Improving the thermal performance of the transparent building envelope: finite element analysis of possible techniques to reduce the U-value of the glassblocks

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ABSTRACT

U-value of glazed elements is often a critical issue because these components, due to their small thickness and to the poor resistance of the glass and frame materials, cause very relevant heat fluxes. This paper presents an investigation on the thermal properties of a particular glazed component: the glassblock. Generally standard glassblocks have high U-values in comparison to the maximum values allowed by energy efficiency standards for glazed surfaces. This paper reports a summary of possible solutions that could improve the performances of the glassblock. A set of new configurations of the glassblock has been defined by schematic models and their overall thermal resistance has been assessed by the means of Finite Element software. The resulting performances are presented in terms of the global thermal transmittance of the modified glassblocks, also considering the effects of sealing and mortar. The paper also shows some significant potential improvements to address new production lines.

INTRODUCTION

Glassblocks are widely used as transparent materials. Especially when large interior areas must be illuminated by solar radiation, it is possible to use glassblocks as bricks to obtain translucent walls [1]. Modern technologies can provide transparent elements with very good thermal and noise damping characteristics. In comparison to glazed windows surfaces, glassblocks often have higher thermal resistance due to the higher thickness of the layers. However, although the greater thickness of the glassblocks is comparable to that of opaque walls, the thermal performance is generally worse. Many attempts to increase the thermal resistance of glassblocks have been made by researchers and manufactures. Starting from the analysis of the most significant ideas described in worldwide patents, new possible improvements in glassblock layout are reported and discussed in this paper. The ability to predict the energy performance of transparent surfaces is of great importance in the assessment of the overall energy performance of buildings. Indeed, heat transfer through glazed surfaces is very often the most important type of the transmission heat losses during the winter season. For this reason, it is important to minimize the thermal transmittance or U-

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value [W/m^{2}K] of glazed elements [1]. Many European regulations concerning building energy efficiency (i.e. the Italian one) require a prescriptive approach regarding the minimum performance of building elements (opaque walls, glazed surfaces, roofs, etc.). Generally, thresholds regarding glazed surfaces U-values are very tight. Windows manufacturers have tailored their products in order to comply with rules and standards by enhancing the performances of glasses and frames.

This paper presents and numerically investigates some ideas for the improvement of the U-value of the glassblocks. In many cases, the improved U-value complies with the maximum values imposed by the Italian law for glazed surfaces that are comparable with other rules in force in south Europe area [2]. These ideas are mainly based on some modifications of the air cavity geometry. The first one implies the subdivision of glassblock's cavity in two or three parts in order to reduce convective transmission. The second possibility is to fill it with a layer of a transparent insulation material, increasing the thermal resistance of the block. The third possibility is represented by the introduction of a thermal break along the interface of two glass shells that compose the glassblock. The U-values of such configurations have been calculated through the modeling of the glassblock with Finite Element and Computational Fluid Dynamics (CFD) software.

THE STANDARD GLASS BLOCK

An extensive analysis of glassblock's patents that have been registered since the 120s, has been conducted by the authors. Generally, three different categories of patents have been defined, among the 354 analyzed, in relation to the:

- improvement of glassblock's thermal and mechanical performance (151 patents);
- installation systems and techniques (135 patents);
- functional accessory elements for the production and the installation of glassblocks (59 patents).

Since the beginning (1920), innovative techniques have been suggested to better control light transmittance and to improve thermo-physical performance. In 1939, a new technology solution was presented to increase the thermal insulation. This idea, which was very innovative for that time, consists in the insertion of two or more transparent sheets inside the cavity of the glassblock. It was not realized at that time, probably due to the high costs. In late 1990s, increasing the thermal insulation performance of glassblocks become one of the main goals of manufactures. The most frequently proposed solutions were:

– the introduction of a thermal break between the two glass shells by the interposition of an element characterized by low conductivity [4];
– the filling of the entire cavity with a transparent insulation material [5];
– the increasing of the thickness of the glass shells [6].

In some cases, these solutions can also improve the fire resistance of the glassblock, as well. To assess how the application of one or more of these techniques can affect the thermal transmittance of the glassblocks, some possible new configurations have been created by the authors, and their performance have been studied and simulated. In the following work the results are described in detail.

