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NUMERICAL INVESTIGATIONS OF THE THERMAL PROPERTIES OF WINDOW SYSTEMS: A REVIEW

PRZEGLĄD NUMERYCZNYCH METOD OKREŚLANIA WŁAŚCIWOŚCI CIEPLNYCH OKIEN

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Abstract

Windows are an essential part of building envelopes since they enhance the appearance of the building, allow daylight and solar heat to come in, and allow people to observe outside. However, conventional windows tend to have poor U-values, which cause significant heat losses during the winter season and undesired heat gain in summer. Modern glazing technologies are therefore required to improve thermal resistance and comfort of the occupants, whilst mitigating the energy consumption of buildings. In the present work, a comprehensive review of the numerical investigations of the thermal properties of window systems and glazed buildings partitions is presented. However, the proposed models to predict the thermal performance most often concern only specific cases of window systems related to geometry and used material solutions, focused on specific physical processes, thus they contain a lot of simplifications, such as omitting the influence of radiation, temperature changes or velocity profiles.

Keywords: windows, windows thermal resistance, thermal transmittance, heat transfer coefficient, mathematical modelling

Streszczenie

Istotnymi elementami budynków są okna, które wpływają na ich wygląd, umożliwiają dostęp światła dziennego i ciepła pochodzącego z promieniowania słonecznego, a także pozwalają na obserwowanie otoczenia. Jednakże w porównaniu do pozostałych przegród budowlanych konwencjonalne okna charakteryzują się zwykle gorszymi wartościami współczynnika przenikania ciepła U, generując znaczne straty ciepła w sezonie zimowym i niepożądane zyski ciepła w lecie. W związku z tym konieczne jest poszukiwanie nowoczesnych rozwiązań w technologii okiennej, które poprawią opór cieplny i komfort mieszkańców, jednocześnie zmniejszając zużycie energii przez budynki. W niniejszej pracy przedstawiono przegląd numerycznych metod określania właściwości cieplnych okien i przeszklonych przegród budowlanych. Analiza literatury pokazuje, że proponowane modele dotyczą jednak najczęściej tylko konkretnych przypadków systemów okiennych, związanych z określoną geometrią i zastosowanymi rozwiązaniami materiałowymi, w których uwzględnia się jedynie wybrane procesy fizyczne. Skutkiem tego jest przyjmowanie podczas modelowania wymiany ciepła szeregu uproszczeń, takich jak pomijanie wpływu promieniowania czy nieuwzględnianie zmian temperatury i prędkości.

Słowa kluczowe: okna, opór cieplny okien, przenikalność cieplna, współczynnik przenikania ciepła, modelowanie matematyczne

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1. INTRODUCTION

Windows represent essential elements of buildings' envelope, which determine natural daylight and direct solar energy gains, provide view of the outdoors and supply fresh air [1, 2]. In addition, they significantly contribute to the heat transfer between the outside and inside environments, thus have a significant impact on overall building energy consumption [3, 4]. Nevertheless, glazing systems usually have the lowest energy efficiency of building envelope components [5, 6]. They are the most problematic in terms of heat loss, generating to 60% of the total energy loss through the building envelopes [7, 8]. Changes in architectural trends have shown that the number and dimensions of windows in buildings are increasing. Today large glazing windows and curtain walls are frequently designed and integrated in modern housing, which makes it necessary to ensure their high thermal resistance [9-11]. On the other hand, in existing buildings old window structures have low thermal resistance, thus an effective way to improve buildings envelope energy performance and reduce heat loss, is the replacement of old window structures by modern windows. Innovative windows should control solar radiation and have high thermal resistance which allow to decrease heat loss in the winter and heat gain in the summer, dynamically responding to varying weather conditions and occupant preferences [12]. There is thus a call for new advances aiming at improving the overall performance of building fenestration by considerably decrease both building energy demand and peak heat loads. Heat transfer in tall cavities where aspect ratio is high such as glazing, takes place through conduction through the glass panes, convection in the gaseous medium filling the gap between the panes and radiation. Therefore, a reduction in the overall heat transfer coefficient of windows can be achieved by minimizing the convective and radiative components [13].

Recently, a variety of technologies have been developed to improve the thermal resistance of windows and building glazing systems. Inhibiting convection in the gaseous medium filling the gap can be achieved by using approaches such as multiple glass panes [14, 15], optimization of the gap width [16-19], inert gases as gap fill [20, 21] and vacuum glazing [22, 23]. Glass used in windows provide adequate illumination levels in the interior of buildings receiving the visible part of solar radiation. The other part of solar radiation in the infrared region entering through windows causes increase of interior temperature, thus glazing is a significant component in investigating problems such as energy demands, assessment of heating and cooling loads and thermal comfort in a building [24, 25]. Proper selection of glazing material can reduce the solar heat gain component in summer as also heat loss in winter [26]. Controlling solar radiation and daylight can be achieved through application of tinted coatings, reflective coatings [27], solar control films [28, 29], interstitial shading devices (e.g, external blinds' [30, 31], single and double curtains [32, 33], roller shades [34], window shutters [35], angular selective shading systems [36-39] and smart window techniques (e.g. electrochromic [40], thermochromic [41], photochromic [42] glazing). Windows are also expected to facilitate sufficient air change rates [43]. To achieve these attributes, various transparent building components have been developed, including ventilated windows [44-48] and ventilated double skin facade [49-52].

This paper presents a review of the modeling of heat transfer in windows systems with the aim of identifying the different approaches and applications implemented, as well as the research gaps. Firstly, the methods of the numerical investigations of the thermal properties of window systems present in the literature are summarized. Then, the most common thermal models are described, considering the influence of the gap thickness, internal surface temperature difference and the radiative heat transfer. Finally, the shortcomings and research gaps are discussed.

