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Factors in a Sustainability Assessment of New Types of Closed Cavity Façades

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***Abstract*—**With the current increase in CO_2 emissions and global warming, the sustainability of both existing and new solutions must be assessed on a wide scale. As the implementation of closed cavity façades (CCF) is on the rise, various factors must be included in the analysis of new types of CCF. This paper aims to cover the relevant factors included in the sustainability assessment of new types of CCF. Several mathematical models are being used to describe the physical behavior of CCF. Depending on the type of CCF, they cover the main factors which affect the durability of the façade: thermal behavior of various elements in the façade, stress and deflection of the glass panels, pressure and the moisture control in the cavity. CCF itself represents a complex system in which all mentioned factors must be considered mutually. Still, the façade is only an envelope of a more complex system, the building. Choice of the façade dictates the heat loss and the heat gain, thermal comfort of inner space, natural lighting, and ventilation. Annual energy consumption for heating, cooling, lighting, and maintenance costs will present the operational advantages or disadvantages of the chosen façade system in economic and environmental aspects. Still, the only operational viewpoint is not all-inclusive. As the building codes constantly demand higher energy efficiency as well as transfer to renewable energy sources, the ratio of embodied and lifetime operational energy footprint of buildings is changing. With the drop in operational energy CO_2 emissions, embodied energy emissions present a larger and larger share in the lifecycle emissions of the building. Taking all into account, the sustainability assessment of a façade, as well as other major building elements, should include all mentioned factors during the lifecycle of an element. The challenge of such an approach is a timescale. Depending on the climatic conditions on the building site, the expected lifetime of a glazed façade can exceed 25 years. In such a timespan, some of the factors can be estimated more precisely than the others. However, the ones depending on the socio-economic conditions are more likely to be harder to predict than the natural ones like the climatic load. This work recognizes and summarizes the relevant factors needed for the assessment of a new type of CCF, considering the entire lifetime of a façade element in an environmental aspect.

***Keywords*—**Assessment, closed cavity façade, life cycle, sustainability.

I. Introduction

CCF is a glazed element of a building envelope consisting of outer glass pane, closed cavity where sun shading is located and an inner double-glazed or triple-glazed insulated glass unit (IGU). Although term "closed" suggests a hermetically sealed cavity, it is not the case. A small amount of air permeability exists between the cavity and the surroundings. In the case of double skin façades, where the cavity is ventilated and air permeability is high, the pressure difference between the cavity and outer air is almost nonexistent. The mechanical forces affecting the outer glazed pane are reduced to wind load and heat stress. Unlike in single or double skin façades, components in CCF are faced with greater loads in terms of temperature and pressure buildup inside the closed cavity, which can affect the behavior and durability of the façade [1]. Understanding dynamic and mutually dependent physical processes occurring inside CCF requires insight into the thermal, structural and hygrothermal behavior of the façade element. An accurate model allows for various component combinations and types of CCF to be analyzed before real scale test models are assembled.

The thermal quality of the envelope is a vital factor in the energy efficiency of a building. As the source of energy in buildings transfers from fossil fuels to renewable energy, and zero energy standards are adopted, both operational and embodied energy in buildings become an important sustainability indicator [2]. The sustainable building design incorporates more than energy efficiency. It should cover a wide spectrum of socio-economic and environmental aspects – durability, affordability, resource conservation, social equity. The environmental aspect of building element sustainability is assessed by embodied energy footprint of the element alongside operational energy footprint of the building [3]. Thermal behavior and thermal characteristics of construction elements in the envelope are the base of energy efficiency in buildings.

II. CCF Heat Transfer

The primary factor in the CCF behavior model is the temperature of each component. The pressure difference, glass deflection and dry air exchange rate all depend primarily on the temperature [1]. Understanding the thermal behavior of complex CCF systems requires recognition of façade elements, climatic parameters and heat transfers to cover in the model.

Components of the CCF which influence the overall thermal behavior are the outer glass pane, air gap (cavity), sun blinds inside the cavity and the interior IGU. For improved model precision, IGU also should be observed as three components – middle glass pane, inert gas filling and interior glass. The majority of the heat transfer takes place by these elements, while some of the heat is also transferred by façade frames and spacers and should also be considered.

