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Temperature Evaluation of a Building Facade with a Thin Plaster Layer under Various Degrees of Cloudiness

Elena V. Korkina [1,2], Ekaterina V. Gorbarenko [1,3], Elena V. Voitovich [4], Matvey D. Tyulenev [2] and Natalia I. Kozhukhova [5,*]

1 Research Institute of Building Physics, Russian Academy of Architecture and Construction Sciences, 21, Lokomotivny Proezd, Moscow 127238, Russia; elena.v.korkina@gmail.com (E.V.K.); tulenevm@gmail.com (E.V.G.)
2 Department of Heat and Gas Supply and Ventilation, Moscow State University of Civil Engineering, 26, Yaroslavskoe shosse, Moscow 129337, Russia; e.voitovich@mail.ru
3 Faculty of Geography, Lomonosov Moscow State University, 1, Leninskie Gori, Moscow 119234, Russia
4 Department of Industrial and Civil Engineering, Moscow Polytechnic University, 38, Bolshaya Semyonovskaya St., Moscow 107023, Russia; catgor@mail.ru
5 Department of Material Science and Material Technology, Belgorod State Technological University Named after V.G. Shukhov, 46, Kostukov, Belgorod 308012, Russia
* Correspondence: kozhuhovanata@yandex.ru

Abstract: In this paper, we investigate the surface temperature of a wall with a facade heat-insulating composite system (FHIC), which has a thin plaster layer, taking into account solar radiation exposure at different degrees of cloudiness during the month. The object of study is a wall with FHIC, on the outer surface of which temperature sensors were mounted and measurements were taken. Air temperatures were also measured for one month of the warm period of the year. The coefficient of absorption of solar radiation by the surface of the facade is calculated based on the measurement of the spectral reflection coefficient. Measurements of direct and scattered solar radiation arriving on a horizontal surface were carried out, and the cloudiness of the sky was also recorded. The calculation of direct and scattered solar radiation was carried out, taking into account the shading of surrounding buildings using the authors' novel methods. The experimental days were divided into three groups according to the degree of cloudiness; statistically significant differences between the groups for the studied parameters were demonstrated. The temperature of the outer surface of the wall was calculated according to A.M. Shklover's formula. The measured values of the temperature of the outer surface of the wall were compared with the calculated ones. It was shown that there is a good correlation between the measured and calculated temperatures for different degrees of cloudiness. At the same time, for days with no or slight cloudiness (Group I), when direct solar radiation predominates, the differences reach 1.7 °C; smaller differences are observed for days with average cloudiness (Group II) during daytime hours, with a maximum difference of 0.5 °C; and on days with continuous cloudiness (Group III), when only scattered radiation is present for daytime hours, the maximum difference is 0.3 °C. Statistically significant differences were found between the measured and calculated temperatures for groups of days, divided by the degree of cloudiness, for the experimental period of a day from 10 a.m. to 5 p.m., which indicates the possibility of considering amendments to A.M. Shklover's formula for sunny days. The results of comparing the measured and calculated heating temperatures of the facade surface also indirectly confirm the correctness of the author's calculations of the incoming solar radiation, taking into account the effect of the surrounding buildings. The results obtained can be used to study the inertia and durability of building structures under solar radiation.

Keywords: solar radiation; absorption of solar radiation; heating temperature; energy saving; degree of cloudiness

Citation: Korkina, E.V.; Gorbarenko, E.V.; Voitovich, E.V.; Tyulenev, M.D.; Kozhukhova, N.I. Temperature Evaluation of a Building Facade with a Thin Plaster Layer under Various Degrees of Cloudiness. *Energies* **2023**, *16*, 5783. https://doi.org/10.3390/en16155783

Academic Editor: Edward Halawa

Received: 30 June 2023
Revised: 25 July 2023
Accepted: 1 August 2023
Published: 3 August 2023

