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DISTRIBUTION OF THE TEMPERATURE FACTOR IN TERMS OF BUILDING ENVELOPE PROTECTION AGAINST MOULD GROWTH

ROZKŁAD WARTOŚCI CZYNNIKA TEMPERATUROWEGO W ASPEKCIE OCHRONY PRZEGRÓD BUDOWLANYCH PRZED ROZWOJEM PLEŚNI

A b s t r a c t

This paper describes the criterion for the protection of building envelopes against the growth of mould. As a criterion for assessing the risk to envelopes, the f_{Rsi} temperature factor is adopted. The paper provides the resultant temperature factor $f_{Rsi,\max}$ for the critical month in 61 areas in Poland for which typical year-long meteorological data is available on the website of the Ministry of Infrastructure and Development. While calculating the temperature factor, various room humidity classes were taken into account. The results of calculations of the temperature factor $f_{Rsi,\max}$ have been illustrated with isolines drawn for the whole area of Poland.

Keywords: *building envelopes*, *isolines*, *mould*, *temperature factor*

S t r e s z c z e n i e

W artykule opisano kryterium ochrony przegród budowlanych przed rozwojem grzybów pleśniowych. Jako kryterium oceny zagrożenia przegród przyjęto czynnik temperaturowy f_{Rsi} . Podano wyniki obliczeń wartości czynnika temperaturowego $f_{Rsi,\max}$ dla miesiąca krytycznego w 61 miejscach w Polsce, dla których dane dotyczące typowych lat meteorologicznych są dostępne na stronie internetowej Ministerstwa Infrastruktury. W obliczeniach czynnika temperaturowego uwzględniono różne klasy wilgotności pomieszczeń. Wyniki obliczeń wartości czynnika temperaturowego $f_{Rsi,\max}$ zilustrowano izoliniami sporządzonymi dla całego obszaru Polski.

Słowa kluczowe: *przegrody budowlane*, *izolinie*, *pleśń*, *czynnik temperaturowy*

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1. Introduction

The presence of mould on wall surfaces is a problem affecting buildings in many European countries [3]. In Western Europe, the presence of mould on walls was not recognised as a problem until the mid-nineteen-eighties. It was then that countries like Belgium, the Netherlands, Italy, Germany and the United Kingdom created a working group investigating, among other things, the phenomena of surface condensation and the associated formation (and growth) of mould on the surfaces of building envelopes [5]. It was noted that the problem of the presence of mould on the surfaces of the envelopes appears not only when the surfaces are damp due to condensation of water vapour – as we know, this occurs when the relative humidity at the surface of the envelope reaches 100% (i.e. when the partial pressure of water vapour in room air p_i is equal to the pressure of saturated vapour p_{si}).

Specifically, it was noted that moulds also appear and develop on building envelope surfaces having contact with air, the relative humidity of which being less than 100%. Actually, the risk of mould development is already present when the relative humidity is around 80% – this occurs in situations of contact with moisture sensitive materials when the moisture persists for at least several days. Therefore, recognising 80% relative humidity of air as the critical humidity [2], the following condition for the possibility of mould growth was formulated:

$$p_i \geq 0.8 \cdot p_{sat}(\theta_{si}) \tag{1}$$

where:

p_i – partial pressure of water vapour in the air of the room,
$p_{sat}(\theta_{si})$ – saturated vapour pressure.

As follows from the above formula, surface condensation and mould growth heavily depends upon the partial pressure of water vapour in the room p_i, and on the saturated vapour pressure on the surface of the envelope $p_{sat}(\theta_{si})$.

According to the regulations which were in force in Poland until the end of 2008, it was only required to prove that the surface temperature of the envelopes was 1 K higher than the dew point of the air in the room in the so-called design conditions to allow a conclusion that there would be no condensation and mould growth on the surface of the envelopes. Detailed regulations in this respect were formulated in the regulation on technical conditions to be met by buildings [6]. As we now know, this condition has been proven to be insufficient to protect homes against the occurrence of mould.