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Of the three types of heat transfer – radiative, convective and conductive – in the case of glazes elements, heat transfer is primarily convective and radiative, while smaller amount of heat transfer by conduction occurs only in thin layers of inert gas and glass [4].

Radiative heat transfer includes infrared radiation transfer between the two surfaces or the ambient. Such heat transfer in glazed elements is mostly represented on the outer surfaces – between inner glass and interior ambient and outer glass and exterior ambient – since those surfaces are not covered with low emissivity coatings [5]. Radiative transfer between inner glass pane surfaces is significantly diminished, while applied coatings reduce surface emissivity up to 50 times [6]. Other than glass, sun blinds inside the cavity are another element in which a great amount of radiative heat transfer occurs. Depending on the surface color, solar ray incidence angle and the blind slat tilt angle, the sun blinds will reflect a certain amount of solar radiation and absorb the rest [7]. A large amount of radiative transfer is expected as the temperatures of the sun blinds can reach up to 90 °C and the coating surface emissivity of blinds is of high value [8].

Convective heat transfer in building envelope takes place between solid surfaces and the fluid. In the CCF case, the fluid is inner and outer air and the air inside the cavity. As there is a greater difference in temperatures, the convection in the fluid film layer is increased as well as the heat transfer coefficient. Other factors influencing the convective heat transfer are surface size and inclination. In the case of outer glass exposed to outer elements, windspeed is another factor in convective heat transfer.

A convective transfer is calculated by dimensionless Nusselt, Reynolds, Grashof and Prandtl number, including properties of the fluid such as cinematic and dynamic viscosity, pressure, heat capacity, and conductive heat transfer coefficient [9].

The convective heat transfers through and inside the façade cavity are highly complex due to numerous factors affecting them. Air buoyancy and flow are determined by surfaces of different temperatures and obstacles inside the cavity. The temperature difference between the glass panes and the sun blinds, the position of sun blinds, and the blind slat tilt angle govern the airflow pattern and the heat transfer through the cavity. While the modeling of radiative and conductive heat transfers is relatively simple, an accurate model of fluid-driven heat transfer inside the façade cavity requires a computational fluid dynamic (CFD) approach [4], [10].

Conductive heat transfers in glazed elements occur in glass panes, laminated glass interlayers and a thin layer of inert gas filling. Heat conduction through glass panes is the most intense since the thermal resistance of glass is almost negligible compared to the one of an inert gas layer [5]. Inert gas layer thermal resistance is proportional to the thickness of the layer only in the case of thin layers and small temperature differences between glass panes. As the thickness of the layer increases, enough room is created for the convective movement of the gas. A similar case occurs with a greater temperature difference between glass panes - the difference in levels of gas buoyance is induced at a level when convection becomes possible [11].

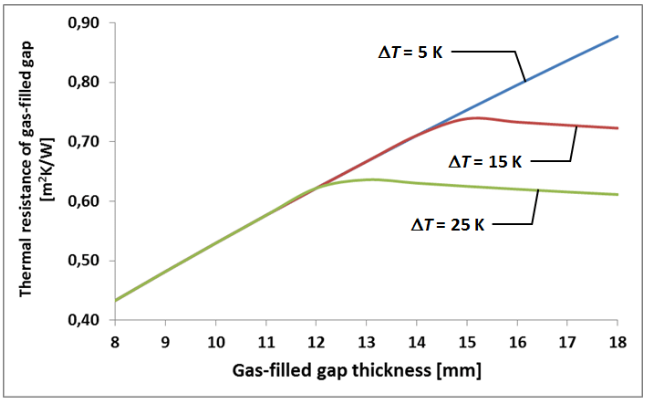

Fig. 1 Heat transfer through argon layer depending on the thickness of the gas layer and glass pane temperature difference [11]

TABLE I
CONDUCTIVE HEAT TRANSFER RESISTANCE OF IGU COMPONENTS

Material / Component	Heat transfer coefficient, λ [W/(mK)]	Thickness, d [mm]	Heat transfer resistance, R [m²K/W]
Glass	1	5	0.005
PVB layer	0.22	0.76	0.003
Laminated glass*	-	10.76	0.013
95% Argon, 5% Air	0.025	16	0.640

