Engineered Transparency 2018

Glass in Architecture and Structural Engineering

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Foreword

The conference »Engineered Transparency« was founded in 2007 at the Columbia University in the City of New York and since 2010 accompanies the »glasstec« in Düsseldorf – the world's leading trade fair of the glass industry. The unique liaison of research, novel developments and built examples always meets the demands of a broad expert audience that brings together the worlds of glass, architecture and engineering.

The conference covers various subjects ranging from conceptual design, to planning and realization as well as to relevant research topics in glass, structures and facade constructions. Additionally, the mini-symposium »standardization and design« focuses on current standardization activities, for example the new draft of the design standard *Eurocode* (CEN-TS Structural Glass) and their appropriate application in the design of glass. The second mini-symposium »thin glass« discusses novel ideas to integrate thin glass in the fields of glass in architecture, engineering and related applications. Both mini-symposia were initiated and organized in cooperation of Technische Universität Darmstadt and Technische Universität Dresden.

Almost 60 pre-reviewed contributions received from authors of nearly 20 different nations create this exceptional spectrum of topics. We want to express our sincerest thanks to all contributing authors and speakers who share their ideas and knowledge with great commitment and often in addition to their day-to-day business. Furthermore, it is a great pleasure for us to welcome Chris McVoy (Steven Holl Architects, New York), Markus Feldmann (RWTH Aachen), Jan Wurm (Arup, Berlin) and Rob Nijsse (TU Delft) as keynote speakers who lead to the conference with their inspiring ideas.

We would like to thank the members of the scientific committee for their valuable suggestions and the review of all papers. Particular thanks are due to Mrs. Stürmer and her team at Ernst & Sohn and Mrs. Horn and the staff at Messe Düsseldorf for their understanding and active support.

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A new building envelope – increasing daylight and energy efficiency with water flow glazing

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Building industry is still chasing the dream of fully transparent glass facades. However, available technologies of today show severe contradictions to the main purpose of such fully glazed facades: on the one side, the clear and unobstructed view from the inside into the outside environment, on the other side enabling maximum daylight autonomy to the building users. The main reason is the inevitable requirement of solar protection to avoid solar heat gains and consequently high cooling capacities in buildings. Solar coatings, tinted glass, switchable windows and classic interior and exterior sun shading devices all have the same general effect: The quality of the views to the outside is reduced, the amount of available daylight decreases. The European Union has funded the project InDeWaG (Industrial Development of Water Flow Glazing Systems) within the framework of the European research program HORIZON 2020. During the research period of three and a half years the international consortium incorporating research institutes, industry and designers is developing a new insulation glass unit. In the cavity of this unit a water-glycol mixture is circulating. Due to the spectral properties of water, it captures most of the infrared solar radiation: it is transparent to visible wavelengths of the sunlight but opaque to NIR wavelengths. Consequently, water flow glazing has the same natural light transmission as conventional glazing whilst reducing the heat transfer towards the interior space. Moreover, the water circulation allows to use, store or dissipate the energy captured by absorption of the waterfilled cavity.

Keywords: daylight, energy efficiency, water flow glazing

1 Introduction

Glass façades have an immense share in terms of the energy losses and gains of buildings. The ideal glass has optical properties that can easily adapt to changing climatic conditions. Concepts for multifunctional building envelopes try to come close to this ideal, using motorized shading elements, switchable glasses and multilayer façade systems with and without ventilation. In most systems, the implementation of summer heat protection

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usually leads to a deficit in the daylight autonomy inside the building as well as to constraints of the views from the inside to the outside environment. Both have an impact on the well-being, health and productivity of building users [1].

Fluid Flow Glazing (FFG) allows the control of solar heat gains through the glass without significantly impairing its transparency. A water-based fluid is circulating through one of the glass cavities of the insulation glass unit (IGU) within a closed loop. Due to its spectral properties, it captures most of the infrared solar radiation: it is transparent to visible wavelengths of the sunlight but opaque to NIR wavelengths. Consequently fluid flow glazing has almost the same natural light transmission as conventional glazing whilst reducing the heat transfer towards the interior space. This achieves energy savings in building operation. The objective of InDeWaG is to contribute to the building envelope of nZEB (nearly Zero Emission Buildings) by means of FFG. In addition, FFG offers potential to absorb and use energy, as well as to reduce cold radiation of the inner glass pane in winter.