Checking whether the condition specified in formula (1) has been fulfilled entails the necessity to calculate the minimum allowable surface temperature $\theta_{si,\min}$, i.e. the lowest temperature of the inner surface of the outer envelope, below which mould growth begins. By knowing the value of the minimum allowable surface temperature $\theta_{si,\min}$, the temperature of the air in the room θ_i and the temperature outside the building θ_e, it is possible to calculate the minimum value of the dimensionless temperature of the inner surface $f_{Rsi,\min}$ for each month of the year. This value is also known as the minimum temperature factor or the minimum temperature coefficient. The critical month, as is mentioned in [8], is the one in which the required value of $f_{Rsi,\min}$ is the highest. The value of the temperature factor for this month is known as $f_{Rsi,\max}$. Thus, in order to prevent the appearance of mould, building envelopes should be designed so that the value of $f_{Rsi,\max}$ will always be lower than the temperature factor f_{Rsi} – which describes the thermal performance of the building envelope:

$$f_{Rsi} > f_{Rsi,\max}, \tag{2}$$

where f_{Rsi} can be written as:

$$f_{Rsi} = \frac{\theta_{si} - \theta_e}{\theta_i - \theta_e}, \tag{3}$$

which in practice, for flat envelopes, i.e. for a one-dimensional heat flow system, allows the calculation of the temperature factor f_{Rsi} from the formula:

$$f_{Rsi} = 1 - \frac{U}{R_{si}^{-1}}, \tag{4}$$

where:

- U – the heat transfer coefficient, determined according to [11],
- R_{si} – the resistance of heat transfer (the value assumed for the calculations is 0.25 m^2K/W).

However, in the case where the heat transfer takes place in a two- or three-dimensional heat flow system, f_{Rsi} can be determined by use of the method provided, for example, in standard [9].

In Poland, the temperature factor f_{Rsi} began to be used as a criterion for assessing the risk of the appearance and growth of mould on the inner surfaces of building envelopes at the beginning of 2009, when the Minister of Infrastructure changed the regulation on technical conditions to be met by buildings and their location [7]. At this point, the question of why these changes were introduced so late arises, considering that the method of calculating the temperature factor $f_{Rsi,\min}$ had been known for many years and had been available, among others, in standard [8]. The reason for this must have been the lack of universal access to data from a typical meteorological year for a large number of areas in Poland. Files with typical meteorological year-long data for 61 places in Poland were prepared by the Ministry of Infrastructure and Development and published on its website [11] in July 2008 (mainly for the requirement of energy performance certification of buildings). This enabled the practical application of the temperature factor as a criterion for assessing the risk of mould growth on the interior surfaces of building envelopes. More information on typical meteorological year data for Poland can be found in [4].

The aim of this work is to provide, in tabular and graphic form, the temperature factor $f_{Rsi,\max}$ for the critical month in 61 locations in Poland for which typical meteorological year data has been published on the website of the Ministry of Infrastructure and Development [11]. The results of the calculations of $f_{Rsi,\max}$ are provided for various room humidity classes. In order to evaluate the distribution of the temperature factor $f_{Rsi,\max}$ for the entire Polish territory, and not just for the 61 selected locations, the paper provides the results of calculations of the temperature factor in the form of isolines. The authors believe that the proposed way of calculating the temperature factor $f_{Rsi,\max}$ will allow a fast determination of this factor for designing needs.

2. Room air humidity

To define room air humidity conditions, we may use either the partial pressure of water vapour or moisture by volume. Partial pressure of water vapour (in the room) depends on:
- partial pressure of water vapour in the outside air p_e or condensation of water vapour in the outside air c_e,
- multiple air exchange rate in the room n,
- volume (cubic capacity) of the room V,
- water vapour production in the room (internal moisture production) G.

As long as there is no surface condensation and no hygroscopic absorption and storage of moisture by envelope materials, we can write the moisture balance of the room in the following way [1]:

$$\Phi_{in} + G = \Phi_{out}, \tag{5}$$

where:

Φ_{in} – the moisture flowing into the room from outside the building,
G – internal moisture production,
Φ_{out} – the moisture leaving the room.

Assuming that there is no difference between the air temperature outside the building and in the room, the amount of moisture flowing into the room from outside the building is:

$$\Phi_{in} = n \cdot V \cdot c_e, \tag{6}$$

where:

n – the multiple air exchange rate in the room,
V – the cubic capacity of the room, and c_e is water vapour concentration outside the room.

In contrast, the amount of moisture leaving the room can be written as:

$$\Phi_{out} = n \cdot V \cdot c_i \tag{7}$$

where:

c_i – water vapour concentration in the air of the room.

Taking into account the moisture balance written as formula (5), we can obtain the difference of concentrations of water vapour between the air inside and outside the room:

$$c_i - c_e = \frac{G}{n \cdot V}. \tag{8}$$

By adjusting formula (8) due to changes in air volume caused by the difference in air temperature inside and outside of the room and using Boyle Gay-Lussac's law [5] we obtain:

$$c_i - c_e \frac{T_e}{T_i} = \frac{G}{n \cdot V}, \tag{9}$$

where T_e and T_i are the absolute temperatures in K.

