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The effect of changing surface emissivity on the natural ventilation rate of a narrow air cavity integrated in a transparent insulation façade

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Abstract. A transparent insulation material (TIM) can be incorporated in a building element in order to improve its thermal performance, including solar heat gain. However, some overheating protection needs to be implemented. The provision of natural ventilation in a façade cavity to avoid overheating, along with other potential techniques, could require a completely different approach to TIM integration in solar façade concepts. This paper concerns an analysis of the effect of different absorber emissivity behind a transparent insulation system. The emissivity changes are primarily studied in order to determine their effects on the overall radiation - natural convection heat transfer through a narrow façade air cavity. A comparative investigation was conducted using experimental full-scale dynamic outdoor tests and the building energy simulation (BES) approach. The thermodynamic response affected by the radiation - natural convection transfer is identified, specifically during the summer peak period, that corresponds to overheating. Depending on the ventilation regime, a low emissivity solar absorber inside a narrow air façade cavity may increase the cooling energy load and temperature response of a façade by 25 and 36%, respectively, in comparison with a high emissivity absorber. When the emissivity of the zone inside the cavity was changed, significant limitations were identified in the BES calculation methods for both vented and unvented cases.

1. Introduction

The improved thermal performance offered by incorporating low emissivity functionalities into building materials can basically influence the overall thermal efficiency of building components. The effect that changing the emissivity can have is typically exploited in the design of solar cavity receivers. A numerical study simulating the thermal performance of a solar cavity receiver with different absorber emissivities was conducted in [1]. The results showed that the thermal efficiency increases and total heat loss decreases with increasing absorber tube emissivity. However, the increase in thermal efficiency is only about 1.6% when the emissivity varies from 0.2 to 0.8. The change in absorber emissivity has a slight effect on the thermal performance of the receiver. Therefore, in order to absorb more solar energy so as to achieve high thermal efficiency, the layer of coating applied to the surface of absorber tubes should have a solar absorptivity which is as high as possible, but its emissivity is not an important factor. In addition, the reason for the decrease in total heat loss was also carefully analyzed. It was found that the temperature reduction of the cavity walls causes the decrease in radiative and convective heat losses. An integrated simulation approach was employed to quantify the influence of surface optical and radiative properties on the thermal performance of a typical solar cavity receiver. It was found that the thermal efficiency of a receiver with two selective coatings was respectively enhanced by 12.5% and 7.8% compared with that of a non-selective receiver [2]. In a similar way [3], a parametric study was conducted to quantify the potential efficiency gain that may



result from spectral selectivity with the solar absorption and infrared emissivity of a central receiver solar concentrating system. It was shown that spectral selectivity may result in an increase in overall solar power plant efficiency of about 6% (or 28% in relative value) compared with conventional systems.

The integration of low emissivity functionalities may also achieve a significant improvement in building envelope performance. In particular, a reduction of ~18% in the equivalent conductivity can be achieved in hollow bricks [4]. Surface radiation modifies flow and temperature fields. The modification starts at low surface emissivity and increases gradually with it. The distribution of heat flux by conduction and natural convection is affected by surface radiation; the heat flux is an increasing function of the surface emissivity, as a result of which heat fluxes due to natural convection and conduction decrease with the surface emissivity [5]. At the building component scale, it has already been demonstrated that a transparent insulation façade component with a low emissivity absorber and effective solar layers provides the same thermal performance as conventional types of thermal insulation [6]. However, at the building envelope scale, there can be a significant effect on the maximum cooling energy load [7]. Another related aspect is when a low emissivity effect needs to be adequately calculated based on the proper performance prediction models of available building energy simulation (BES) tools [8]. Significant limitations were found in BES specifically concerning the surface radiant heat exchange when a low emissivity surface affects the enclosed zone of an air cavity [7]. In this relation and based on previous authors' studies [6] [7], the additional aim of this paper to identify the effect of changing emissivity on the natural ventilation aspect of a narrow air cavity and the overall heat transfer with two integrated solar absorbers.

2. Materials and methods

Two transparent insulation façade (TIF) models were analyzed in order to provide an analysis of the effect of changing the emissivity of absorbers placed behind a transparent insulation system. Results based on building performance prediction models are provided in order to identify the limitations of simulations conducted on vented and unvented effects in the vicinity of the low emissivity surface of a façade air cavity zone.