The current research project InDeWaG is not the first to deal with fluid-filled insulation glass units. During the past few years, different emphases have been put on comparable systems, two of which mentioned below. On the one hand, the project FLUIDGLASS - Solar Thermal Glass Facades with Adjustable Transparency [2], where a focus was on the solar thermal use of solar energy absorbed in the cavity. On the other hand, the research focus of the Universidad Politécnica de Madrid (UPM), where fluid flow glazing has been investigated during more than the past ten years with regard to its physical behavior, the construction practice and the longterm behavior during the lifetime of such glazing units [3]. At UPM, also participating as a research partner in the InDeWaG project, research results have already been implemented in the built environment, e.g. a façade in Carcagente, Spain, which was completed in 2010.

2 Structural behavior

The composition of the insulating glass unit for the FFG modules is schematically shown in Figure 2-1. The two laminated glass panes consist each of 2 x 8 mm heat strengthened glass and a 1.52 mm thick Sentryglas Plus interlayer. The water chamber is located in between the two laminated safety glass panes, in the second cavity there is an argon-air mixture. Due to the aspired storyhigh unit dimensions of approximately W x H = 1300 x 3000 mm, the hydrostatic pressure in the waterfilled cavity represents as a matter of fact the relevant load case for the structural design of the pane. The above mentioned dimensions of the unit would lead to a hydrostatic pressure of 30 kN/m² which is 10 to 20 times higher than the relevant wind load for a typical highrise façade.

Figure 2-1 Schematic composition of the insulating glass unit (IGU).

The chosen approach to react to the high hydrostatic loads is the filling process for the glass units. The units are filled lying down in a first step. After the fluid has been degassed, parts of the fluid get extracted via a pump and a vacuum is established before the unit is set up. This vacuum is currently being investigated within the following limits.

- Compensation of the entire hydrostatic pressure of 3 m height, 30 kN/m²
- Compensation of half the hydrostatic pressure, 15 kN/m²

An exemplarily resulting pressure curve shown in Figure 2-2.

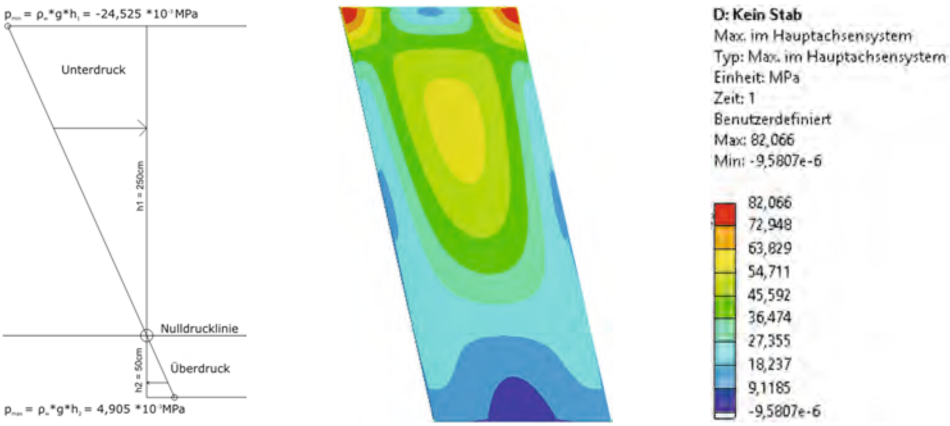

Figure 2-2 Pressure distribution in the cavity and corresponding equivalent tensile stresses.

The following boundary conditions have been assumed for the calculation:

- The third glass pane of the triple insulation glass unit has been neglected in order to simplify the simulation model.
- Interactions between the adjacent glass panes through the water have not been taken into account.
- Temperature changes have not been taken into account.
- Linear hinged support conditions on all four sides.
- Square shell finite elements with geometric nonlinearity.