* 5 mm float glass + 0.76 PVB layer + 5 mm float glass

Numerous factors regarding heat transfer through CCF have been pointed out. Heat transfer from one side of the façade to the other, due to differences in interior and exterior ambient temperature, represents only a small share in the thermal behavior of glazed façades. For a triple-glazed façade with glazing U value of 0.6 W/m^2 and temperature difference of 40 °C (20 °C in the interior and -20 °C on the outside), heat transfer amounts to 24 W. The main drive in extreme temperatures changes in such façade is solar radiation [4]. Peak solar radiation, or irradiance, reaching the Earth's surface is approximately 1050 W/m^2 incident on a surface directly facing the sun on a clear summer day, depending on the location's latitude [12]. According to calculations by Meteonorm 8.0 software, solar irradiance on south-oriented façade panels in the northern hemisphere at a latitude of 45°, reaches up to 980 W/m^2 during winter and 320 W/m^2 during summer. For such a tilt and orientation, irradiance is greater during winter due to lower solar altitude angle. Therefore, solar energy irradiated on the outer surface of the façade is up to 30 times greater compared to energy transfer through the façade due to the thermal difference between interior and exterior ambient. Outer glazing and sun protection elements are the elements most exposed to solar radiation. Therefore, these elements become the main source of heat inside CCF, as they are the elements that will absorb most of the solar irradiance.

Since the façade represents only a skin of a building, both cannot be analyzed separately. However, an accurate thermal model of the façade provides baseline data for other behavior analyses of CCF, like the mechanical and hydrothermal, as well as the calculation of energy efficiency of the entire building

III. Glass Deflection in IGU

IGU comprises two or three glass plates connected by a steel structure around the perimeter. The product needs to be made as a closed airtight box.

The difference between internal and external pressure, defined by climatic conditions, creates pressure in the cavity under which the glass is deformed. As the glass deforms, there is a change in air volume inside the cavity, the pressure decreases and most of the load disappears. The pressure inside the IGU, i.e., the difference between the internal and external pressure, is caused by the change in air temperature inside the cavity. Climatic factors change continuously throughout the year, which affects changes in the shape of the glass. Changes in the shape of the glass due to deformation can have visual and constructive consequences. To reduce the visible deformation of the outer glass, it is possible to use sea rigid outer glass, façades with vacuum IGU, etc. [13].

Triple-glazed and quadruple glazed IGUs have better thermal properties but tend to have higher deformations and stress due to the temperature change, wind load and atmospheric pressure. Although all mentioned, gaps are beneficial for wind load pressure. Therefore, different methods have been used to equalize pressures, such as valves for periodical equalization. In addition, properly designed spacers will reduce the glass thickness by around 2 mm [11].

The gas difference in the cavities distributes the outer loading to all glass panels in the unit. More cavities will increase the total thickness of the gas and result in more sensitivity to the atmospheric pressure and temperature changes. Deflection of the glass panels can result from increased or decreased atmospheric pressure, increased or decreased temperature in the cavities and wind loading on the outer glass panel (Fig. 1). Gas equalization in the gaps can be continuous or one time period. The first equalization occurs during the installation of the IGU when there can be a significant difference between the atmospheric pressure, temperature and altitude between production location conditions and mount conditions. Gas in the gap during the production has some initial parameters of pressure, temperature and volume, while during the service life of the unit, climatic changes are causing pressure inside the gap and deformation of the glass panels. For example, altitude decrease will result in lower atmospheric pressure and vice versa. The deformation form could be convex (Fig. 2 (a)) or concave (Fig. 2 (b)). In the case of climatic wind load, both glass panels deflect in the same direction (Fig. 2 (c)). Through the gas, the load is transmitted uniformly to the inner glass. All mentioned leads us to conclude that during the winter, IGU shape will most likely be deformed in concave form and in the summer in convex form.

After the mount temperature difference will result in gas pressure difference. For example, [11] showed that 1 K temperature increase leads to a drop of atmospheric pressure by 0.341 kPa.

Laminated glass is a composite made of two or more glass plies bonded together through polymeric interlayers. The flexural performance of such composite depends on shear coupling between rigid glass elements, which occurs across the interlayer [14]. The influence of polymeric interlayer is taken into account through the effective thickness, a substitutional thickness of glass monolith with the corresponding parameters needed for computing deformations and stresses.

