THE IMPACT OF CLERESTORY LIGHTS ON ENERGY EFFICIENCY OF BUILDINGS

by

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The buildings are among major energy consumers, whose energy efficiency is rather low. Clerestory windows are responsible for a large portion of energy losses from the buildings. The energy efficiency of buildings can greatly be improved by upgrading clerestory and other windows. This paper focuses on the theoretical and experimental investigations on how this can be performed in an old school building in the town of Bor in eastern part of Serbia. For that purpose a modern measuring technique has been applied to identify the existing status, and to compare theoretical and actual conditions.

Key words: *energy efficiency, heat loss, thermal imager, fluxmeter*

Introduction

In developed countries global contribution of buildings, both residential and commercial, to total energy consumption is between 20% and 40%. During the last two decades, primary energy input has increased by 49% and CO_2 emission by 43%, while current predictions indicate that this upward trend will continue [1]. Moreover, it was shown that the use of conventional energy efficiency technologies, such as thermal insulation, low emission windows, window overhangs, and daily lighting control, reduces energy consumption by 20-30% on average in new commercial buildings and up to 40% in some older facilities and buildings [2-4].

The building selected for this research was built in 1933 and it was originally used as a facility to situate the army. In 1944 it was reconstructed to become the secondary school (gymnasium). In 1957 it got its present name "Bora Stanković" after a famous Serbian writer. Building covers an area of 3,131 m^2 and its volume is 10,960 m^3. Figure 1 presents the entrance side of the building, while the clerestory lights are on the rear side, opposite to the entrance.

During its construction, the builders had neither taken care of the energy efficiency of the building, nor of any other construction elements which are present in modern constructions. All windows are of poor quality, made of ordinary glass. Similarly, clerestory windows in the school halls have a lot of holes, both on the windows and on the window frames which are made of wood. All these elements indicate that the heat loss in the school building is quite large.

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Figure 1. View of "Bora Stanković" gymnasium building in Bor

The surface area of the clerestory lights consists of two parts, one on the first floor and other on the second floor. The first part consists of three vertical rows, the two of which count 44 window panes each, and a third counts 55 window panes, making it a total of 143 window panes. The second part also consists of three vertical rows, the two of which count 60 window panes each, and a third counts 75 window panes, making it a total of 195 window panes, fig. 2. Each window pane is a square with sides of 265 mm, while the thickness of glass is 5 mm. The window pane is 70.225 mm^2 in area, and its volume is 351.125 mm^3. Frames between the shafts are 30 mm wide and 40 mm thick.

Figure 2. Clerestory lights – the inside view

Based on figs. 1 and 2, the area of the vertical rows at the first floor are 3,120,905 mm^2 (44 panes) and 3,902,125 mm^2 (55 window panes) and area at the second floor 4,254,045 mm^2 (60 window panes) and 5,319,345 mm^2 (75 window panes). The total area of all the windows for clerestory lights on the first floor is 10.162 m^2 and that on the second floor is 13.827 m^2.

The authors of this paper focus on the measurements of temperature, heat flux and heat losses during the month of February 2011. The results of the measurements are shown in diagrams. This paper not only does show the calculated values of heat loss and possibility to predict losses, but it also shows comparison of these results with the results of the measurements obtained using the infrared (IR) camera, flux meter, and with outside temperatures recorded by the Mining and Metallurgy Institute in the city of Bor. Apart from the actual conditions in which the measurements and calculations were carried out, predicted values of heat consumption and heat flux are also given so as to show the theoretical conditions if the windows were of better quality.

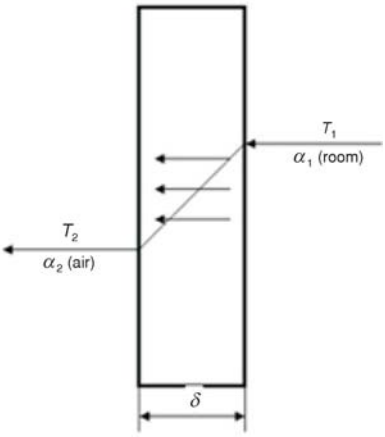


Figure 3. Heat transfer through a barrier (glass)