- Conservative shear modulus G = 0 in accordance with the certification of SGP (Sentryglas plus) for overhead glazing (overhead glazing is the only practical reference for glass panes constantly under bending stress due to permanent loads).
- The simulation models were calibrated with the Finite Element software tools ANSYS and DLUBAL.

The structural analysis has been conducted in accordance with the German DIN 18008: "Glass in buildings" for the following additional loads:

- Dead load of glazing unit
- Wind pressure 0,65 kN/m² / wind suction 1,1 kN/m²
- Horizontal line load 1 kN/m in 0,9 m and 1 m height representing people impact and the fall protection requirements.

The equivalent bending stresses for all tested configurations of the pressure distribution in the cavity show clearly too high bending stresses and deformations in the glass, even assuming high stress limits as for heat strengthened and tempered glass. It has to be mentioned that exceeded stress and deformation limits could be easily eliminated by increasing the number of laminated single glass layers for the panes adjacent to the fluid filled cavity, i.e. producing triple or even quadruple laminated safety glass panes. However, this would significantly increase the thickness and especially the weight of the units. Consequently, the development of a lighter and thus smarter solution by means of additional bracing measures within the fluid filled cavity of the IGU.

2.1 Bracing components in the cavity

Different alternatives for bracing the fluid cavity are currently under investigation. Both geometrical variations and material opportunities have been developed and tested.

Figure 2-3 Prototypes for punctual (left) and linear (right) bracing components in the cavity.

Geometrically, punctual pinlike elements and linear fins have been integrated in between the two adjacent glass panes, consisting out of glass or UV-resistant polycarbonate materials (Figure 2-3). The connection to the glass panes depends on the resulting stresses between bracing component and glass pane: Either the underpressure in the cavity ensures no or only very little locally limited tension stresses. Consequently, pure contact between the two glass panes would satisfy their deformation compatibility. On the other hand, in the case of higher tensions stresses in the bracing components, they have to be mechanically glued to the glass panes. Then, particular attention must be paid to the connection between glass panes and bracing component and especially to the compatibility of any adhesives with the fluid mixture. The Fraunhofer Institute for Solar Energy Systems ISE carries out extensive testing series for this purpose.

The calculation results (Figure 2-4) show that the limits for the glass bending tensile stresses can be easily met by means of the bracing measures in the cavity. A very accurate simulation of the transition areas using high-resolution FE models leads to a better distribution and thus a reduction of the maximum stresses. However, the crucial and decisive factor for the bracing system will be the compatibility of the materials (adhesive, sealants, fluid) used in order to ensure the durability of the mechanical connection.

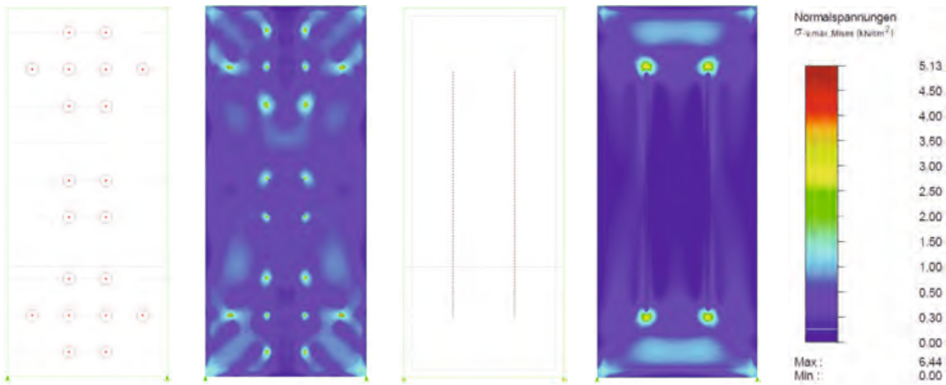

Figure 2-4 Bracing in the cavity: geometry and resulting glass bending stresses for punctual pins (left) and linear fins (right).

