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PRELIMINARY ASSESSMENT OF A FLAT ROOF RADIATION ON RADIATIVE HEAT GAINS OF NEARBY WINDOWS – A CASE STUDY

This paper presents the results of preliminary assessment of radiative heat flux received by selected windows from tar paper coated flat roof of the adjacent building. This study was conducted on an actual object: building “P” at the University of Technology in Rzeszow. Windows located on south-western elevation of “P” building are subjected to thermal and diffused solar radiation, coming from a flat roof of a nearby gym. It was suspected, that this extra heat flux may have significant influence on compartment overheating, that is observed by occupants of “P” building. For the purpose of this study, various atmospheric data, such as temperatures, solar irradiance and wind speed were collected on site. In order to gain more detailed insight into investigated problem, Finite Elements model of occurring phenomenon was developed. FE modelling along with calculations of necessary view factors were performed in Matlab 2019a. Our study demonstrated, that analysed windows receive twice the heat gains from the flat roof, that they would have received from grass covered ground surface in absence of the gym. It has been concluded, that the proximity of the flat roof with bituminous cover considerably influences radiative heat gains of the windows, especially these located at lower floors and the phenomenon seriously contributes to overheating of the compartments in studied building.

Keywords: thermal radiation, flat roof, view - factor, diffused radiation, radiative heat flux

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1. Introduction

New trends in building engineering observed for about twenty years, Focus on decreasing building Energy consumption and on introducing applications based on renewable Energy sources. One of possible solutions applied to cover building demand for heat and electricity are active and passive solar systems [1, 2]. Another solution for improving thermal balance of a building may be limiting overheating of transparent building barriers by using phase change materials [3, 4, 5].

Analyses conducted in [3–5] point out for a need for modifying insulated glass units in order to minimize diurnal temperature amplitudes of the glazing, which will result in improving thermal comfort of a room.

As it is described in [6, 7] thermal comfort of a compartment is strongly influenced by a shape of building's envelope, as well as by thermal and optical properties of its transparent building barriers.

An issue of overheating flat-roofed buildings is a subject of numerous research. It is concluded in [8], that excessive absorption of incident solar radiation by bituminous roofing may substantially increase Energy demands for air conditioning, most especially in urban areas.

Basing on the above literature review, it has been found purposeful to conduct preliminary assessment of radiative heat transfer between flat roof with bituminous coating and a nearby windows, to explain a potential cause of compartment overheating. The objective was accomplished by performing a case study. As the Object of the study, two windows in P building at Rzeszów University of Technology were selected. The elevation of P building that contains studied windows is adjacent to tar paper coated flat roof of a gym building.

Reliable modelling of a complex heat exchange between a flat roof and a nearby window requires to take into account a convective heat transfer.

This type of heat transfer between solid and a fluid may be described using Jacob equation [9].

Radiative heat transfer between two surfaces is realised by both thermal radiation, that is described by Stefan-Boltzmann law, and by reflecting and diffusing incident solar radiation.

2. Materials and Methods

2.1. Equipment

All the data necessary to perform our study were obtained using:

- Data logger COMET MS-6D MS6R,
- Data logger ALMEMO 2890-9,
- Temperature probe PT 1000,
- Energy meter FQA020 C,

- Pyranometer Almemo FLA 613 GS,
- Thermographic camera FLIR i7,
- Meteorological station GWS - 570,
- Laser rangefinder Leica Disto D2.

2.2. Research workstation description

Field research were conducted by two independent sets of measuring equipment.

The first set consisted of temperature probe with data logger, thermographic camera and laser rangefinder. These were used to measure flat roof temperature as well as the temperature of ground Surface in the immediate vicinity of the gym. Laser rangefinder was used to measure necessary distances and architectural dimensions.

The second set of apparatuses functioned simultaneously as a part of a permanent field workstation, located about fifty metres from the gym. There, external air temperature, total irradiance on vertical southward Surface and wind speed were measured. All the data were collected with one minute intervals. Figure 1 present a photography of mentioned flat roof.