Calculation of heat losses

Theoretical background

The heat is lost from inside the building (the room temperature T_1) to the environment (the outside temperature T_2) by the heat transfer process through the barrier (glass) of thickness δ as shown in fig. 3. If the glass thermal conductivity is λ and the internal and external heat transfer coefficients are α_1 and α_2, respectively, the overall heat transfer coefficient U is determined by using the expression:

$$U = \frac{1}{\frac{1}{\alpha_1} + \sum_{i=1}^{i=n} \frac{\delta_i}{\lambda i} + \frac{1}{\alpha_2}} \ [\mathrm{Wm^{-2}K^{-1}}] \tag{1}$$

The internal and external heat transfer coefficients, α_1 and α_2, respectively, are determined by using the expression (2):

$$\alpha = \frac{\overline{\mathrm{Nu}}\lambda}{d(a)} \ [\mathrm{Wm^{-2}K^{-1}}] \tag{2}$$

where Nu is the Nusselt number and d (a) – the dimension of the side of the window pane.

The Nusselt number in eq. (2) is determined by using the expression (3):

$$\overline{\mathrm{Nu}} = 0.021\varepsilon_1 \ \mathrm{Re}^{0.8} \ \mathrm{Pr}^{0.43} \left(\frac{\mathrm{Pr}}{\mathrm{Pr}_z} \right)^{0.25} \tag{3}$$

where

$$\varepsilon_1 = \frac{d(a)}{\delta} = \frac{265}{5} = 53 > 50 \Rightarrow \varepsilon_1 = 1 \tag{4}$$

Re – the Reynolds number, Pr – the Prandtl number, and Pr_z – the Prandtl number of the barrier (glass).

The Reynolds number is determined by using the formula (5):

$$\mathrm{Re} = \frac{wd(a)}{\nu} \tag{5}$$

where w is the air velocity [$\mathrm{ms^{-1}}$], and ν – the physical characteristic of air (from $12.5452 \cdot 10^{-6}$ to $15.06 \cdot 10^{-6}$ m^2/s).

The Prandtl number is determined by using the formula (6):

$$\mathrm{Pr} = \frac{\nu}{a} \tag{6}$$

where a is the physical characteristic of air (from $16.584 \cdot 10^{-6}$ to $21.4 \cdot 40^{-6}$ m^2/s).

Calculation of heat transfer coefficients

For calculation of the heat transfer coefficients, the relevant dimensions of the clerestory light panes and characteristics of the glass (float) and the wood (dry pine) are presented in tab. 1 .

Table 1. Dimensions and properties of the material used for clerestory lights

No	Material	δ [mm]	ρ [kgm^{-3}]	C_p [kJkg^{-1}K^{-1}]	λ [Wm^{-1}K^{-1}]	δ/λ [m^{2}KW^{-1}]
1	Glass (float)	5	2400-3200	0.77	0.482-1.047	0.01
2	Wood (pine)	40	546	2.7	0.10	0.4

Resistance to heat flow that occurs in the glass is $R = \delta/\lambda \approx 0.01$ m^{2}K/W if λ has the value $\lambda = 0.5$, while in the wood R is $\delta/\lambda = 0.4$ m^{2}K/W. Therefore, the heat transfer coefficients U are $1/R \approx 100$ W/m^{2}K for glass and $U \approx 2.5$ W/m^{2}K for wood. These heat transfer coefficients clearly show that the insulation is very bad in the glass area as the coefficient is extremely high, while the insulation in the area of frames is better because the coefficient is below the maximum value of the heat transfer coefficient according to the Serbian standard SRPSU.J5.510, which is $U_{max} = 2.7$ W/m^{2}K for wood.

Measurement of the heat losses

Measuring equipment

For the measurement of heat flux, fluxmeter of the ITI type was used which enabled direct insight into the values of heat flux from the surface of the clerestory window panes. A school thermometer and a thermal imager were used to measure the internal temperatures of the air, while the outside temperatures were determined with the thermal imager and by using the data of a local measuring station. For measurement of the heat flux, a fluxmeter was used.