1. Introduction

Solar access to the translucent enclosing structures of buildings is taken into account when calculating the energy spent on the heating and ventilation of the building during the heating season [1]. In this case, the selection of glazing with multifunctional properties is considered, i.e., contributing to protection against overheating in summer, but at the same time reducing heat loss in winter [1,2]. The influence of such glazing on natural lighting and insulation is also considered [3,4]. In Russia, the calculation and design of the thermophysical characteristics of non-translucent enclosing structures is carried out exclusively for winter operating conditions [5]. Meanwhile, when taking into account the heat transfer of non-translucent structures in summer conditions for some climatic zones of the Russian Federation, it is possible to achieve the effect of energy saving by eliminating air conditioning while ensuring thermal comfort in the room. So, for these purposes, in [6], the selection of materials in a wall fragment in laboratory conditions is considered. From this point of view, for the climatic zones of the Russian Federation, it is interesting to study, for example, changes in the characteristics of a heater in summer, for which it is necessary to calculate the transfer of heat from the outer surface of the wall to the inner one.

There are few works in the literature that consider the calculated or experimental determination of the heating temperature of the outer surfaces of walls [7] or roofs. Basically, the calculated and measured inflow of solar radiation to the roof [8] and inclined surfaces [9] is considered. In some works, the issues of the absorption of solar radiation by the surface of a facade with ribbing [10] and the absorption of solar radiation in ventilated facades [11] were studied. The issues of reducing the heating of the facade from solar radiation to reduce the load on the air conditioning system [12,13] are also considered, as well as, on the contrary, the influx of heat from solar radiation to save energy during the heating process [14]. For such studies, it is useful to know the temperature of the heating of the facade due to solar radiation, as well as to have a verified method for calculating incoming solar radiation, taking into account the building system, which is often found in urban environments. The approach proposed in this paper can be applied in similar studies, as well as in the study of the inertia and durability of facade materials.

In some of the following works, theoretical methods for calculating the heating temperature of facade surfaces due to solar radiation are considered.

In the work of Z.I. Pivovarova [15] the calculation of the wall heating temperature taking into account solar radiation, radiant heat transfer, the intensity of air exchange between the internal air and the external environment, and the thermal resistance of the walls was studied. The calculation, taking into account all these factors, showed that due to heating from direct solar radiation, an increase in the temperature of the outer surface of the wall up to 4 °C is possible relative to the calculation without taking into account solar radiation.

In the same work [15], it is shown that the calculation using A.M. Shklover's formula [16], which takes into account the influence of only solar radiation, gives similar values to the author's calculation from [15] at negative air temperatures, and an increase of up to 2 °C at positive air temperatures.

The differences are explained by the fact that A.M. Shklover's formula does not take into account heat transfer processes, in contrast to the formula proposed by Z.I. Pivovarova [15]. However, in the literature there is no comparison of the calculated and measured values of the heating temperature of the outer surface of the wall. Such a comparison is made in this article for various irradiation conditions.

In this article, the dependence of the calculated facade heating temperature on the incoming solar radiation is determined by the A.M. Shklover's formula [16] for each daylight hour (Formula (1)):

$$t_{\text{calc}} = t_{\text{out}} + \frac{\mathrm{I}^{\text{vertical}} \cdot \rho}{\alpha_{\text{out}}} \tag{1}$$

where t_{out} is the outdoor air temperature in the shade, °C; $\mathrm{I}^{\text{vertical}}$ is the total solar radiation entering the vertical surface of the facade for the studied period of time, W/m^2; ρ is the absorption coefficient of solar radiation by the facade surface; and α_{out} is the heat transfer coefficient near the facade surface, $W/m^2 \cdot °C$ (heat flow through 1 m^2 of the facade surface at a temperature gradient of 1 °C), calculated using empirical Formula (2),

$$\alpha_{out} = 5.8 + 11.6\sqrt{v}, \quad (2)$$

where v is the wind speed, m/s, taken according to the reference data [17]. When processing the results of the experiment, the wind speed was assumed to be 2.3 and 2.2 m/s in accordance with the measurement period. Below, the calculation of the $I^{vertical}$, t_{out}, and ρ values included in Formula (1) is considered in more detail.

