ON TAKING WIND-DRIVEN RAIN AND CAPILLARY CHARACTERISTICS OF MATERIALS INTO ACCOUNT WHILE CALCULATING DAMPNESS OF SHIELDING STRUCTURES FOR BUILDINGS

[1]Vadzim Nikitsin, [2]Beata Backiel-Brzozowska

[1] Pope John Paul II State School of Higher Education,
Faculty of Economic and Technical, Department of Technical Sciences
SidorskaSt. 95/97, 21-500 Biała Podlaska, Poland
[2] Bialystok University of Technology, Faculty of Civil and Environmental Engineering,
Wiejska St. 45E, 15-351 Bialystok, Poland
e-mail b.backiel@pb.edu.pl

Summary:
The first aim of this paper was to analyse some basic methods of determining the thickness of streams of rain water falling diagonally on vertical surfaces of shielding structures. It was shown that for determining the horizontal component of wind-driven rain, the standard ISO method yields the best results for low buildings, while in the case of buildings of the tower type, the best results gives the CFD model.
The main aim of this paper was to propose a method of determining the thickness of streams of moisture absorbed by vertical surfaces of shielding structures exposed to rain falling diagonally. The developed method takes into account the horizontal component of wind-driven rain, the water sorption coefficient, the actual material humidity and the material humidity in the capillary saturation state.

Key words: wind-driven rain, capillary-porous ma materials, water capillary transport, shielding structures dampness

Introduction

Negative results of external shielding structures for buildings, made of capillary-porous materials, becoming damp, are widely known (accelerating mechanical, chemical, and biological corrosion, lowering physical and chemical properties of materials, etc.). In a number of works (e.g. Witczak et al., 2003; Blocken and Carmeliet, 2004, Blocken et al., 2006; Ali et al., 2005); it is emphasised that one of the major reasons for shielding structures becoming damp is wind-driven rain (WRD). The phenomenon of rain falling diagonally (WDR), consisting in precipitation and wind simultaneously influencing the fragment of the surface of the external shielding structure for the building under concern, should therefore be taken into consideration while calculating the dampness level of shielding structures.

The applicable European standard EN 15026: 2007 (Hydrothermal performance of building component and building elements – Assessment of moisture transfer by numerical simulation) also recommends taking into account the phenomenon of wind-driven rain while calculating non-stationary moisture transfer processes in capillary-porous materials of shielding structures. As a result of this phenomenon, capillary rise of moisture takes place through the material surface into its walls. In order to start calculations for the initial moment of time and the subsequent period of time, the w specific humidity of the given material [kg/m^3], and the weight of the liquid absorbed by one surface area unit of a given shielding structure during one unit of the period of exposure to wind-driven rain (the thickness of the stream of moisture), g_w, [kg/(m^{2}s)], have to be known. The value of g_w is directly connected to the weight of rain falling on one surface area unit of the shielding structure under concern during one time unit, g_p, kg/(m^{2}s), and it does not exceed the value of the thickness of the stream of water absorbed by the material on the shielding structure surface, $g_{w\,\max}$ (g_w=g_p if g_p<$g_{w\,\max}$). Pursuant to EN 15026: 2007, it is assumed, without any explanation, that:

$$g_w = \min(g_p, g_{w\max}) \qquad (1).$$

The value of the g_p thickness of the stream of moisture depends on a number of factors defining the local climate (the precipitation density as well as the wind direction and speed), the geometry of the building under concern, and also on its surrounding (the neighbouring buildings and trees, and the topography of the city, town or village). The factors mentioned above are to a different extent taken into consideration by different models described, among others works by Blocken and Carmeliet, (2004) and by Blocken et al. (2011). These models make it possible to calculate, with various degrees of accuracy, the intensity of rain falling on vertical surfaces of shielding structures.

In determining the g_w thickness of a stream of moisture ($g_w \leq g_{w.max}$, $g_{w.max} \geq 0$), the ability of the surface layer of a structure to absorb moisture, that is, the $g_{w.max}$ stream of moisture, needs to be taken into account. This indicator depends on the humidity of the material and its water sorption coefficient before it starts to rain, and also on the changes in these parameters as a result of wind-driven rain, as well as on the humidity of the material at the moment of capillary saturation (when it can be assumed that g_w=$g_{w.max}$=0). Neither EN 15026: 2007 nor any of the literature known to the authors of the present paper give information on the way how the previously mentioned features of capillary rise of water are to be taken into consideration in calculating the level of dampness for shielding structures exposed to wind-driven rain. It also has to be underlined that in a popular computer application for analysing heat and moisture phenomena in construction barriers, WUFI (Witczak et al., 2003), the value of the g_w stream of moisture is established using the equation

$$g_w = k \cdot g_p \qquad (2)$$

where k – rain water absorption factor equal to 0.7.