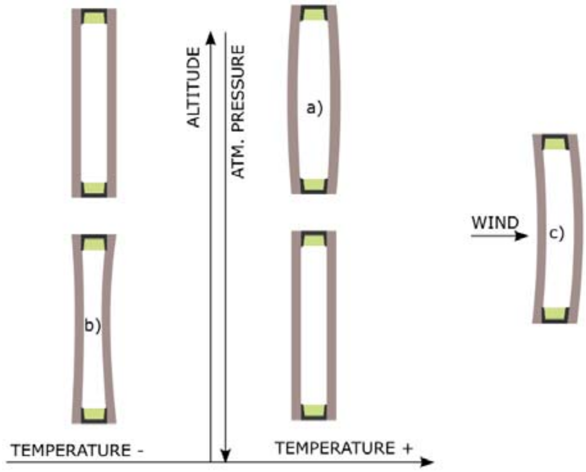

Fig. 2 Forms of IGU deformations

Due to the deformability of polymeric interlayer, fully composite behavior is not possible to obtain between the glass plies. Therefore, the shear stiffness of the interlayer becomes a crucial factor for the calculation of the shear coupling effect. Flexural performance of laminated glass lies somewhere in-between perfect bond (monolithic limit) and independent frictionless relative sliding of plies (layered limit).

Composites of concrete and steel [15] could be relevant in the case of laminated glass. However, analytical definition and computation of deformations and stresses inside of the laminated glass are difficult. In the case of a simply supported plate along four sides, an analytical approach has been proposed by [16]. Precise calculation of the stress and strain state is quite complex and usually requires complex numerical analysis that takes into account the nonlinearity, viscoelasticity of the polymer and the influence of temperature on the properties of the polymer.

A simplified approach takes polymers as linearly elastic with a secant modulus of elasticity that considers load duration and temperature. Various polymeric films are available on the market [17]: polyvinyl butyral (PVB), ethylene-vinyl acetate (EVA), and sentry glass (SG).

Depending on the type of polymer, temperature T and the characteristic duration of the load t_0, the secant shear modulus of the interlayer can vary from 0.01 MPa (PVB at T = + 60 °C under constant load) to 300 MPa (SG at T = 0 °C and t_0 = 1 s) [14]. On the other hand, the glass remains linearly elastic to fracture (Young's modulus E = 70 GPa and Poisson's ratio ν = 0.2).

The method used to calculate the sandwich panel was later used in the case of laminated glass. The interlayer itself has negligible axial and bending strength but can transmit shear coupling stresses. Therefore, the formula considers the length and width of the "beam" composed of two layers of glass of thickness h1 and h2 with the corresponding modulus of elasticity (Young modulus) and an intermediate layer of thickness *t* and elastic shear modulus *G*.

An incomplete composite behavior between glass panels is presented through the reduction of bending properties of composites. Deflection-effective thickness can be taken into account to calculate the deflection of the laminate.

IV. Embodied and Operational Energy CO_2 Footprint

Since 2020, nearly zero-energy standard is an obligation for all new buildings in Europe. According to the European Commission, "nearly zero-energy building (nZEB) means a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby" [18]. Such standard is achieved by implementing renewable energy sources like biomass, heat from the environment, solar energy and waste heat from powerplants. The transfer to renewable energy sources in buildings reduces the use of primary energy and CO_2 emissions from operational energy (OE) compared to fossil energy sources [19], [20]. The savings in CO_2 emissions are primarily due to higher energy efficiency of building envelope, HVAC systems, passive cooling, implementation of LED lighting as well as electricity production on-site [21]. Renewable energy production on buildings utilizing PV modules further reduces energy consumption down to net-zero energy building (NZEB) standard, in which the amount of annually produced energy on-site is equal to the one spent annually [20].

OE CO_2 emissions can vary greatly depending on the energy source, climate conditions, building purpose and overall energy efficiency of building systems and envelope. nZEB and NZEB standards significantly reduce OE and OE CO_2 emissions from buildings compared to prior energy standards.

