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Investigation of thermal behaviour of innovative Water Flow Glazing modular unit

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Water Flow Glazing (WFG) modular unit is an innovative system specifically designed under the Horizon 2020 project "Industrial development of water flow glazing systems" (InDeWaG). It is a vertical-shaped module, which consists of a triple glazing sized 1.3 m x 3 m (one water/fluid chamber: 24 mm; one argon chamber: 16 mm). Each separate modular unit has an individual circulator incl. heat exchanger, a micro pump and a control unit. The circulator allows for flow rates up to 8 l/min per window. A novel spacer is specifically designed to assure a laminar flow of the fluid. The glazing and the circulator are enclosed by an aluminium frame. In this paper we investigate the thermal behaviour of WFG by using mathematical models covering all relevant physical processes - heat exchange, fluid flow dynamics, optical and structural behaviour as well as environmental influences. These models and a simulation tools integrated in the IDA ICE program are developed within the InDeWaG project. We obtain the most important parameters such as thermal transmittance of the glazing U, thermal transmittance between water chamber and indoor U_w, and also depending on climatic and operational conditions – the flow rate v_w, solar irradiation I, internal T_i and external temperatures T_e. The climatic and operational conditions for the location of Scientific Campus II of the Bulgarian Academy of Sciences in Sofia, Bulgaria are used.

Keywords: WFG thermal transmittance, solar heat gain coefficient, water flow rate, climatic conditions

INTRODUCTION

In modern life, the energy consumption is constantly rising and buildings are among the main consumers. This huge energy production leads to increasing harmful effects on the environment. This was the reason that in 2016 in Paris, France the Kyoto Protocol (2005) was replaced. The European initiatives have been focused on the energy consumption reduction in the EU 2020 strategy. Moreover, the Directive 2010/31/EU (2010) aims to improve the energy performance of buildings, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness.

Energy consumption in buildings is approximately one third of the total energy consumption. This fact motivates architects and engineers to work towards improving energy efficiency and create innovative technologies for nearly Zero Energy Buildings (nZEB).

In modern architecture glazing takes up most of the facade surface and windows increasingly influence the energy efficiency of the buildings. A huge amount of electricity is consumed to provide a comfort room temperature through air conditioning but advance glazing technologies and materials can be used instead to reduce energy demands and improve indoor environment.

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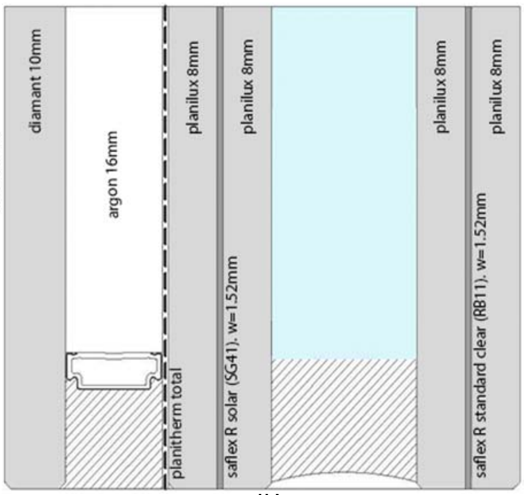
Windows are the biggest part of the commercial buildings and provide the light and thermal comfort, health [1], acoustic comfort [2] and photo-protection [3]. Processes in the windows can be divided into optical and thermal, although they are interconnected. The glass is a heat conducting material with a thermal conductivity that does not depend significantly on its composition. Its optical characteristics can be controlled by its appearance and by coating the low-emission [4] anti-reflective [5] or reflective coatings. Polymer films with different spectral properties in foil form are also used. Most often, the thermal insulation effect is achieved by used a closed gas layer between two glasses filled with air, argon, krypton or xenon but the limitations in this case are well known. Insulating materials from aerogels can be placed between the glasses [6, 7], but they are translucent not transparent. In order to eliminate convective and convective loss of windows, the gas between glasses is removed in the case of vacuum glazing [8, 9]. Heat exchange in this case is mainly radiant. For windows filled with Phase change materials, reliance is placed on the creation of an isothermal layer and the accumulation of heat, but they are not transparent [10, 11, 12]. Leakage of light through the windows except through shading devices is controlled by the use of Solar cell glazing or Smart windows. Big advantage of Solar cell glazing or PV glazing is the extraction of electricity from the window. Solar cell glazing products incorporating both transparent and translucent properties of glass can be used in windows regulating daylight, solar thermal gain, solar shading, and solar energy gain by converting solar radiation into electricity [13, 14, 15, 16, 17]. Smart windows can be divided into three different categories: (thermo-, photo- and electro-) chromic materials, liquid crystals and suspended particle devices [18]. The electrochromic materials change its colour and optical properties when a small DC voltage is applied to it. Consequently, a change occurs in transmittance of the visible and near infrared spectra. There exists electrochromic glazing based on both inorganic and organic materials that allows user control on daylighting. ChromoGenics has an electrochromic foil that can be applied to existing windows, which shows the retrofit possibilities for smart windows [19]. The use of multilayer glass and the combination of various methods results in a lower U-value in the case of Multilayer glazing [20], Electrochromic vacuum glazing [21,22], Evacuated aerogel glazing. Evacuated aerogel glazing can be produced using monolithic silica aerogel [23] “Air sandwich” [24, 25].