It is clearly visible that applying one of the dependencies, (1) or (2), might result in inaccuracy while determining the level of dampness for shielding structures exposed to wind-driven rain.

The present paper discusses and analyses some basic methods of determining the thickness of streams of rain water falling diagonally on vertical surfaces of shielding structures, and proposes a method of determining the thickness of streams of moisture absorbed by vertical surfaces of shielding structures exposed to rain falling diagonally.

Modelling wind-driven rain

According to Blocken and Carmeliet (2004), quoting 303 literature sources, scientists working within the field of construction have been investigating the phenomenon of wind-driven rain (WDR) and the results of its influence on shielding structures of buildings for over 60 years now, and in order to determine the intensity of free and non-free (falling on shielding structure surfaces) rain, empirical, semi-empirical and computational (computer simulations) methods have been developed so far.

If it is assumed that all raindrops have identical sizes, and that wind blows from the same horizontal direction at the same speed and it is always perpendicular to vertical surfaces, then, according to Blocken and Carmeliet (2004), a simple theoretical equation is obtained for determining the amount of free wind-driven rain R^f_{wdr} falling through one surface unit of a vertical plane of airspace (the horizontal component of wind-driven rain)

$$R^f_{wdr} = R_h \frac{U}{V_t} \tag{3}$$

where:

R_h – intensity of wind-driven rain falling on horizontal plane in one time unit, mm/h or l/(m^{2}h),
U – wind speed, m/s,
V_t – final speed of falling rain drops, m/s.

The assumptions adopted when deriving the equation (3) on an ideal stream of rain are, however, not often met. Rain drops are of different sizes, they fall at different speeds and at different angles. They also crash into each other, thus becoming bigger or smaller. To take into account the aggregate range variability of falling rain drops in 1955 Hoppestad (Blocken and Carmeliet, 2004) suggested transforming the equation (3) to the following dependency connecting the value of R^f_{wdr} and the R_h horizontal component of free wind-driven rain

$$R^f_{wdr} = k \cdot U \cdot R_h \tag{4}$$

where k – free wind-driven rain factor, s/m.

If data concerning the values of U, R_h, and R_{wdr} are collected with the use of specific measuring devices (rain gauges and anemometers) in the open space at specified periods of time and when wind-driven rain is falling, then, on the basis of the equation (4), it would be possible to calculate the value of the k coefficient. Devices for simultaneous measuring of the indicators of free wind-driven rain R_h and R_{wdr} and questions pertaining to the accuracy of these devices are presented by Blocken and Carmeliet (2004). After having analysed the results of numerous experimental studies in 1965 Lacy R. E. increased the accuracy of the equation (4) suggesting adopting the mean value for the coefficient of free-falling rain k= 0.222s/m (Blocken and Carmeliet, 2004). Then

$$R^f_{wdr} = 0.222 \cdot U \cdot R_h^{0,88} \approx 0.222 \cdot U \cdot R_h \tag{5}$$

The equation (5) allows for determining the mean value of the thickness of free-falling rain R^f_{wdr} on the basis of standard U and R_h data measured by weather stations. It is emphasised in by Blocken and Carmeliet (2004) that results of numerous measurements of intensity of free-falling wind-driven rain are consistent with results obtained on the basis of calculations using the equation (5). This issue can be also solved on the basis of equation (3), after determining the $V_t(d)$ final velocity of falling rain drops (m/s). If the d rain drop diameter (mm) is known, then the following third order polynomial developed on the basis of experimental data and presented by Dingle and Lee (1972) and by Blocken et al. (2011) may be applied to determine the $V_t(d)$ final velocity:

$$V_t(d) = -0.166033 + 4.91844d - 0.888016d^2 + 0.054888d^3 \leq \frac{9.2m}{s} \quad (6).$$

