Innovations in façade engineering and a glass façade for the future

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Today it feels that the dream of façades with a maximum transparency is further away from reality than ever. Clear and unobstructed views from the inside into the outside environment and maximum daylight autonomy are in clear contradiction to available technologies of today. 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 contribution concentrates on a project funded by the European Union (InDeWaG - Industrial Development of Water Flow Glazing Systems) within the framework of the European research program HORIZON 2020. An international consortium incorporating research institutes, industry and designers is developing a new insulation glass unit. In the cavity of this unit, a fluid mixture is circulating within a closed loop. It absorbs the infrared radiation of the sunlight and thus reduces the solar gains into the interior. Maximum daylight use with appealing glass façades and at the same time meeting nearly zero energy building (nZEB) performance is the main objective of the InDeWaG approach. The contribution gives an overview of the current state of the project and enlightens the possible potential of the technology.

Keywords: Daylight, energy efficiency, fluid flow glazing (FFG)

1 Introduction

Glass façades play a significant role in terms of 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 multi-layer façade systems with and without ventilation. In most systems, the implementation of summer heat protection 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 (Boubekri et al. 2014).

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 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 leads to 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 insulating glazing units. Pilkington filed the first patent for a fluid flow façade in 1972: a fluid circulating in a glass cavity with spacers (Woods 1972). Another patent was filed by Frederick McKee in 1982 (McKee 1982) for windows filled with a dyed heat-transfer fluid which is connected to a closed fluid loop and to the MEP system of the building. Test results and parameters have been published in depth (McKee 2007). Another patent, called “All season window” was also filed in 1982 by

R. Seemann. A triple glazing unit was placed in a fluid-filled frame. The absorbing fluid was either filled into the exterior cavity during summer or the interior cavity during winter (Seemann, 1982).

Over the past few years, different emphases have been put on fluid flow façade systems, two of which mentioned below. First, the project FLUIDGLASS which is based on the extensive research activities of Dietrich Schwarz who developed the patent „Method for Transparent Heat Insulation in a Building“ (Schwarz 1998). The focus of Fluidglass is a solar-thermal glass façade with adjustable transparency (Stopper 2018).

Second, 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 long-term behavior during the life-time of such glazing units (Del Ama Gonzalo 2016). 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. With regard to thermal simulations, Chow and Li carried out studies of water flow façades, in which the performance of a water-filled insulation glass unit has been simulated and compared with experimental data (Chow and Li 2011).

2 Structural behavior

The composition of the insulating glass unit for the FFG modules is shown schematically in Figure 1. Each of the two laminated glass panes consists of 2x8 mm of heat-strengthened glass and a 1.52 mm thick Sentryglas plus interlayer. The water chamber is located in between two laminated safety glass panes and there is an argon-air mixture in the second cavity.

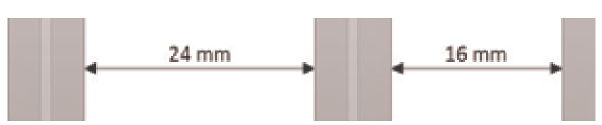

Fig. 1 Schematic composition of the insulating glass unit (IGU).

Due to the aspired story-high unit dimensions of approximately W x H = 1300 x 3000mm, the hydrostatic pressure in the water-filled 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 30kN/m² which is 10 to 20 times higher than the relevant wind load for a typical high-rise façade. 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 are 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. An exemplarily resulting pressure curve shown in Figure 2.

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

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 non-linearity.
- 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).