2. Study Object

The investigated wall, made in the form of a facade heat-insulating composite system (FHIC), was mounted on a wall based on sand–lime brick masonry. The wall was oriented to the south and located in a "closed yard" building type, which provides partial irradiation and partial shading during daylight hours (Figure 1). The outer surface of the studied wall was covered with a thin plaster layer, on the inner and outer surfaces of which three pairs of temperature sensors were mounted.

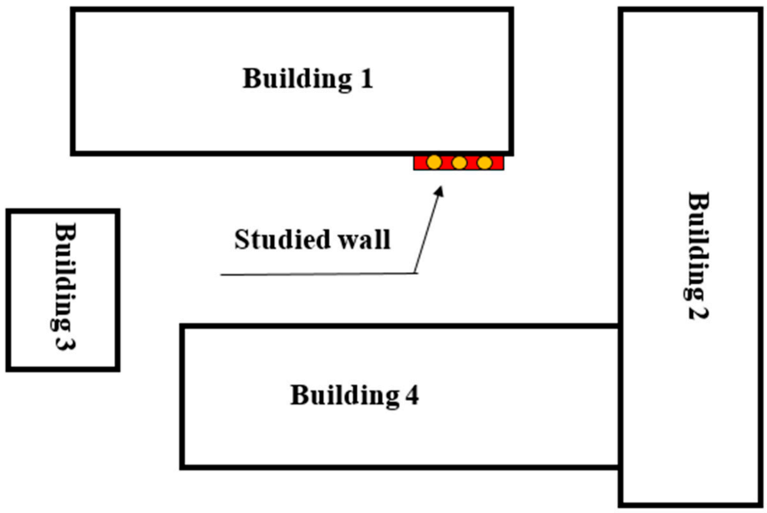

Figure 1. Scheme of the building campus location of the studied wall with temperature sensors of the "closed courtyard" type.

The sensors were mounted at a height of about 2 m from the underlying surface (Figures 2 and 3) to avoid the influence of moisture coming from the ground surface and shading by non-building objects.

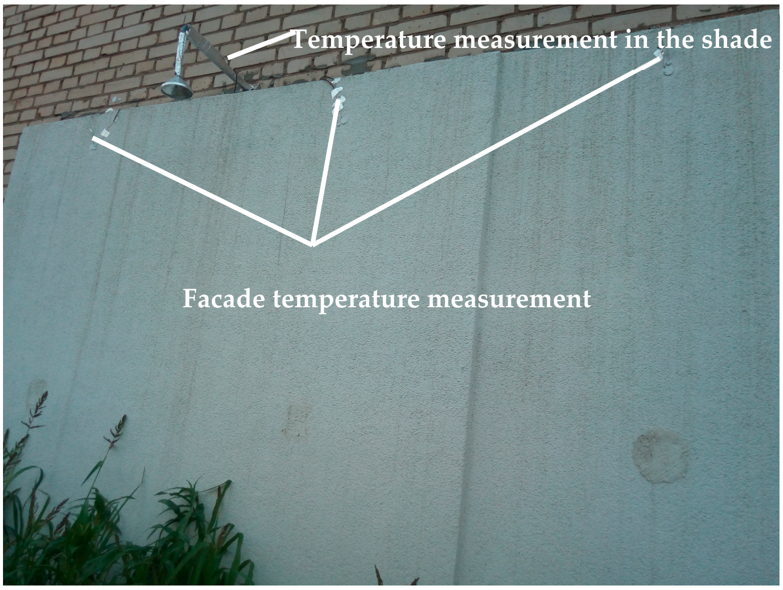

Figure 2. The studied wall with temperature sensors on the building facade and on the carry-out under the canopy.

(**a**) (**b**)

Figure 3. Location of the studied wall (**a**) and temperature sensor (**b**) on the building facade.

3. Methodology

In accordance with A.M. Shklover's formula (Formula (1)), to determine the heating temperature of the wall surface, the following data are required: the incoming solar radiation for one hour, air temperature, and absorption coefficient of the wall surface. These parameters can be determined by measurement or by calculation based on the measured data. The procedure for determining these values is as follows:

(1) The measured heating temperature of the outer surface of the wall, t_{meas} °C, designed according to the FHIC system, located in the building, and the air temperature at the outlet under the canopy in the shadows, t_{out}, °C, were measured during 28 days

of the warm period of 2019. The measurements were carried out on the device ITP-MG 4.03/20(I) "POTOK" with a minimum interval of 15 min. Limits of permissible additional temperature measurement error caused by the temperature deviation of the electronic unit from 20 °C (for every 10 °C of deviation) were ±0.05 °C.