2. THE NUMERICAL INVESTIGATIONS OF THE THERMAL PROPERTIES OF WINDOW SYSTEMS

There are two ways of numerical investigation of the thermal properties of window systems: (1) one-dimensional calculation based on standard calculation methods and (2) two- or three-dimensional mathematical modeling using finite element or finite volume models [12]. Standards describing the thermal properties of window systems include International Standards ISO 10292 [53], ISO 15099 [54] and European Standard EN 673 [55]. A crucial parameter characterizing thermal properties of windows is the overall heat transfer coefficient *U*, which defines the heat flow through 1 m^2 of building partition surface with a temperature difference on both sides $\Delta T = 1$ K. Under these standards, the *U*-factor of window systems can be expressed as (Fig. 1):

$$U = \frac{1}{R_T} = \frac{1}{\frac{1}{h_i} + \sum_{s=1}^{n} \frac{\delta_g}{k_g} + \sum_{s=1}^{n-1} \frac{1}{h_{gap}} + \frac{1}{h_o}} \quad (1)$$

where R_T is total thermal resistance of window, h_i, h_{gap}, and h_o are the heat transfer coefficients at the inner surface of the window, the gap between the glass panes, and the outer surface of the window, respectively, $h_{gap} = h_{rad,gap} + h_{conv,gap}$ is the combined radiation and convection heat transfer coefficient of the gap between the glass panes, is the thickness of the glass pane, k_g is the thermal conductivity of the glass pane, n is a number of glass panes.

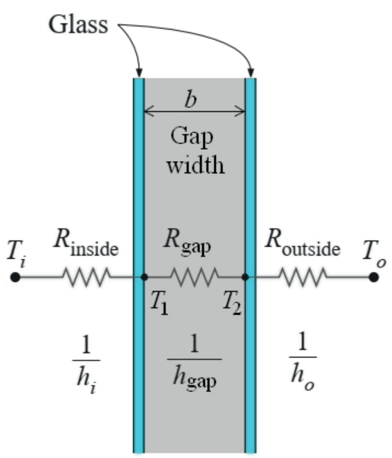

Fig. 1. The thermal resistance network for heat transfer through a double-pane window

Heat transfer in enclosed spaces, such as gap between glass panes, is complicated by the fact that the gas in the enclosure, in general, does not remain stationary. While the gas flows over the glass surface as a result of gravitational movements, there is a significant influence of the gas viscosity on its velocity. The region of the flow over the glass panes, in which the viscous effects and the velocity changes are significant is called the boundary layer [56]. Close to the panes surfaces, value of the velocity is zero, and it increases with increasing distance from the glass surface. In the inviscid flow region, the frictional effects are negligible and the velocity remains essentially constant. The thickness of the boundary layer depends on the temperature and the physical properties of the gas, thus the heat transfer by convection is influenced by physical parameters of the fluids such as specific heat, density, thermal diffusivity and viscosity. It follows from the above that the convective heat transfer coefficients (i.e. h_i, h_{gap}, h_o from eq. 1) are a function of the temperature of the heat exchanging surface as well as the flow velocity, temperature and physical properties of the gaseous medium.

The accuracy of heat transfer calculations is a function of three dimensionless parameters: the aspect ratio of the gap, the Prandtl number, Pr, and the control parameter of the flow, the Rayleigh number, Ra. The relative thickness of the velocity and the thermal boundary layers is best described by the dimensionless parameter Prandtl number, defined as

$$Pr = \frac{\nu}{a} = \frac{c_p \mu}{k} \quad (2)$$

where ν is kinematic viscosity, a is thermal diffusivity, c_p is specific heat, is dynamic viscosity, k is the thermal conductivity of the fluid.

The Rayleigh number, which is the product of the Grashof and Prandtl numbers, can be expressed as:

$$Ra = Pr \cdot Gr \quad (3)$$

The Grashof number, Gr, is a dimensionless number which approximates the ratio of the buoyancy to viscous force acting on a fluid, can be expressed through following equation:

$$Gr = \frac{g \beta \Delta T L^3}{\nu^2} \quad (4)$$

where g is gravitational acceleration, β is coefficient of volume expansion, ΔT is internal glass surface temperatures difference across the gap, L is the characteristic length, which in the case of double pane window is the distance between the two glass panes ($L = b$, where b is width of the gap between two glass panes).

In particular, for $Ra < 1750$ viscosity prevents the onset of buoyancy-driven convective motions. Within the range $1750 < Ra < 3000$ the onset of convection is increasing, depending on the geometric parameters. For $Ra > 3000$ heat transfer is a growing function of the Rayleigh number, which means a reduction of thermal resistance caused by the thermal conductance [57]. The ratio between the pure conduction resistances to a convection resistance represents the Nusselt number, given by:

$$Nu = \frac{hL}{k} = Const\left(Gr \cdot Pr\right)^e \quad (5)$$

where $Const$ is a constant and e is an exponent that makes it possible to account for the orientation of the glazing. For vertical glazing, these are 0.035 and 0.38, respectively [52]. Apart from standard equation calculation methods, the most common approach

environment

used in order to determine the thermal properties of window systems are finite element or finite volume simulations, especially when the air flow pattern in the gap between glass panes is investigated. Modeling methods are numerous but the majority of models incorporate CFD analysis [58-63]. In the CFD model, the fluid medium is modeled based on two- or three-dimensional assumptions by meshing the fluid region into a finite number of control volumes. The finite volume method used to study natural convection in the gap of double pane windows, follows assumptions below: 1) heat transfer through a double-pane windows is considered in a stationary two-dimensional formulation; 2) free-convective flow of a gas medium in the window′s compartments is considered laminar and is described by a system of Navier–Stokes equations for a compressible medium; 3) the glass panes surfaces facing into the gap are set as two isothermal walls each with a different temperature to represent the temperature difference between indoor and outdoor environments; 4) the top and bottom surfaces bounding the gap are assumed to be adiabatic; 5) the influence of separating frames is disregarded; 6) all thermophysical properties of the fluid are assumed to be constant, except for the gas medium density and viscosity, which are considered temperature-dependent by the linear law. The governing equations for these finite volume models for steady two-dimensional flow of a fluid with constant density are:

Mass balance:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{6}$$

Momentum balance:

$$\frac{\partial u^2}{\partial x}+\frac{\partial uv}{\partial y}=$$

$$-\frac{1}{\rho}\frac{\partial p}{\partial x}+v\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)\frac{\partial uv}{\partial x}+\frac{\partial v^2}{\partial y}= \tag{7}$$

$$-\frac{1}{\rho}\frac{\partial p}{\partial y}+v\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+g\beta\left(T_1-T_2\right)$$

Energy balance:

$$C_p\rho\left(\frac{\partial uT}{\partial x}+\frac{\partial vT}{\partial y}\right)=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+S_h \tag{8}$$

where u is velocity component in x-direction, v is velocity component in y-direction, is density, S_h is the radiative heat transfer.

However, in most of these studies, long-wave radiation heat transfer, which accounts for two thirds of the total heat transfer across the air cavity [63], is neglected in the numerical modeling. This means the radiative heat transfer, S_h, in Equation (8) was not included.

2.1. The influence of the gap thickness and internal glass surface temperatures difference across the gap

The thermal resistance of a tall air cavity associated with conductive heat transfer increases with the width of gap filling by gaseous medium, thus increasing the width between two panes of glass decreases the thermal transmittance and improves the insulation effect in windows systems. Manz investigated overall convective heat transfer in an air layer within a rectangular cavity using a commercial CFD code [64]. It was reported that Nusselt numbers do not deviate more than 20% from the correlations based on experimental data. A similar numerical study is conducted in paper [65] considering both laminar and turbulent natural convection in cavity for aspect ratios of 20, 40 and 80 and for Rayleigh numbers in the range of 102 to 108. They presented convective Nusselt number correlations for both laminar and turbulent flows. However, it is known that there is a limit in the effect of increasing the gap on the improvement of insulation. This limit is the ‘optimum’ separation of the panes and depends on the phenomenon of free convection within the gap, which depends both on the geometry (characteristic size and aspect ratio) and on the temperature boundary conditions. In particular, convection enhances the heat flux through the window, reducing thermal insulation. In the case of narrow gaps ($Nu < 1$) it is assumed that convection does not occur and thermal resistance of the gap increases linearly with its width. The influence of convection is taken into account while a certain gap width limit (for $Nu = 1$) is exceeded. In the case of non-linear range (for $Nu > 1$) thermal resistance of the double-pane window does not improve [66]. For cases with a small gap width, the heat transfer by convection is insignificant due to the low values of the velocity of free convective gas flow. With an increase in the distance between the glasses, the thermal resistance of the thermal conductivity of the gas layer increases. However, in this case, due to a decrease in the hydrodynamic resistance of the plane-parallel channel, represented by two vertical glasses, the flow of the gaseous medium is intensified and, as a result, the convective heat transfer in the gaseous layer increase. As a result of the interaction of two opposite tendencies, the total convective heat flux on the inner surfaces of the glasses first decreases with increasing distance between the glasses, and then begins to increase. The influence of the width of gap between the panes and temperature difference on the thermal resistance of double-pane window were presented in paper [16]. Figure 2 shows the predicted heat transfer coefficients for the same temperature difference between the internal surfaces of 10 K. When the width of gap is larger than 25 mm, the convective heat transfer coefficient increases slightly with air space, because the increase in the convective heat transfer is larger than the decrease in the conductive heat transfer. For the internal surface temperature difference of 10 K the predicted overall heat transfer coefficient was 3.33, 2.93 and 2.71 W/m^2 K, for an air space width of 5, 10 and 25 mm, respectively. If the air gap width exceeds 25 mm, the window's thermal transmittance remains almost constant, because a slight increase in convective heat transfer is offset by a similar magnitude of the decrease in radiative heat transfer. The thermal transmittance vary with the temperature difference. Figure 2 shows the variation of U-value with the width of gap for internal surface temperature differences of 5 K, 10 K, 15 K and 20 K, respectively. As seen in the figure, the U-value decreases with the width of air space up to 25 mm regardless of the magnitude of the temperature difference.

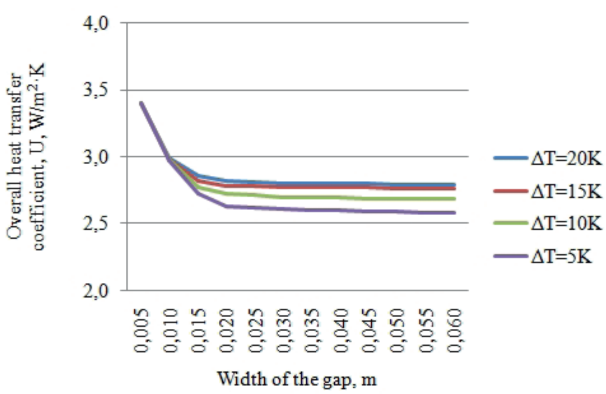

Fig. 2. Variation of overall heat transfer coefficient with the width of gap

The value of the optimum gap related to the velocity and temperature fields in double-pane window were investigated in paper [63]. Authors assigned fourth-kind conditions on the pane surfaces facing the interior of the window, taking into account the presence of radiant heat fluxes between pane surfaces. The distributions of the vertical velocity and temperature over the gap are presented in Figure 3. Figure 3 shows that near the heated pane occurs ascending flow, and near the cold pane, descending flow. In this case the temperature distribution within the gap is different from the linear one, and natural convection in the gap now exerts an appreciable influence on the process of heat transfer. The distributions of the dimensionless vertical velocity, the dimensionless temperature and heat-flux densities on the exterior and interior surfaces of double-pane window are presented in Figure 4 and Figure 5. As can be seen, the maximum heat-flux densities are observed on the upper portion of the outside pane (curve 2) and there is no region in which the heat-flux densities are constant, in practice. This also points to the significant impact of natural convection on the process of heat transfer in double-pane window. The value of the total heat flux is Q = 127.5 W. Although convective heat transfer in double-pane window is appreciable, its share in the total heat flux amounts to only 34% of the overall heat flux. The radiative heat flux is Q_r = 84.7 W (i.e., 66% of the total heat flux). The thermal resistance of double-pane window of the indicated geometry is equal to R = 0.19 m^2·K/W.