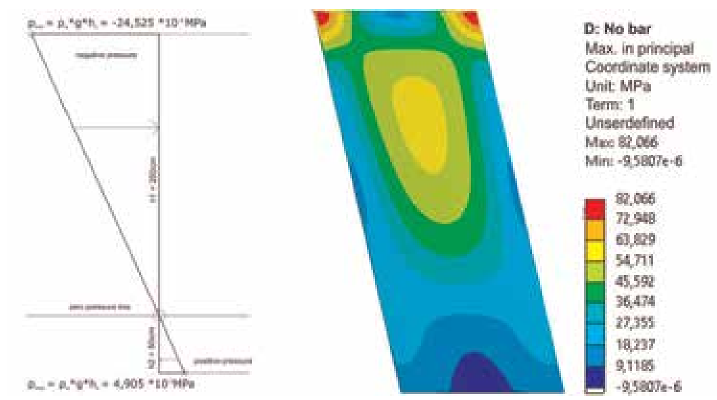

Fig. 2 Pressure distribution in the cavity (left) and corresponding equivalent tensile stresses (right).

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 the glazing
- Wind pressure 0,65kN/m² / wind suction 1,1kN/m²
- Horizontal line load 1kN/m in 0,9m and 1m 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. leading to 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, the geometrical variations and the material opportunities have been developed and tested. Geometrically, punctual pin-like elements and linear fins have been integrated in between the two adjacent glass panes, consisting of glass or UV-resistant polycarbonate materials (Figure 3). The connection to the glass panes depends on the resulting stresses between bracing component and glass pane: the negative pressure 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 tension 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. Merchantable adhesives are screened for the influence of the heat carrier fluid by means of accelerated aging tests and mechanical characterization of the material properties. The material test specimen are designed based on the application in the glazing unit and allow a maximum transfer of the obtained results into the development process. The investigated adhesives are butyl rubbers and two component silicones.

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

The calculation results (Fig. 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.

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 and calorimetric measurements (Chapter 5).

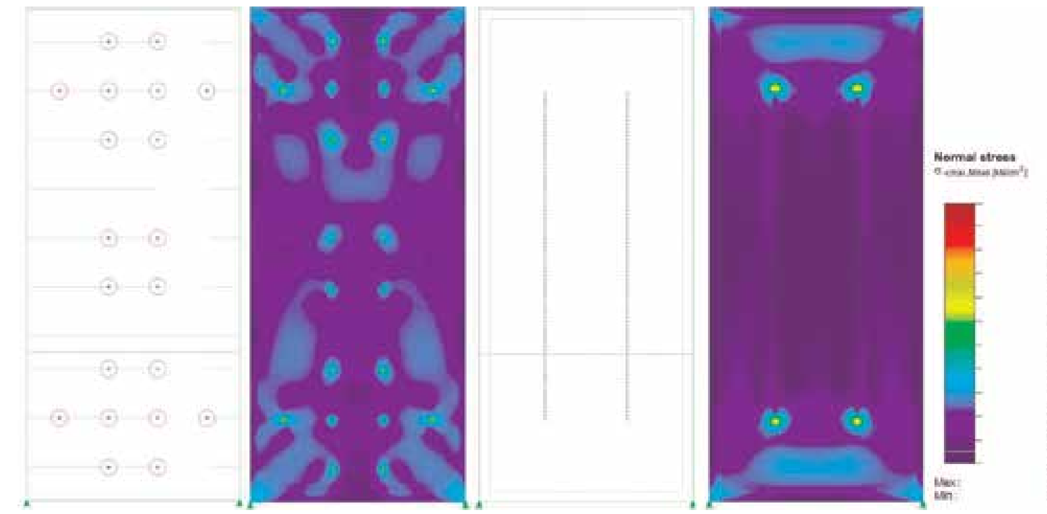

Fig. 4 Bracing in the cavity: geometry and resulting glass bending stresses for punctual pins (left) and linear fins (right).

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 5. 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.