(2) The total radiation $I^{vertical}$ (x,y) (the sum of direct and scattered solar radiation), entering the investigated section of the wall in one hour, was calculated as follows, W/m^2:

$$I^{vertical}(x,y) = S^{vertical}(x,y) + D^{vertical}(x,y), \tag{3}$$

At the same time, the direct $S^{vertical}$ (x,y), (W/m^2), and the scattered $D^{vertical}$ (x,y), (W/m^2), solar radiation entering the vertical surface of the wall under consideration, taking into account the shading by the buildings, were determined by calculations according to the methods considered in [18,19] and using experimental data. These data are the values of direct, $S^{gorisontal}$ ($t_\odot$), (W/m^2), and scattered, $D^{gorisontal}$ ($t_\odot$), (W/m^2), solar radiation entering a horizontal surface, according to the hours of real solar time $t_\odot$ for the same experimental observation period (28 days). The calculation of direct solar radiation is based on its summation for the studied periods of exposure to direct sunlight, determined by the program, taking into account the shading of the surrounding buildings [18]. The calculation of scattered solar radiation is based on determining the difference between scattered solar radiation arriving at an open horizon and scattered solar radiation shaded by surrounding buildings [19].

Cloudiness was also fixed in points (where 0 points is a clear sky, and 10 points is a completely overcast sky). The measurements were carried out at the Meteorological Observatory of the Department of Meteorology and Climatology, Faculty of Geography, Lomonosov Moscow State University (Russia).

(3) The absorption coefficient of solar radiation ρ (the ratio of the value of the flux of solar radiation absorbed by the sample to the value of the flux of solar radiation normally incident on the sample) was calculated based on the assumption that there is no transmitted component of solar radiation, so it is only necessary to determine the reflection coefficient of the finished coating of the wall under study with the FHIC system.

To achieve this, the reflection coefficient was measured according to [20] using an SF 256 UVI spectrophotometer with a PDO-7 attachment and an SF-256 BIK spectrophotometer with a PDO-8 attachment (absolute measurement error is ±0.25–1.0%); its value was 0.66. The absorption coefficient of solar radiation ρ in the absence of a transmitted component is calculated as follows (Formula (4)):

$$\rho = 1 - 0.66 = 0.34 \tag{4}$$

All measurements were carried out on verified equipment with verification certificates.

4. Results and Discussion

4.1. Processing of Meteorological Data

Taking into account the relationship between incoming solar radiation and cloudiness, 28 experimental days of the warm season were divided into three groups depending on the degree of cloudiness (in points) and, accordingly, the degree of irradiation by direct radiation. At the same time, scattered radiation is present every day.

1. Group I—These are free-of-cloudiness days and days with slight cloudiness. These days, direct radiation is practically, or not at all, obscured by clouds—5 days.
2. Group II—These are the days on which cloudiness with gaps and average cloudiness is observed. These days, direct radiation is partially obscured, partially present—16 days.
3. Group III—These are days with 100% cloudiness. On these days there is no direct radiation—7 days.

Typical curves of wall surface heating temperature for each pair of sensors and air temperature, as well as direct, scattered and total solar radiation for one day from each group, are shown in Figures 4–9.