Figure 4. Woehler thermal imager IK21

Thermal imager used was a Woehler IK 21 (fig. 4) produced by Woehler GmbH, whose work is based on uncooled linear thermoelectric germanium detector [6]. It forms a thermal image by measuring the infrared radiation of the whole body or of a particular scene. The use of software which the camera possesses the necessary correction were made in converting thermal images into the corresponding thermogram, which is approximately accurate temperature of the recorded object or temperature distribution of the object in the scene. Also, the camera runs on standard batteries for video cameras. Moreover, the images are displayed on a color LCD screen with 10.2 cm long diagonal. The digital infrared thermal imager is based on patent camera with thermal-electronic effects, and it covers the range from –20 ºC to 3500 ºC, with thermal sensitivity of less than 0.1 ºC. Measurement accuracy is between –2 ºC to +2 ºC. Detector type is FPA 320 × 240, with the wave lengths in the range from 3.6 μm to 5 μm, using a set of batteries of 4 metal hybrid batteries, and with working temperature from –15 ºC to 50 ºC. The mass of the camera is 2 kg, while the dimensions are 220 × 132 × 140 mm. Figure 4 shows the thermal imager Woehler IK 21 which was used [6].

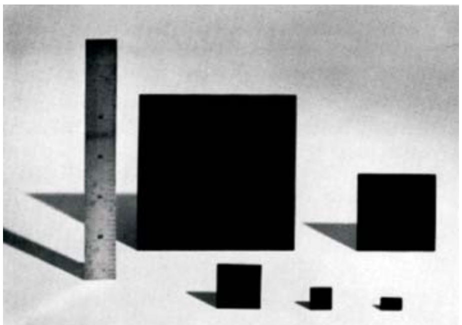


Figure 5. ITI fluxmeter

To measure the heat flux ITI fluxmeter was used, fig. 5 [11]. This device possesses converter with flat plates which is used for direct measurement of heat flux by placing the device on the surface through which the heat flux is measured. Fluxmeter is specifically calibrated at a temperature of 20 ºC like all devices of this type. There are different models of this device. Fluxmeter which was used is of the A-type with dimensions 244 × 179 mm. Its accuracy is 1% and it works at a temperature range of –250 to 290 ºC with a nominal sensitivity of 7 BTU/HrFt2Mv. It is made of polyamide and glass.

Thermal imaging

During the winter 2011, or more precisely, during the period from 1st to 28th February 2011, when measurements were made on the building, the total number of persons in it was 391, 356 of which were students and 35 were employees. Measurements were carried out in the area of the ceiling, of the floor, near and further from them, in the area of first and second floor and between the floors. The temperatures of glass were also measured near the glass and at a certain distance within the school. The same procedure was followed with frame temperatures. Since the area of the clerestory lights consists of two parts, one on the first floor and other on the second floor, the internal measurements were done in the corridors of the stairs on the first and second floors in the area of clerestory lights (fig. 6). The properties measured were temperature and heat flux, while the wind effects were neglected because the clerestory lights are sheltered from the wind blows, see the picture of clerestory lights with the thermal image depicting the outer side.

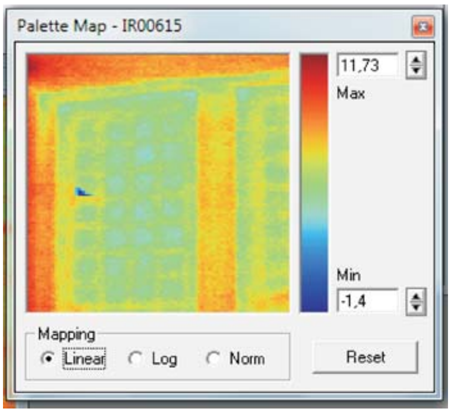


Figure 6. Clerestory lights – thermal image

The measurements from the outside of the building was from the ground, also in the area of clerestory lights (fig. 7). The measurements performed from the outside at ground level, were carried out for both the first and the second floor. Figure 7 shows the results for the clerestory lights (left) and the external wall (right) obtained for the second floor. All the measurements were done using the Wohler IC digital thermal imaging camera IC21 [7].