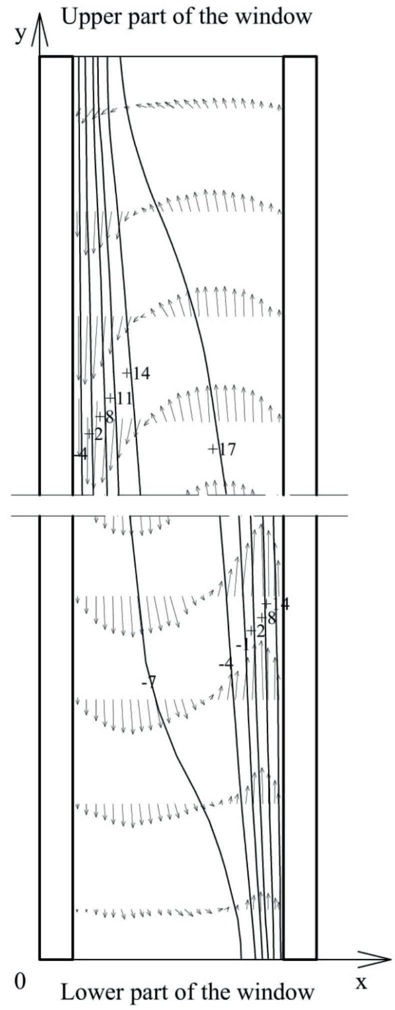

Fig. 3. Temperature fields (°C) and directions of velocity of the gas medium in vertical cross sections of the double-pane window

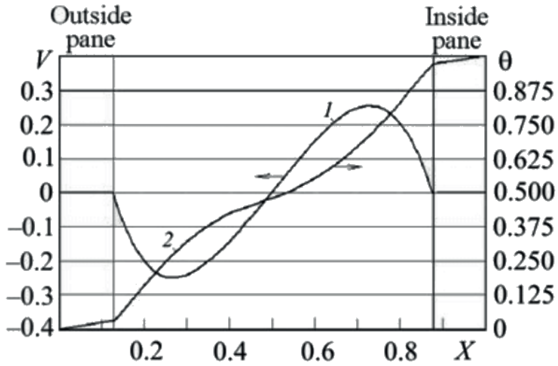

Fig. 4. Distributions of the dimensionless vertical velocity (1) in gap and of the dimensionless temperature (2) across the thickness of the double-pane window [63]

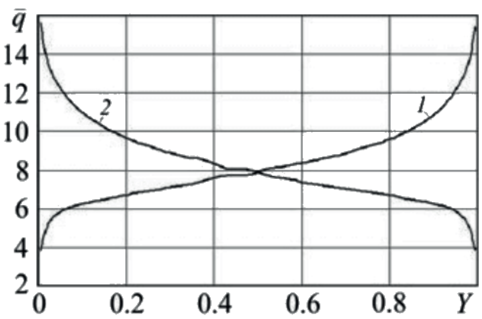

Fig. 5. Distributions of the dimensionless heat-flux densities on the exterior (1) and interior (2) surfaces of the double-pane window [63]

Arıcı et al. carried out numerically flow and conjugate heat transfer in double-glazed windows considering five different gap widths (L = 6 mm, 9 mm, 12 mm, 15 mm and 18 mm) and five different emissivity values (ε = 0, 0.25, 0.50, 0.75 and 1.0) [18]. Surface to Surface (S2S) mathematical model which ignores any absorption, emission or scattering of gas is employed to account radiative heat transfer between panes. Solar heat gain are not considered in the computations. Figure 6 shows variation of the *overall heat transfer coefficient* of air-filled double-pane window with various emissivity values and gap widths. As seen in the figure, while the overall heat transfer coefficient decreases considerably up to gap width of 12 mm, beyond this value the influence of gap width on the overall heat transfer coefficient diminishes. The overall heat transfer coefficient curves of gap width of 12 mm, 15 mm and 18 mm are almost overlapped, thus the most adequate value of the gap width is 12 mm.

The velocity and temperature profiles presented in Figure 7 signify why the U-value is almost constant beyond gap width of L = 12 mm. At its value of L = 6 mm, the gas flow velocity is low, so heat transfer by convection is negligible. In this case, the Nusselt number (except for the bottom and top of the window) is about 1, so heat transfer occurs equally by heat convection and conduction.

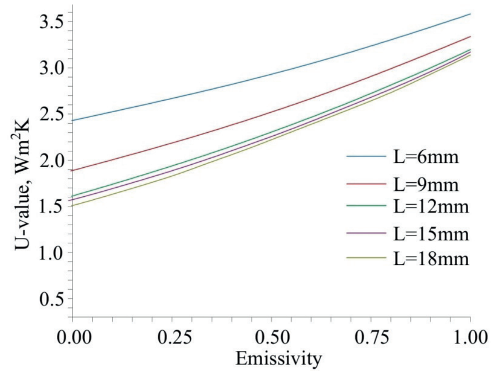

Fig. 6. Variation of the overall heat transfer coefficient of air-filled double-pane window with various emissivity values and gap widths