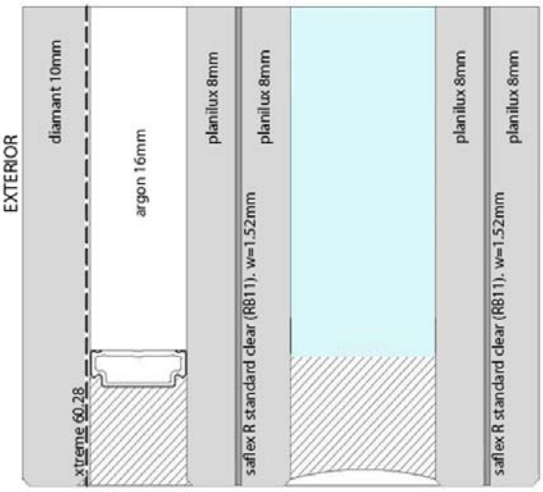
The Water Flow Glazing (WFG) is an innovative system which harvests solar energy for various use at large scale. It could become a necessary element of the nZEB facade increasing the daylight use, variable ventilation/conditioning and individual comfort control. The main goal of the paper is to investigate the thermal behaviour of WFG units and the amount of usable heat transfer. Three different structural combinations of WFG are studied at the climate zone of Sofia, Bulgaria in order to estimate the proper one.

WFG MODULE PROTOTYPS

Based on construction and architectural design trends and due to its unique characteristics the water flow glazing - WFG module is a product of the future. It is a vertical-shaped modular unit which consists of a triple glazing sized 1.3m x 3m (one fluid/water chamber and an argon chamber), a circulator allowing fast flow rates up to 8 l/min per window, and a modular aluminium frame that encloses the glazing and the circulator. WFG is a combination of: Active Facade with integrated Monitoring and Control System, Radiant Panel providing cooling and heating, transparent solar collector, Sunlight protection window and/or an Internal Partition wall. In the paper three different WFG prototypes according to the position of the coating and the water chamber are investigated. Fig.1 presents the three combinations.



a)



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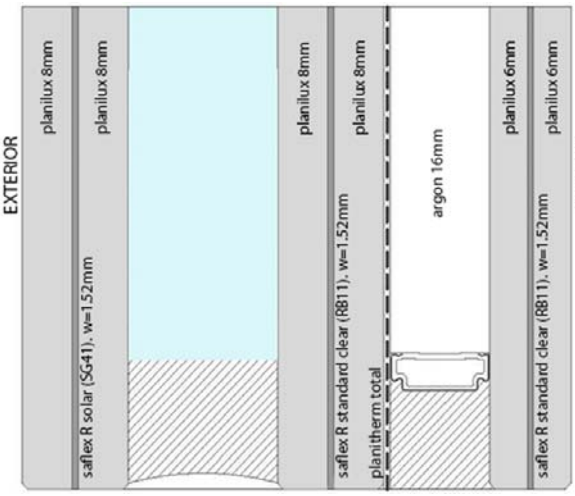

c)

Fig.1. WFG modular units: a) HeatGlass, b) CoolGlass and c) iThermGlass.