Water vapour concentration can be expressed by its partial pressure as:

$$p = c \cdot R \cdot T, \tag{10}$$

where:

R – the gas constant for vapour, amounting to 462 J/kg·K.

The difference of the partial pressure of water vapour in the air in the room and outside the building can then be written as the following formula:

$$p_i - p_e = \frac{462 \cdot (\theta_i + 273) \cdot G}{n \cdot V}. \tag{11}$$

As seen from the above formula, the difference of the partial pressure of water vapour in the air inside the room and outside of Δp, also known as the excess internal pressure of water vapour, depends on the air temperature in the room as well as the type, size and usage of the room. In the absence of Polish studies conducted in buildings of various purposes and usage, in order to calculate the temperature factor f_{Rsi} the values of the excess internal pressure Δp provided in [8] have been adopted as for buildings located and designed in Western Europe. In this case, the values of the excess internal pressure depend on the so-called room humidity class. For the calculation of the temperature factor f_{Rsi}, three (i.e. the second, third and fourth) of the five humidity classes are taken into account. In the calculations of f_{Rsi}, the upper limits for each of the classes were adopted. Table 1 shows examples of rooms assigned to given humidity classes.

Table 1

Room humidity classes according to [8]

Room humidity classes	Examples of rooms and buildings	Δp*), [Pa]
1	storage facilities, dry production plants	≤ 270
2	offices, shops	> 270 ≤ 540
3	low occupancy flats	> 540 ≤ 810
4	high occupancy flats, sports halls, kitchens, canteens, rooms in buildings heated with gas heaters without flues	> 810 ≤ 1080
5	rooms in special buildings, e.g. laundries, breweries, swimming pools	> 1080

*) the given values relate to excess internal pressure Δp at air temperature $\theta_e \leq 0$°C

3. The results of calculations of the temperature factor for the critical month

With the help of the files published on the Ministry's website containing typical meteorological year data [11], average monthly air temperatures θ_e and average monthly relative humidity values φ_e for 61 selected Polish meteorological stations were calculated. By adopting the calculated average monthly temperature and air humidity values outside the building, defining the air temperature inside the room θ_i = 20°C and adopting the excess internal water vapour pressure values Δp for three room humidity classes and the maximum allowable relative humidity at the surface φ_{si} = 0.8, the minimum allowable pressure of saturated vapour $p_{sat}(\theta_{si})$ for each of the 12 months of the year and each of the mentioned 61 meteorological stations was calculated.

On the basis of the calculated minimum allowable pressures at saturation, for each month, the minimum allowable surface temperature $\theta_{si,\min}$, was determined, i.e. the lowest allowable temperature of the inner surface of the envelope, below which mould growth begins. Knowing the value of the minimum allowable surface temperature $\theta_{si,}$ the minimum value of the temperature factor $f_{Rsi,\min}$, for each month was calculated, the critical months and the corresponding temperature factors $f_{Rsi,\max}$ assigned to 61 meteorological stations were then determined.

The results of the calculations of the temperature factor $f_{Rsi,\max}$ with critical months indicated are shown in Table 2. From the analysis of the above results, it becomes clear that the highest values of the temperature factor $f_{Rsi,\max}$ occur in Chojnice and Suwałki. In Chojnice, $f_{Rsi,\max}$ for humidity class 2 equals 0.618, and in Suwałki it equals 0.616. For humidity class 3, the highest value of the factor $f_{Rsi,\max}$ also occurs in Chojnice and in Suwałki (and equals 0.793), while for humidity class 4, it equals 0.942 in Suwałki and 0.939 in Chojnice. The critical month in Chojnice is December, whereas in Suwałki, it is November. The lowest value of the temperature factor occurs in Zakopane, where for humidity class 2, $f_{Rsi,\max} = 0.566$, humidity class 3 $f_{Rsi,\max} = 0.741$ and for humidity class 4, $f_{Rsi,\max} = 0.891$.