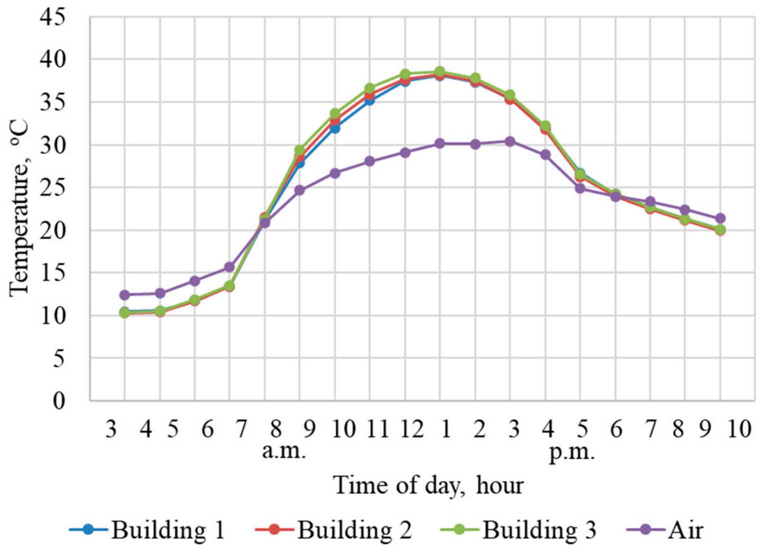

Figure 4. Kinetics of heating temperature of the wall surface and air during the 8th day.

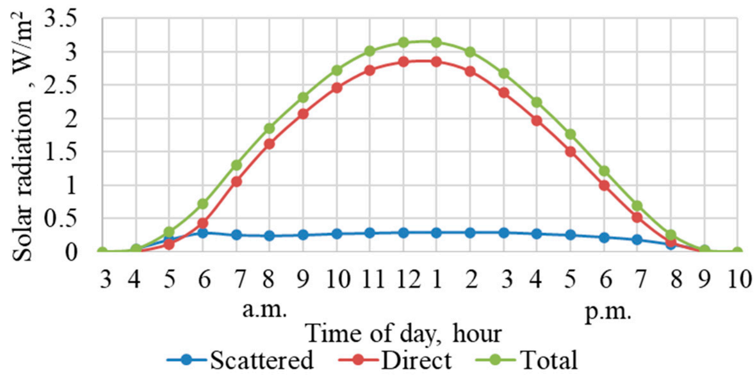

Figure 5. Incoming solar radiation (direct, scattered, and total) in daylight hours during the 8th day.

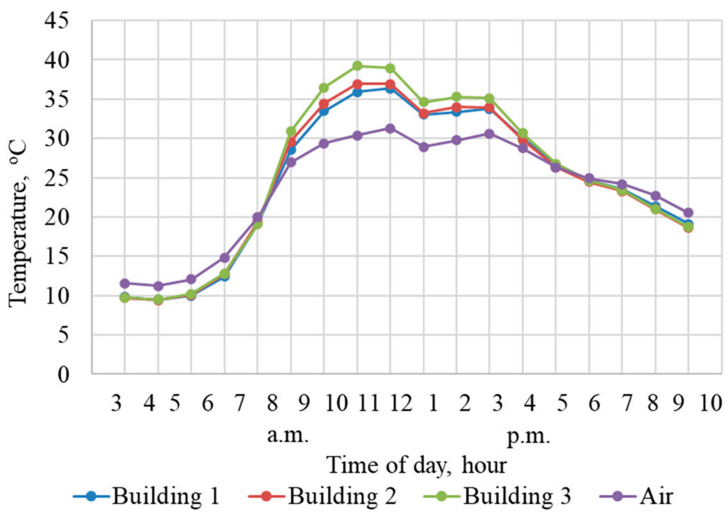

Figure 6. Kinetics of heating temperature of the wall surface and air during the 2nd day.

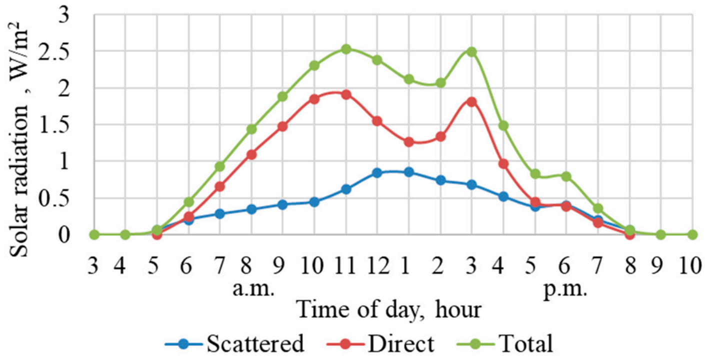

Figure 7. Incoming solar radiation (direct, scattered, and total) in daylight hours during the 2nd day.