HeatGlass and Cool Glass units have the following structure:

- front glass pane - tempered extraclear glass
- 16 mm Argon chamber
- 8 mm float glass
- 1,52 mm PVB Saflex R Solar (SG41)
- 24 mm Water chamber
- 8 mm float glass (Planilux)
- 1,52 mm PVB Saflex R Standard Clear (RB11)
- 8 mm float glass (Planilux)

The only difference between HeatGlass and CoolGlass is the position and the type of the coating layer. In the HeatGlass modular prototype the coating is after the Argon chamber. This is a low-emissivity coating which very effectively reflects long-wave heat radiation back into the water and so the heat loss from the water is minimized. At the same time this coating maximizes natural light transmission. In the CoolGlass module the coating is after the Argon chamber and before the water chamber. The CoolGlass module has a Cool-Lite Xtreme coating which is very transparent with very high light transmission. At the same time, it has low solar factor and blocks energy at the surface.

The iThermGlass layer configuration is different. The water chamber is on the outside and the Argon chamber on the inside. The water chamber is directly exposed to the outside climate conditions and the Argon chamber serves as thermal insulator. The Planitherm Total coating comes after the water chamber and before the Argon chamber. As in the HeatGlass module, it reflects long-wave heat radiation back into the water and it blocks the heat entering the Argon chamber.

SIMULATION MODEL

To predict the performance and behavior of the WFG, as well as to optimize the modular unit and its components, mathematical and simulation models were developed by UPM Spain [26]. These models cover all relevant physical processes – heat exchange, fluid flow dynamics, optical and structural behavior, as well as environmental influences. They are based on thorough research and modern computer simulation methods. The software model is successfully integrated under the existing and widespread software product IDA-ICE and describes the change of the thermal conductivity of the glazing due to varying fluid flow rate (g- and U-values) as well as the energy gain in the WFG. This allows calculations of different energy management strategies at building level taking into account local meteo data, solar radiation, shading objects, wind speed and direction, type of the building, orientation, insulation and other parameters. Since the demonstrational Pavilion will be built in Sofia (Bulgaria), the assessment of the most appropriate and efficient type of WFG was made using local meteo data in the simulation. The input parameters for the simulations are:

- WFG position – vertical (90 degree).
- Module orientation - south.
- The results are simulated for area of 1 square meter.
- The climate model used in the program is based on real measurement data for the specific location of Sofia.
- Interior temperature is set at 20°C.
- Temperature of the water entering the WFG is set to 20°C for all seasons.
- Water flow rate is set to 2 liters per minute per square meter. Previous investigations [5] found that this is the optimal flow rate.

For only comparing the thermal performance of the different units, the temperature of the inflowing water was set at 20°C, which is the average of the optimal temperatures for each season. Depending on the energy strategy for different buildings with different profiles, this temperature could vary within 3 to 4 degrees above or below that value. The water flow rate is also subject to adjustment for the specific energy requirements of the building. The chosen rate of 2 $l/min.m^2$ is the required rate for transporting the absorbed radiation. Depending on the season and the adopted energy strategy, this rate could be reduced to achieve higher internal heat flux.

Based on these inputs, for each module type, the Water Heat Gain (which is measure of the thermal energy absorbed by the water in the water chamber) and Internal Heat Flux (measure of thermal energy transfer from the room to the module) are simulated according to the local weather conditions.

SEASONAL ANALYSIS AND RESULTS

In this section the thermal behaviour of WFG for one month per season is presented. Each month is selected based on the highest fluctuation in the climate model parameters. In the tables below the whole month is taken while the charts show the first 10 days of the month. The performed important simulation parameters are the following: Internal heat flux [W] – gives the room thermal heat gain; R_{diffus} [W/m^2] – diffuse solar radiation; R_{direct} [W] – direct solar radiation; T_{ext} [$^{\circ}$C] – external temperature; Water heat gain [W] – gives the net energy power of the glazing per unit of the surface.