In order to determine the mean diameter $\bar{d}$ (on the basis of the median), the equation proposed in 1950 by Best A. C. (Blocken et al., 2011) may be applied

$$\bar{d} = 1.105 R_h^{232} \quad (7).$$

It has to be underlined that for k=0.222s/m, the final speed of rain drops of the same size, applied in equation (5), amounts to V_t=(1/0222)=4.5km/s, and that this speed, according to equation (6), corresponds to rain drops of the mean diameter of 1.2mm. A calculation performed on the basis of equation (7) revealed that rain drops of the same mean diameters (d=1.2mm) are formed for the rain intensity R_h=2mm/h. The calculated indicator is characteristic of moderate (medium intensity) rain for which the k coefficient of free-falling rain ranges from 0.2 to 0.25s/m. For drizzle, d≈0.5mm and k≈0.5s/m, and for heavy rain d≈5mm and k≈0.1s/m.

As a result of a complex interaction of free-falling wind-driven rain and vertical surfaces of shielding structures, the R_{wdr} intensity of wind-driven rain falling on the surface under study will differ from the R^f_{wdr} intensity of free-falling rain and will be unevenly distributed on the surface of the building façade it falls on.

For determining the intensity of wind-driven rain falling on vertical surfaces of shielding structures, a number of models based on the same equation (7) were proposed

$$R_{wdr} = \alpha \cdot U_{10} \cdot R_h^{0.88} \cos\theta \quad (8),$$

where:

U_{10} – speed of wind at the height of 10m above the ground level, m/s,

θ – angle between the φ_{10} direction of wind at the height of 10m above the ground level and the normal to the vertical surface of the building façade

α – coefficient of wind-driven rain, s/m.

Input meteorological data used for calculating R_{wdr} on the basis of equation (8) are composed of mean values of U_{10}, φ_{10}, and R_h, measured simultaneously at one-hour or ten-minute intervals adopted as the Δt time interval. The only difference for each of the models considered further is the method with which the α coefficient is determined.

When the SB model developed by Straube and Burnett in 2000 is applied, the α coefficient is described with the following equation (Blocken et al., 2011)

$$\alpha = DRF \cdot RAF \cdot \left(\frac{Z}{10}\right)^{\beta} \cdot R_h^{0.12} \tag{9,}$$

where:

DRF – driving rain function,
RAF – rain admittance factor,
Z – height above the ground level, m.

The value of *DRF* is inversely proportional to the V_t final speed of rain drops, determined on the basis of equation (6), taking into consideration equation (7). *DRF* depends on the R_h rain intensity which changes in time. The *RAF* factor does not change in time, and, irrespective of the building type or the fragment of the façade under concern, its values range from 0.2 to 1.0, see Fig. 3 in (Blocken et al., 2011). The third coefficient in equation (9), introducing *z* and *β*, takes into account the influence of the natural topography of the building location on the wind speed profile.

The α coefficient in the applicable ISO (International Organization for Standardization) standard EN ISO 15927-3:2009 takes on the following form

$$\alpha = 0.222 C_R \cdot C_T \cdot O \cdot W \tag{10,}$$

where:

C_R – roughness coefficient,
C_T – topography coefficient,
O – obstruction factor,
W – wall factor.

The C_R roughness coefficient provides for changes in the mean wind speed, depending on the *Z* height above the ground level and the 'roughness' of the area in the direction that the wind is blowing from. The value of the C_R coefficient in the *Z* function is determined from one of the equations (Blocken and Carmeliet, 2004):

$$C_R(Z) = K_R \ln\left(\frac{Z}{Z_0}\right) \quad \text{for} \quad Z \geq Z_{\min} \tag{11,}$$

or

$$C_R(Z) = C_R(Z_{\min}) \quad \text{for} \quad Z < Z_{\min} \tag{12,}$$

where K_R (terrain factor) is the parameter, and Z_0 and Z_{min} (heights) are selected depending on the terrain category. There are four terrain categories. Thus, for terrains of category II (country town or village) from Table 1 in EN ISO 15927-3:2009 we obtain K_R=0.19, Z_0=0.05m, and $Z_{\min}$=4m. Then, for example, at the height of *Z*=10m > $Z_{\min}$=4m, the value of the roughness coefficient can be calculated from equation (11)

$$C_R(10) = 0.19 \ln\left(\frac{10}{0.05}\right) = 1.007,$$

and for *Z*=3m < $Z_{\min}$=4m, from equation (12) the following is obtained

$$C_R(3) = C_R(4) = 0.19\ln\left(\frac{4}{0.05}\right) = 0.8326.$$

The C_T topography coefficient providing for changes in the wind speed over terrain elevations or slopes is determined taking into account the Φ tangent of the inclination angle of the hill under concern, the λ location on the hill, as well as the Z height. Thus, for the windward side of the hill (Φ=0.3) for Z=0 the following are obtained: x=0, C_T=1.6 at the top; (x=-1) C_T=1.03 at the foot, and (x=-05) C_T=1.18 at the middle of the hill slope. For flat areas, (Φ <0.05) C_T=1.0.

