EXPERIMENTAL VERIFICATION AND PERFORMANCE EVALUATION OF AN INNOVATIVE FACADE DURING THE SUMMER PERIOD

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Abstract

This paper presents the results of experimental measurements carried out at a Twin Rooms facility under real climatic conditions during the summer period. Based on previous research, two facade prototypes were created. We investigated a simple facade and an innovative double skin facade, which uses solar energy in several stages by transforming short-wave solar radiation into long-wave heat in the cavity of the double transparent facade and using the photovoltaic transformation of short-wave solar radiation into electrical energy. The aim of the measurements is to verify the functionality of the aerodynamics of the narrow cavity, evaluate energy flows through the facade, and assess the efficiency of systems related to solar radiation. The results correlate well with assumptions.

Keywords

Innovative facade, double skin facade, experimental facility, test cells, real climatic conditions

1 INTRODUCTION

In order to meet the sustainability goals set for the building construction sector, it is necessary to continue with the development of new construction concepts, technologies and materials that can further improve the energy efficiency of buildings and, at the same time, increase the comfort of the buildings' occupants. Adaptive building envelopes have the ability to significantly reduce the energy consumption of buildings [1] while simultaneously improving the quality level of the indoor environment [2]. The double skin facade (DSF) is a modern architectural element of the building envelope. It is able to minimise the energy efficiency of buildings while providing a pleasant indoor environment, daylight, sound and wind protection, and both aesthetic and structural advantages. When functioning correctly, a double transparent facade should ensure significant energy savings during the entire period of use compared to a classic simple facade. A properly designed and dimensioned double transparent facade can reduce the energy load of the indoor environment (from solar radiation) by 90–95% in the summer [3]. Such a climate-adaptive facade dynamically reacts to changes in the parameters of the external climate (dynamic shading systems, closing the space between the elements of the double facade, etc.) and thus optimises energy flows through its construction. Renewable energy sources, primarily solar radiation, are utilised by all available systems: passive (direct, indirect, isolated, convective circuits, physical cavity), active (photovoltaic panels, solar collectors) and hybrid.

The role of shading devices in the cavity of the double transparent facade is to perform the thermal regulation of the cavity, which is mainly to protect the interior spaces from excessive energy gains from solar radiation [4], [5]. Shading devices are a relatively large source of local aerodynamic resistance, which can increase the total aerodynamic resistance of the cavity of the DSF to such an extent that it will be greater than the force of convective buoyancy of the air in the cavity, meaning that the desired air flow will not occur when there is no wind. In addition to the air flow, the optical properties of transparent structural elements can also affect the temperature increase in the cavity due to the heat absorbed in the shading devices [6], [7]. A state-of-the-art overview of the various systems and components of adaptive building envelopes was created by Loonen et al. [8]. Among the wide range of technological options, switchable glazing [9], movable solar shading [10], phase change materials integrated into walls [11], dynamic insulation [12] and multifunctional facades are identified as the most promising [13]. However, studies show that there is wide room for further improvements [8], [14].

Research in the field of double transparent facades is ongoing at the Department of Building Construction, where a new design was created for an innovative modular element climate-adaptive transparent facade. The new innovative facade is designed with integrated elements whose structural and physical nature allows them to

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respond to changes in the external climate, use available ecologically clean and renewable energy sources, and optimize energy flows through their structures with a favourable effect on the physical-energy quantification of buildings. This facade design is verified by calculations and CFD simulations. Thanks to cooperation with external companies, two prototypes were produced according to the designs, which are being investigated at an experimental facility called Twin Rooms (test cells).

2 METHODOLOGY

The structural module of the investigated innovative facade (Fig. 1) has dimensions of 2300 × 3360 mm and is formed by a double transparent facade with a narrow cavity that is 280 mm wide. The facade construction is designed to employ the Schüco aluminium modular system with a thermal bridge break, with three levels of functional seals, and with controlled drainage of rainwater and condensation in each segment of the facade blocks.