1. Spring – here the chosen month is May and the table presents the main simulated parameters for the three different WFG units illustrated on fig 1. In HeatGlass the water heat gains is more than 20 times higher than in the other two units and only in the case of iThermGlass it is negative. Also in the HeatGlass the internal heat flux is lowest, which means that we have minimum heat losses. There isn't significant difference between the internal heat fluxes for the investigated units because in the simulations the T_{inlet} is the same as T_{room}.

Table 1. Simulated results for spring month May

May		Internal heat flux	R_{diffus}	R_{direct}	T_{ext}	Water gain,
		W/m^2	W/m^2	W/m^2	^{o}C	W/m^2
Heat Glass	mean	5.6	60.45	53	15.55	39.88
	min	3.82	41.04	0.21	12.44	10.31
	max	7.34	77.27	140.9	19.87	70.19
Cool Glass	mean	7.52	60.45	53	15.55	2.038
	min	6.96	41.04	0.21	12.44	-4.559
	max	8.08	77.27	140.9	19.87	8.56
iTherm Glass	mean	6.74	60.45	53	15.55	-2.799
	min	5.48	41.04	0.21	12.44	-59.54
	max	7.99	77.27	140.9	19.87	57.1

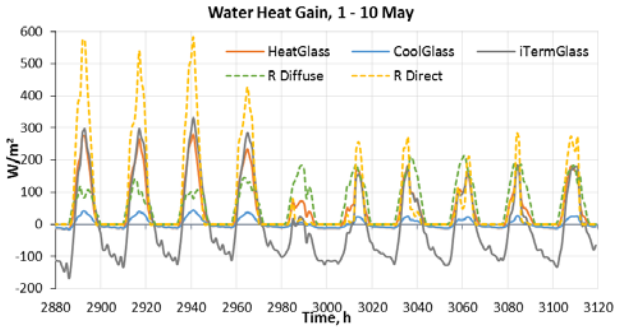

Fig.2. Water heat gain parameter as a function of total solar radiation for the first 10 days in May.

Fig.2 shows the water heat gain for first 10 days in May including the 24 hours solar radiation distribution. As it can be seen the maximum deviation is in the case of iThermGlass because of the configuration of the WFG unit. The water chamber is from the outside of the glazing which means that it is strongly influenced by the environmental conditions. In this modular unit the low-e coating is after the water chamber which keeps the heat in the water. The lowest fluctuations of the water heat gain are observed in the case of CoolGlass due to the type of coating and the water chamber position. The HeatGlass unit is more efficient due to the low heat losses during the night period and high value of the water heat gain during the day.

2. Summer – the chosen month is July. The water heat gain in all WFG modular units is positive. The highest mean water heat gain is for iThermGlass where it has a negative minimum and the highest positive maximum values. This result confirms that this WFG type is working as effective radiant heating/cooling. The water heat gain for HeatGlass is higher than in the spring time. The internal heat flux for the all WFG is similar to these in May. As it can be seen from the table the investigated parameters for CoolGlass are quite similar to these in the spring time.

Table 2. Simulated results for summer month July

July		Internal heat flux	R_{diffus}	R_{direct}	T_{ext}	Water gain,
		W/m^2	W/m^2	W/m^2	^{o}C	W/m^2
Heat Glass	mean	4.739	57.26	81.39	20.7	55.07
	min	3.673	33.94	9.544	15.48	22.45
	max	6.633	75.23	145.8	25.93	73.67
Cool Glass	mean	7.069	57.26	81.39	20.7	9.037
	min	6.571	33.94	9.544	15.48	-0.391
	max	7.794	75.23	145.8	25.93	16.27
iTherm Glass	mean	5.848	57.26	81.39	20.7	65.68
	min	4.861	33.94	9.544	15.48	-18.8
	max	7.387	75.23	145.8	25.93	134