TABLE II
CO_2 Emissions per kWh of Heat from Different Fuels and Heat Sources [22], [23]

Energy/Heat source	CO_2 emissions gCO_2/kWh
Not suitable for nZEB	
Oil	330
Natural gas	277
Anthracite, Coal	394
Lignite	433
Electricity (Europe avg.)	231
Suitable for nZEB	
Electrical heat pump (COP = 3)	77
Biomass (wood)	13

Contribution of a glazed façade in energy efficiency solely regards the envelope of the building. Ideally, transparent elements of the envelope should minimize unwanted heat loss or gain, and at the same time enable solar gains during winter, prevent overheating during summer and to ensure enough natural light in the interior. Parameters of the glazed façade which will contribute most to the envelope thermal quality are glazing and frame properties [24].

Even though the lifetime OE presents the majority of energy consumption in buildings, it should not be considered separately from embodied energy (EE). With the further improvement in the energy efficiency of buildings and the drop in OE during building lifetime, EE in building materials will present larger and larger share in building lifecycle energy consumption [25].

CO_2 emissions for the production of building materials are presented as a ratio of kg of CO_2eq per kg material. CO_2eq includes the global warming potential of CO_2 and all other greenhouse gasses released in the process of production. Most CO_2 per kg of material is emitted in the production of thermoplastic materials (polystyrene, polyethylene, etc.) and the least in wooden products that absorb carbon from the atmosphere (carbon sink). Ratio of CO_2 emitted per kg of material must be observed along with the mass of material used in the structure. Even though the production of thermoplastic materials emits the most CO_2 per kg of material, the weight of those materials in the construction of the building is negligible compared to load-bearing construction. Load-bearing construction is the most massive element in the building and therefore the greatest source or sink of EE CO_2 emissions.

Of all types of load-bearing constructions, reinforced concrete is responsible for the greatest EE CO_2 emissions due to the energy-consuming cement production process.

TABLE III
Material Production and Building Construction CO_2 Emissions [26]

Material	Material production emissions $kgCO_2eq/kg$	Mass in construction [kg/m^2]	Emissions per m^2 of construction $kgCO_2eq/m^2$
Polystyrene	4.17	2.39	9.88
PE sheeting	3.30	0.19	0.65
Mineral wool	2.45	3	7.35
Glass	0.98	25	24.50
Perforated brick	0.18	250	45.50
Reinforced concrete	0.16	400	61.82

In the glazed elements of the building envelope, the most represented materials are glass and aluminum. Approximately 1.00 $kgCO_2eq/kg$ is emitted to make glass, what makes it one of the more represented materials in EE [26]. Primary production of aluminum from bauxite ore results in 5.92-41.10 $kgCO_2eq/kg$ as the process incorporates a lot of primary energy for ore mining and processing. On the other hand, recycled aluminum requires much less energy and results in 0.32-0.74 kg CO_2eq/kg, approximately 20 times less than the primary production [27]. While gaskets and sealants are other indispensable elements in the façade, they represent a minor share in the mass of the façade and are rarely recycled.

The expected lifetime of a glazed façade is approximately 15 years. Of the metal, glass and sealant components, the sealants are the weakest link in the façade. Prediction of sealant service life is difficult due to many factors affecting it, where joint movement due to glass deflection and weathering are among the main factors. The service life of building components varies from 15 to 50 years depending on the component and is another relevant factor to consider in the EE sustainability assessment.

In addition to the economic one, the environmental assessment will validate or rebut the choice of the façade or façade components.

V. Conclusion

This paper points out relevant factors in thermal and structural behavior of CCF. Complex physical processes inside the CCF simultaneously combine conductive, convective and radiative heat transfers, solar irradiance absorption, moisture control and pressure equalization dependent on the temperature and glass stiffness. Understanding the interaction of these processes is vital for the computational modeling of CCF. Furthermore, an accurate model allows for behavior assessment of various CCF elements and types and their contribution to the energy efficiency of the building.

Sustainability assessment of building components does not end with the component itself but covers its contribution to the entire building during its service life. Knowledge of the thermal characteristics of the envelope is vital as the envelope determines the energy efficiency level of the entire building as well as OE use and CO_2 emissions. With the transfer from fossil fuels to renewable energy sources in buildings and constant improvement of energy efficiency of buildings, OE use is reducing as well as OE CO_2 emissions. With the drop in OE use, EE in buildings presents a growing share in overall energy use and becomes an unavoidable factor in a sustainability assessment. Only an overall assessment including as much as possible economic and environmental factors will prove real benefits or deficiencies of building components such as CCF.

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