2.1. Experimental models and tests

Two test models (Figure 1a) were developed using a system based on the Kapipane TIM and were fitted with honeycomb transparent (also may be considered as light translucent) PMMA-based insulation. Each was equipped with a different type of integrated solar absorber (a selective low-e $e0.05$ and a nonselective $e0.95$ solar absorber). Thus, the absorber used was the main difference between both prototypes. Both had practically the same solar absorbance level (around 0.94 and 0.96, respectively), whilst their emissivities were diametrically opposite: 0.05 and 0.95, respectively. The difference in thermal performance between the various emissivities is up to 18% due to the different solar absorbers.

Both models were subsequently tested outdoors throughout the heating and cooling seasons. The TIM system comprises a low-e insulating glazing unit that incorporates honeycomb transparent insulation with a krypton-filled cavity. As shown in Figure 1, this model enables a natural ventilation regime to be used, and thus it was activated for this study.

The evaluated TIF models utilize the commercially available TIM Kapilux TWD system, which comprises transparent honeycomb plastics (PMMA) enclosed by glazing within a structure filled with krypton gas. There is an air cavity with optional ventilation between the TIM system and the solar absorber with either a selective $e0.05$ or non-selective $e0.95$ coating. Hence, the key variable in both models is the different emissivity of their thermal absorbing parts. The air cavity is the key element for this study, where the main focus is intended to be on the effect of changing emissivity on the natural ventilation and velocity of a narrow air cavity. This model utilizes a porous material (gypsum board of 25 mm thickness) as the base layer for the integration of the solar absorber. Temperatures were measured using Pt100 sensors (Type CRZ 2005-100, class A, tolerance $0.15+0.002t$). The solar radiation rate was measured by BPW 34 silicon pin photodiodes placed on the absorber plate inside the air cavity layer to measure solar radiation penetrating the TIM glazing unit. The velocity in the air

cavity was measured with an AHLBORN FVAD35TH4 device at a resolution of 0.01 m/s and an accuracy of 0.05 m/s.

A twin-box measurement apparatus was used to identify and compare the amount of heat transferred through the measured building elements. Dynamic outdoor tests were performed based on the guarded hot box method. This involves the use of two identical metering boxes to compare the thermodynamic performance of tested experimental models [9]. It allows the measurement of heat flows and other thermophysical parameters of tested samples, which are directly exposed to outdoor conditions. The second illustration presents a functional scheme of two identical boxes surrounded by a compensation room in which both samples (reference ($e0.95$) and experimental ($e0.05$)) were installed facing south-east at the Central Lab at the Faculty of Civil Engineering at the Slovak University of Technology (48°10'36" north and 17° 10'32" east).

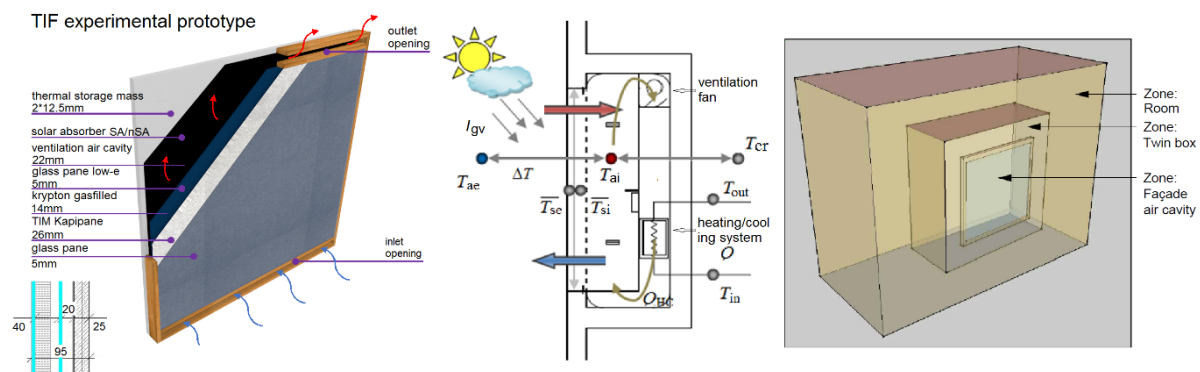


Figure 1. The tested transparent insulation façade (TIF). (a) Experimental TIF model, (b) Scheme of the experimental twin-box apparatus, (c) The BES simulation model