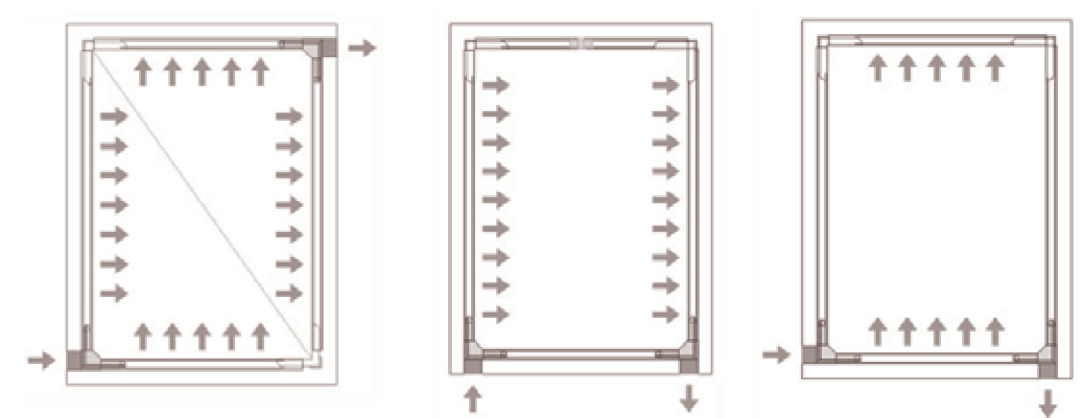

Fig. 5 Investigation of possible flows through the FFG.

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 (Fig. 6).

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 to provide 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 future consideration in the overall thermal dynamic building simulation.

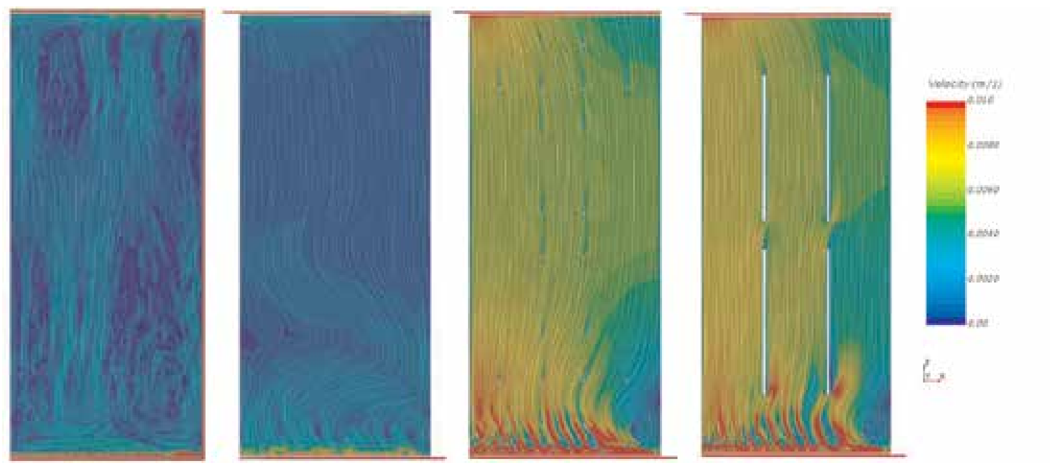

Fig. 6 Flow distribution for (a) perforated standard spacer, (b) optimized spacer, (c) with punctual bracing, (d) with linear bracing..

3.3. Spectral and thermal modelling

A newly developed optical simulation tool based on years of metrological experience (Sierra 2017) allows the prediction of the optical performance (absorption, transmission and reflection) of the various FFG modules from the InDeWaG Glazing catalogue. Fig. 7 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 period).
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 serve as information input for the thermal dynamic building simulation.