3 Flow simulations

3.1 Modelling of the FFG modules

In order to ensure the optimal integration of the FFG modules into the climate concept of the entire building, the understanding of their exact spectral, thermal, mechanical and fluid dynamic properties is indispensable. For this purpose mathematical models for the relevant physical processes (heat exchange, fluid flow dynamics, optical and structural behavior as well as environmental influences) are represented within a software model of the FFG unit using highly complex flow simulations (CFD = Computational Fluid Dynamics). The results are validated by spectrophotometer measurements and calorimetric measurements (Chapter 5). The CFD-simulations are also required to derive an optimum geometry and flow through the FFG units with regard to heat capacity, reduction of the thermal loads and total energy consumption. Different alternatives for the flow of the fluid with inlets and outlets are represented in Figure 3-1. It is essential for the efficiency of the system to produce the most laminar and homogeneous possible flow distribution in the cavity. Numerous parameter studies helped to optimize the FFG components, to understand and visualize the exact flow distribution and to predict the resulting solar heat gains before building physical prototypes for metrological validation.

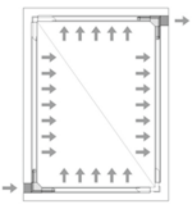

Figure 3-1 Investigation of possible flows through the FFG.

The shape of the spacer turned out to be crucial for the optimized flow of the fluid within the cavity. Perforated standard elements lead to unsatisfactory results. Out of dozens of investigated geometrical alternatives, a newly developed spacer leads to a considerably more even flow and a minimized pressure drop of 87 mbar for the maximum flow rate of 8 l/min in the fluid chamber (Figure 3-2).

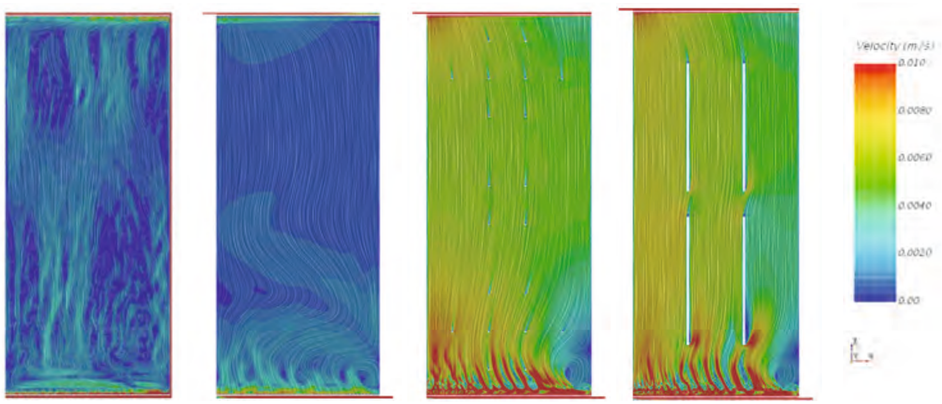

Figure 3-2 Flow distribution for (a) perforated standard spacer, (b) optimized spacer, (c) with punctual bracing, (d) with linear bracing.

3.2 Local climate simulations

The interaction between the FFG modules and the outside climate is calculated by means of solar altitude and weather modelling for different climate zones in order to be able to make a performance prediction for different scenarios. Parametric studies of different operating conditions with regard to geometry, material properties, fluid flow rate and ambient conditions complete the understanding of the behavior of the FFG modules for later consideration in the overall thermal-dynamic building simulation.

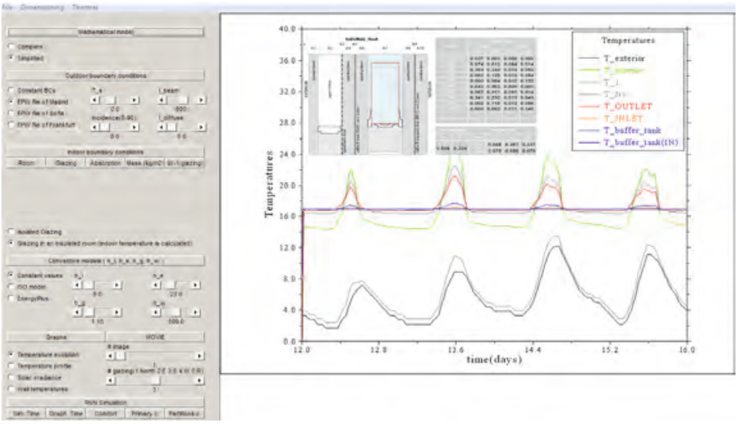

Figure 3-3 Calculation software of physical characteristics and temperature profiles in FFG modules.