In a first step of the analysis, the heat transmission through a standard glassblock in a steady state condition was investigated using an empirical lump parameters approach. The results coming for this first simulation were used to define a more realistic model which was set up in a finite elements software. The numerical results obtained by using the finite elements model have been compared with the values declared by the manufacturer of standard glassblocks. Furthermore, starting from this "simple" configuration, new variants of the glassblock have been defined and investigated. Detailed simulations have allowed to calculate their thermal transmittance. A standard glassblock produced by a multinational company (A1 configuration) was selected and then modeled as a reference to compare the performance of other configurations. Its geometric design is described in Fig.1 and Table 1.

Table 1. . Geometric characteristics of Standard glassblock

Description	Legend	[m]
Width	B	0.190
Height	H	0.190
Total thickness	S	0.080
Glass sheet thick.	Sv	0.006
Cavity thick.	L	0.068

The U-value of the glassblock declared by the manufacturer is 2.67 W/(m^{2}K) and it is based on the result of a test made by a third part actor.

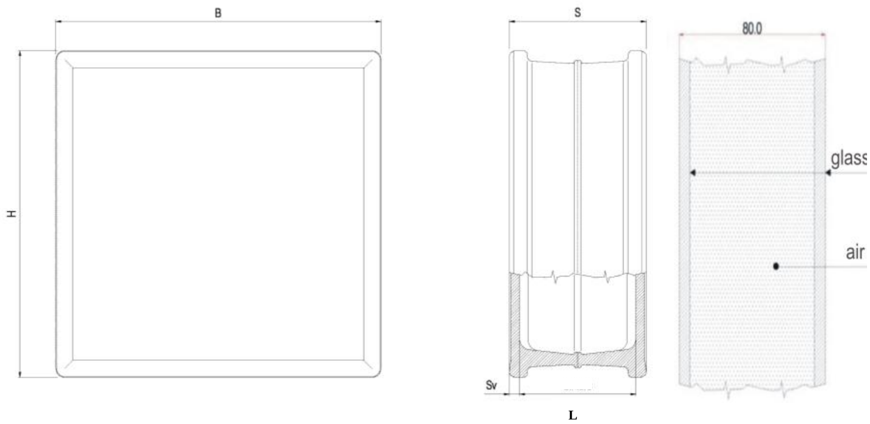


Figure 1. Standard glassblock (A1 configuration)

EMPIRICAL HEAT TRANSFER ANALYSIS

In order to properly assess the glassblock global thermal resistance the main goal is to study the heat exchange phenomena occurring inside the cavity between the two glass shells. Convection heat exchange that occurs inside an enclosure is the results of the complex interaction between a finite-size fluid system in thermal communication with all the walls that border with it, and depends on its geometry and orientation. The enclosure phenomena can be organized into two categories: enclosures heated from the side and enclosures heated from below [6]. The cases investigated in this work are represented by the first category.

A complete empirical solution for the calculation of thermal flow and temperature field is possible when the sidewalls are heated or cooled, with uniform heat flux. Upon a steady state condition, in the boundary layer the temperature decrease linearly along the direction of the heat flux. A fist assumption must be made about the thermal resistance and the other properties of the fluid filling the cavity. For the given glassblock it is then possible to calculate the convection and radiative heat transfer coefficients in the cavity itself (Fig.2).

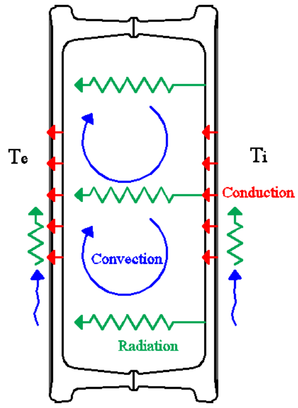


Figure 2. Sketch of the heat transfer in a glassblock

In this specific case, the convective heat transfer coefficient for vertical air cavity can be calculated by using the well-known correlation:

$$h_c = \frac{(\mathrm{Nu} \cdot \lambda_{air})}{L} \tag{1}$$

where:

- L is the mean thickness of air layer,
- λ_{air} is the thermal conductivity of the air (0.025 W/mK, from 10°C to 20°C).