Table 2

Temperature factor $f_{Rsi,\max}$ values (the critical $f_{Rsi,\max}$ values) for 3 humidity classes

No.	Town/City	Humidity Class 2		Humidity Class 3		Humidity Class 4	
		$f_{Rsi,\max}$	critical month	$f_{Rsi,\max}$	critical month	$f_{Rsi,\max}$	critical month
1	Białystok	0.598	December	0.772	December	0.918	November
2	Bielsko Biała	0.575	December	0.760	December	0.913	December
3	Bydgoszcz	0.604	February	0.784	February	0.933	February
4	Chojnice	0.618	December	0.793	December	0.939	December
5	Częstochowa	0.602	December	0.775	December	0.919	December
6	Elbląg	0.606	December	0.785	December	0.935	December
7	Gdańsk	0.572	December	0.752	December	0.904	December
8	Gorzów Wlkp.	0.600	December	0.780	January	0.930	January
9	Hel	0.607	January	0.786	January	0.935	January
10	Jelenia Góra	0.587	December	0.769	December	0.920	December
11	Kalisz	0.606	December	0.782	December	0.927	December
12	Kasprowy Wierch	0.583	May	0.762	May	0.913	May
13	Katowice	0.581	December	0.756	December	0.900	December
14	Kętrzyn	0.615	December	0.790	December	0.935	December
15	Kielce	0.610	December	0.789	December	0.938	December
16	Kłodzko	0.593	December	0.769	January	0.918	January

continued Tab. 2

17	Koło	0.605	December	0.781	December	0.926	January
18	Kołobrzeg	0.583	January	0.765	January	0.917	January
19	Koszalin	0.595	January	0.772	January	0.920	January
20	Kraków	0.591	December	0.770	December	0.917	December
21	Krosno	0.591	December	0.768	December	0.916	November
22	Łeba	0.604	December	0.784	December	0.934	December
23	Lębork	0.583	February	0.765	February	0.916	February
24	Legnica	0.597	December	0.778	December	0.928	December
25	Lesko	0.577	December	0.759	December	0.910	February
26	Leszno	0.597	December	0.776	January	0.924	January
27	Łódź	0.605	December	0.782	December	0.932	December
28	Lublin	0.595	November	0.773	November	0.923	November
29	Mikołajki	0.606	December	0.781	December	0.925	December
30	Mława	0.602	December	0.775	December	0.918	December
31	Nowy Sącz	0.569	December	0.754	January	0.907	January
32	Olsztyn	0.612	December	0.788	December	0.934	December
33	Opole	0.603	December	0.782	December	0.932	December
34	Ostrołęka	0.601	December	0.776	December	0.922	December
35	Piła	0.613	December	0.788	December	0.933	December
36	Płock	0.608	December	0.785	December	0.933	December
37	Poznań	0.609	December	0.788	December	0.936	December
38	Przemyśl	0.584	December	0.762	December	0.908	December
39	Racibórz	0.586	January	0.769	January	0.920	January
40	Resko	0.592	January	0.768	January	0.917	December
41	Rzeszów	0.587	December	0.764	December	0.916	February
42	Sandomierz	0.611	December	0.789	December	0.936	December
43	Siedlce	0.598	December	0.771	December	0.915	December
44	Słubice	0.597	January	0.776	January	0.926	January
45	Śnieżka	0.608	April	0.783	April	0.928	April
46	Sulejów	0.605	December	0.782	December	0.928	December
47	Suwałki	0.616	November	0.793	November	0.942	November
48	Świnoujście	0.601	January	0.780	January	0.930	January
49	Szczecin	0.597	January	0.775	January	0.925	January

continued Tab. 2

50	Szczecinek	0.606	January	0.785	January	0.934	January
51	Tarnów	0.589	December	0.770	December	0.920	December
52	Terespol	0.598	December	0.772	December	0.916	December
53	Toruń	0.598	January	0.775	January	0.922	January
54	Ustka	0.590	January	0.771	January	0.921	January
55	Warszawa	0.602	December	0.780	December	0.929	December
56	Wieluń	0.599	December	0.773	December	0.917	December
57	Włodawa	0.606	December	0.780	December	0.924	December
58	Wrocław	0.595	December	0.771	December	0.919	February
59	Zakopane	0.566	January	0.741	January	0.891	November
60	Zamość	0.603	November	0.783	November	0.932	November
61	Zielona Góra	0.605	January	0.784	January	0.933	December

4. Summary

This paper presents calculations of the temperature factor for the locations of 61 meteorological stations in Poland and determines the values of $f_{Rsi,\max}$ for the critical months at these locations. Based on the results provided in Table 2, it can be hypothesised that the factor having the greatest impact on the value of the temperature factor $f_{Rsi,\max}$ is the room humidity class. The room humidity class is dependent on internal moisture production as well as room ventilation (multiple air exchange rate) and thus, on the type and usage of the room. Moreover, a belief has to be expressed at this point that it is necessary to conduct research of flats and rooms in non-residential buildings in Poland in order to enable their correct classification (i.e. their assignment to an appropriate humidity class). The calculated differences between the average values of $f_{Rsi,\max}$ for the whole Polish territory determined for humidity classes 2 and 3 equal 0.178 and for classes 3 and 4 differences equal 0.148.