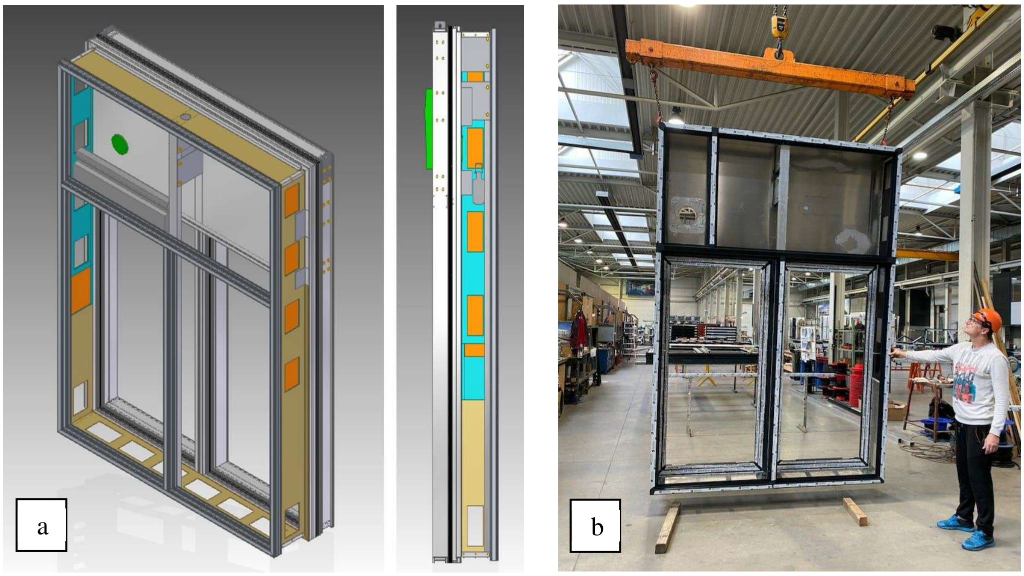

Fig. 1 Model of the innovative facade, a – 3D model, b – prototype during production.

The load-bearing static part of the facade element consists of three vertical aluminium columns and three horizontal crossbars (two peripheral crossbars with the function of a gap and one in the middle separating the element's transparent and parapet non-transparent filling). This construction creates a supporting grid for the DSF facade element in its inner part (skin). In the lower window section of the element, the inner part consists of two windows with an integrated wing. The windows are glazed with AGC Glass Thermobel TG Top triple glazing units with high physical quantification (heat transfer coefficient U_g = 0.6 W/(m^2·K), total solar radiation transmittance g = 53%, light transmittance T_L = 75%, air soundproofing index R_w = 35 dB). The upper, opaque parapet part of the inner part of the facade element is closed with a galvanized steel sheet, behind which there is a heat-insulating element made of mineral wool (75 kg/m^3).

The outer part of the facade in its lower window section is made of simple clear glass, while in the opaque parapet part, VSG/TVG 4.4.4 photovoltaic glass is used (2x TVG 4 mm low-iron, 60 cells polycrystal (156 × 156 mm), nominal power 230 Wp, nominal voltage 32.04 V, nominal current 7.2 A, module transparency 12%). The glass is installed in aluminium frame profiles.

The inner and outer part of the double skin transparent facade are connected to each other by means of steel brackets, and the narrow cavity of the element is closed on the sides by a steel sheet. The air supply to the double transparent facade is provided through the lower contact joint of the elements, which has six openings of dimensions 150 × 250 mm, and through the side contact joints in their lower levels, which have two openings of dimensions 150 × 250 mm, i.e., a total of eight openings. The air outlet from the double skin transparent part is built into the lateral contact joints of the elements in their upper levels, with eight openings of dimensions 150 × 250 mm being provided. The air outlet openings can be closed mechanically. The air supply and outlet openings are equipped with a net to prevent ingress by birds and insects. In the cavity of the double skin transparent facade, automatic mobile shading blinds give protection against bright sunlight.

In the summer season, short-wave solar radiation is transformed into long-wave thermal radiation in the cavity of the naturally ventilated double skin transparent facade under the effect of solar radiation and activated sun

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protection. The resulting heat, which is secondarily absorbed by the air in the cavity, is released from the cavity by natural aerodynamics, which significantly reduces the thermal load of the building in the summer and thus also the energy requirements for its cooling. The energy efficiency of a properly designed and operated double skin transparent facade in the summer is between 85 and 95%.