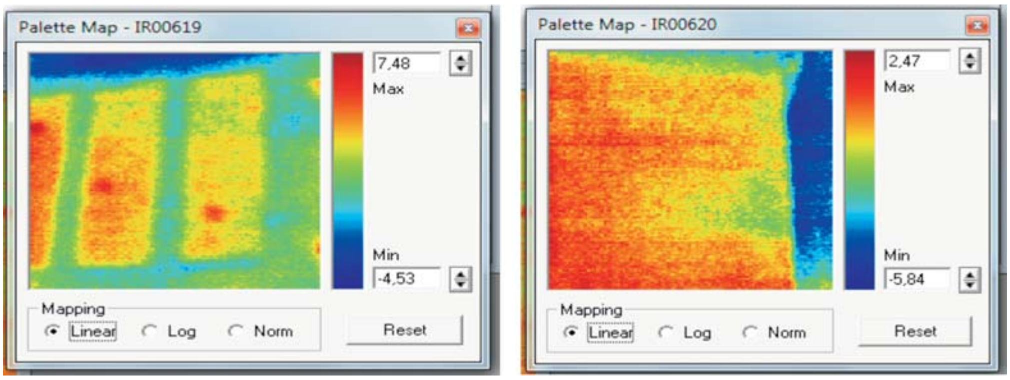


Figure 7. External thermal images of the clerestory lights (left) and wall (right) at the second floor

Temperature measurements

The graphs presented in figs. 8, 9, and 10 show the measured temperatures of the outside environment (fig. 8), and of the clerestory lights inside (fig. 9) and outside the building (fig. 10). The temperatures have been measured from the school hall on the first floor, and from the ground outside the building during February 2011 [3-6].

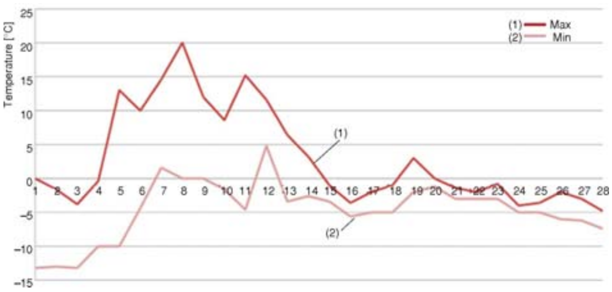


Figure 8. The outside air temperatures in Bor during February 2011

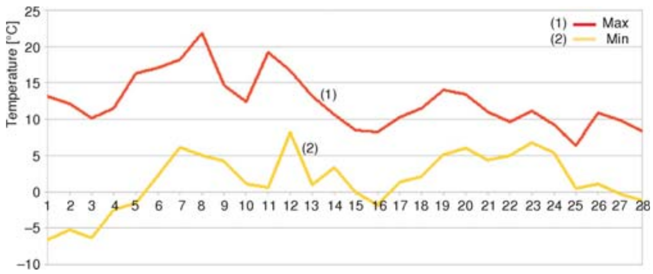


Figure 9. The temperatures at the clerestory lights inside the building

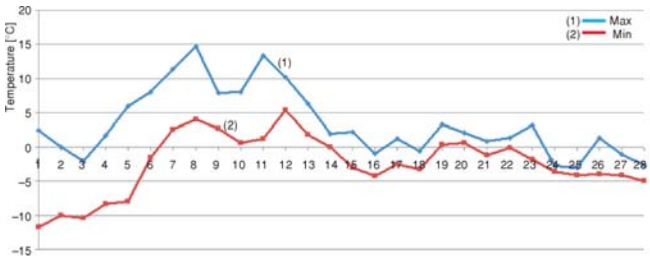


Figure 10. The temperatures at the clerestory lights outside the building

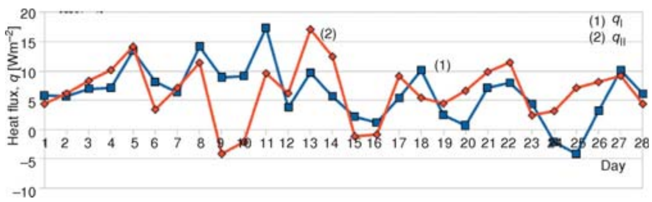


Figure 11. The measured values of heat flux on the first (q_I) and second (q_{II}) floor