The O obstruction factor provides for the effect of walls being protected from wind by nearby obstacles (e.g. buildings, forests), and its value is adopted depending on the L distance from the shielding structure. For example, if L=4-8m, then O=0.2, and for L>120m (practically an open space) O=1.0. While determining the O factor, heights of shielding structures proportional to the height of the wall under study need to be taken into consideration. In addition, the fact that the presence of nearby buildings might result in creating such dynamic effects for which it is recommended to adopt the maximum value for the O factor (O=1), needs to be taken into account.

The W wall factor is an attempt to provide for the wall type (its height, roof overhang, etc.) and for unevenness of the distribution of the amount of rain on the surface of a façade, caused by streams of air around external edges of buildings. According to EN ISO 15927-3:2009, values of the wall factor can range from 0.2 to 0.5.

The considered values of C_R, C_T, O, and W are not dependent on time, which results from the fact that they are not connected to meteorological data of U_{10}, ϕ_{10}, and R_h, which are variable in time.

According to Blocken et al. (2011), the α coefficient in the CFD (Computational Fluid Dynamics) model has the following form

$$\alpha = \frac{\eta \cdot R_h^{0.12}}{U_{10}\cos\theta}, \tag{13}$$

where c is determined from the ratio R_{wdr}/R_h. It is easy to explain by substituting expression (13) to equation (8). Coefficient η values are determined by means of CFD simulation for each Δt time interval characterised by the mean values of U_{10}, φ_{10}, R_h, and for any fragment (point) on the surface of a shielding structure. Results of CFD simulation are presented in different forms, including the graphical form, for example in the form of an equal level line (Blocken and Carmeliet, 2006).

The forecasting abilities of the described methods in determining the R_{wdr} intensity of wind-driven rain were tested experimentally with the use of containers for measuring wind-driven rain, installed on walls of low (type I) and high (type II) structures (Blocken et al., 2011). The façade of the type I building with a flat roof was a surface measuring 4.26 x 11.25 m, facing west. Eight containers were installed on this façade. The middle of the lower row of these devices was located at the height of 1.4m above the ground level. On the façade of the high structure (a tower of 34.5m in height), facing north-west, 4 containers were installed – one at the height of 18m, and the remaining ones at the height of 29m above the ground level.

In order to determine the R_{wdr} and R_h components of wind-driven rain, 120 one-hour intervals were chosen for the type I building, whereas for the type II building 144 ten-minute intervals were applied. After having added the data from the particular intervals, the ΣR_{wdr} and ΣR_h accumulated amount of rain and also the ratio $\eta_s=(\Sigma R_{wdr})/(\Sigma R_h)$ were determined.

The results of comparing the η_s ratio determined by the measurements and calculations on the basis of the described models for type I and type II buildings proved to be significantly different. For example, for the type I building, the mean value of the $\overline{\eta_s}$ ratio, determined on the basis of eight measurement points, was best forecast with the ISO method (the calculated values exceeded the experimental data by +7.1%). The results provided by the CFD method were not as good (the computed values were lower than the experimental data by -19.5%). The SBmax model proved to be the worst for forecasting the $\overline{\eta_s}$ values, yielding a result which exceeded the experimental data by 96.1%. In the case of the type II building, the order of models which best forecast the mean value of $\overline{\eta_s}$, determined on the basis of four measurement points, was different. The measurement results were best reflected by the CDF model (-15.6%). The SBmax method gave a significantly increased result (+51.6%), and the least accurate value was the value obtained with the use of the ISO model – this value was 2.78 times smaller than the corresponding experimental data. On the basis of the performed comparison, it can be stated that for calculating the R_{wdr} horizontal component of wind-driven rain for type I buildings it is best to use the ISO model, while the CFD method is the best one for type II buildings.