The use of a DSF allows natural ventilation of the core of the building through open windows from their cavity during a limited time period (approx. 50 to 55% of the year). In the remaining time interval, due to the climatic conditions in the cavity (high temperatures in summer with intense sunlight, aerodynamic discomfort at high wind speeds, etc.), natural ventilation through windows from the cavity is not recommended, and therefore it is necessary to provide forced ventilation of the building core at this time. In an effort to eliminate this handicap and increase the efficiency of the naturally ventilated DSF in the winter, we decided to integrate a facade ventilation recuperation unit into the inner shell, which in the summer will draw in fresh air directly from the outside climate through the contact joint between the elements, and in the winter will use preheated air from the cavity of the DSF.

The new innovative double skin facade is compared with a simple facade that has the same geometric and physical parameters as the inner wall part of the DSF.

Experimental verification

Two prototypes of the facade were placed in the Twin Rooms experimental facility at the end of 2021. During the following months, finishing work was carried out (installation of PV panels, location of measuring devices, interior modifications, etc.). In March 2023, the equipment was put into test operation, based on which the measurement devices were debugged, and control software was developed to display the current state of the whole system. This article summarises the results obtained after debugging took place, and therefore from the measurements taken in the summer period.

The facility for the experimental measurement of facade fragments, the Twin Rooms test cells – Fig. 2, are located on the premises of the Slovak University of Technology's Central Laboratories in the Trnávka district of Bratislava. The advantage of test cells is that they provide a well-controlled, realistic, unoccupied room (cell) environment [15]. The Twin Rooms test cells are used to determine thermal properties (U-value, thermal resistance, surface temperatures, temperature fields) and energy flows through facade elements throughout the range of real climatic conditions. The technical equipment installed at the Twin Rooms ensures controllable, stable, homogeneous, and repeatable internal temperature conditions are present in the two measuring cells and in the compensation room. This makes it possible to perform measurements of heat balances, total and local heat flows as well as surface temperatures simultaneously on two tested structures installed in measuring holes under the influence of non-stationary external climatic conditions.

Fig. 2 A view of the facades installed at the Twin Rooms experimental facility (a simple facade installed on the left side, with the same geometric and physical parameters as the inner wall of the double skin facade and an innovative double skin transparent facade installed on the right side), a – the facades in the summer period, b – the facades in the winter period.

Physical quantities, measurement techniques and equipment

In order to evaluate the local thermo-technical parameters of the measured structures, it is necessary to measure local heat flows using heat flux sensors, surface temperatures on the outside and inside of the structure using Pt100 sensors, flow velocities along the measured structures, air pressure differences on the outside and inside of the structure, and the intensity of solar radiation on the vertical surface of the outer part. All of the measured quantities will be continuously recorded by the Data Acquisition Systems (DAQ) at 5-minute intervals. The temperature, aerodynamic and energy regime of the measured double skin transparent facade with a narrow cavity is determined from the measured physical quantities during a long-term in-situ experiment.

A summary of all the measured quantities is presented in Tab. 1, alongside the measuring equipment used and their specific types. Fig. 3 and Fig. 4 show the measuring equipment installed in the test cells.

Tab. 1 Summary of measured quantities and measuring devices [16].

	Measured quantity	**Equipment**	**Specific type**
PT	Air temperature in the narrow cavity	Pt 100	CRZ-2005-100-A-1-Ni
PT	Element surface temperature	Pt 100	CRZ-2005-100-A-1-Ni
-	Temperature in the heat recovery unit	Pt 100	CRZ-2005-100-A-1-Ni
GT	Radiant air temperature in the cell	Globe thermometer	Testo - 0602 0743
TD	Flow velocities along the measured structures	Heat flux sensor	FQA017C FQA020C FQA017CSI
AN	Air flow rate	Anemometer	EE671
AN	Air flow rate	Anemometer	EE576
PYR	Intensity of solar radiation	Pyranometer	Kipp&Zonen CMP 6
-	Heat recovery unit	-	Lunos Nexxt
-	Temperature and humidity of the outside air, speed and direction of wind, intensity of solar radiation on the vertical and horizontal plane, amount of precipitation	Meteorological station	AMS 111

Fig. 3 Measuring equipment installed in the double skin transparent facade with a narrow cavity (280 mm wide): anemometers, Pt 100 sensors and heat flux sensors (equipment used for analysing DSF values in this paper).