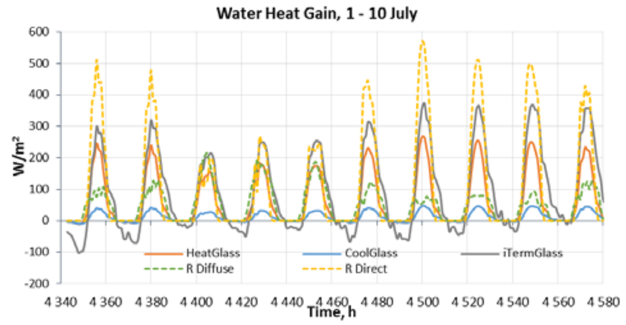

Fig.3. Water heat gain parameter as a function of total solar radiation for the first 10 days in July.

As it can be seen from the Fig.3 in the case of HeatGlass and iThermGlass the water heat gain is highest due to the favourable climate conditions for harvesting of solar energy. Only for CoolGlass we observed very small fluctuations in the internal heat flux.

3. Autumn – the chosen month is October. The water heat gain values are different for all WFG types compared to the previous investigated months. In case of HeatGlass there is a negative min. value and maximum value is the highest. For the other two units this parameter is negative, which means that we have loss of energy. Only for HeatGlass we still have positive water heat gain, which for the location in Sofia this could be a good solution. The Internal heat flux in all WFG remains approximately the same as in May and July.

Table 3. Simulated results for autumn month October

October		Internal heat flux	R_{diffus}	R_{direct}	T_{ext}	Water gain,
		W/m^2	W/m^2	W/m^2	^oC	W/m^2
Heat Glass	mean	5.563	30.05	91.64	11.15	39.85
	min	2.452	18.63	1.665	3.148	-6.914
	max	8.296	43.06	205.4	19.12	93.44
Cool Glass	mean	7.707	30.05	91.64	11.15	-2.1
	min	6.565	18.63	1.665	3.148	-14.63
	max	8.618	43.06	205.4	19.12	12.92
iTherm Glass	mean	7	30.05	91.64	11.15	-48.01
	min	4.492	18.63	1.665	3.148	-166.9
	max	9.072	43.06	205.4	19.12	88.8

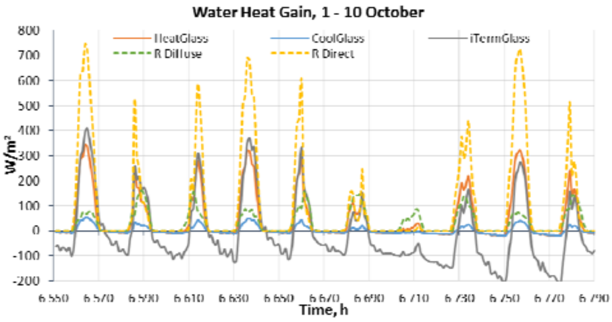

Fig.4. Water heat gain parameter as a function of total solar radiation for the first 10 days in October.

In autumn time (Fig.4) the water heat gain parameter for HeatGlass and CoolGlass follows the solar radiation daily profile. Again due to the coating type and its position in the WFG structure a very low heat losses are observed during the night time. In the case of iThermGlass the effect of the lower T_{ext} dominates and although it has a maximum water heat gain parameter during the sunny days, in the cloudy days it is not so efficient.

4. Winter – the chosen month is January, which for the Bulgarian location is one of the coldest months of the year. During this period, we have positive values for water heat gain only in the case of HeatGlass. The difference in energy harvested between HeatGlass and CoolGlass is approximately 20 times, while compared to iThermGlass it is more than 200 times. For HeatGlass, again the internal heat flux is lowest, which means that we have minimum heat losses. Fig.5 shows the water heat gain for first 10 days in january. As it can be seen all values in the case of ithermglass are negative. The position of the water chamber in the glazing and combined effect of low solar radiation levels and low ambient temperatures defines the behavior of the module. Despite the unfavorable weather conditions in this period, only for heatglass we obtained positive values for water heat gain.