2.2. Building performance prediction models

The simulation model (Figure 1) was modelled based on experimental measurements in the BES tool that works under the EnergyPlus dynamic simulation engine. When the structure of a building has different optical surface properties, it is necessary for radiation and convection heat transfer phenomena to be investigated in detail. This should be ensured by the application of a proper mathematical model which takes surface emissivity into account. The overall heat transfer in the cavity within the studied models is based on internal zone heat transfer principles, i.e. it occurs via transmitted solar radiation, longwave radiation reflected from the internal surface and zone interior convection. Internal longwave radiation exchange is calculated in EnergyPlus according to the grey interchange model along with the exchange coefficient “*ScriptF*” [10], which is based on the assumptions and limitations of the grey surface property (surface emissivity is equal to its absorptivity) and diffuse radiation.

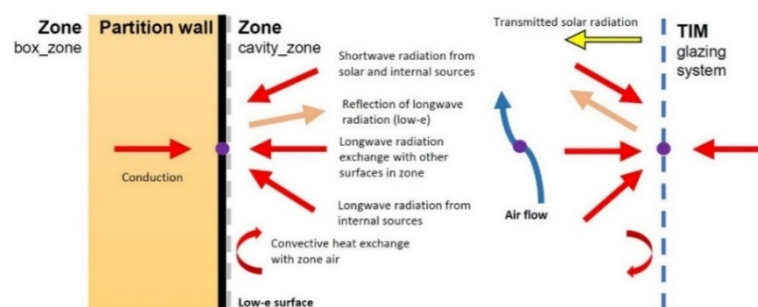


Figure 2. Internal heat balance of the façade air cavity

The transmission of solar radiation into the zone is ensured by the solar distribution function “*Full Interior and Exterior*”, where the zone should be convex. Interior convection flux to the zone air is

based on the inside convection coefficient (h_c), which can be calculated using different modelling methods. In the presented case, the calculation of h_c was adjusted specially for a narrow sealed vertical cavity using the “*TrombeWall*” algorithm in accordance with ISO 15099 [11]. The low-e surfaces inside a zone represent a special challenge for BES programmes and are not taken into computational consideration in all partial structures. In the case of the heat exchange in a cavity with natural air flow movement (Figure 2), the low emissivity surface is intended to act as a reflector for long-wave thermal radiation with increasing air temperature.

3. Experimental results

Two test scenarios were measured by varying the activation of natural ventilation in the façade air cavity in front of the solar absorber plates of two different experimental models. Both of the models were tested in the same natural ventilation mode. The first test scenario represents an unvented case, which means both openings of the façade cavity were closed, while the second demonstrates a vented case with the inlet and outlet openings both opened. This means that both the unvented and the vented test cases were tested. The two tests were conducted during the cooling season over three representative days at a time when overheating was a potential issue. The experimental results were obtained under outdoor conditions where the maximum sun height above the horizon (around 60°) was at midday. This corresponds to a 60° incline from the normal angle of incidence representing the maximum solar incidence (I_{gv}) at the tested location. The testing period was thus specified for the thermal performance analysis of the dynamic solar thermal response regarding the overheating aspect and the maximum solar heat gain achieved. Overall, the outdoor ambient temperature (T_{ae}) varied from a nocturnal $+12.1^\circ\text{C}$ up to a diurnal $+33.5^\circ\text{C}$. The incident solar radiation rate (I_{gv}) reached a maximum of 650 W/m^2 in the area where the samples were measured during totally clear sky conditions. The data presented in the graph (Figure 3) show the real measured values for both the unvented and the vented test case. The difference in the heat flow measured representing the maximum cooling energy load of the $e0.05$ compared to the reference $e0.95$ experimental model is shown. There is a difference in the heat flow peaks of roughly up to 25 W for the unvented case and up to even 40 W for the vented case. With regard to the natural ventilation effect, a difference of 15% to 25% was measured in the maximum cooling energy load when the ventilation was activated (Figure 3(b)), while with no ventilation it was only about 10% (Figure 3(a)). This means that depending on the activation of natural ventilation, a more effective reduction in the maximum cooling energy load can be achieved by a combination of both the activation of natural ventilation and the use of a high emissivity solar absorber. In contrast, the solar thermal conversion process in the vicinity of the low emissivity solar absorber is more significantly affected.