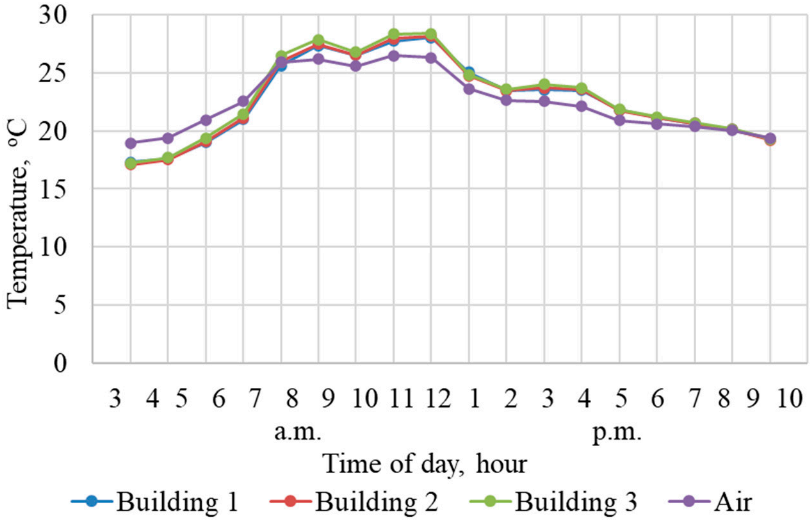

Figure 8. Kinetics of heating temperature of the wall surface and air during the 10th day.

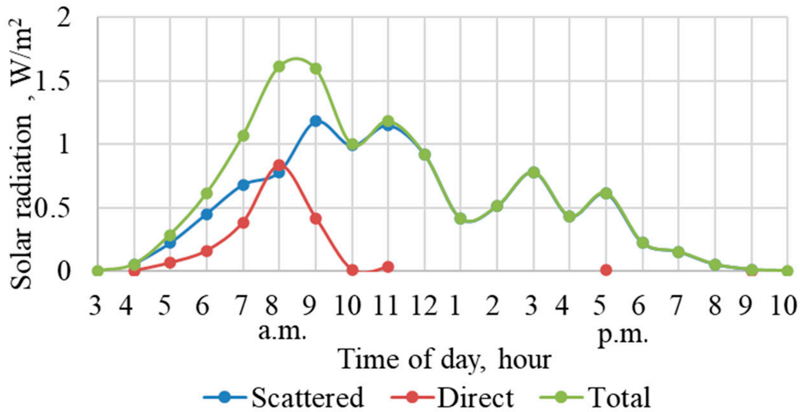

Figure 9. Incoming solar radiation (direct, scattered, and total) in daylight hours during the 10th day.

Based on Figures 4–9, it can be seen that the heating temperature significantly depends on the influx of direct solar radiation, and has maximum values for the days included in Group I. However, it should be statistically confirmed that there is a difference between the groups. To identify statistically significant differences, a criterion should be selected based on the characteristics of the data obtained. With such a small number of days in Groups I and III, it is impossible to correctly test the normality of the distribution.

Therefore, to compare several groups, a non-parametric criterion for the analysis of statistically significant differences should be chosen. The Kruskal–Wallis criterion is suitable for this [21]. The Kruskal–Wallis test consists of ranking the measurement data in all groups and then calculating the criterion according to Formula (5):

$$H = \frac{12}{N(N+1)} \sum_{i=1}^{k} \frac{R_i^2}{n_i} - 3(N+1) \tag{5}$$

where k is the number of groups; n_i is the number of elements in the group; N is the sum of the elements of all groups; and R_i is the sum of the ranks of elements in the ith group.

The criterion value H is compared with the critical value H_p at the significance level p; in cases where $H \geq H_p$, the hypothesis of differences is rejected.