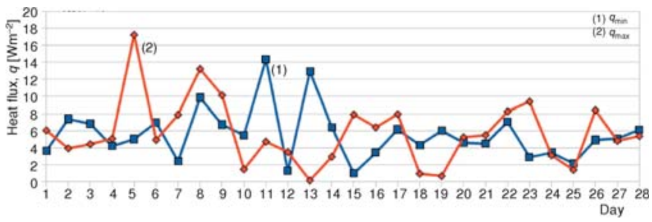


Figure 12. The calculated values of heat flux on the first floor

The results of measurements presented in figs. 9 and 10 show that changes in maximum and minimum temperatures are much higher at the interior of the building due to environment temperature increase. Evidently, there was a much wider discrepancy between maximum and minimum temperatures in the internal measurements than in the external measurements. The results also show that the discrepancies between maximum and minimum temperatures at the clerestory lights are higher on the second floor than on the first floor (average discrepancy is about 1 ºC higher), which affects the respective heat losses.

Measurements and calculation of the heat flux

Figure 11 shows the results of daily measurements of the average heat flux through the clerestory lights carried out during February 2011. The q_I line shows the results obtained for the first floor through the clerestory lights of a smaller surface, while the q_{II} line shows the results obtained for the second floor through the clerestory lights of a larger surface [6-11].

Figure 12 shows calculated extreme values of the heat flux through the clerestory windows for the existing conditions on the first floor, where the q_{min} line shows minimum flux values, while the q_{max} line shows maximum flux values. Similarly, fig. 13 shows the calculated values of the heat flux for the existing conditions on the second floor, where the maximum and minimum values of the heat flux are presented with q_{max} and q_{min} lines, respectively.

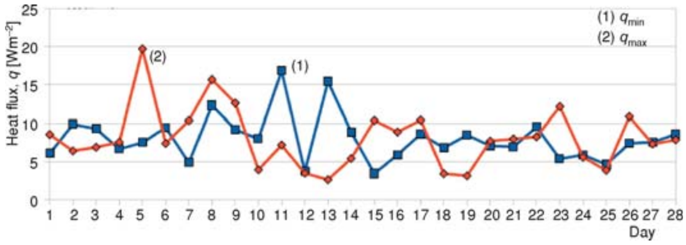


Figure 13. The calculated values of the heat flux on the second floor

From the calculated and the measured values of the heat flux, one can notice that the largest changes are present when the greatest temperature fluctuations occur (figs. 8, 9, and 10). As the flux is directly proportional to the temperature difference, the smaller temperature fluctuations are desirable in order to get smaller flux oscillations and consequently lessen the heat loss.

It is obvious that the heat loss through the clerestory windows is quite large and that better windows are necessary so as to lessen the temperature fluctuations, and consequently the heat losses. The calculated values of the heat flux are obtained by the use the expressions (1) to (6) and the measured minimum and maximum temperatures and the data from tab. 1. For the turbulent air flow (w = 10 m/s) and respective Reynolds number, the calculated value of the overall heat transfer coefficient of the clerestory windows is high because the thermal insulation is bad. Its calculated value (U = 2.464 W/m^{2}K) exceeds the maximum allowed value of heat transfer coefficient for windows which, according to most of the building standards, should be below U_{max} = 1.8 W/m^{2}K. Some of the possible solutions include insulated glazing, insulation glass, Ceyssens glass or other types of glass with a lower coefficient of heat transfer [9].

Based on the results obtained by measuring the heat flux (fig. 11) and temperature (figs. 8, 9, and 10), the calculations of heat flux are performed for a variety of windows in the clerestory lights on the two floors to show what would happen if the existing windows would have been replaced with the improved windows that meet the standards of heat transfer coefficient $U_{max} \leq 1.8$ W/m^{2}K. Figures 14 and 15 show the calculated values of the heat flux on the first and second floor, respectively, if the clerestory windows were replaced by new ones with heat transfer coefficient U = 1.8 W/m^{2}K [5].