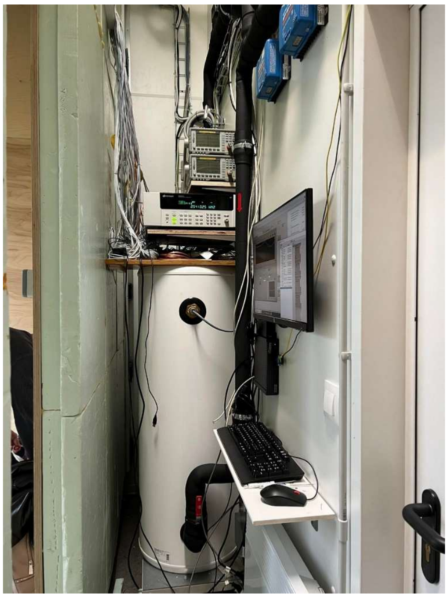
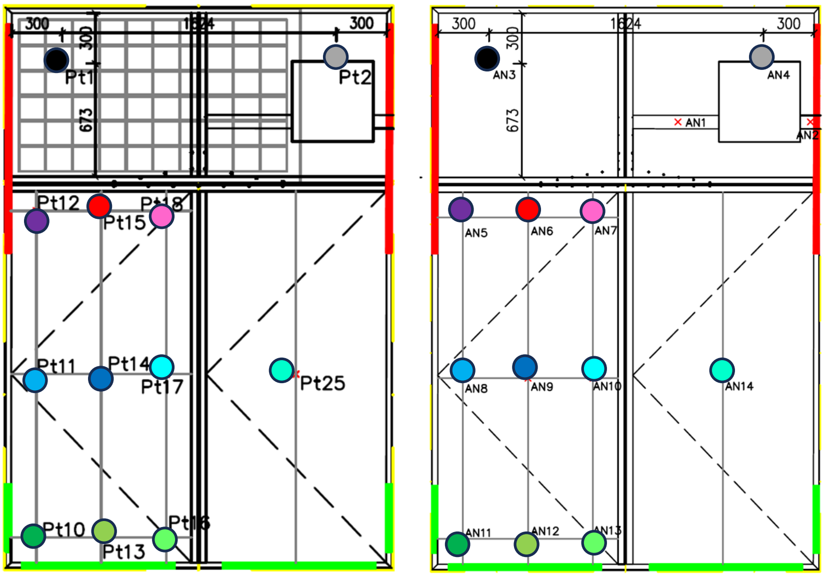


Fig. 4 Compensation space in the Twin Rooms – the space in which the DAQ, a computer with special software and the technical equipment of the experimental facility are located.

The data obtained from the measuring DAQ are processed into graphs. The graphs are divided on the grounds of several criteria: according to the measured period or according to the specific mode of the facade. Fig. 5 displays the measurement points in the DSF that show the reference values. This article deals with the results from the summer period, specifically from the months of July and August. It concerns the verification of the functionality of aerodynamics in a naturally ventilated narrow cavity, with the aim of ensuring that air flow is present within it, this being dependent on the wind speed and the intensity of solar radiation.

Fig. 5 shows the positions of selected measuring devices (Pt 100 sensors and anemometers) in the narrow cavity. All of the analysed sensors are located in the middle of the cavity in the raster that corresponds to the image.



a b

Fig. 5 Sensors used for summer mode analysis. Layout of Pt 100 sensors (PT) and anemometers (AN) in the innovative DSF (view from interior). The green lines represent inlets and the red lines denote outlets.

The anemometers marked AN3-AN14 are of the EE576 type, optimised for measuring low air velocity. This type uses a hot wire and has an accuracy of ± 0.05 m/s + 2% of the measured value at a flow speed of 0.2 to 1 m/s and ± 0.08 m/s + 4% of the measured value at a speed of 0.2 to 2 m/s. An anemometer of type EE671, marked

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AN1, and another anemometer from the recuperation unit marked AN2, also of type EE671, are installed in the pipe to the recovery unit. This type uses a hot wire and has an accuracy with an accuracy of ± 0.2 m/s + 3% of the measured value at a flow speed of 0.5 to 5 m/s, ± 0.3 m /s + 4% of the measured value at a speed of 1 to 10 m/s, ± 0.35 m/s + 5% of the measured value at a speed of 1 to 15 m/s, and ± 0.4 m/s + 6% of the measured value at a speed of 1 to 20 m/s.