Because the temperature increases linearly along the normal direction between the two walls, the wall-to-wall temperature difference is expected to be constant at every level, $T_1(x)$-$T_2(x)=\Delta T$. If we neglect the bottom and top borders geometry of the cavity we can assume that it is rectangular shaped. The correlation to obtain the average Nusselt number for rectangular enclosure with uniform heat flux on the sidewalls, when H/L >1 (tall enclosure) is:

$$\overline{\mathrm{Nu}} = 0.22\left(\frac{\mathrm{Pr}}{0.2+\mathrm{Pr}}\mathrm{Ra}_L\right)^{0.28}\left(\frac{H}{L}\right)^{-1/4} \tag{2}$$

where:

- Ra_L is the Rayleigh number based on the enclosure thickness;
- H is the height of the glassblock.

The R_{aL} value is:

$$\mathrm{Ra}_L = \mathrm{GrPr} = \frac{g\beta\Delta T L^3}{v\alpha} = w\Delta T L^3 \tag{3}$$

where w is defined as:

$$w = \frac{g\beta}{v\alpha} \tag{4}$$

It can be noted that Ra_L is function of the average temperature inside the enclosure and the difference temperature across the cavity.

The radiation heat transfer coefficient is given by the following equation:

$$h_r = \varepsilon\sigma F\left(T_1^2 + T_2^2\right)\left(T_1 + T_2\right) \tag{5}$$

where:

– σ is the Boltzmann constant equal to $5.67 \cdot 10^{-8}$ W/(m^2 K^4);

– ε is the emissivity of the two surfaces and it is equal to 0.837 for a standard glass;

– F is the view factor for aligned parallel rectangles and it is equal to 0.5;

– T_1 and T_2 are the inner glassblock temperature of the two surfaces.

In order to evaluate the global convection and radiative heat transfer coefficient, a fast iterative solution was implemented using the value indicated by technical standard (0.16 m^{2}K/W) as first attempt value of air cavity thermal resistance. The internal hi and external he convective heat transfer coefficients are respectively assumed 8 W/(m^2 K) and 25 W/(m^2 K) while the internal and external temperatures are respectively 20°C and 5°C [7,8]

A first step of calculation, in addition to the total U-value, gives a temperature distribution along the surfaces of the walls and an average temperature wall-to-wall. Since both the convective coefficient h_c and the radiative coefficient h_r depend directly of the wall-to-wall temperatures, calculation must be repeated until the values of h_c, h_r and ΔT do not converge. The first attempt thermal resistances of the layers composing the standard glassblock is described in the following table:

Table 2. The initial series composite of glassblock

Glass section	Thickness (m)	Conductivity (W/mK)	Resistance (m^{2}K/W)
Inner Convective			0.125
Glass	0.006	1	0.006
Air	0.068		0.15
Glass	0.006	1	0.06
External Convective			0.04

Once the first solution for the temperature profile inside the cavity has been calculated taking into account the convective and radiative heat transfer, the related coefficients have been calculated again until the values converge towards a stable solution. The iterative procedure gave the results described in Table 3.

Table 3. The results of the empirical approach

h_c (W/m^{2}K)	h_r (W/m^{2}K)	Ra_L	U (W/m^{2}K)
2.0109	2.177	$3 \cdot 10^5$	2.436

The results reported in the Table 3 highlights that inside the cavity of the glassblock an average Rayleigh number of 3·105 is established. Under this condition there is a cellular air flow concentrated in a thin boundary layer adjacent to the sidewalls, while in the core of the cavity the established air flow is nearly stagnant. This preliminary empirical analysis allowed to state that the convective heat transfer process inside the glassblock is complex and we must assess carefully the effect of the convective cells inside the cavity. To fulfil this goal authors decided to improve the study with a more detailed analysis based on a finite element approach.