The values presented in figs. 14 and 15 show that the heat flux would be much smaller if the windows were of better quality. As one can see, the values of the heat flux under the existing conditions on the first floor reach values of q = 17.25 W/m^2, while the improved conditions could give much smaller values of q = 12.59 W/m^2. The same proved to be true for the second floor, where the maximum values reached q = 19.71 W/m^2, while for the improved conditions of the clerestory lights this value is less, q = 14.40 W/m^2. The results would be different if the windows were of better quality which could lead to even smaller values of heat flux, and thus con-

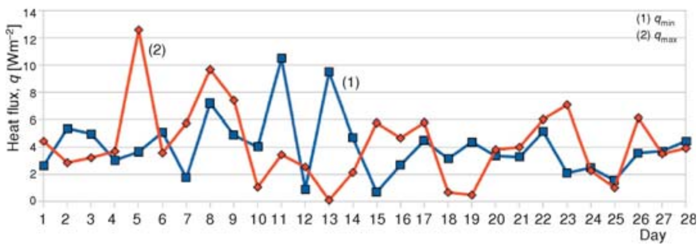


Figure 14. The calculated heat flux on the first floor with improved clerestory windows

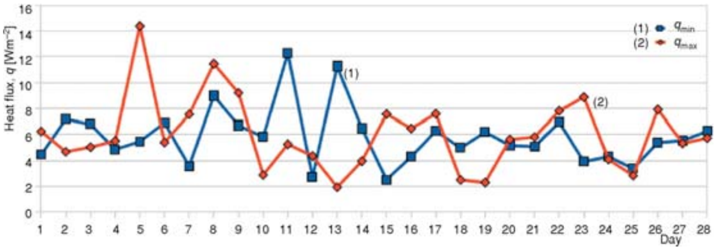


Figure 15. The calculated heat flux on the second floor with improved clerestory windows

tribute to a lower energy consumption for heating the building, and consequently less financial costs that currently are high due to a poor isolation including that for windows [13].

The heat losses through the clerestory windows

Calculation of the heat losses

To determine the heat losses through the clerestory windows, measurements of temperature and heat flux have been performed. The measurements have been performed in the area of the ceiling, the first and second floor, near and further from them, and as well as between the floors. The outside measurements were performed only from the ground level, for both the first and the second floor. The glass temperatures were measured near the glass surface and at a certain distance from it. The frame temperatures have also been measured. The conditions for measurements were good almost every day, and the position of clerestory lights, which are sheltered by the building, made them protected from the fog and other external impacts, so that those factors did not have much influence on the recording and formation of the thermogram. The minimum and maximum temperatures have been measured daily at all parts of the clerestory lights from different positions [6, 7]. The reasons why the temperatures were rather low are several damaged clerestory lights, a broken window pane and a hole in the lights, as well as a few more damages of that kind, so that a large heat loss was unavoidable.

The data on heat losses from the building are obtained by calculation based on the heat transfer coefficient U and measured temperatures. The heat loss (minimum and maximum values) in the area of clerestory lights in the building was calculated by using the formula:

$$\dot{Q} = U A \Delta T \tag{7}$$

where $\dot{Q}$ is the heat loss (min, max), U – the heat transfer coefficient, either calculated (U = = 2.464 W/m^{2}K), or assumed lower values, according to the standards for windows ($U \leq 1.8$ W/m^{2}K), A – the area of the windows (clerestory lights) on the first floor (10.162 m^2) and on the second floor (13.827 m^2), and ΔT – the difference between the maximum and minimum temperatures.

Figure 16 presents the calculated heat losses through clerestory lights on the first floor for the conditions recorded in February 2011 [9]. With the existing windows (U = 2.464 W/m^{2}K)

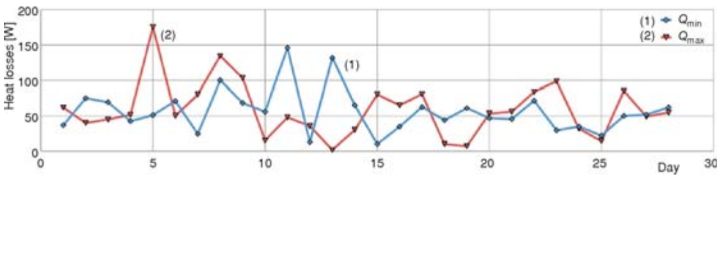
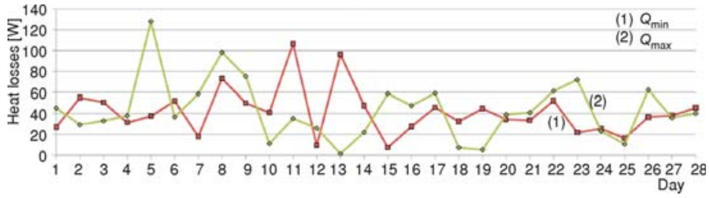