Fig. 1. Photography of the gym’s flat roof, that is adjacent to P building at Rzeszów University of Technology

2.3. Finite Elementsmodel parameters

It was expected, that due to its structure, upper Surface of analysed flat roof reaches thermal equilibrium very quickly in changing weather conditions, and functions in quasi-steady state in relatively short periods of time. To verify that assumption, a steady state FE model of the flat roof was developed, for further comparison with actual measurements.

The model was constructed in Matlab 2019a, applying Partial Differential Equations (PDE) thermal toolbox. We used triangular elements with six nodes each, and dimensions of the mesh were no larger than five millimetres. Structure of the flat roof's cross-section were learned from actual project of the building, and it was as follows:

- tar paper 5 mm,
- rockwool 250 mm,
- reinforced concrete 150 mm,
- cement plaster 20 mm.

It was assumed, that upper part of the gym has constant air temperature of 22°C throughout the year, while the Surface of tarpaper absorbs and emits heat as a grey body of absorptivity 0.93 and emissivity 0.92. It was also assumed, that external Surface of the flat roof loses heat by Convection according to equation [9].

$$q = \alpha \cdot \delta_T \tag{1}$$

where: $\alpha = 1/R_{se}$- onvection coefficient [$W/m^{2\cdot}K$];

δ_T - temperature difference between flat roof and ambient air [K];

R_{se}-external Surface heat resistance, based on wind speed [$m^{2\cdot}K/W$] [10].

2.4. Calculating the view factors

In order to determine how much of total radiant Energy emitted by the flat roof is actually received by a specified window, values of necessary view factors were calculated in Matlab 2019a using numerical integration tool.

It was accomplished using equation 2. presented by Pogorzelski in [9].

$$\varphi_{1-2} = \frac{1}{F_1} \int_{F_1}^{N} \int_{F_2}^{N} \frac{\cos\beta_1 \cos\beta_2}{\pi R^2} dF_1 dF_2 \tag{2}$$

Equation Formula for view factor calculation

where: φ_{1-2} – view factor 1-2 i.e. fraction of total Energy radiated by Surface 1 received by Surface 2;

F_1 – area of heat radiating Surface;

F_2 – area of heat receiving Surface;

β_1, β_2 – are the angle between the surface normals and a ray between the two differential areas;

R – distance between surfaces F_1 and F_2.

3. Results

3.1. Geometry and view factors

Basing on manual measurements using laser rangefinder, the geometry of studied setting was established. The most important results are presented below:

Table 1. Geometry parameters of the site

Height of flat roof top	4.52 [m] above ground
Height of 1st floor window sill	4.73 [m] above ground
Height of 4th floor window sill	13.74 [m] above ground
Distance between centre of the flat roof and elevation of "P" building	6.12 [m]
Surface area of each window glazing	1.08 [m^2]
Surface area of the flat roof	216.24 [m^2]

Values of view factors were calculated for 1st and 4th floor windows for two cases:

- actual flat roof as the source of radiation;
- surface of the ground beneath the gym as comparative source of radiation.

Table 2 View factors calculated for four studied spatial settings

Setting	1stfloor - ground	1stfloor - flatroof	4thfloor - ground	4thfloor - flatroof
Viewfactor	$1.20 \cdot 10^{-3}$	$2.30 \cdot 10^{-3}$	$3.80 \cdot 10^{-4}$	$6.75 \cdot 10^{-4}$

For intended qualitative assessment, five sets of measured parameters were selected. These are presented in table 3 below:

Table 3. Measured parameters for five selected moments

No	**Date and time**	**Solar irradiance on vertical surface [W/m²]**	**Solar irradiance on horizontal surface [W/m²]**	**Ambient (air) temperature [°C]**	**Temperature of the ground surface [°C]**	**Wind speed [m/s]**	**Temperature of the flat roof [°C]**
		E_{90sol}	E_{0sol}	T_a	T_g	v_w	T_{fl}
1	2018-03-21 11:40	885.0	571.0	1.1	3.8	2.1	33.4
2	2018-03-23 16:00	481.0	521.0	13.6	8.0	1.5	47.3
3	2018-05-29 15:02	418.0	441.0	36.2	43.5	2.4	58.9
4	2018-06-13 10:30	192.0	217.0	25.1	17.5	1.2	40.2
5	2018-01-19 12:50	628.0	766.0	2.5	0.0	1.6	0.0

Basing on the data presented in Tables 1–3 incident radiative heat fluxes received by 1st and 4th floor windows were determined. It was assumed, that grass, snow and tar paper uniformly diffuse incident solar radiation.