NUMERICAL SIMULATION

To improve the calculation of the glassblock thermal performance a partial differential equations (PDEs) solver was used and implemented in the FEM software. A three dimensions model of the glassblock has been built and analysed. By this way, the temperature distribution along the section of the glass, the velocity field inside the cavity, the convection and radiation transmissions and the overall heat flux through the glassblock have been calculated**.**

For the standard glassblock analysis, the following assumptions have been made:

- only heat conduction is supposed to be inside the glass domain;
- laminar convection and surface-to-surface radiation; is inside the air cavity and, concerning the air flow, there is no slip on the inner surfaces;
- the glassblock boundaries are considered adiabatic except the two vertical surfaces facing the inner and outdoor environments;
- hi= 8 W/(m^2 K) and he =25 W/(m^2 K);
- Ti= 20°C and Te= 5°C;
- the buoyancy force is set equal to the product of the gravitational acceleration g and the density ρ of the fluid.

Once the boundary conditions have been fixed, a mesh with tetrahedral elements has been created. Under these conditions the overall thermal transmission through the glassblock together thermal and velocity fields have been evaluated under stationary conditions. In Figs.3 and 4 it is possible to see the results obtained considering the A1 configuration. Inside the air cavity a convective cell is developed, fully consistent with the results of the preliminary empirical analysis. In the central part of the cavity the air is steady, while the movement is maximum along the vertical surfaces.

The established natural convective flow, although the maximum velocities are less than 5 m/s, strongly affects the temperatures distribution and worsens the insulating properties of the air layer of the glassblock.

A comparison between figures supplied by the manufacturer and results obtained from the simulations, is shown in Table 4.

Table 4. U value results

Sample tested	U-value (W/m²K)		
	Declared	**Empirical approach**	**3D simulation**
GlassBlock	2.67	2.46	2.88

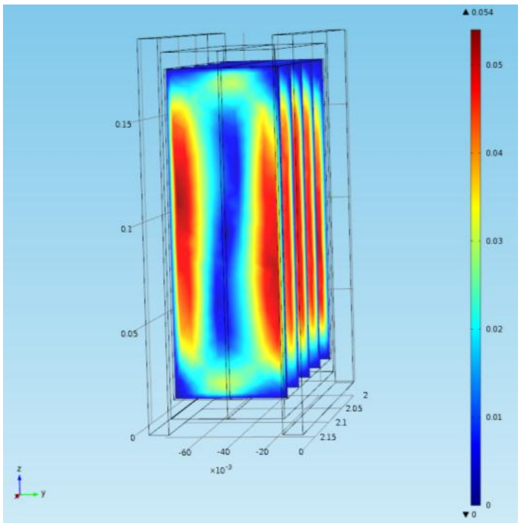


Figure 3: Air velocity field [m/s] of A1 configuration

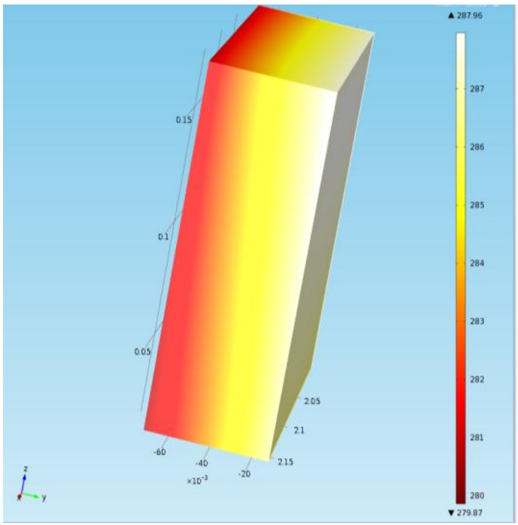


Figure 4: Thermal field of A1 configuration [K]

The U-value obtained with the 3D FEM simulation is slightly higher than the declared and empirically calculated values. The deviation respect the value obtained with the empirical approach is due to a more precise assessment of the three dimensions conductive heat flux through the solid. The difference with the declared U-value, however, that was also calculated by a similar software, can be explained by a different approach to the calculation of cavity convection. In Fig. 5 (provided by the manufacture) it can be observed a very symmetric thermal field probably due to a simplified velocity distribution which does not take into account the presence of a convective cells inside the air cavity.