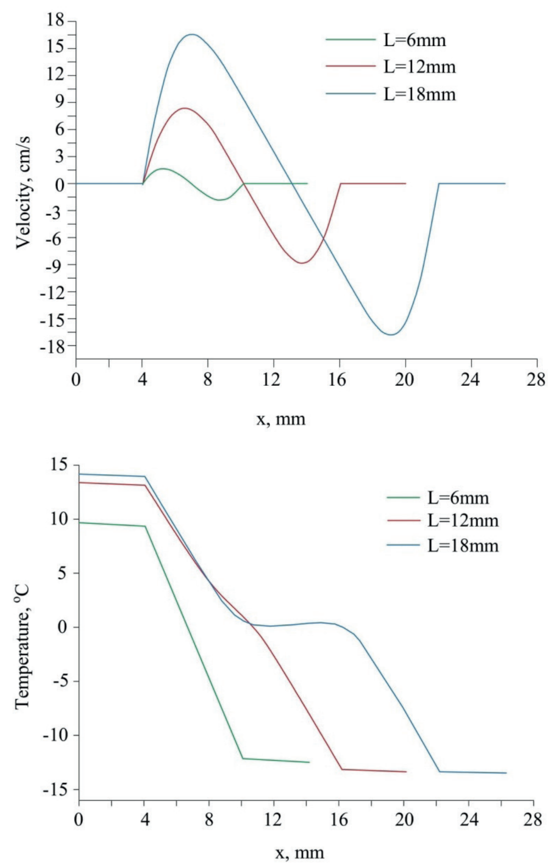

Fig. 7. Effect of gap width on the velocity and temperature profiles of air-filled double-pane window

As the gap width increases, the magnitude of velocity increases, thus the importance of convection and consequently the Nusselt number also increases. At this stage, it is observed that the Rayleigh number exceeds 6300, causing a transition flow between laminar and turbulent and degradation of the linearity of the temperature profiles. The heated air is transported from hot side to cold side horizontally and creates a short cut in heat transfer, which causes a deteriorating the linearity of temperature profiles. Thus, the decrease in the overall heat transfer coefficient is insignificant for $L > 12$ mm.

The thermal properties of double-glazed window depending on the changes in outdoor temperatures are presented in paper [67]. Figure 8 shows dependence of distance between the panes and external air temperature on overall heat transfer coefficient.

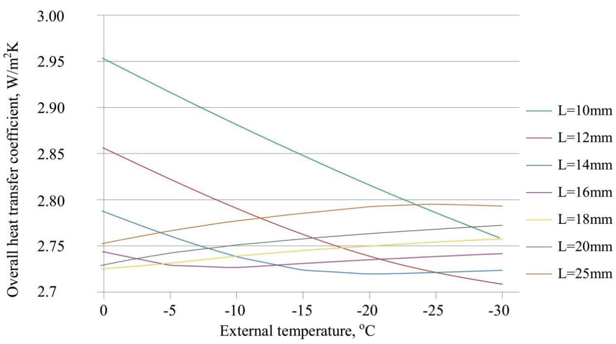

Fig. 8. Dependence of overall heat transfer coefficient of a double-pane window on distance between the panes and external air temperature

As can be seen, the decrement of the external air temperature causes a decrement of the overall heat transfer coefficient for small gap width of 10 and 12 mm. However, for larger distances between the panes, the *U*-factor slightly changed (mainly increased) to 2%. The decrement of thermal transmittance with the decrease in external air temperature can be considered a positive phenomenon at extremely low temperatures and slight changes in the *U*-factor value can be treated as insignificant. These results confirm why the change in the heat transfer coefficient of double-pane window due to the outside temperature has been ignored in the past. The thermal behavior of ventilated double-pane window with varying gap width was developed in paper [68]. The model takes into account the physical phenomena present in the heat and flow processes and also the real boundary conditions while in normal operation. The numerical simulations were compared with available results and the agreement was found satisfactory. Effects of the gap width on the temperature distribution, the velocity field, the coefficient of the total heat gain, the coefficient of the solar heat gain and the shading coefficient were investigated. Ignoring at least for the moment, the solar radiation, the heat gain or loss due to the temperature difference between the internal and the external temperatures depends of width of the gap between glass panes. Figure 9 shows the heat gain due to the temperature difference in terms of the gap between the window sheets. As can be seen the increase of the size of the gap leads to increasing the thermal resistance.

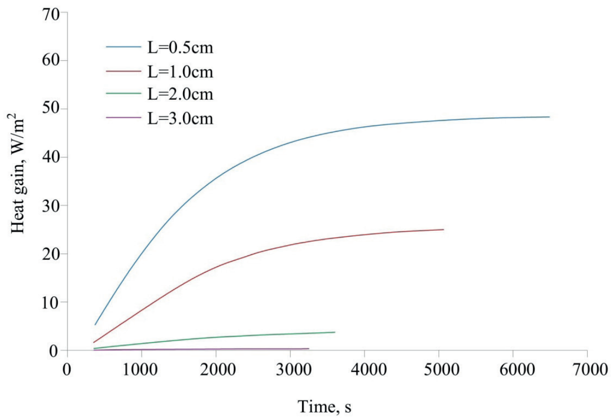

Fig. 9. Effect of the gap width on the heat gain due to temperature difference for a ventilated double-pane window

Table 1. Summary of heat transfer coefficients of windows depending on the geometry, the width of the gap and the internal surface temperature difference

Ref.	Gap width [mm]	*H* [m]	*L* [m]	Δ*T* [K]	*ε*	*U* [W/m²K]
[16]	5	1.50	1.50	10	0.84	3.33
	10	1.50	1.50	10	0.84	2.93
	25	1.0	1.50	5	0.84	2.63
	25	1.0	1.50	10	0.84	2.71
	25	1.0	1.50	15	0.84	2.78
	25	1.0	1.50	20	0.84	2.85
[18]	6	1.0	0.50	35	0.84	3.39
	9	1.0	0.50	35	0.84	3.05
	12	1.0	0.50	35	0.84	2.90
	15	1.0	0.50	35	0.84	2.86
	18	1.0	0.50	35	0.84	2.81
[63]	24	1.08	0.75	30	0.84	2.78
[67]	10	1.48	1.23	20	0.84	2.95
	10	1.48	1.23	30	0.84	2.88
	10	1.48	1.23	45	0.84	2.79
	14	1.48	1.23	20	0.84	2.79
	14	1.48	1.23	30	0.84	2.74
	14	1.48	1.23	45	0.84	2.72
	25	1.48	1.23	20	0.84	2.75
	25	1.48	1.23	30	0.84	2.78
	25	1.48	1.23	45	0.84	2.80

Table 1 present the summary of overall heat transfer coefficients of windows depending on the geometry, the width of the gap and the internal surface temperature difference.