For known values of R_{wdr} measured in mm/h (1mm/h=1l/(m^{2}h)=2.777·10^{-4}kg/(m^{2}s)), the thickness of streams of rain falling on vertical surfaces can be determined from the equation

$$g_p = 2.777 \cdot 10^{-4} R_{wdr} \qquad (14).$$

This value is used in assessing the g_w thickness of streams of moisture absorbed into a shield by its surface.

Modelling of streams of moisture absorbed by vertical surfaces of shielding structures during wind-driven rain

As it was already emphasised, in order to start calculations of the non-stationary process of moisture transfer in capillary-porous materials of shielding structures during wind-driven rain whose value of the horizontal component is equal to g_p, the g_w thickness of the stream of moisture absorbed by the vertical surfaces of shielding structures needs to be known. The ability of a material to absorb moisture from the surface of a shielding structure is described by the capillary characteristics of the material and its *w* specific humidity (kg/m^3), and in the issue under concern it is characterised by a stream of moisture moving into the shielding structure $g_{x=0}=g_{w\,max}$.

For totally dry materials (w=0), the $g_{w\,max}$ stream of moisture has the highest value, while for total capillary saturation ($w=w_k$) it has the lowest value (approaching zero). Such phenomena can be observed when a specified layer of water falls down a vertical surface. Issues connected to modelling the process of liquids falling down vertical surfaces were considered in detail, among others, by Kutateladze and Styrikovič (1976). Using the dependency presented by Kutateladze and Styrikovič (1976), a calculation was performed which demonstrated that a layer of water of 0.25mm in thickness under room conditions falls down a vertical surface of a barrier at the speed of 0.2m/s under laminar conditions.

If it is assumed that, when wind-driven rain starts to fall, $g_p > g_{w\,max}$ (which is a rare case) and that there is a stable layer of water on the vertical surface of a shielding structure, and the material is completely dry, homogeneous, and isotropic, then the amount of water absorbed by the surface of an unlimited half-space during the τ period can be calculated from the equation

$$W = A \cdot \sqrt{\tau}\ , \tag{15}$$

where

A – water sorption coefficient, kg/(m^{2}s$^{0.5}$).

A graphical interpretation of this phenomenon is presented in Fig. 1, with the actual material humidity profile in the direction of the $w(x, \tau)$ capillary moisture transfer being replaced by the simplified, effective profile shown in Fig. 2. The size of the equivalent profile can be computed using the following equation

$$w_k \cdot x_e = \int_0^l w(x,\tau)\,dx = A\sqrt{\tau}, \tag{16}$$

where:

w_k – material humidity in capillary saturation state, kg/m^3,
x_e – boundary between dry and humid parts of material, m.

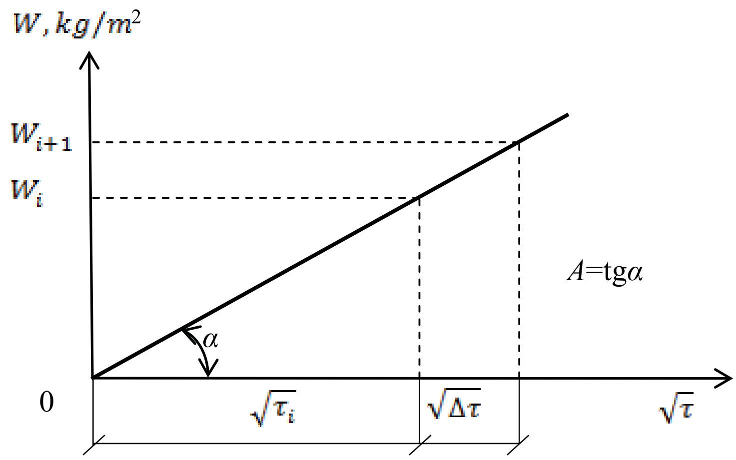

Fig. 1. Dependence of W amount of water absorbed by homogenous and isotropic capillary-porous material of unlimited thickness per surface unit