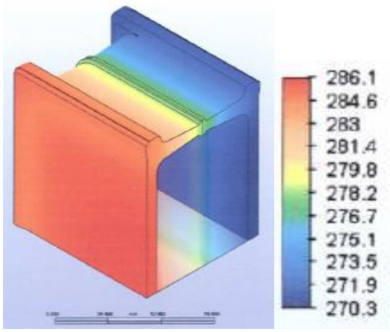


Figure 5: Thermal field inside the glassblock according to the manufacturer test report

POSSIBLE IMPROVEMENT OF THE U-VALUE OF THE GLASSBLOCK

In this chapter some techniques suitable to reduce the glassblock thermal transmittance, are described.

Glassblock with single cavity

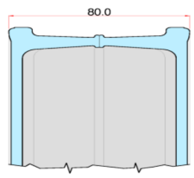
According to the above mentioned results, the reference standard glassblock (A1 configuration) is characterised by a thermal transmittance of 2.88 W/(m^2 K). Two new different configurations adopting filling materials inside the cavity have been analysed**.**

A2: cavity filled with aerogel

The single cavity has been assumed filled with a low conductivity material; in this case, the size and the layout of the glass interface remained unchanged. Granular aerogel made by granules of irregular shape with sizes ranging between 0.0005 m and 0.0035 m has been selected for the calculations, and the results are summarised in the following Table 5.

Table 5. Properties of the aerogel utilised for the glassblock A2 configuration and its schematic standard section

A2	Aerogel
Thermal Conductibility (W/mK)	0.018
Density (kg/m$_3$)	160

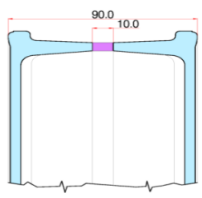


A3: introduction of polycarbonate element as thermal break

In this configuration a belt of polycarbonate with a thickness of 0.01 m is inserted between the glass shells to obtain a thermal break (Table 6).

Table 6: Data for standard glassblock with thermal break (A3 configuration).

A3	Policarbonate
Thermal Conductibility (W/mK)	0.12
Density (kg/m$_3$)	1200
Emissivity	0.86



The addition of 1 cm of polycarbonate's belt slightly improves the thermal performance of the glassblock allowing to reach a U-value of 2.66 W/m^{2}K.

Insertion of a single inner sheet to create two cavities inside the glassblock

According to one of the first patented ideas to reduce the U-value of the glassblock [9] a subset of configurations where the glassblock's inner space was divided into two different cavities by inserting a sheet between the glass shells, have been defined. Different configurations have been modelled, considering different sheet materials (glass and polycarbonate), different thickness of the sheet and different type of thermal breaks. In all cases, an improvement in thermal performance was found because of the reduction of thermal convection; at the same time, there was an increase of the total thickness of the glassblock.

In the following are schematized different solutions and configurations that have been modelled.

B configuration: Glassblock cavity divided from 0.004 m sheet:

B1 Insertion of a glass sheet;

B2 Insertion of a glass sheet with thermal break;

B3 Insertion of a polycarbonate sheet;

C configuration: Glassblock cavity divided from 0.01 m sheet:

C1 Interposition of a glass sheet;

C2 Interposition of a glass sheet with thermal break;

C3 Interposition of aerogel sheet;

C4 Interposition of aerogel sheet with nylon thermal break;

C5 Interposition of aerogel sheet with glass thermal break;

C6 Interposition of glass sheet with nylon thermal break;

C7 Interposition of glass sheet with glass thermal break.

D configuration: Glassblock cavity divided from 0.01 m sheet and thermal break:

D1 Interposition of aerogel sheet with nylon thermal break;

D2 Interposition of aerogel sheet with glass thermal break;

D3 Interposition of glass sheet with nylon thermal break;

D4 Interposition of glass sheet with glass thermal break.

Concerning the mechanical resistance of the glassblock, the interposition of a polycarbonate sheet represents for sure a weak factor (B1-B3, C1-C3). For this reason, an additional element was designed to ensure the mechanical resistance of the glassblock and the thermal break. A “thermal belt” profile was inserted into the glassblock to hold the sheet of polycarbonate + aerogel (C4-C7, D1-D5). It was assumed to use polyamide 6 (nylon) reinforced with 30% of glass fibres in order to increase the strength and the elasticity. Nylon has a thermal conductivity of 0.3 W/mK and a density of 1360 kg/m^3. Figure 6 shows an example of how the thermal belt can be inserted into the glassblock together with the cavity separator. The simulated thermal belt has the following measures: 0.01 m for C4-C7 configurations and 0.02 mm for D1-D5 configurations.