Figure 16. The calculated heat losses on the first floor for the existing conditions

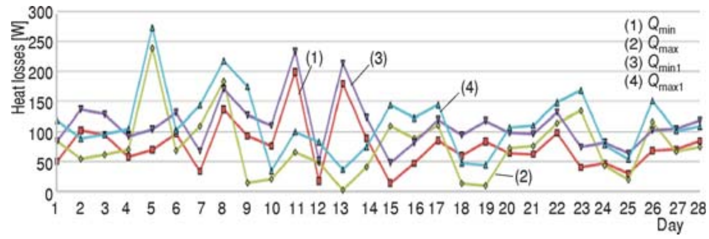
Figure 17. The calculated heat loss on the first floor in case of U_{max} = 1.8 W/m^{2}K



the heat loss vary widely between the minimum $\dot{Q}_{min}$ and maximum $\dot{Q}_{max}$ values so that on February 5th fluctuations ranged from 51.08 W to 175.27 W. Similar oscillations are noticeable on February11th and 13th, which led to large heat losses [1]. Figure 17 presents the values of maximum ($\dot{Q}_{max}$) and minimum ($\dot{Q}_{min}$) heat loss through the clerestory lights on the same (first) floor under the assumption that the existing glass is replaced by the glass of much better performance (U = 1.8 W/m^{2}K).

Figure 18 presents the calculated values of heat loss through the existing clerestory lights on the second floor in February 2011. The lines min and max present, respectively, the minimum and maximum values of the heat loss, calculated under the existing conditions of difference between maximum and minimum temperatures at the clerestory lights are higher on the second floor than on the first floor (average discrepancy is about 1 ºC higher). For the purpose of comparison, it was assumed that the difference between minimum and maximum temperatures on the second and first floor is the same, the calculated values of minimum ($\dot{Q}_{min\,1}$) and maximum ($\dot{Q}_{max1}$) heat loss through the existing glass are also presented.

Figure 18. The calculated heat losses on the second floor in real and assumed conditions



Like in fig. 18, in fig. 19 the calculated heat loss is shown under the existing and assumed equal difference of the maximum and minimum temperatures on the first and second floor. However, it is now assumed that the existing clerestory lights are replaced by new ones, so that the overall heat transfer coefficient is U = 1.8 W/m^{2}K, and thus the heat losses ($\dot{Q}_{min}$, $\dot{Q}_{max}$, $\dot{Q}_{min\,1}$ and $\dot{Q}_{max1}$) from the building proportionally reduced.

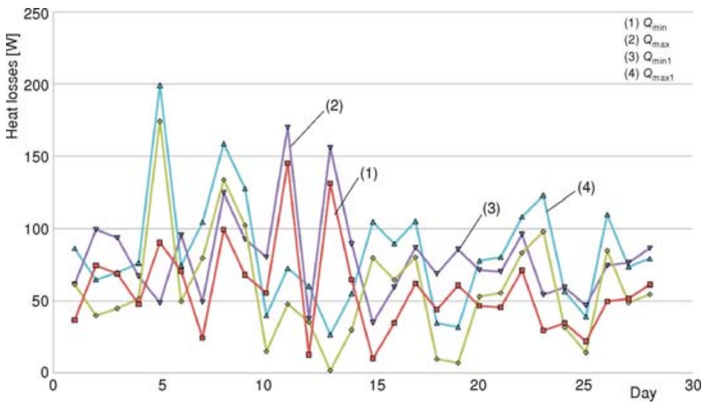


Figure 19. The calculated heat loss on the second floor in real and assumed conditions

Calculation of possible energy savings

On the basis of the data presented so far, there exist a possibility to reduce heat loss through the clerestory windows. The estimates of savings made for the first and second floor are presented in figs. 20 and 21, respectively. The minimum savings were obtained by taking into account the difference of the minimum values in the existing and improved conditions. The same was done for the maximum savings by preventing the heat loss. It is evident that the savings during February vary from day to day and so would be throughout the overall heating seasons.