Table 4. Simulated results for winter month January

January		Internal heat flux	R_{diffus}	R_{direct}	T_{ext}	Water gain,
		W/m^2	W/m^2	W/m^2	^oC	W/m^2
Heat Glass	mean	7.757	17.98	42.82	-0.86	1.075
	min	4.402	9.125	0.680	-9.1	-23.85
	max	9.192	26.63	182.8	4.95	57.56
Cool Glass	mean	8.786	17.98	42.82	-0.86	-19.01
	min	7.926	9.125	0.680	-9.1	-27.53
	max	9.378	26.63	182.8	4.96	-10.31
iTherm Glass	mean	9.15	17.98	42.82	-0.86	-209.6
	min	6.994	9.125	0.680	-9.1	-281.2
	max	10.33	26.63	182.8	4.96	-140.1

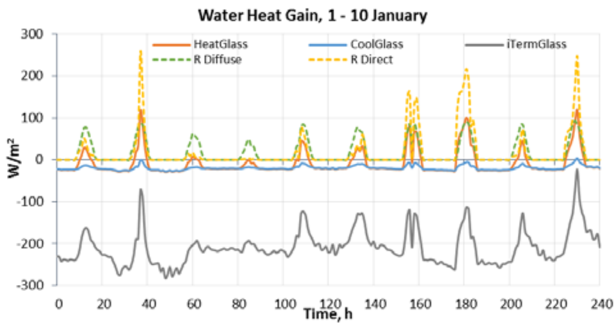

Fig.5. Water heat gain parameter as a function of total solar radiation for the first 10 days in January.

YEARLY BEHAVIOUR OF WFG

In this section the yearly thermal behaviour of WFG is presented. In iThermGlass unit the biggest fluctuation in monthly mean water heat gain parameter (Fig.6) are observed on yearly base. CoolGlass is stable during this period. Only for HeatGlass this mean parameter is positive which means that we are harvesting energy through the whole year.

The yearly variations of the internal heat flux are presented on Fig.7. These variations are strongly related to the annual changes of the T_{ext} and solar radiation. The internal heat flux is an indicator for the energy consumption to insure the indoor comfort. The internal heat flux should be at minimum during the winter and this is when HeatGlass performs best with the lowest reading for this parameter. At the same HeatGlass underperforms the other units during the summer with lowest internal heat flux, but this performance could be improved through controlling the water flow rate and T inlet.

For a location like Sofia the best performing WFG unit is HeatGlass.

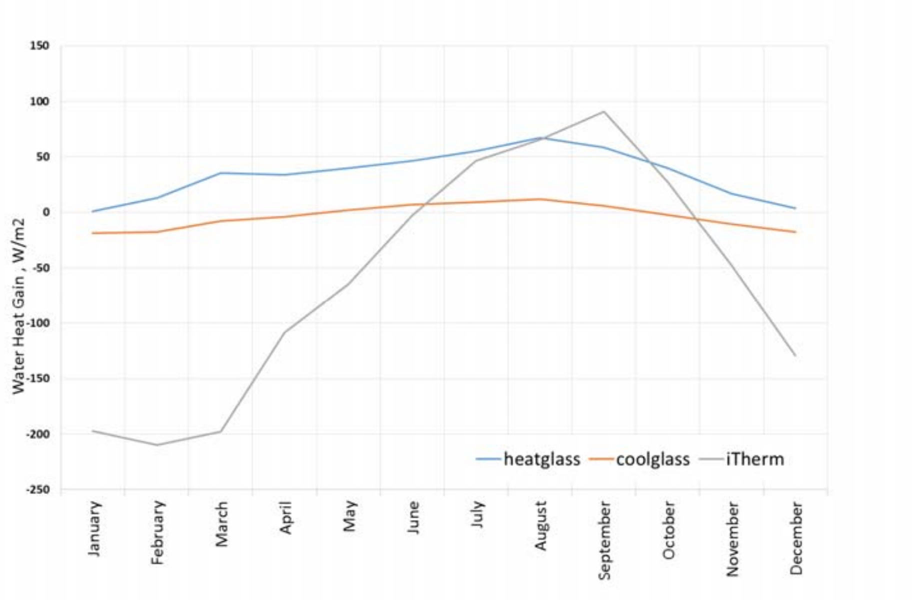

Fig.6. Water heat gain parameter for the whole year of 2017 year in Sofia.