The average value of the maximum temperature factor $f_{Rsi,max}$ for Poland (for 61 selected meteorological stations) for humidity class 2 is 0.597, for humidity class 3, it is 0.775, and for humidity class 4, it equals 0.923.

The distribution of the values of the temperature factor $f_{Rsi,max}$ on Polish territory for each humidity class has been shown in the Figures 1–9 below in the form of graphs and isolines. On the basis of the visual material it can be concluded that the values of $f_{Rsi,\max}$ vary within the following ranges:

0.566 – 0.618 for humidity class 2,
0.741 – 0.793 for humidity class 3,
0.891 – 0.923 for humidity class 4.

The presented results show that if the external walls meet the requirements regarding the heat transfer coefficient U (as provided in Regulation [8], for the condition where

$U \leq U_{(max)}$ = 0.3 W/m²K) then both residential and non-residential rooms assigned to humidity class 3, everywhere in Poland, fulfil the condition that the value of the temperature factor $f_{Rsi} > f_{Rsi,\max}$ – this is illustrated in Figs. 1, 2 and 3. In these cases, it is not necessary to perform calculations to ascertain whether the condition $f_{Rsi} > f_{Rsi,\max}$, is met. This is also the case for all external walls whose heat transfer coefficient is less than U = 0.75 W/m²K. The presented results show that if the external walls meet the requirements regarding the heat transfer coefficient U (as provided in regulation [7], for the condition where $U \leq U_{(max)}$ = 0.3 W/m²K) then both residential and non-residential rooms assigned to humidity class 3, everywhere in Poland, fulfil the condition that the value of the temperature factor $f_{Rsi} > f_{Rsi,\max}$ – this is illustrated in Figs. 1, 2 and 3. In these cases, it is not necessary to perform calculations to ascertain whether the condition $f_{Rsi} > f_{Rsi,\max}$, is met – this is also the case for all external walls whose heat transfer coefficient is less than U = 0.75 W/m²K.

Of course, the above conclusion does not apply to external walls with thermal bridges; in their case, it is necessary to calculate the temperature factor f_{Rsi} for such a wall for the place where the thermal bridge is located and to compare the result with the values of $f_{Rsi,\max}$ provided in this paper.

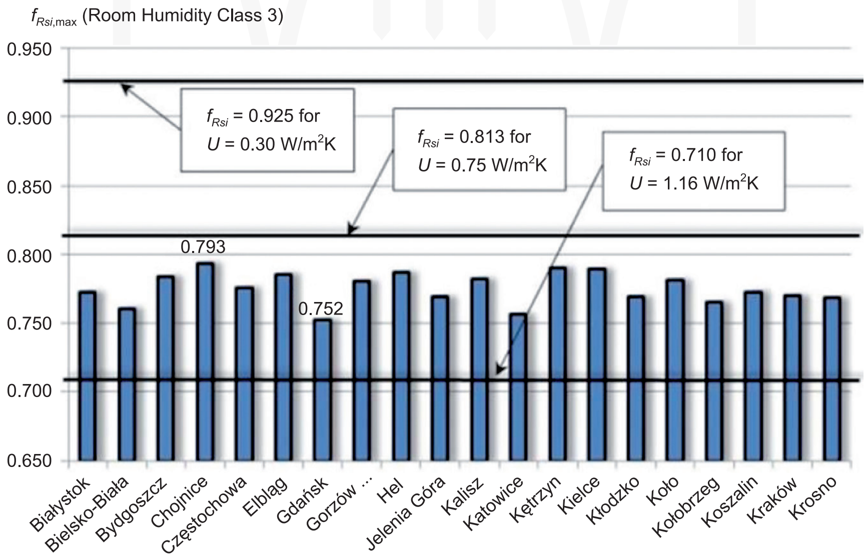

Fig. 1. Comparison of the temperature factor f_{Rsi}, determined for three types of building envelopes characterised by the heat transfer coefficient U with the maximum temperature factors $f_{Rsi,\max}$, determined for 20 meteorological stations and for room humidity class 3