2.2. The influence of the radiative heat transfer

Solar irradiance, incident on the window glass, which consists of the direct component from the Sun and the diffuse component from the sky, clouds, and surrounding objects, is partly transmitted and reflected, while the remaining portion is absorbed within the glass material. The absorbed portion is transmitted inward, as well as outward, by the processes of conduction, convection and longwave radiation, thus causes increase of interior temperature. The total energy transmittance is quantified by the solar heat gain coefficient, SHGC, which is the sum of the direct transmitted solar radiation plus the inward thermal convection and radiation heat transfer due to the increased inner glazing temperature above the room environment, then normalized by the incoming solar irradiance. The sum of this combined solar heat transfer, which depends on SHGC and the convective heat transfer, which depends on *U*-factor, is the total room heat gain through window system [69]. The significant impact on such energy distributions have also the polarization, frequency spectrum as well as the directions of the incident rays. An experimental approach to measure the light transmittance and solar energy transmittance of double-pane window separated by argon filled space and solar controlling film at any incidence angle was developed by Rosenfeld et al. [70] Van Nijnatten [71] measured the directional reflectance and transmittance of coated and uncoated glass samples by setting new accessories in a spectrophotometer. The thermal performance of glazing with films of different types under solar radiation was analyzed in the paper [72]. Ismail and Henríquez [73] numerically investigated solar heat gain coefficient and shading coefficient of double glass panels filled with PCM. Later, author extended his study and developed the mathematical models of heat transfer through windows formed by a single glass sheet and double glass sheets with natural or forced air flow between them under incident solar radiation [68, 74, 75]. The airflow is induced by the buoyancy forces due to the thermal effects in a gap formed by two parallel walls with non-symmetric heating as shown in Figure 10. The heat transfer consist of incident solar radiation, convection and also radiation exchange between the walls and the internal and external ambient. The two-dimensional transient model is formulated based upon the fundamental equations of mass conservation, momentum and energy, the associated constant and time varying boundary conditions.

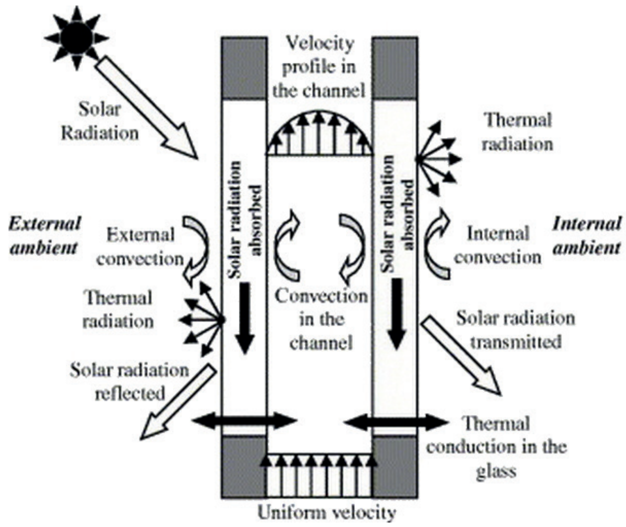

Fig. 10. Heat transfer in a ventilated window [68]

As a result, the heat gain due to the solar radiation, composing of the heat gain due to incident solar radiation which crosses directly to the internal ambient and the solar radiation absorbed by the glass sheets and reemitted to the internal ambient, was determined. Figure 11 shows the solar heat gain for three different values of gap width.

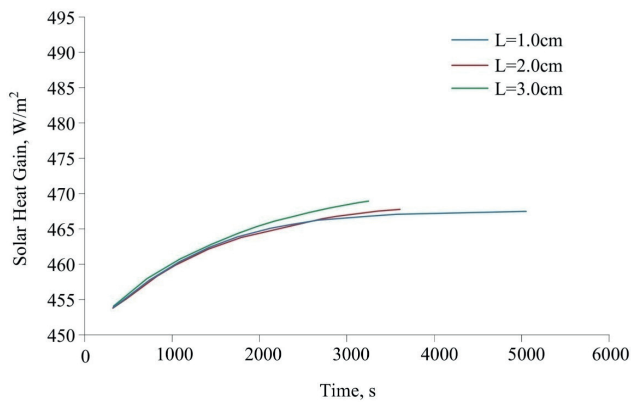

Fig. 11. Effect of the gap width on the solar heat gain of a ventilated double-glazed window

As can be seen, there is a little difference between the solar heat gain of the three arrangements, because of the optical transmittance of the arrangements is nearly the same. The results indicate that the gap width has little effect on the mean coefficient of solar heat gain and the mean shading coefficient. Jaber and Ajib [76] investigated the optimum window type and size for heating demands in three different climate zones – Amman, Aqaba and Berlin. The results showed that as the overall heat transfer coefficient decreases, the annual heating energy for all sites decreases. The heat demand depends on the location of the façade in relation to the directions of the world, thus on the intensity of the incidence of solar radiation. The highest occurres at the Northern façade at all sites, as it received a low solar incident radiation. On the other hand, the Southern façade induced the lowest heating energy because of high solar incident radiations. Alvarez et al. [77] developed heat transfer model to evaluate the convective heat transfer coefficient and heat gain coefficient due to the optical properties of coated glass in the visible and solar spectra region. The overall heat transfer coefficient of window and the solar heat gain of building interior were predicted from the simulation to evaluate the glazing performance in increasing the inside temperature due to the incidence of global radiation through window [26]. A solar simulation model was developed to predict the glazing temperature due to global radiation consisting of direct, diffuse and reflected components and hence the solar heat gain of building interior. The another thermal model was concerned with laminar heat transfer for natural and forced convection process according to the variation of inside and outside atmosphere with seasons and was solved by finite difference technique. For the outer glazing surface, time-dependent incident solar radiation acts as source of heat flux. Heat flow from simulation are presented in Figure 12.