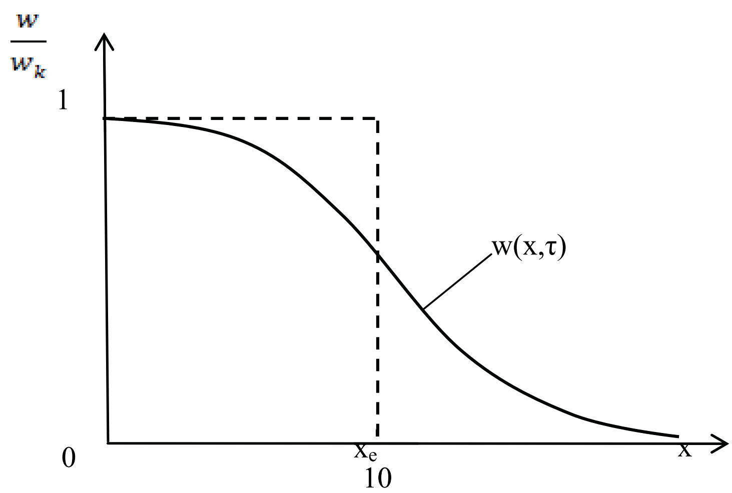

Fig. 2. Typical humidity profile of a sample of material of unlimited height $x=\infty$ for $w(x,\tau)$ capillary rise of water (solid line) and the substituting equivalent profile (dashed line)

A and w_k values are usually determined by special experiments in which the weight gain of water in a sample of $x=h$ in height and an unvarying cross-section in the process of one-direction capillary rise of water is monitored. The issues of determining the A and w_k coefficients experimentally are described with sufficient precision, among others, by Janz (1997), Nikitsin et al. (2005) and Nikitsin and Backiel-Brzozowska (2012).

The $g_{x=0}$ thickness of a stream of moisture transferred through the surface of a shielding structure for the entire x_e saturated layer is a derivative of the w value after the τ time

$$g_{x=0} = g_{w\max} = \frac{dW}{d\tau} \approx \frac{\Delta W}{\Delta\tau}, \qquad (17),$$

where $\Delta\tau$ – computational time interval, s.

According to Fig. 1 and equation (15), for the (i+1)th stage of calculations, the following is obtained

$$g_w = g_{w\max} = \frac{\Delta W}{\Delta\tau} = \frac{W_{i+1} - W_i}{\Delta\tau} = \frac{A\left(\sqrt{\tau_i + \Delta\tau} - \sqrt{\tau_i}\right)}{\Delta\tau}, \qquad (18).$$

From equation (18) it follows that the $g_{w\,max}$ thickness of a stream of moisture decreases in time, and that rain water absorption ceases after the humidity reaches the w_k value of capillary saturation in the elementary computational surface layer whose thickness is d. The humidity value in the computational layer whose thickness is d needs to be monitored at each stage of calculations, using the equation

$$w = \frac{W}{d}, \qquad (19).$$

If no layer of water is present on the vertical surface of a shielding structure when wind-driven rain starts to fall (a typical situation), it means that the $g'_p \leq g_{w\ max}$ horizontal component of wind-driven rain as well as the rain water falling on the surface of the shielding structure under concern are entirely absorbed. In that case, for each (i+1)th stage of calculations in the $\Delta\tau$ time interval and for the d thickness of the surface material layer, the following holds true:

$$g_w = g'_p = \frac{W'_{i+1} - W'_i}{\Delta\tau} \text{ and } w = \frac{W'}{d}, \qquad (20).$$

As it was the case earlier, $w \leq w_k$. At the same time, at each stage of calculations, the g'_p and $g_{w\ max}$ values need to be compared. If $g'_p > g_{w\ max}$, then the g_w thickness of the stream of moisture absorbed by vertical surfaces of shielding structures is computed on the basis of equation (18).

Fig. 3 shows a graphical interpretation of the method of calculating the g_w thickness of a stream of moisture, using equations (18) and (20). It follows from Fig. 3 that in cases where the inequality g_p (or g'_p)$>g_{w\ max}$ holds (dashed line), the g_w value is established from equation (18). If, however, $g'_p \leq g_{w\ max}$, then equation (2) is applied in calculations.