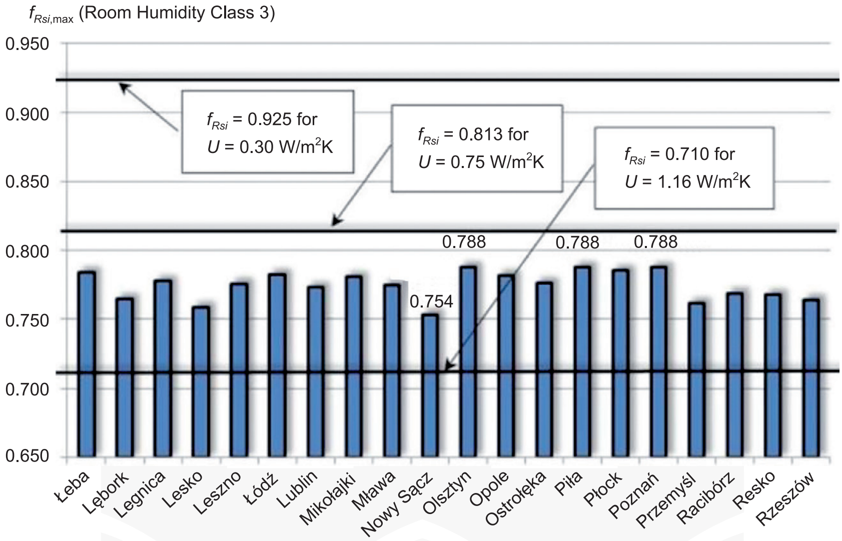

Fig. 2. Comparison of the temperature factor f_{Rsi}, determined for three types of building envelopes characterised by the heat transfer coefficient U with the maximum temperature factors $f_{Rsi,max}$, determined for 20 meteorological stations and for room humidity class 3

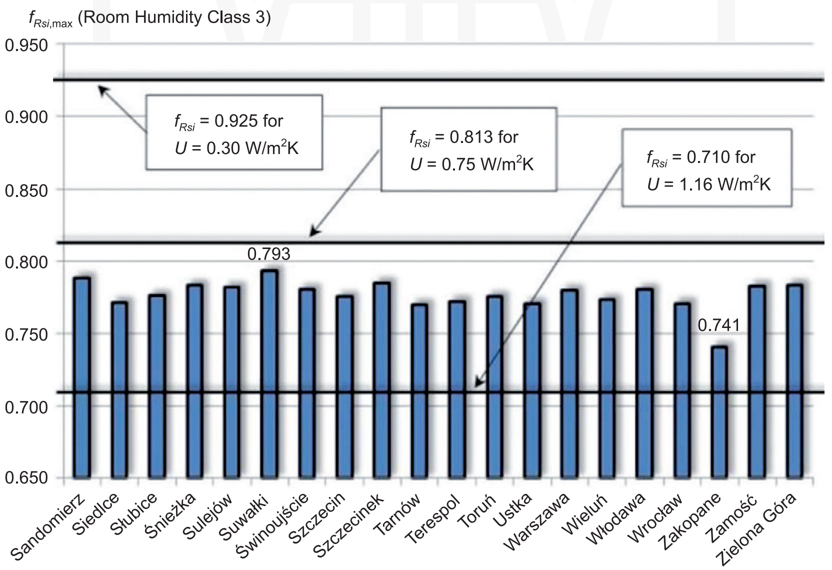

Fig. 3. Comparison of the temperature factor f_{Rsi}, determined for three types of building envelopes characterised by the heat transfer coefficient U with the maximum temperature factors $f_{Rsi,\max}$, determined for 20 meteorological stations and for room humidity class 3

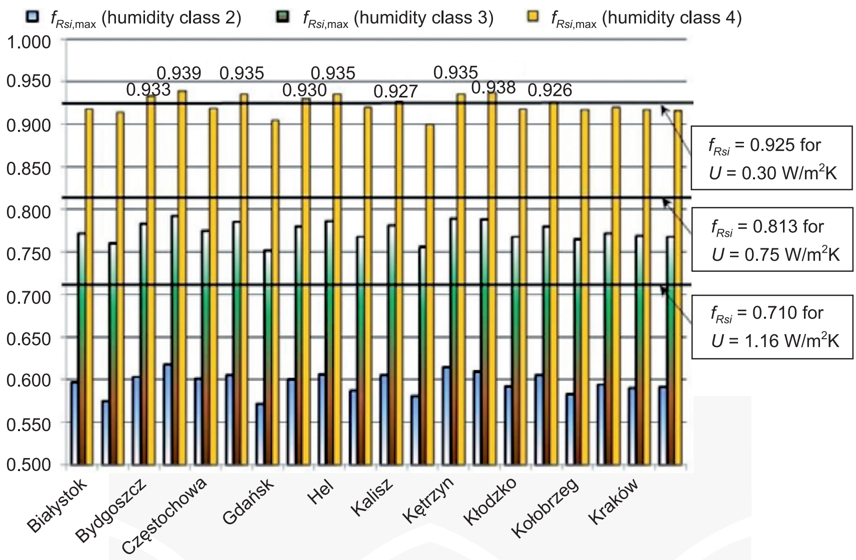

Fig. 4. Comparison of the temperature factor f_{Rsi}, determined for three types of building envelopes characterised by the heat transfer coefficient U with the maximum temperature factors $f_{Rsi,max}$, determined for 20 meteorological stations, depending on room humidity class