Pt100 RTD sensors are used to measure the temperature in the cavity (PT1, PT2, PT10-PT18, PT25), protected by a silver shield from direct sunlight. They are also used to measure the temperature on the surface of elements (glazing, windowsill, wing, frame, pillar, blind), in which case they are protected by sealant.

3 RESULTS

The results are presented in graphs (Fig. 6 to Fig. 9). The values were selected for Fig. 6 to Fig. 8 from 10 days representing a typical summer period from 3. 7. 2023 to 12. 7. 2023. The colour of the curves for the anemometers and the Pt 100 sensors are identical to the coloured dots in Fig. 5. Fig. 9 displays a graph of the energy used for cooling by both test cells with the investigated facades in July and August 2023.

The graphs of the dependence of the air flow rate in the narrow cavity on the wind speed and on the intensity of solar radiation show data obtained from anemometers AN3 to AN14. The position of the anemometers in the narrow cavity is pictured in Fig. 5b. They are located in the middle of the depth of the cavity see Fig. 3.

The air velocity values in the cavity for individual anemometers correspond to obtained average wind speed or pyranometer values.

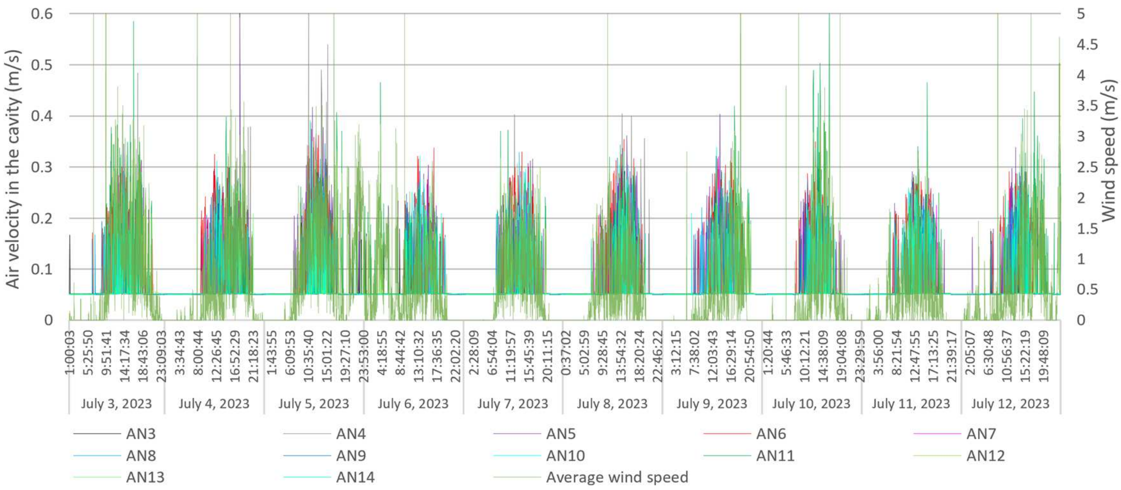

Fig. 6 Graph of the dependence of the air flow rate in the narrow cavity on the wind speed from 3rd to 12th July.