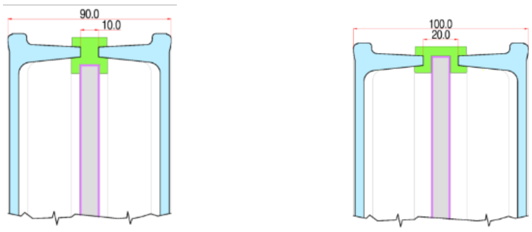


Figure 6. Some new configuration of glassblock with thermal break (C4 and D1configurations).

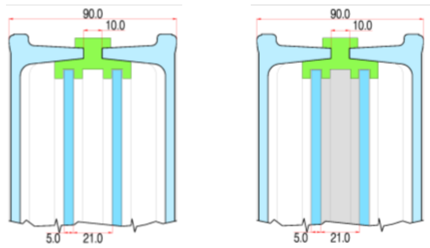


Figure 7: Scheme of glassblock with three layer (E1 and E3 configurations).

Insertion of two inner sheets to create three cavities inside the glassblock

The solutions for reducing the heat flux through the glassblock also take into account the design of a multi-cavity glassblock. A “capsule” composed of two sheets held by the belt that ensure the thermal break made of nylon (Fig.7) was designed. Such geometrical configuration can be realised with different materials: two separating glass sheets, two separating polycarbonate sheets, air or aerogel between the two sheets.

E configuration: Glassblock cavity divided from two sheets with nylon thermal break:

E1 Two glass sheets and air in the cavity;

E2 Two polycarbonate sheets and air in the cavity;

E3 Two glass sheets and aerogel in the cavity;

E4 Two polycarbonate sheets and aerogel in the cavity.

RESULTS AND DISCUSSIONS

The results of simulations, in terms of U-Value of the glassblock are reported in Table 7. Fig. 15 provides the schematic constructive sections of the simulated models. For the first family of configurations (A2) it can be noted that the presence of aerogel in the cavity allows to reach good thermal resistance. The calculated U-value is 1.66 W/m^2K (below the limit of Italian national law for all areas of the peninsula, except that the area F).

This good performance of the A2 configuration is due to the fact that aerogel completely avoids the convective heat transfer and inhibits the radiation heat exchange due to its high absorptivity. The addition of 1 cm of polycarbonate’s belt (A3) slightly improves the thermal performance of the glassblock allowing to reach a U-value of 2.68 W/m^2K. Several considerations must be made concerning the separation of the cavity in two or three cameras. The analysis of the following figures (8 and 9) that show the air velocity field inside the cavity, indicates that not always the presence of a single divider sheet, creating two separate cavities, is able to prevent the development of convective cells. When this happens, the ability of the glassblock to conduct heat is always increased, thus worsening the thermal performance. Indeed, it is possible to see in Table 7 and Fig.10, that even in B1-B3 and C1-C3 configurations, the presence of convection cells decreases their thermo-physical performance. Only the C3 configuration is able to reach an efficient transmittance value thanks to the presence of a good insulated sheet. The C4-C7 and D1-D5 configurations represent a good compromise between a great reduction of thermal transmittance and the real possibility to achieve a different level of tension.