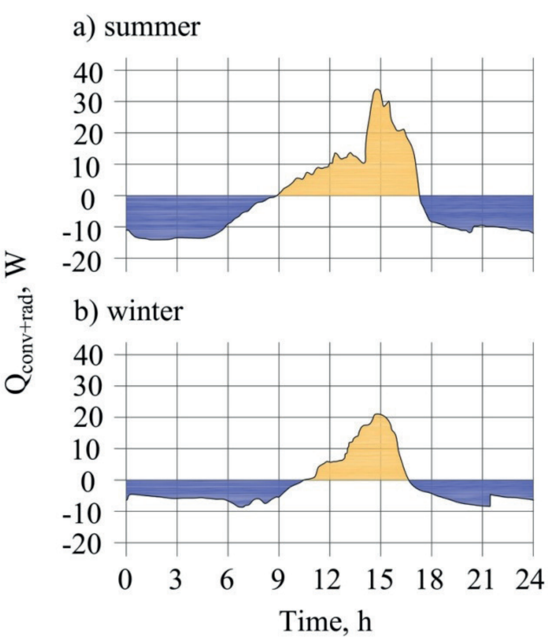

Fig. 12. Heat flow from simulation

Figure 12 shows that heat flow increases with time, due to the increase of global radiation on window and ambient temperature. In the model of heat transfer through windows, the phenomenon of solar radiation beam reflection from the internal environment of the building, is proposed in paper [78]. A correlation created by the authors takes into account the entering solar radiation effective absorption coefficient, which depends upon the optical and geometrical properties of the indoor environment and the transmission coefficient of the diffuse radiation of the transparent surfaces. Solar energy absorbed by the indoor environment is calculated as the sum of three contributions: the first optical, produced by solar radiation transmitted by glazed surfaces, the second direct convective-radiative, which evaluates the fraction of solar radiation absorbed and provided to the indoor environment by the glazed surface which is radiated directly by the sun, the third indirect convective-radiative, produced by solar radiation reflected by internal surfaces and absorbed by glazed surfaces. The proposed new calculation procedure of solar heat gains allows for more accurate monthly evaluations. Some improved simulation methods were investigated by Avedissian and Naylor [79] and Sun et al. [80], who used a "surface-to-surface" (S2S) model to take into account radiation during heat transfer through ventilated window systems. All the surfaces were assumed to be grey bodies, diffuse and opaque to thermal radiation. The air in the cavity was assumed to be a non-participating medium. The view factors, which depend on surfaces' size, separation distance and orientation, were computed before simulating the radiation. A mathematical model of the long-wave radiation heat transfer between the inside room surfaces and the outside environmental surface through a glazing considering the transmittance of glass is presented in paper [81]. The effects of the transparence radiation characteristics of glass, convection heat transfer coefficient of inside and outside of the glazing, and the difference between the surface temperature (including inside room surface temperature and outside environmental surface temperature) and the air temperature (including indoor and outdoor air temperature) on the overall heat flux and the ratio of the heat flux due to the transparence radiation to the overall heat flux are developed. However, short-wave radiation (solar radiation) was neglected by the authors in the process of model developing.

In some advanced windows systems, the absorbed portion of solar radiation can be extracted through other means such as electricity conversion and natural

environment

airflow, thus can be taken as the additional heat source. Numerical solutions to the energy equations for laminar natural convection in the air gap of double-pane window with integrated see-through PV glass with low-e coating were investigated in paper [82]. The study provides obtaining of U-value and accurate heat transfer model which is significant for predicting the PV conversion efficiency considering solar cell temperature and investigating the thermal behaviors of see-through PV double-pane window. Results show that a large quantity of heat transfer by radiation within the air gap can be reduced by employing PV double-pane window with low-e coating. A comprehensive review of the modeling of transparent- and semi-transparent Building Intagreted PV systems in windows is presented in paper [83]. Despite the interest in the topic, there are relatively few studies on modeling the performance due to these technologies. Some models were investigated for obtaining the windows overall heat transfer coefficient and SHGC, taking into account the PV effect. In this sense, a methodology for estimating the thermal behavior of a photovoltaic–thermal (PVT) double semi-transparent façade was proposed in paper [84]. The transmission losses and ventilation gains were presented with four parameters (thermal transmittance, ventilation thermal transmittance, solar gain and ventilation solar gain, which were calculated by the one-dimensional single-node energy balance, including the electric production on the PV surface. Another one-dimensional power balance model for a PV window was developed by Misara et al. [85] to obtain the U, SHGC, and solar reduction ratio values. Authors indicated that the normative methods used in the calculations are not applicable to PV windows, thus the models need to be adjusted to include the internal heat sources of PV modules and the new thermal parameters, such as the internal and external heat transfer coefficient and heat transfer coefficient of insulated glass. More detailed two-dimensional models were investigated into T- and ST- BIPV windows in order to evaluate the impact of natural and forced convection in the window gaps on the vertical axis, as is shown in Figure 13.

Two-dimensional model for a ventilated double-pane window was developed in paper [87] to compare the PV output, heat transmission, daylight, and energy use varying with the orientation and transparency.

A similar modeling approach was developed and validated by Han et al. [88] in order to determinate accurate heat transfer coefficients for a see-through glazing system with the integration of Semi-transparent building-integrated photovoltaic (ST-BIPV) with naturally ventilated air gaps.