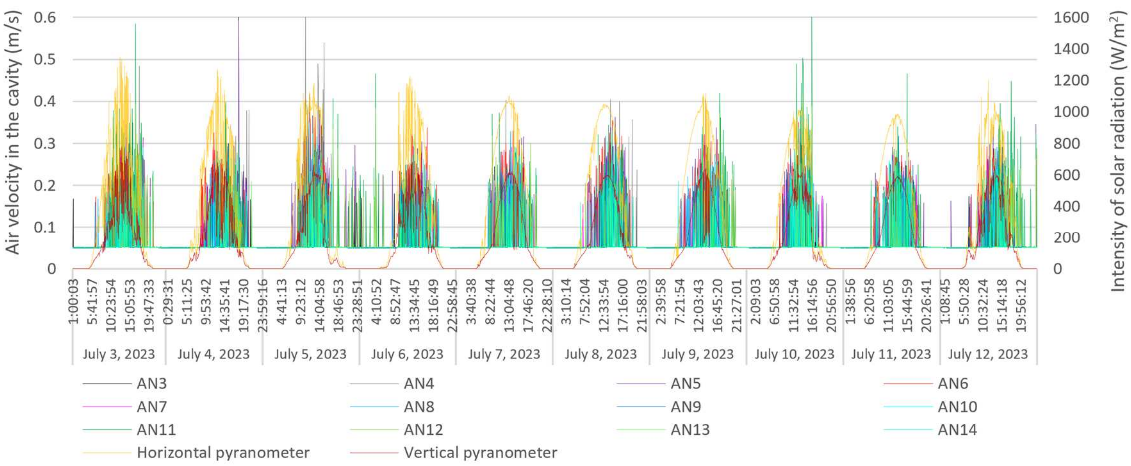

Fig. 7 Graph of the dependence of the air flow rate in the narrow cavity on the intensity of solar radiation from 3rd to 12th July.

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The graph of the dependence of the air temperature in the narrow cavity on the outside air temperature and the intensity of solar radiation Fig. 8, below shows data obtained from Pt100 sensors PT1, PT2, PT10 to PT18, and PT25. The position of the Pt 100 sensors is same as the position of the anemometers see Fig. 5a. The temperature curve presents the current outside temperature (exterior air temperature).

The shape of the curves of the Pt sensors proves that the temperature in the narrow cavity responds correctly to the outside temperature and also corresponds to the intensity of solar radiation at the given time.

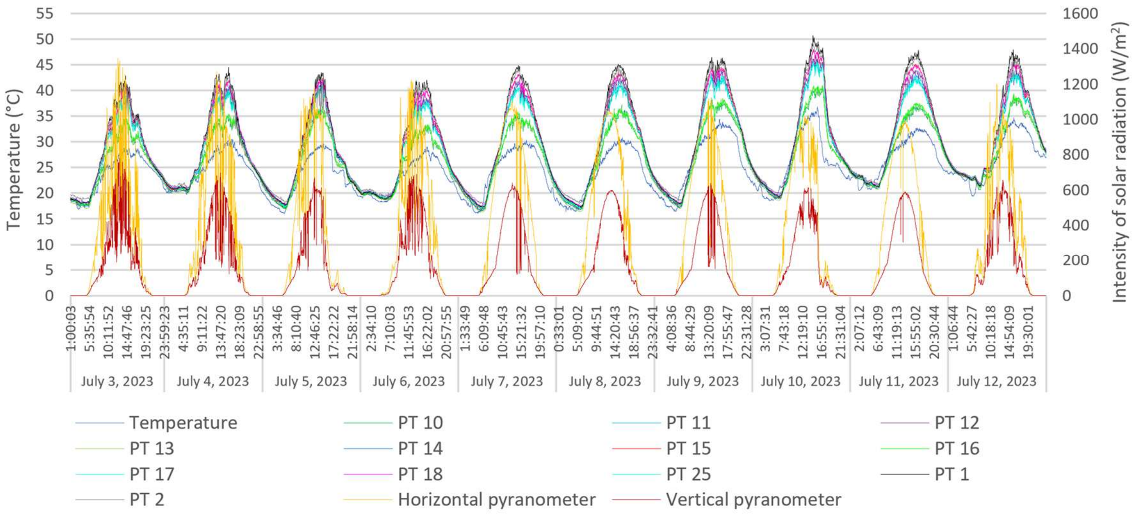

Fig. 8 Graph of the dependence of the air temperature in the narrow cavity on the outside air temperature and the intensity of solar radiation from 3rd to 12th July.

The graph in Fig. 9 shows the daily cooling performance in both test cells from 1st July to 31st August 2023. The data is obtained from software developed for the Twin Rooms experimental facility, where the inputs can be checked or modified (cooling set point = 23 °C). The blue curve represents the test cell with the simple facade and the yellow curve represents the test cell with the new innovative double skin facade. The difference in the energy requirements for cooling can be clearly seen at first glance.