3.3 Spectral and thermal modelling

A newly developed optical simulation tool based on years of metrological experience [4] allows the prediction of the optical performance (absorption, transmission and reflection) of the various FFG modules from the InDeWaG Glazing catalogue. Figure 3-3 shows the calculated absorption of each layer of the FFG unit as well as its transmission properties, its SHGC and *U*-value and the resulting temperature profiles (as an example for the winter case).

These optical properties form the input parameters for the CFD simulations of the single FFG unit as described above. The results of the CFD simulations are then used as information input for the thermal-dynamic building simulation.

3.4 CFD simulation of room climate

Figure 3-4 shows the spatial temperature distribution in InDeWaG demonstrator-pavilion under construction (see chapter 5) on a summer day, while the FFG modules operate in cooling mode (high flow velocity). All physical effects such as solar radiation, shading, etc. have been taken into account. The simulated temperatures and air velocities for this scenario show comfortable results. Due to the widespread but very moderate cold radiation, neither uncomfortable temperature stratification nor negative draft effects will occur.

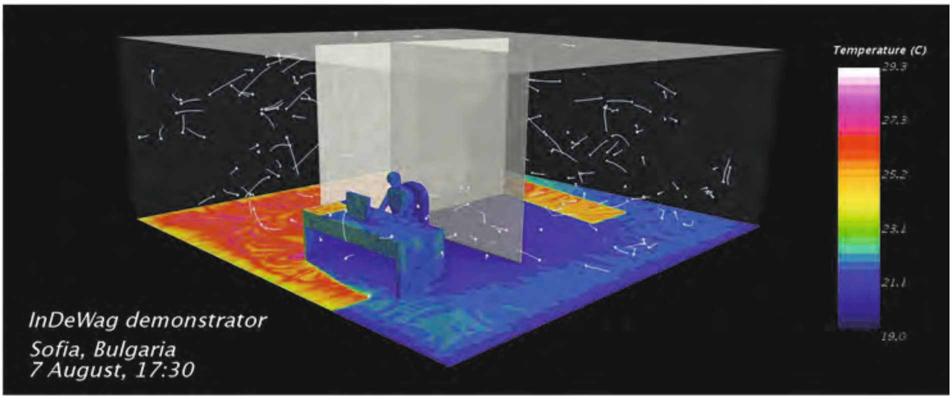

Figure 3-4 Temperatures and air movements in the demonstrator pavilion resulting from CFD simulation.

4 FFG in thermal-dynamic building simulation

One of the primary goals of the InDeWaG research project is the implementation of the thermal behavior of the FFG modules into the thermal building simulation, which is becoming more and more the standard design tool for summer-heat protection analysis, climate engineering and dimensioning of the cooling and heating components. Commercial software tools for thermal simulation cannot simulate FFG modules, since these modules are dynamic and do not have constant spectral and (solar) thermal properties. Properties of the FFG units are changing in interaction with the exterior site-specific and climate conditions. In the present project InDeWaG , the behavior of the FFG modules was coded in a special language called NMF (Neutral Model Format) and then compiled into Fortran. Subsequently, a DLL file has been generated and implemented within the popular simulation software IDA-ICE [5]. Detailed information of a possible program implementation of elements with time-variant properties in IDA-ICE can also be taken from [6]. The enhancement of the simulation software will provide engineers and specialists with the possibility to model FFG modules physically correct within thermal simulations. This feature will be indispensable in order to establish the FFG technique not only as an industrial product but also within modern design and planning processes for buildings.

4.1 Modelling of FFG modules within the building model

The following boundary conditions are essential for the performance of the FFG modules and must consequently be considered in the modelling process:

- Outside and inside temperature (climate database),
- Solar radiation (climate database),
- Flow rate in [kg/m²s] of the fluid in the cavity,
- Fluid inlet temperature in [K].