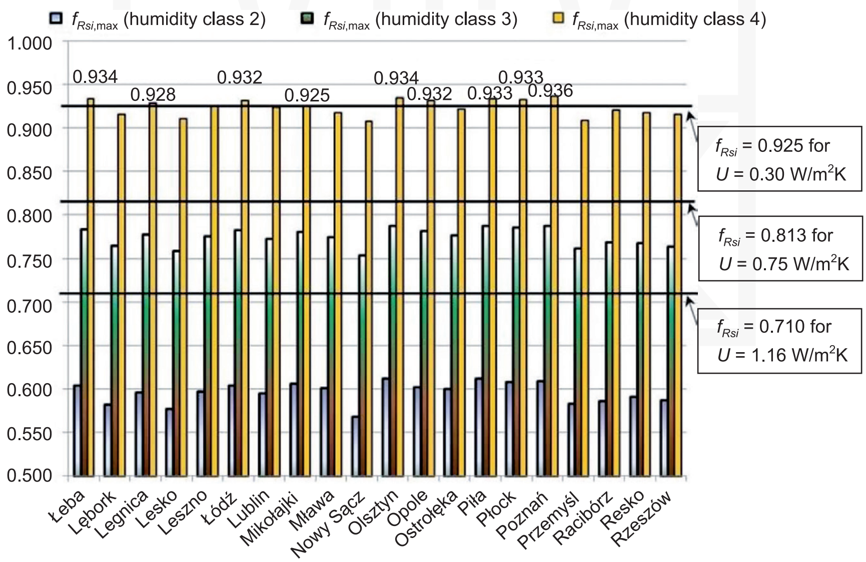

Fig. 5. Comparison of the temperature factor f_{Rsi}, determined for three types of building envelopes characterised by the heat transfer coefficient U with the maximum temperature factors $f_{Rsi,\max}$, determined for 20 meteorological stations, depending on room humidity class

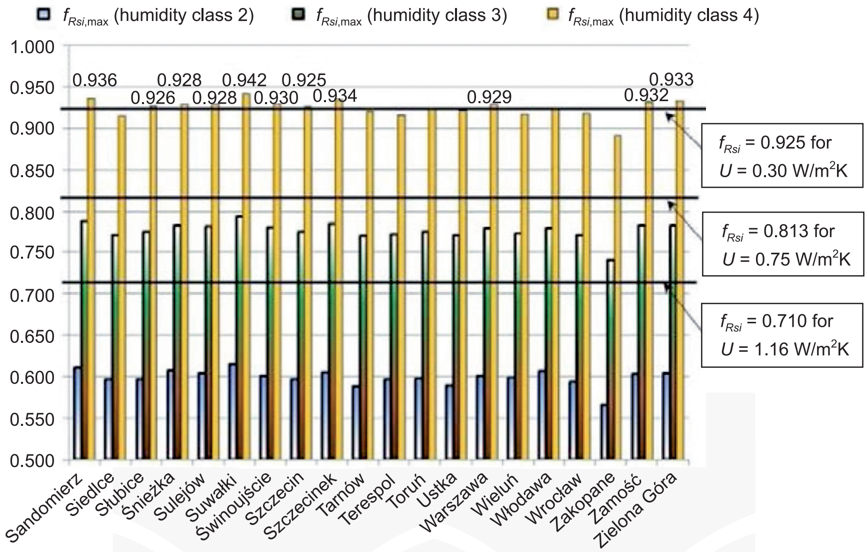

Fig. 6. Comparison of the temperature factor f_{Rsi}, determined for three types of building envelopes characterised by the heat transfer coefficient U with the maximum temperature factors $f_{Rsi,\max}$, determined for 20 meteorological stations, depending on room humidity class