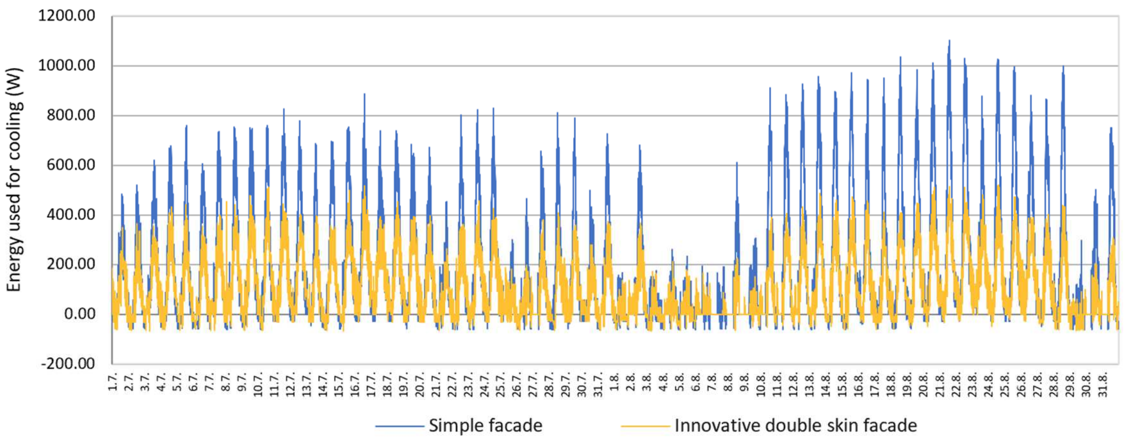

Fig. 9 Graph showing the cooling performance of the simple facade and innovative double skin facade from 1st July to 31st August 2023.

4 DISCUSSION

The evaluation of the aerodynamic effects on DSF surfaces is more complicated than for classic facades. Both buoyancy and wind force affect natural ventilation. DSFs were mainly developed for cold climates, but studies have nevertheless analysed their performance in hot and dry climates (our summer period), where their use is possible if a shading system is installed in their cavities [6], [17], [18], [19], [20].

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From the graphs in Fig. 6 and Fig. 7 it is obvious that in any climatic situation, i.e., even during critical windless weather (wind speed less than 0.5 m/s), there is constant movement of air through the cavity of the double transparent facade, which testifies to its correct design in terms of functional aerodynamics.

When short-wave radiation hits a glazed surface, it turns into long-wave thermal radiation, which causes a change in the temperature in the cavity and thus also a change in air density, which creates a pressure difference between the outside air and the air in the cavity.

From the graph in Fig. 8 it can be seen that the air temperature rises in the narrow cavity of the facade depending on the intensity of solar radiation up to a maximum value of 15 to 16 K, which correlates very well with the results of computational simulations from the design period of the facade in question. The total aerodynamic resistance of the cavity is lower than the convective lift of the air (buoyancy), so even in periods of no wind there is an air flow in the cavity, and thus the double skin transparent facade is correctly designed.

The incorrect design of the cavity of a DSF can increase the need for energy for cooling. The warm air layer becomes an obstacle when cooling the building. The application of cooling strategies is more important in DSFs than in the case of buildings with a classic simple facade [21]. Fig. 9 shows a comparison of the energy required for cooling the Twin Rooms for a simple and double skin facade. A constant temperature of 23 °C was maintained in both rooms and in the compensation space of the container. The total energy consumption for cooling in the period of July–August for the room with the simple facade was 266.217 kWh. The total energy demand for cooling in the same period for the room with the innovative double transparent facade was 150.622 kWh. The construction of a double skin transparent facade with a mobile shading blind in the narrow cavity can thus be said to significantly reduce the need for energy for cooling in the summer (compared to a simple facade, whose external shading in high-rise buildings is highly problematic).

The obtained results from the laboratory experiment will be compared and contrasted with the results of computational simulations in detail. Another task is to verify the performance of the innovative facade in the autumn, winter, and spring periods.

5 CONCLUSION

The measured values air flow speeds and temperature increases (around 16 K) in the narrow cavity in the summer prove that the aerodynamics of the narrow cavity are functional, i.e., correctly designed. The difference between the energy requirement for cooling in the room with a single facade and the room with a double transparent facade was found to be 115.595 kWh, which represents an energy saving of up to 43%.

In the next step, we will continue the experimental measurements into the winter period and compare the energy consumption for heating for the simple facade and the innovative double transparent facade. The follow-up part of the research is to create a new conceptual design and perform the technical optimisation for an improved version of the prototype of the innovative double skin transparent facade, which in its properties is based on the currently verified facade but differs in shape and in the integration of several new elements. It involves the use of photothermal conversion of solar energy from solar collectors as a heat source for an ejector cooling system for direct cooling of the building's interior.

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