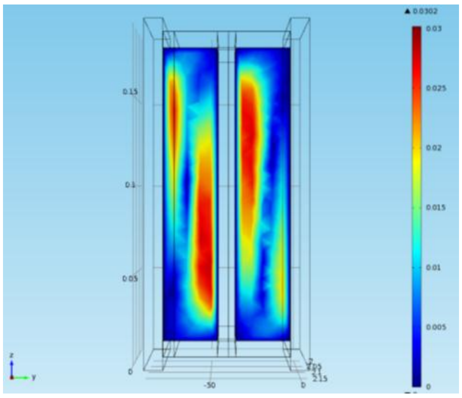


Figure.8. Convective cell in C3

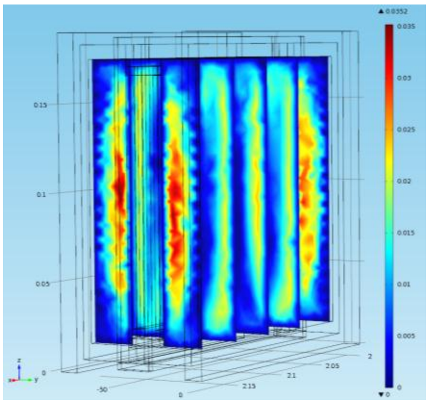


Figure 9. Absence of convective cell in C4

CONCLUSIONS

This work has investigated the thermal performances of a set of glassblock's configurations that have been studied by numerical simulations in order to assess possible improvements of some ideas coming also from a selection of patents that have been studied in depth.

A careful analysis of the results shows how the first solution (single layer) that uses only polycarbonate as a thermal break between the two glass shells, is not sufficient to reduce the U-value of the glassblock. Furthermore, the use of polycarbonate implies that it is always necessary to fix the cavity using silicone sealants or gaskets in EPDM or silicone elastomer type, which requires carefully taking into account the expansion resulting from temperature changes (polycarbonate thermal expansion coefficient is higher than the one of traditional materials and 8 times greater than the one of glass).

Filling the interspaces with granular aerogel gives a reduction of the U-value, although it reduces the passage of light through the glassblock, which is obviously a drawback of the technical characteristics of the product. However, in current production, glassblocks with low level of light transmission due to particular treatments of the glass shells already exist. In configurations that provide the insertion of a polycarbonate sheet between the two glass shells, filled with a material with a thermal conductivity approximately 10 times lower than that of glass, the thermal transmittance value decreased. The lower value of U-value is obtained by D5 configuration, when the aerogel sheet is inserted in polycarbonate structure with a thickness of 0.01 m and there is a nylon thermal belt. This solution combines the excellent insulating properties of aerogel in a polycarbonate structure and excellent mechanical resistance of the nylon profile reinforced with glass fibre.

In this case the value obtained is significant thanks to aerogel that reduces the heat transfer in the cavity. In configurations that include the insertion of the "thermal belt", very low U-values are obtained but the increase of the thickness of the glassblock could weaken the product. The numerical analysis of the configuration with three cavities gives a quite good U-values. On the other hand, this solution implies an increasing of the technological complexity of the "thermal belt". It is worth noting that, other important performance figures of the glassblock are related to light and solar radiation transmission. Main indoor microclimate problems arising in buildings with large glazed areas are related to overheating indoor spaces because of the direct sun. In some cases, U-value improvements imply significant drawbacks on these parameters. Further analysis has been conducted by authors to assess the light transmission and solar factor of the investigated glassblock, which will be presented in future papers.