For a comparative analysis, the temperature was averaged for each hour for all pairs of sensors and then the following parameters were selected (Table 1): maximum differences in calculated temperature between the heating of the wall and air max ($t_{\text{meas}} - t_{\text{out}}$), °C, (hour); cloudiness during this hour (in points); the ratio of direct and scattered radiation, $S^{\text{horisontal}}/D^{\text{horisontal}}$, for this hour; the difference between the average temperature of the wall and the average air temperature from 7 to 17 h $\left(\bar{t}_{\text{meas}} - \bar{t}_{\text{out}}\right)$, (°C); and the ratio of the sum of the values of the straight line to the sum of the values of scattered radiation from 7 a.m. to 5 p.m., $\sum S^{\text{horisontal}}/\sum D^{\text{horisontal}}$. The time period from 7 a.m. to 5 p.m. was chosen based on the irradiation conditions of the wall.

Table 1. Statistically significant differences.

Experimental Day	Group ID	*Max* ($t_{\text{meas}} - t_{\text{out}}$), °C	Experimental Hour/Cloudiness (Points)	($\bar{t}_{\text{meas}} - \bar{t}_{\text{out}}$), °C	$S^{\text{horisontal}}/D^{\text{horisontal}}$	$\Sigma S^{\text{horisontal}}/\Sigma D^{\text{horisontal}}$
8	1	9.2	12 a.m./2	6.8	9.8	9.2
9	1	8.5	11 a.m./0	6.4	9.6	9.29
11	1	8.9	12 a.m./2	6.3	10.6	9.37
17	1	7.9	11 a.m./1	5.4	6.23	4.52
18	1	8.7	12 a.m./2	5.9	4.14	3.26
1	2	8.5	12 a.m./8	4.4	3.17	2.27
2	2	8.9	11 a.m./3	4.9	3.08	2.44
3	2	5.3	3 p.m./9	1.7	2.51	0.61
4	2	6.8	2 p.m./12	2.8	2.68	1.06
5	2	6.5	12 a.m./12	4.7	0.88	0.94
6	2	6.7	1 p.m./7	4.3	3.54	2.02
7	2	6.1	1 p.m./8	4.6	1.02	1.14
14	2	6.2	2 p.m./7	2.6	1.37	0.61
15	2	7.2	12 a.m./6	4,4	1.95	1.66
16	2	7.3	12 a.m./4	3.9	4.31	1.27
19	2	5.6	10 a.m./6	3.6	2.21	1.09
20	2	6.4	12 a.m./7	4.2	1.23	0.76
21	2	7.9	12 a.m./5	5.5	3.49	1.41
22	2	7.3	12 a.m./8	5.7	4.29	5.62
23	2	7.8	12 a.m./12	5.1	3.83	2
28	2	7.1	12 a.m./9	3.8	0.78	0.45
10	3	2.1	12 a.m./10	1.3	0	0.08
12	3	4.3	11 a.m./8	1.3	0.02	0.29
13	3	4	12 a.m./10	2.6	0.02	0.09
24	3	3.1	11 a.m./10	2.2	0	0.09
25	3	1.2	10 a.m./10	0.7	0	0.02
26	3	0.4	9 a.m./10	0.2	0	0
27	3	0.6	11 a.m./10	0.3	0	0
H value		20.9	-	13.6	22.8	10.6
Significance level, *p*		<0.05	-	<0.05	<0.05	<0.05

Statistically, significant differences were found for all considered characteristics (Table 1). This means that the division into groups is correct. Experimental data on solar radiation and the heating temperature of the wall surface and outside air were used to compare the measured and calculated results.

4.2. Correlation between Measured and Calculated Heating Temperature for Wall Surfaces under Different Irradiation Conditions

For comparative analysis, the measured wall heating temperature was averaged for all pairs of sensors for each hour of each experimental day, i.e., for each hour and each day, the value of t_{meas} was obtained. Additionally, for each hour of each experimental day, t_{calc} was calculated using Formula (1). Then, for each hour of each day, the temperature differences ($t_{meas} - t_{calc}$) were calculated and the average difference was calculated for each hour of each group of days (Formula (6)):

$$\bar{\delta} = \frac{\sum_1^{n_i} (t_{meas} - t_{calc})}{n_i}, \tag{6}$$

where n_i is the number of days in the ith group.