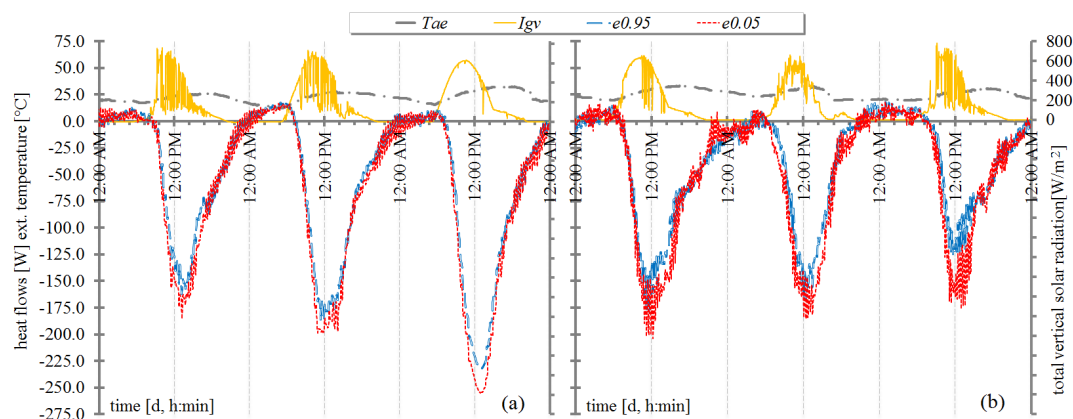


Figure 3. The data measured for heat flows, the ambient air temperature and the total vertical solar radiation for (a) the unvented test case; (b) the vented test case.

While the solar absorption parameters of both models are practically the same, the emissivity changes had a key effect on the test results combined with the natural ventilation mode. The absorber

temperature in the unvented test case reached practically the same value of up to 65°C. This corresponds to the maximum cooling load measured. When the natural ventilation was activated for the vented test case, the absorber temperature reached a maximum of approximately 53°C, which is a roughly 12 K difference between both tested scenarios. The difference between both solar absorbers is around 2.5K. The effect of natural convection heat transfer combined with high emissivity solar absorber $e0.95$ can decrease façade air cavity temperature compared to the $e0.05$.

4. Simulation results

The simulation of the above described models using BES programmes is a challenge. Basically, the modelling approach of installing TIF samples in a Twin-box apparatus involves three main zones, where the TIF sample itself is divided into two zones. The zoning scheme is based on the creation of a naturally ventilated air cavity between the absorber and the inner glass pane. The overall thermodynamic analysis is performed after the model has been calibrated according to the experimental measurements from the $e0.95$ model. The performance predictions for the maximum cooling energy load and the air flow movement in the cavity were observed and compared with the experimental data. The reference $e0.95$ case indicates good agreement, while the $e0.05$ model has lower peak values for the simulation results, the simulated $e0.95$ model is adequate for modelling and simulating thermodynamic response, and demonstrates good agreement between both of the results obtained (Figure 4). However, the simulated $e0.05$ model does not correspond to the measured progressions that are identified specifically at the maximum peaks. Instead, it responds in the opposite manner than was measured. This leads to the fundamental obstruction of the BES calculation concerning the radiation exchange between surfaces with low-emissivity (view factors). As result, the BES approach employed for calculation appears to have significant limitations specifically with surface radiant heat exchange mainly during high rates of impinging solar radiation. Due to this, the effect of the change in emissivity on the surface heat balance in the vicinity of narrow air cavity zones in the overall computation process based on the one-dimensional heat transfer method is not adequately considered.