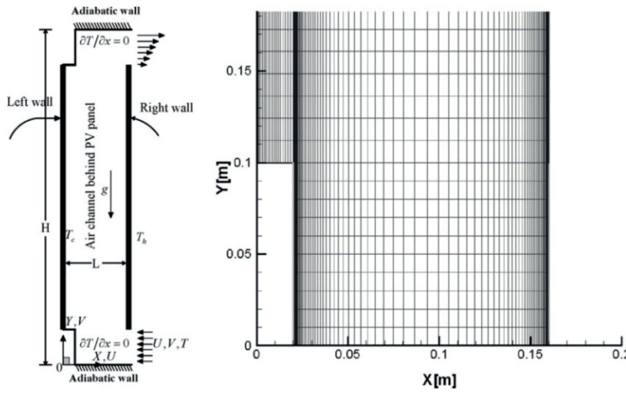

Fig. 13. Two-dimensional model for a ventilated double-sided PV façade [86]

A double-pane semi-transparent and transparent building-integrated photovoltaic (T-BIPV) cladding window were evaluated in paper [89], finding that façade orientation, the window-to-wall ratios, and lighting power density did not affect the selection of the ST- and T-BIPV optical properties. In opposite, Ng et al. [90] compared single-pane window, double-pane window, double-pane window with low-e glaze and double-pane window with low-e tinted glass with ST- BIPV systems (six combinations of thin-film and amorphous silicon modules in a single- or double-glass configuration). Results showed that all BIPV systems outperformed conventional windows by reducing the overall energy use, including heating, cooling, lighting, and PV output. Gevers et al. [91] investigated a prototype of frame-integrated BIPV systems in which the glazing system is used to redirect part of the radiation to the frame, thus acting as a solar control window. Nourozi et al. evaluated the Energy Active Windows (EAW) to minimize the building's thermal losses in winter, providing a modern architecture sustainability and interior comfort [92]. EAW utilizes low-grade energy, such as waste heat from the gap between the window panes, provided by built-in heat exchanger combined with a fan. Nusselt numbers for forced convection [93], occurring between symmetrically heated parallel plates with the same surface temperature, have been adapted for use in EAW because of different surfaces temperatures due to the supply of warm air and the large temperature difference between the inside and the outside. Thus, the constant value in the Nusselt number correlations have been changed to more accurately account for the effect of asymmetrically heated windows. The Nusselt number for panes with asymmetric surface temperatures is about 1.9 times lower than for panes with the same surface temperatures [92]. In the EAW, the influence of the gap width on the value of the heat transfer coefficient turns out to be insignificant, while the change of the temperature of the supplied air is significant. In order to maintain a low heat transfer coefficient, the temperature of the air supplied to the window must be higher than the room's internal temperature. The results indicated that windows can reduce the heating load by about 2.2 W/m^2 for window to floor area ratio of 10%. Controlling short and long wave solar radiation passing through the window can be achieved by use the smart glasses. They can regulate the temperature and illumination level indoors depending on the change of the environmental parameters or due to the electric current passing through an active layer of the laminated glass. Some types of modern smart glasses and chromogenic materials are listed in Table 2.

Table 2. Types of glass or chromism and mechanism of action

Type of glass/chromism	Mechanism of action	Ref.
Low-emissivity	Visible spectrum transmission and IR reflection	[94]
Electrochromism	Change in transparency and color on passing electric current	[95]
Thermochromism	Change in reflectance and transmittance at a specific critical temperature	[96]
Thermotropism	Temperature dependent change of light scattering	[97]
Photochromism	Transmission varies with intensity of incident shortwave UV or visible light	[98]
Gasochromism	Change in transmittance by interaction with diluted hydrogen gas	[99]
Mechanochromism	Color change due to change in pH of solution	[100]
Magnetochromic	Controlled by the magnetic field intensity	[101]

3. CONCLUSIONS

The thermal properties of windows systems listed above may vary depending on the ambient temperature, on solar radiation, on infiltration of outside air passing through leaks in the windows, and on their dimensions and geometry. Due to those differences the theoretical (i.e., calculated) and actual values of energy consumption in buildings differ. Therefore, the detailed relationship between the flow, heat transfer condition and the performances of windows are not fully investigated. Therefore, there is still a need to perform in-depth study on the flow and heat transfer characteristics of windows and other glazed buildings partitions.

Abbreviations:

AR – aspect ratio (H/L),
CFD – Computational Fluid Dynamics,
EAW – Energy Active Windows,
Low-E – low emissivity coating,
PCM – phase change material,
PV – photovoltaic,
PVT – photovoltaic–thermal,
SHGC – solar heat gain coefficient,
ST-BIPV – Semi-transparent building-integrated photovoltaic,
T-BIPV – Transparent building-integrated photovoltaic.

Nomenclature:

a – thermal diffusivity, m^2/s,
b – width of the gap with gas layer; distance between panes, m; mm,
β – coefficient of volume expansion, 1/K,
C_p – specific heat, J/kg·K,
ε – emissivity,
g – gravitational acceleration, m/s^2,
Gr – Grashof number,
h – convection heat transfer coefficient, W/m^2·K,
H – high of window, m,
k – thermal conductivity, W/m·K,
L_c – the characteristic length, m; mm,
L – length of window, m,
Nu – Nusselt number,
p – pressure, Pa,
Pr – Prandtl number,
q – heat flux density, W/m^2,
Q – heat flux, W,
Ra – Rayleigh number,
Re – Reynolds number,
RT – thermal resistance, m^2·K/W,
ρ – density, kg/m^3,
T – temperature, K,
t – time, s,
u – velocity component in x-direction, m/s,
U – overall heat transfer coefficient, W/m^2·K,
v – velocity component in y-direction, m/s,
μ – dynamic viscosity, kg/m·s,
ν – kinematic viscosity, m^2/s,
x, y – horizontal and vertical coordinates, m.

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