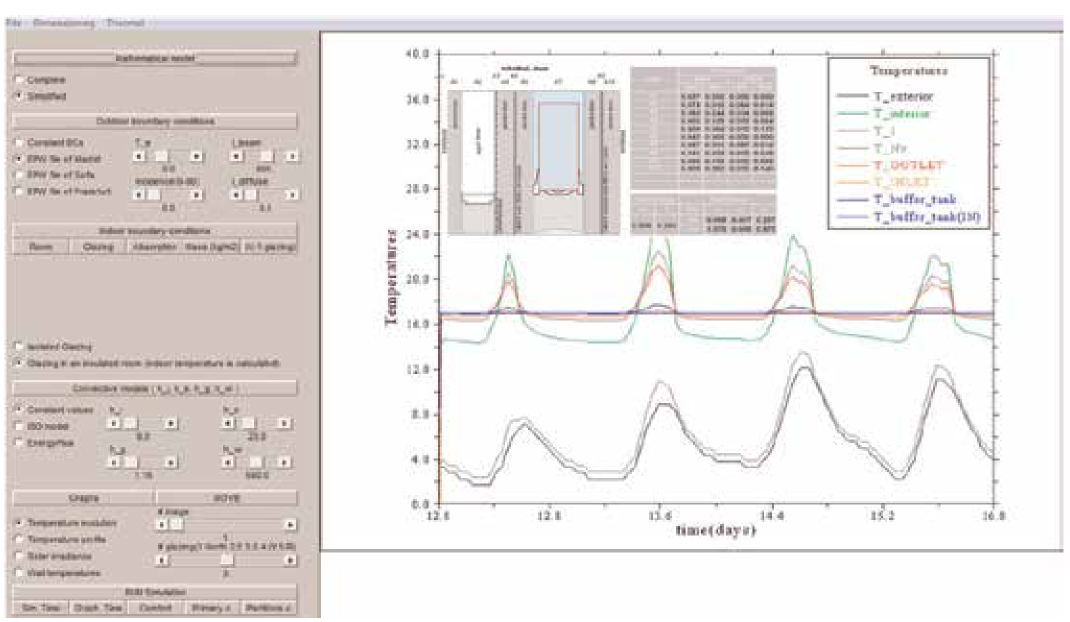

Fig. 7 Software for the calculation of spectral and physical characteristics and temperature profiles in FFG modules.

3.4. CFD simulation of room climate

Figure 8 shows the spatial temperature distribution in the 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 considered. 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.

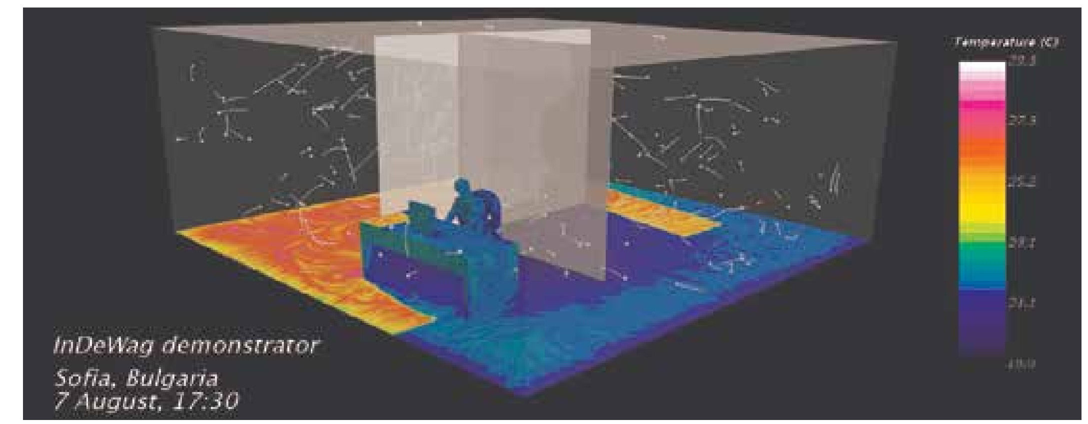

Fig. 8 Temperatures and air movements in the demonstrator pavilion resulting from CFD simulation.

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 do not have the appropriate components for 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 modeling 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 (Equa 2013). Detailed information of a possible implementation of elements with time variant properties in IDA ICE can also be taken from (Plüss 2014). 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 therefore 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 14) is represented schematically in Figure 9.