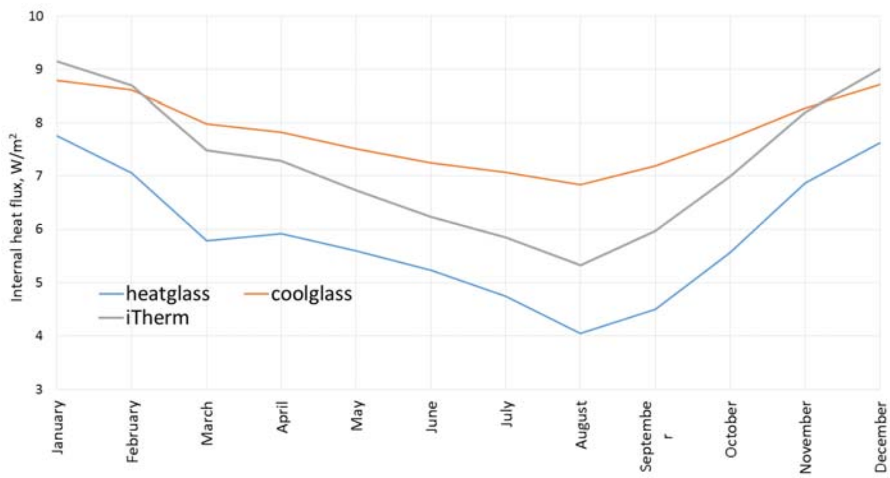

Fig.7. Internal heat flux parameter for the whole year of 2017 year in Sofia.

CONCLUSIONS

This work presents the monthly behaviour of the three investigated WFG units for a specific location in Sofia, Bulgaria. The results show that the structural configuration and the type of coating play important role for the effective work of the units. We can conclude that for all seasons the HeatGlass performed better for this location. Only in this case the water heat gain is positive for the whole investigated period. This is due to the position of the low-emissivity coating layer and water chamber. The behaviour of the CoolGlass does not change significantly, while in the case of iThermGlass the biggest fluctuations are observed.

With the help of the simulation software developed under the InDeWaG project we can successfully predict the behaviour of the WFG modules and we are able to choose the appropriate configuration of the glazing according to climatic conditions.

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REFERENCES

[1] R. Edlich, K.L. Winters, M.J. Cox, D.G. Becker, J.H. Horowitz, L.S. Nichter, et al., Use of UV-protective windows and window films to aid in the prevention of skin cancer, *J. Long Terms Effects Med. Implants* 14 (2004).

[2] H.K. Park, H. Kim, Acoustic insulation performance of improved airtight windows, *Constr. Build. Mater*. 93 (2015) 542–550.

[3] C. Tuchinda, S. Srivannaboon, H.W. Lim, Photoprotection by window glass, automobile glass, and sunglasses, *J. Am. Acad. Dermatology*. 54 (2006) 845–854.

[4] M. Reidinger, M. Rydzek, C. Scherdel, M. Arduini-Schuster, J. Manara, Low- emitting transparent coatings based on tin doped indiumoxide applied via a sol–gel routine, *Thin Solid Films* 517 (2009) 3096–3099.

[5] E. Hammarberg, A. Roos, Antireflection treatment of low-emitting glazings for energy efficient windows with high visible transmittance, *Thin Solid Films* 442 (2003) 222–226.

[6] R. Baetens, B.P. Jelle, A. Gustavsen, Aerogel insulation for building applications: a state-of-the-art review, *En. & Build.* 43 (2011) 711–769.

[7] J.M. Schultz, K.I. Jensen, F.H. Kristiansen, Super insulating aerogel glazing, *Solar Energy Materials and Solar Cells* 89 (2005) 275–285.