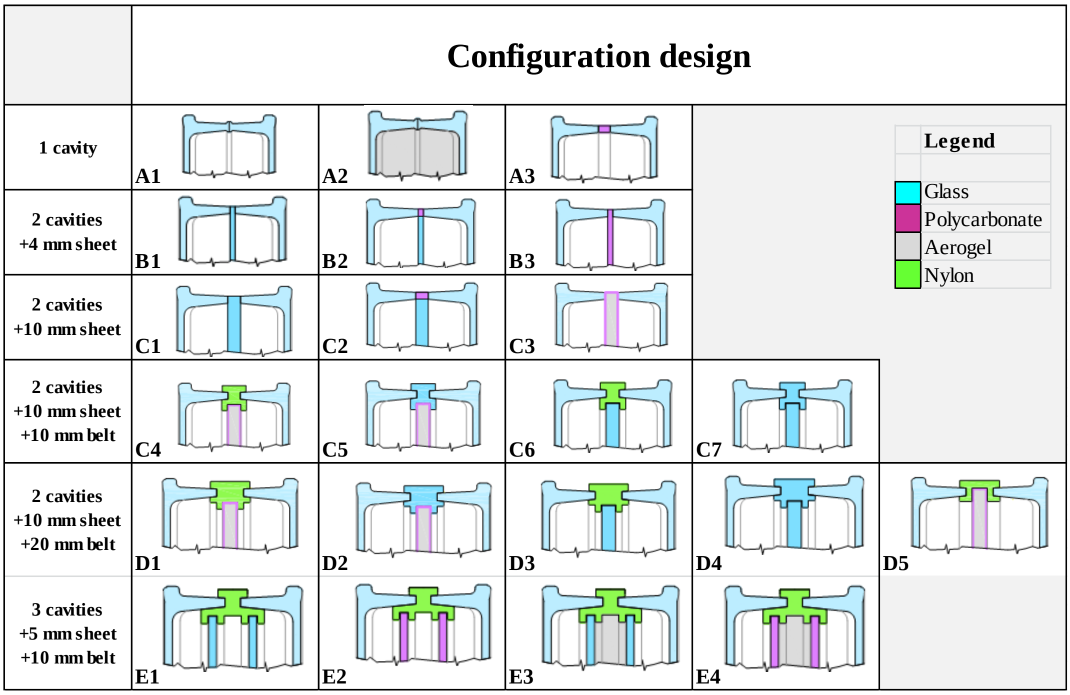


Figure.10. Simulated configurations design

Table 7. Results of the new configurations of glassblocks.

Glassblock configuration								
configuration		material: cavity	material: sheet	material: belt	thermal belt	thickness [cm]	U- value [W/m^{2}K]	Convective Cell
1 cavity	A1	air	no	no	no	8	2.88	Yes
	A2	aerogel	no	no	no	8	1.66	No
	A3	air	no	PC	yes	9	2.68	Yes
2 cavities +4 mm sheet	B1	air	glass	no	no	8.4	2.34	Yes
	B2	air	glass	PC	yes	8.4	2.28	Yes
	B3	air	APC	no	yes	8.4	2.19	Yes
2 cavities +10 mm sheet	C1	air	glass	no	no	9	2.28	Yes
	C2	air	glass	APC	yes	9	2.19	Yes
	C3	air	PCA	no	yes	9	1.37	Yes
2 cavities +10 mm sheet +10 mm belt	C4	air	PCA	FRN	yes	9	1.59	No
	C5	air	PCA	glass	no	9	1.89	No
	C6	air	glass	FRN	yes	9	1.91	No
	C7	air	glass	glass	no	9	2.06	No
2 cavities +10 mm sheet +20 mm belt	D1	air	PCA	FRN	yes	10	1.46	No
	D2	air	PCA	glass	no	10	1.86	No
	D3	air	glass	FRN	yes	10	2.13	No
	D4	air	glass	glass	no	10	2.32	No
	D5	**air**	**PCA**	**FRN+PCA**	**yes**	**10**	**1.06**	**No**
3 cavities +5 mm sheet +10 mm belt	E1	air	glass	FRN	yes	9	1.53	No
	E2	air	APC	FRN	yes	9	1.64	No
	E3	air	glass	FRN	yes	9	1.70	No
	E4	air	APC	FRN	yes	9	1.51	No

Legend

U<1.3W/m^{2}K high efficiency

1.3<U<1.7 W/m^{2}K efficiency

1.7<U<2.0 W/m^{2}K low efficiency

NOMENCLATURE

B	Width	[m]
F	factor view	dimensionless
g	gravitational acceleration	[m/s^2]
Gr	Grashof number	dimensionless
hc	convective heat transfer coefficient	[W/m^2K]
hr	radiative heat transfer coefficient	[W/m^2K]
H	Height	[m]
L	Cavity thickness	[m]
Nu	Nusselt Number	dimensionless
Pr	Prandtl Number	dimensionless
Ra	Rayleigh Number	dimensionless
S	Total thickness	[m]
Sv	Glass sheet thickness	[m]
T	Temperature	[°C]
U	Transmittance value	[W/m^2K]
α	thermal diffusivity	[m^2/s]
β	volumetric thermal expansion coefficient	[K^{-1}]
ε	emissivity	dimensionless
λ	thermal conductivity	[W/mK]
ρ	density	[kg/m^3]
σ	Boltzmann constant	[$W/(m^2 K^4$]
υ	kinematic viscosity	[m^2/s]

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