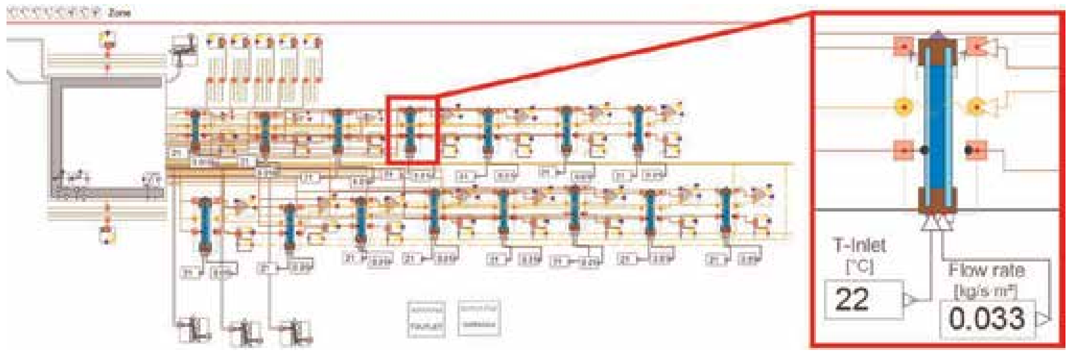

Fig. 9 Schematic representation of the FFG modules within the building simulation model.

4.2. Results of the thermal building simulation

At building or room level, the changes in heat flow and energy demand caused by the FFG modules are of importance. 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 resulting energy demands for heating and cooling are shown in Figure 10.

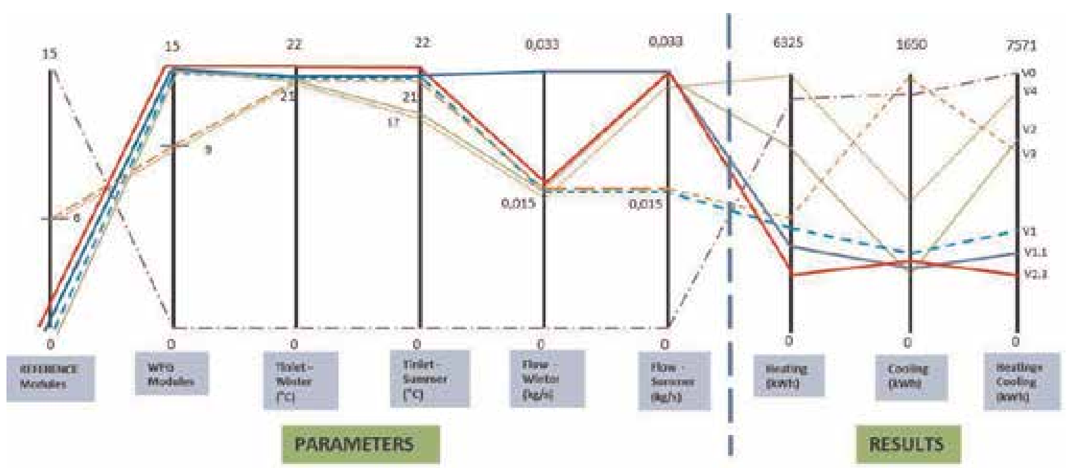

Fig. 10 Parameter study for the energy consumption of the demonstrator pavilion.

The significant reduction of the energy demand 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.

A higher flow rate in summer allows the absorbed solar energy to be transported 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 demand are shown in Figure 11 and give an idea about the potential of the FFG technology.