The implementation of the FFG modules within the IDA-ICE overall model for the demonstrator pavilion with 15 modules (Figure 5-3) is represented schematically in Figure 4-1.

Figure 4-1 Schematic representation of the FFG modules within the building simulation model.

4.2 Results of the thermal building simulation

At building or room level, the changes in heat flow and energy consumption caused by the FFG modules are of interest. These changes are documented in the following for the reference of the demonstrator pavilion described in chapter 5. Simulations for different variations of the parameters described in chapter 4.1 have been carried out for this pavilion. The input parameters (number of reference modules with standard solar coating, number of FFG modules, fluid inlet temperature and fluid flow rate) and the resultant energy consumptions for heating and cooling are represented in Figure 4-2.

The significant reduction of the energy consumption for heating and cooling by the integration of FFG modules into the façade is clearly visible. The flow rate and fluid inlet temperature can be adjusted to the exterior conditions and thus react to the outdoor climate.

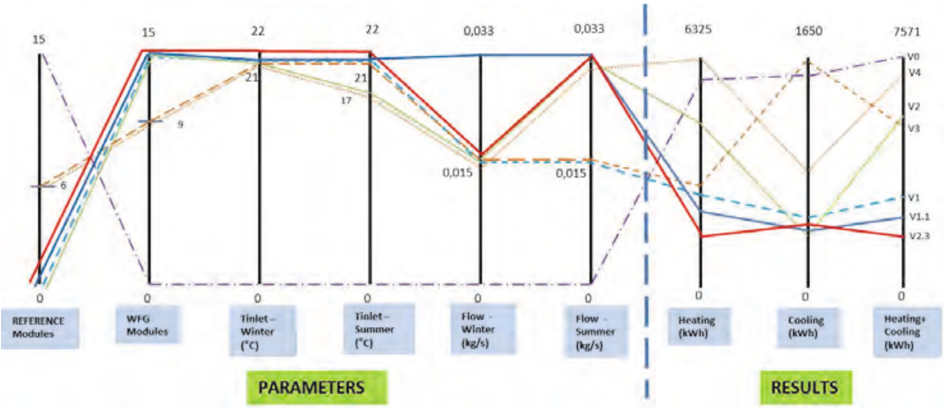

Figure 4-2 Parameter study for the energy consumption of the demonstrator pavilion.

A higher flow rate in summer allows transporting the absorbed solar energy away quickly. During wintertime, the flow rate is reduced so that the fluid in the cavity gets heated by diffuse and direct radiation, leading to positive effects on the heating demand. The exact fractions of the heat flow and energy consumption are shown in Figure 4-3 and give an idea about the potential of the FFG technology.

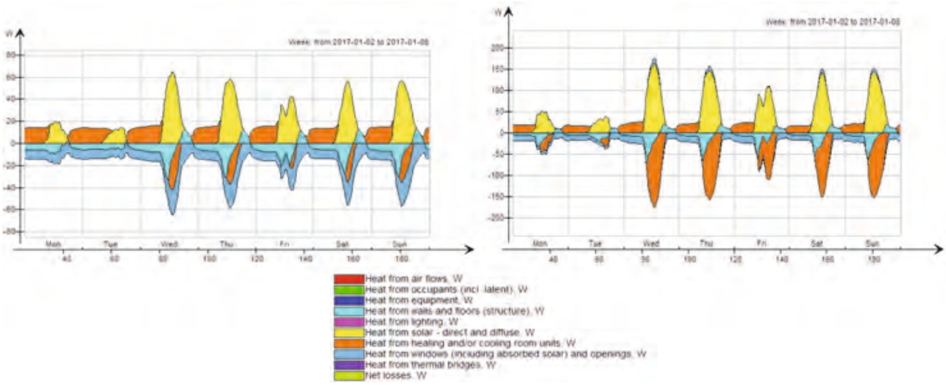

Figure 4-3 Results for 100 % FFG modules (left) and solar coated standard glazing (right).

In the current project phase, the simulation results are verified and quantified by means of optimized modelling of the FFG modules within realistic overall mechanical system concepts for buildings, and by means of comparison and calibration with physical testing procedures.