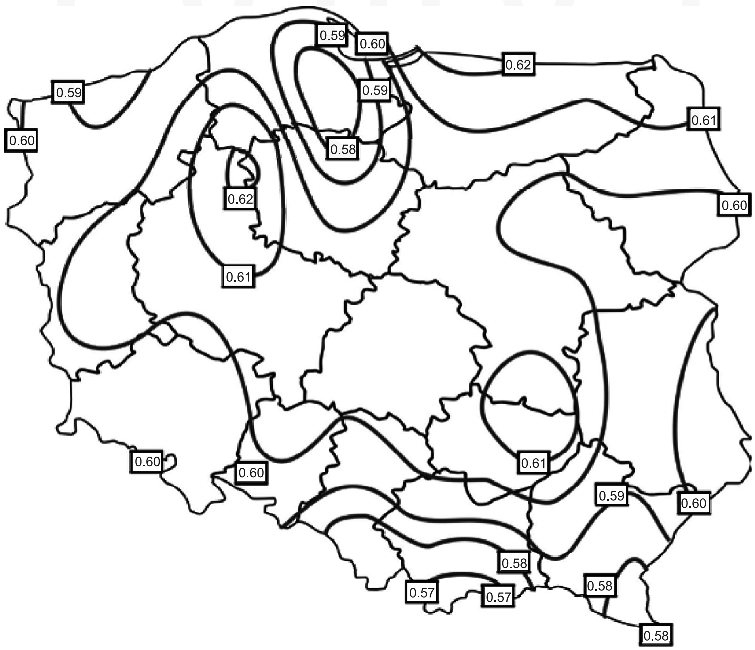

Fig. 7. Isolines of the temperature factor $f_{Rsi,\max}$ for humidity class 2

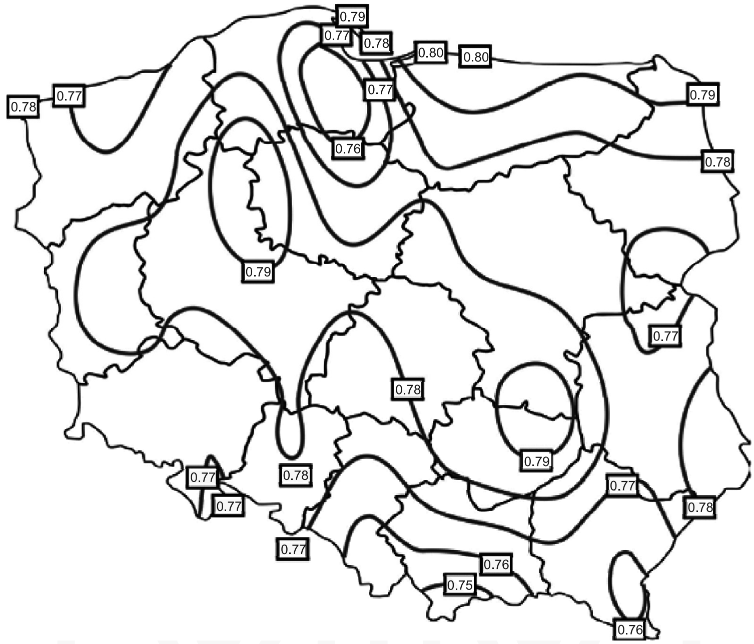

Fig. 8. Isolines of the temperature factor $f_{Rsi,\max}$ for humidity class 3

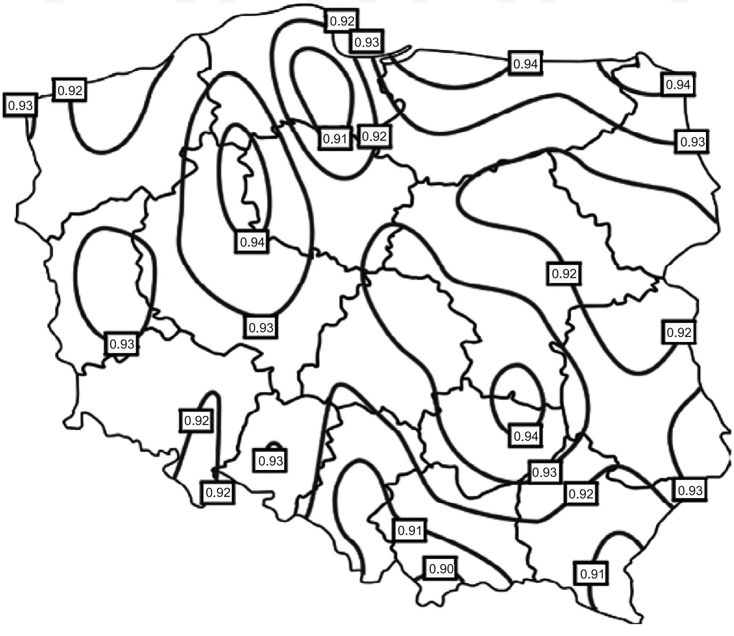

Fig. 9. Isolines of the temperature factor $f_{Rsi,\max}$ for humidity class 4

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