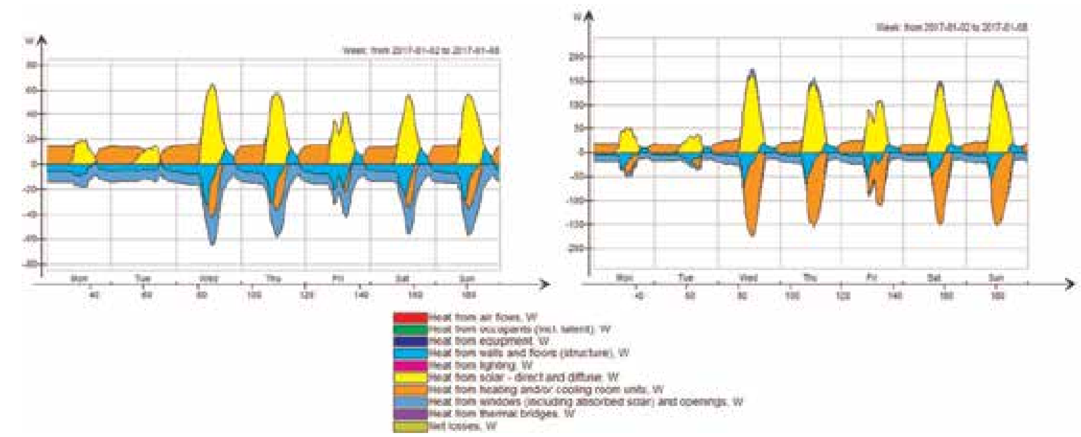

Fig. 11 Results for 100% FFG modules (left) and solar coated standard glazing (right).

In the current project phase, the simulation results are verified and quantified on the one hand by optimized modelling of the FFG modules within realistic over-all mechanical system concepts for buildings, on the other hand by means of comparison and calibration with physical testing procedures. Moreover, the outlet temperature and possibilities to use these energy gains will be investigated in detail (shown in figure 12 for the south façade).

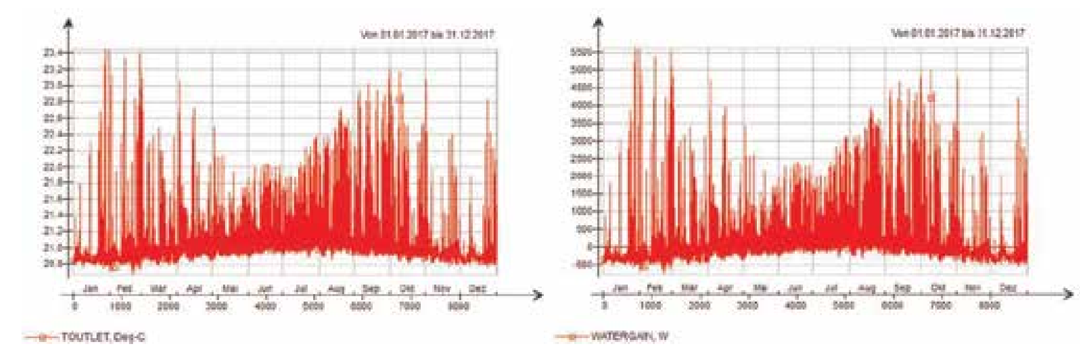

Fig. 12 Outlet temperature and heat gain of the FFG on the south façade.

5 Measurement, calibration and construction

The FFG modules directly influence the temperature and light conditions in the building and thus the energy consumption in terms of heating, cooling, lighting, etc. In addition to the numerical evaluation of this influence in low energy buildings, the project InDeWaG calibrates the results of the CFD simulations as well as the thermal dynamic building simulations by means of measured values determined on prototypes (Fig. 13).

Fig. 13 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.

Moreover, a demonstrator pavilion is currently being built at the Academy of Sciences in Sofia, Bulgaria (Fig. 14). FFG elements will be installed on the entire eastern, western and southern façades and on the interior walls used for additional radiant heating and cooling. 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.

Fig. 14 Demonstrator Pavilion in Sofia, Bulgaria, scheduled completion in August 2018.

6 Conclusion

The ongoing simulation and monitoring works within the research project show that water flow glazing is a very promising system regarding energy savings. The studied simulation variations help to define the optimal flow rate and inlet temperature for the hot climate (Madrid) and the cold climate (Sofia), which will be compared with measurements of the Bulgarian Pavilion and the small prototype in Madrid in the next project phase. The development of control strategies for inlet flow

and temperature will be the next step in order to adjust the flow according to seasonal and energy needs, (e.g. lower flow rate in winter and higher flow rate in summer).

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