5 Measurement, calibration and construction

The FFG modules have a direct impact on the temperature and light conditions in the building and thus on the energy consumption in terms of heating, cooling, lighting, etc. Besides being able to numerically evaluate this influence in low-energy buildings, the project InDeWaG calibrates the results of the CFD simulations as well as of the thermal-dynamic building simulations by means of measured values determined on prototypes (Figure 5-1).

Figure 5-1 Left: Indoor calorimeter, Fraunhofer ISE; right: Test chamber, Valencia, Spain.

In the indoor calorimeter, the solar-thermal loads can be directly compared to the heat gains in the test chamber in order to derive the total solar heat gain coefficient of the system as well as the energy absorbed by the fluid. Similar tests are carried out in a test chamber in Valencia under real exterior climate conditions. The simulation model in IDA ICE and the comparison between measured and simulation data are shown in Figures 5-2 and 5-3.

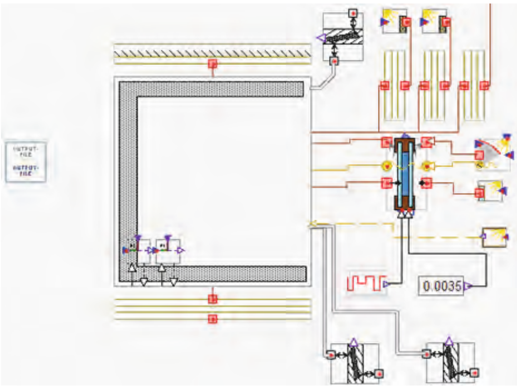

Figure 5-2 Simulation model in IDA ICE of the test chamber in Valencia, Spain.

Moreover, a demonstrator pavilion is currently being built at the Academy of Sciences in Sofia, Bulgaria (Figure 5-4). FFG elements will be installed on the entire eastern, western and southern facades and on interior walls used for additional radiant heating and cooling.

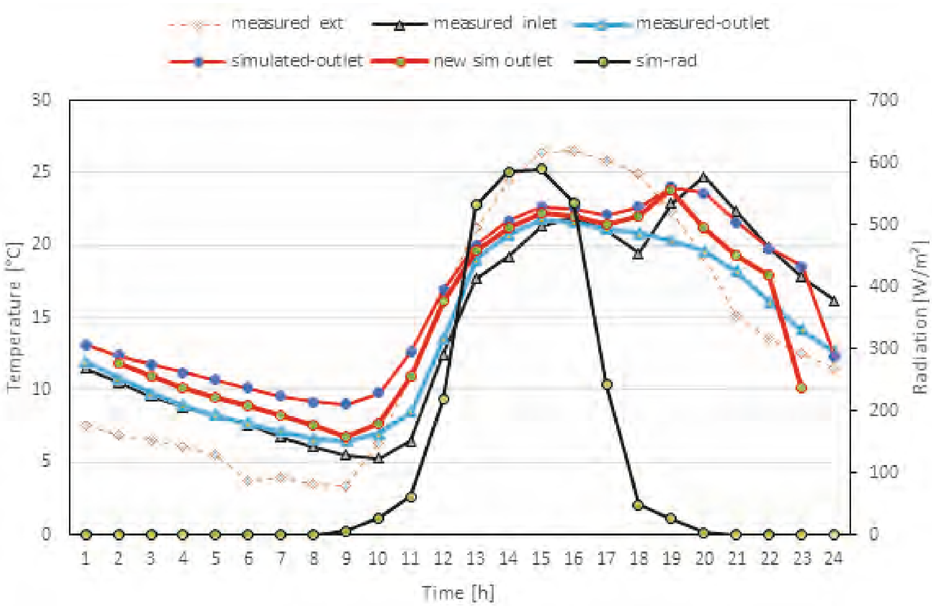

Figure 5-3 Comparison of measured and simulated data on 20th of September.

The building will allow extensive monitoring and thus provide valuable information for both the calibration of the simulation tools and the operation and durability of the modules.

Figure 5-4 Demonstrator Pavilion in Sofia, Bulgaria, scheduled completion in August 2018.

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