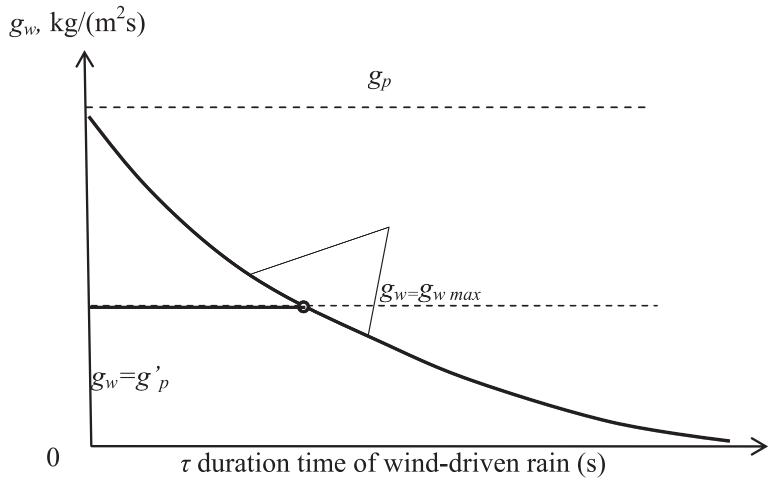

Fig. 3. Dependence of g_w thickness of stream of moisture absorbed by a vertical surface of a shielding construction during τ time for g_p (or g'_p) thickness of wind-driven rain

Summary

In the present paper, a few basic models for establishing the g_p thickness of a stream of wind-driven rain falling on vertical surfaces of shielding structures were considered on the basis of literature work. It was established that for determining the g_p horizontal component of wind-driven rain, the standard ISO method yields the best results for low buildings, while in the case of buildings of 18m in height and higher ones (of a tower type) this method is the one that provides the worst results. For a building of the latter type, the best results were obtained from the CFD model.

A method was developed for determining the g_w stream of moisture absorbed by vertical surfaces of shielding structures. The method takes into account the g_p horizontal component of wind-driven rain, the *A* water sorption coefficient, the *w* actual material humidity and the w_k material humidity in the capillary saturation state. In order to start calculations of non-stationary water transfer in capillary-porous construction materials during wind-driven rain, the g_w value needs to be known.

References:

1. Ali A. R., Nikitin V., Kofanov V. (2005), Wpływ odpadów atmosferycznych oraz parametrów przenoszenia wilgoci materiałów konstrukcji osłonowych na ich wilgotność. Materiały Budowlane, 12, pp. 24-26 (in Polish).
2. Blocken B., Abuku M., Nore K., Briggen P. M., Schellen H. L., Thue J. V., Roels S., Carmeliet J. (2011), Intercomparison of wind-drive rain models based on two case studies with full-scale measurements. Journal of Wind Engineering and Industrial Aerodynamics, 99, pp. 448-459.
3. Blocken B., Carmeliet J. (2004), A review of wind-driven rain research in building science. Journal of Wind Engineering and Industrial Aerodynamics, 92, pp.1079-1130.
4. Blocken B., Carmeliet J. (2006), On the validity of the cosine projection in wind-driven rain calculation on buildings. Building and Environment 41(9), pp. 1182-1189.
5. Dingle A. N., Lee Y. (1972), Terminal fall speeds of raindrops. Journal of Applied Meteorology, 11, pp. 877-879.
6. Janz M. (1997), Methods of measuring the moisture diffusivity at high moisture levels. Lund: Division of Building Materials, Lund Institute of Technology, University of Lund. Report TVBM-3076, p. 73 (in Swedish).
7. Kutateladze S. S., Styrikovič M. A. (1976) Gidrodinamika gazožigkostyh sistem. Moskva: Energiâ, p. 296 (in Russian).
8. Nikitsin V., Backiel-Brzozowska B. (2012), Anizotropia wyrobów ceramiki budowlanej a współczynnik wyrównywania wilgoci. W:Energy-saving and ecological materials, installations and technology in construction/ ed. Stanisław Fic. - Biała Podlaska: Wydaw. PSW JPII, pp. 19-30 (in Polish).
9. Nikitsin V., Backiel-Brzozowska B., Bołtryk M. (2005), Wpływ parametrów procesu wypalania na wskaźniki podciągania kapilarnego wody w tworzywach ceramicznych. Ceramika/Ceramics vol. 91, pp. 1223-1230 (in Polish).
10. Witczak K., Künzel H. M., Gawin D. (2003), Wpływ zacinającego deszczu na stan wilgotnościowy przegród budowlanych w Polsce. XLIX Konferencja Naukowa Komitetu Inżynierii Lądowej PAN i Komitetu Nauki PZITB, t. 4: Bezpieczeństwo pożarowe, fizyka budowli, konstrukcje murowe i drewniane, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa-Krynica, pp. 99-106. (in Polish).