Heat fluxes were calculated for windows located on 1st and 4th floor, for two settings presented in table 3. We analysed two alternative sources of radiative heat flux: an actual flat roof and a hypothetical, grass or snow covered ground if the gym was non-existent there

Table 4. Radiative heat fluxes received by the windows in selected conditions in presence or absence of the flat roof

No	1st floor - ground	1st floor - flat roof	4th floor - ground	4th floor - flat roof
1	123.65	250.76	39.13	73.62
2	125.35	293.86	39.67	86.27
3	173.92	333.25	55.04	97.84
4	116.72	259.64	36.94	76.23
5	263.84	505.69	83.50	148.46

It is to be noticed, that in both cases presence of the flat roof significantly increases total amount of radiant heat reaching surfaces of both windows. The mean ratio of flat roof's to ground radiation received by 1st floor window is 2.09 and 1.97 in case of 4th floor window.

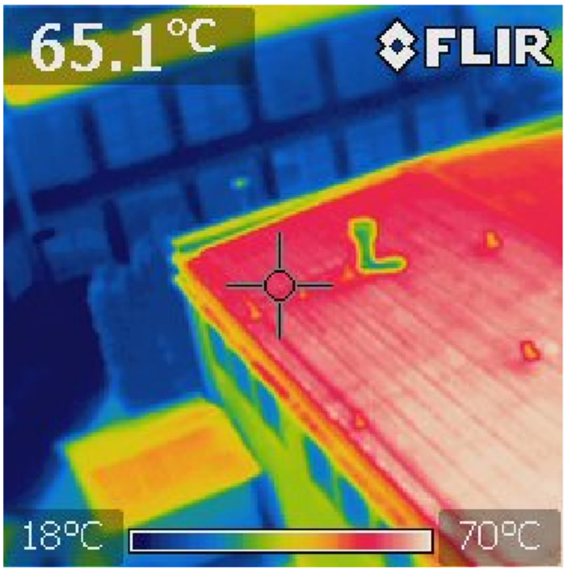

Fig. 2. Thermal image of sunlit flat roof of the gym adjacent to building „P" at Rzeszów University of Technology

3.2. Verification of FE model

Values of flat roof's temperatures obtained from our FE model were compared with actual field measurements. Our simulation was applied to conditions No. 1–4 only. Conditions No. 5 was not considered due to the presence of melting snow covering whole surface of the flat roof. Modelling the last example would have required application of transient thermal model with phase transition, which was not found necessary for this preliminary study.

Table 5. Comparison of actual and modelled temperatures of the flat roof's surface

No	**Actual measurement [°C]**	**FE modeled[°C]**
1	33,4	35,1
2	47,3	45,9
3	58,9	60,4
4	40,2	38,9
5	0,0	n/a

It is to be observed, that actual temperatures and these obtained from FE model does not differ more than ~2 K. Therefore, the model may be considered as satisfyingly accurate. Due to High emissivity of tar paper and considerable heat resistance of rock wool thermal insulation layer, upper portion of the flat roof has little thermal inertia and as expected reaches thermal equilibrium with its surrounding very quickly.

4. Conclusions

Performed study implies, that tar paper coated flat roofs may exert significant influence on heat gains of nearby transparent building barriers. In the studied case, presence of flat roof approximately doubled the amount of radiant heat received by windows located on both 1st and 4th floor. Due to increased distance to the source of radiation, slight attenuation of flat roof versus ground radiation was noticed for fourth floor in comparison with the first floor. If surface of flat roof is not covered by snow, its surface reaches much higher temperature than surface of the ground. The very surface of well insulated flat roofs with bituminous coatings operates in quasi-steady heat flow. In quickly hanging weather conditions such as variable illumination, temperature of these surfaces rapidly adapts to actual conditions and the surface reaches thermal equilibrium with its surrounding. This fact may be applied in further, more detailed studies of the subject e.g. in performing long term thermal balance of transparent building barriers, influenced by nearby flat roof's radiation.

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