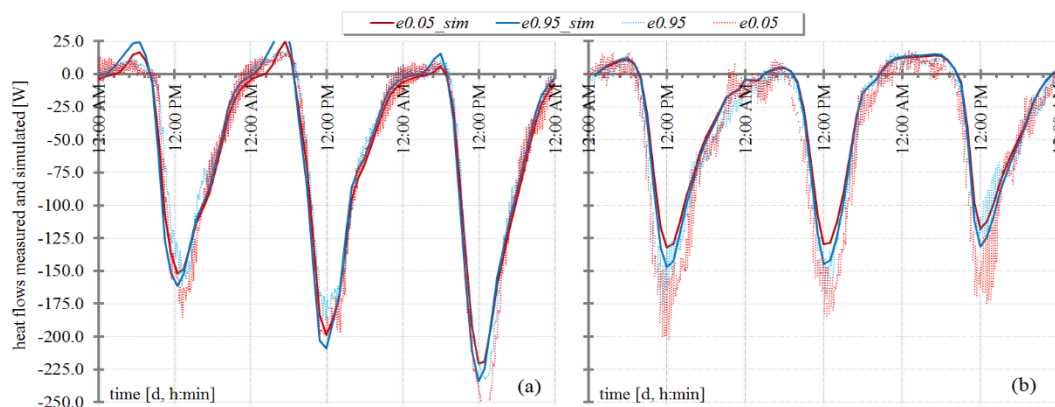


Figure 4. The data obtained experimentally and computationally for heat flows for (a) the unvented test case; (b) the vented test case.

The velocity in the air cavity of each sample was specifically monitored to identify a key aspect of the natural ventilation rate. The air velocity rates (Figure 5) reached a maximum of approximately 0.6 m/s ($e0.05$) and 0.45 m/s ($e0.95$) at the maximum peak when the vented case was tested, while with no ventilation almost the same rates were monitored; the difference is up to 0.025m/s. Different emissivity values have a significant effect on the air velocity and its total rates, though there is almost no effect on the simulated rates. Again, the overall calculation procedure does not consider the influence of the change in emissivity or adequate air flow distribution on the change in air velocity with different surface emissivity values.

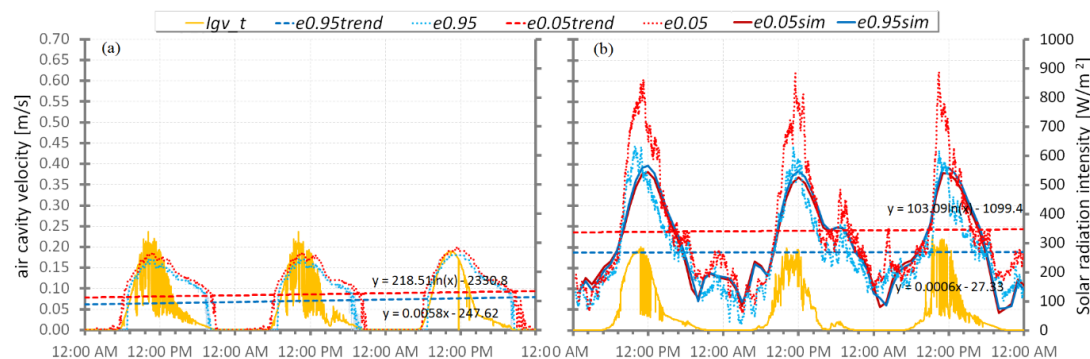


Figure 5. The data obtained experimentally and computationally for air velocity rates and the transmitted solar radiation incidence rates for (a) the unvented test case; (b) the vented test case.

5. Conclusions

The aim of the study was to identify the effect of changing absorber emissivity on the natural ventilation rate of a narrow air cavity integrated in a transparent insulation façade, both during experiments and during building energy simulation (BES). The dynamic outdoor tests show that with a full-scale experimental model, a significant difference is measured with the change in surface emissivity affecting both the enclosed and the opened zone of an air cavity in a transparent insulation façade with the same ventilation regime. Although the low emissivity of the narrow façade air cavity can increase thermal properties by up to 30% compared to standard high emissivity solar absorbers, the highest achieved difference in thermal response was approx. 20% during the tested scenarios (in favour of the high emissivity solar absorber). In other words, Depending on the ventilation regime, a low emissivity solar absorber inside a narrow air façade cavity may increase the cooling energy load and temperature response of a façade by 25 and 36%, respectively, in comparison with a high emissivity absorber. Furthermore, the effect on the air velocity rates affecting the convection heat transfer across the cavity was experimentally demonstrated. However, in the case of the BES, a significant discrepancy was identified between the measured and calculated parameters of the overall heat transfer and air velocity rates through the investigated models with a low emissivity absorber. This is primarily caused by the limitations of the used BES tool, which are specifically connected with surface radiant heat exchange. These predominantly apply to low emissivity surfaces integrated in a narrow façade air cavity zone.

Acknowledgments

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