingly, the maximum level of the measured temperatures is more than 100°C, thus the solar radiation received and transferred into the thermal energy has huge risk of overheating. Here the difference between the non-selective and selective absorber is approximately 2.5K at the maximum peak. This basically corresponds to the measurements obtained for case c_3 during solar simulator testing. The maximum temperature level is different, however. Results presented in Fig. 5a demonstrate temperature increasing during the day, while on the other hand Fig. 5b its dropping. When contrasting the temperature response invoked by solar radiation, based on presented solar experimental model, no significant effect is observed. A difference of up to 3.0 K is principally reached at the maximum obtained temperature level.

For winter period, the maximum level of the measured temperatures is up to 60°C, thus the solar radiation received and transferred into the thermal energy has crucial potential. Here the difference between the non-selective and selective absorber is more significant, approximately 5K at the maximum peak. In addition, the temperatures behind gypsum boards are in more difference. This means that it is even up to 10K. Results presented in Fig. 5c demonstrate temperature increasing during the sunny winter day, while on the other hand Fig. 5d its cooling phase.

The overall results of the laboratory, solar simulator and small-scale outdoor testing is planned to be applied in the measurement of full-scale outdoor thermodynamic performance.

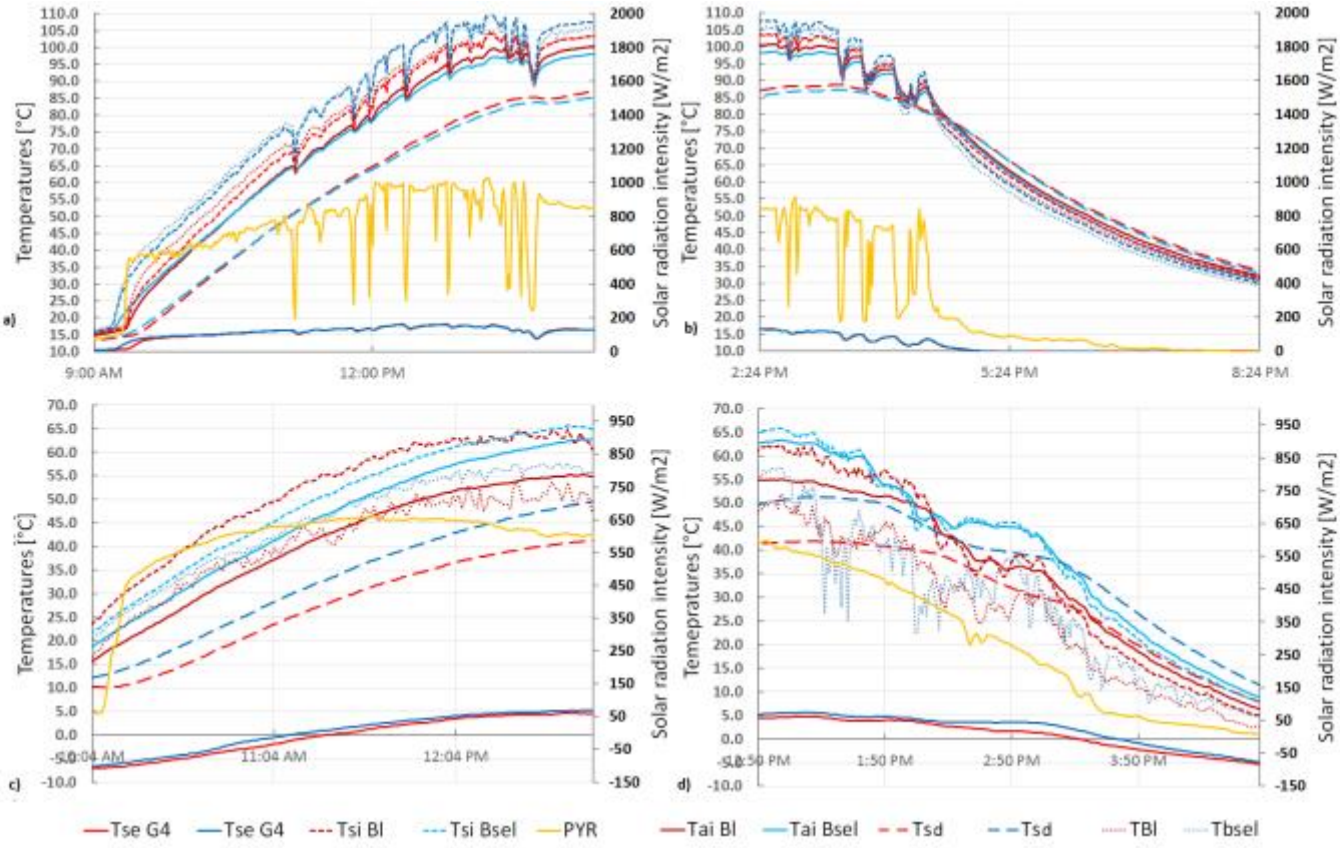

Fig. 5. Results tkaen during small-scale outdoor measurements; a) b) clear summer and c) d) clear winter easurement

V. Conclusion

The paper presents the results of an experimental analysis of a proposed non-ventilated small-scale solar prototype. Selective absorber and transparent insulation materials are implemented for this study. Based on the detailed observation of all the experimental procedures involved, it is demonstrated that from the thermal point of view, the selective absorbent properties could improve thermal performance significantly compared to concepts using high emissivity absorbers, especially for winter periods. At the laboratory, solar simulator and outdoor summer level, the lower tendency was demonstrated. From the thermal resistance point of view, the proposed concept implementing transparent insulation and a selective absorber provides comparable performance to conventional thermal insulation. On the other hand, when contrasting the temperature response invoked by solar radiation, based on solar experimental models, no significant effect is observed. A difference of up to 3.0 K is principally reached at the maximum obtained temperature level.

Further research will be focused on numerical modelling as well as the application of the described concepts in full-scale mode tested outdoors via year-round testing, where heating periods are supposed to be more relevant. Based on this study, it is planned that other functions will be implemented, such as transparent selectivity, and at the heat storage level of the base of PCMs for eliminating of overheating risk in summer periods.

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