Table 2 shows that for the morning and evening hours, when the intensity of the incoming solar radiation is low, the calculated temperature is higher than the measured one. In the daytime, when the intensity of the incoming solar radiation increases, the measured temperature is higher than the calculated one. The average difference increases in the morning at low radiation values. In the absence of direct radiation (Group III), the average difference is small.

Table 2. The average difference between the measured and calculated temperature for three groups of experimental days.

Time of Day, Hour	Average Difference between the Measured and Calculated Temperature, $\bar{\delta}$=($t_{meas}-t_{calc}$), °C		
	Group I, n_i = 5	Group II, n_i = 16	Group III, n_i = 7
7	−2.4	−1.9	−0.9
8	−0.8	−1	−0.7
9	−0.3	−0.2	−0.2
10	0.3	−0.2	−0.1
11	0.8	−0.2	0.3
12	0.7	0.1	0
13	1.2	0.4	0
14	0.9	−0.1	−0.3
15	1.7	0.5	−0.3
16	0.4	−0.2	−0.4
17	−0.1	−0.3	−0.3

In general, for the days included in Group I, the average differences are higher than for Group II, and for Group II, these values are higher than for Group III. Such differences can be explained by the imperfection of the determination of the heat transfer coefficient on the facade surface, α_{out}.

Checking statistically significant differences for the data in Table 2 using the Kruskal–Wallis test showed that when comparing data between 7 a.m. and 5 p.m. for the three groups of days, there are no statistically significant differences in the values of the average relative difference. The same assessment without taking into account the early morning hours, i.e., from 10 a.m. to 5 p.m., shows that differences are present for the three groups of experimental days.

The given comparative results of the measured and calculated temperatures also indirectly confirm the accuracy of the theoretical methods [18,19] enough for construction calculations of the incoming solar radiation, taking into account the effect of the surrounding buildings due to small differences between the measured and calculated heating temperatures of the facade surface.

5. Conclusions

The calculation and measurement of the surface heating temperature of building facades due to solar radiation for 28 warm days of the year are considered. The calculations used the following experimental data: the temperature of the outside air in the shade; incoming solar radiation; the coefficient of absorption of solar radiation by the surface of the façade; and the coefficient of heat transfer at the surface of the wall. The experimental days were divided into three groups according to the degree of cloudiness. A statistical comparison of the calculated and measured heating temperatures of the wall surface for three groups of experimental days was carried out.

The obtained results show that Shklover's formula is valid for any irradiation conditions in an hourly calculation, because the average relative difference is small for each of the considered groups of days, divided by the degree of cloudiness, which allows the use of such calculations. However, there are statistically significant differences between the groups in the time period from 10 a.m. to 5 p.m., which means that it is necessary to introduce a correction factor in Shklover's formula for irradiation according to the degree of cloudiness and the real solar time.

In addition, on the basis of a good correlation between the calculated and experimental data for the heating temperature of the facade, it can be concluded that the calculation accuracy of the incoming solar radiation is enough, taking into account the effect of the surrounding buildings using the author's calculation methods.

The obtained results can be used to study the inertia and durability of building structures under solar radiation.

Author Contributions: Conceptualization, E.V.K. and E.V.G.; methodology, E.V.V.; software, M.D.T.; validation, E.V.V., N.I.K. and E.V.K.; formal analysis, E.V.G. and E.V.V.; investigation, M.D.T.; resources, E.V.K. and E.V.V.; data curation, E.V.K. and E.V.G.; writing—original draft preparation, E.V.K. and E.V.G.; writing—review and editing, E.V.V. and N.I.K.; visualization, E.V.V., E.V.K. and N.I.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work was realized in the framework of the National Project "Science and Universities", under the topic "Creation of a laboratory for the quality of the human environment and energy efficiency of urban economy (FZRR-2022-0007)". The registration number is 1022072100016-6-2.1.3. The work was realized using equipment of High Technology Center at BSTU named after V. G. Shukhov.

Data Availability Statement: The data are available from the corresponding author upon reasonable requests.

Conflicts of Interest: The authors declare no conflict of interest.

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