[8] Y. Fang, P.C. Eames, B. Norton, T.J. Hyde, J. Zhao, J. Wang, Y. Huang, Low emittance coatings and the thermal performance of vacuum glazing, *Solar Energy* 81 (2007) 8–12.

[9] H. Manz, S. Brunner, L. Wullschleger, Triple vacuum glazing: heat transfer and basic mechanical design constraints, *Solar Energy* 80 (2006) 1632–1642.

[10] R. Baetens, B.P. Jelle, A. Gustavsen, Phase change materials for building applications: a state-of-the-art review, *Energy and Buildings* 42 (2010) 1311–1368.

[11] K.A.R. Ismail, J.R. Henriquez, Thermally effective windows with moving phase change material curtains, *Applied Thermal Engineering* 21 (2001) 1909–1923.

[12] F. Goia, M. Zinzi, E. Carnielo, V. Serra, Spectral and angular solar properties of a PCM-filled double glazing unit, *Energy and Buildings*. 87 (2015) 302–312.

[13] D.H.W. Li, T.N.T. Lam, W.W.H. Chan, A.H.L. Mak, Energy and cost analysis of semitransparent photovoltaic in office buildings, *Appl. Energy* 86 (2009) 722–729.

[14] W. Liao, S. Xu, Energy performance comparison among see-through amorphoussilicon PV (photovoltaic) glazings and traditional glazings under different architectural conditions in China, Energy 83 (2015) 267–275.

[15] P.K. Ng, N. Mithraratne, Lifetime performance of semi-transparent building-integrated photovoltaic (BIPV) glazing systems in the tropics, *Renew. Sustain. Energy Rev*. 31 (2014) 736–745.

[16] S.E. Shaheen, D.S. Ginley, G.E. Jabbour, Organic-based photovoltaics: toward lowcost power generation, MRS Bull. 30 (2005) 10–19.

[17] E. Cuce, Toward multi-functional PV glazing technologies in low/zero carbon buildings: Heat insulation solar glass – Latest developments and future prospects, *Renew. Sustain. Energy Rev*. 60 (2016) 1286–1301, http://dx.doi.org/10.1016/j.rser.2016.03.009.

[18] R. Baetens, B.P. Jelle, A. Gustavsen, Properties, requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: a state-of-the-art review, *Solar Energy Materials and Solar Cells* 94 (2010) 87–105.

[19] ChromoGenics, Smart Windows, retrieved 29 July 2010, /www.chromo genics.com/ smart_eng .htmS.

[20] M. Arıcı, H. Karabay, M. Kan, Flow and heat transfer in double, triple and quadruple pane windows, Energy Build. 86 (2015) 394–402, http://dx.doi.org/10.1016/j. enbuild.2014.10.043.

[21] S. Papaefthimiou, G. Leftheriotis, P. Yianoulis, T.J. Hyde, P.C. Eames, Y. Fang, P.-.Y. Pennarun, P. Jannasch, Development of electrochromic evacuated advanced glazing, *Energy and Buildings* 38 (2006) 1455–1467.

[22] Y. Fang, T. Hyde, N. Hewitt, P.C. Eames, B. Norton, Thermal performance analysis of an electrochromic vacuum glazing with low emittance coatings, *Sol. En.* 84 (2010) 516–525.

[23] J.M. Schultz, K.I. Jensen, Evacuated aerogel glazings, Vacuum 82 (2008) 723–729.

[24] Sekisui, Air Sandwich, retrieved 12 August 2010, /www.sekisui.co.jp/min ase/airsand /doc/ 1196214_9172.htmlS (text in Japanese), 2007

[25] Sekisui, Light-collecting & Insulation Building Materials for Construction Use, retrieved 12 August 2010, /www.jase-w.eccj.or.jp/ technologies /pdf/resi dence/R -9.pdf, 2010.

[26] Pablo Sierra, Juan A. Hernandez, Solara heat gain coefficient of water flow glazings, *Energy and Buildings* 139 (2017) p. 133-145.