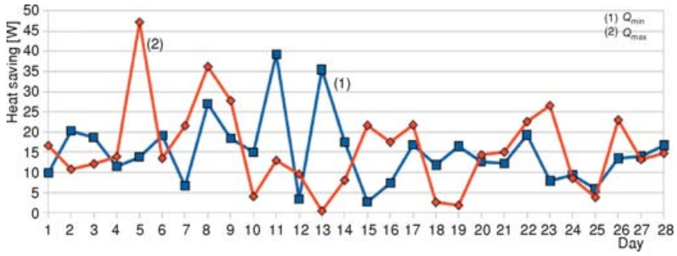


Figure 20. The calculated daily values of the possible heat saving on the first floor

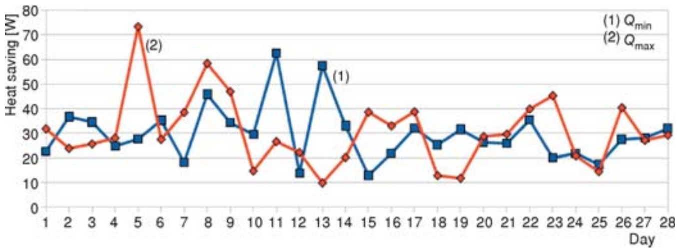


Figure 21. The calculated daily values of the possible heat saving on the second floor

The data on Figures 20 and 21 show that the possible heat saving on the second floor is higher than on the first floor because of larger surface area of the clerestory lights there and larger number of damaged panes on the second than on the first floor. Moreover, these data indicate that the maximum heat saving on the second floor might go up to 73.46 W, while the maximum heat saving on the first floor could be 47.23 W. All that implies that considerable saving can be achieved in the heat loss by the improvement in quality of the clerestory lights, not to mention other improvements of different parts of the building (the doors, the walls *etc.*). It would therefore be necessary to carry out an analysis of the heat losses through all other elements of the school building.

For energy savings by reducing heat losses, it is necessary to replace the existing windows by new ones with another glass of better quality ($U \leq 1.8$ W/m^{2}K). By using the low emissivity window glass, the overall heat transfer coefficient could be as low as $U = 1.5$ W/m^{2}K, while, using insulated glass units (IGU) with low emissivity coatings on surfaces and filled with argon in the cavities, it could reach even lower value ($U = 1.28$ W/m^{2}K). Furthermore, by using this kind of IGU with dry air in the cavity between the units and with three-chambered PVC profile, one can expect a coefficient of heat transfer $U = 1.44$ W/m^{2}K, while applying the six-chambered profile and IGU with dry air in the cavity between the units, one can make the window with coefficient of heat transfer $U = 1.36$ W/m^{2}K. By using the high performance (HP) glass, the heat transfer coefficient would be $U = 1.4$ W/m^{2}K, while by Ceyssens glass (that warms windows), the heat transfer coefficient would be $U = 0.85$ W/m^{2}K only, as it achieves solar gain of 54%, and consequently enables a large reduction in heat losses [9-10].

Conclusions

This analysis demonstrates that the replacement of the clerestory and other windows can lead to considerable savings in energy and financial resources, which would be beneficial for the school building and people who use this facility, as well as for the environment. The findings about heat losses through the existing clerestory windows with a high heat transfer coefficient ($U = 2.464$ W/m^{2}K) indicate that the use of new windows could improve the building energy efficiency, reduce the amount of money wasted on excessive consumption. The same applies all windows in the school, especially to those affected by the wind blows, where the overall heat transfer coefficient is even higher than in the clerestory lights that are sheltered from the wind blows.

Installing better quality glass for the clerestory windows would eliminate large fluctuations in temperature inside the building. The large fluctuations in the heat flux have been found to cause the fluctuations of heat loss so high as 124.19 W, which is affecting the overall energy efficiency in the school much more than if the heat transfer coefficient would have been lower (*e. g.* $U = 1.8$ W/m^{2}K, when the maximum value of the heat loss could be reduced by 47.23 W), particularly if some of the advanced solutions for windows and glass would be applied [12]. For that reason, the clerestory windows should be replaced, and, if possible, other windows in the entire school building.

It should also be noticed that the use of thermal imaging camera shows a very real temperature condition. Varieties which appear clearly show where the windows should be repaired as well as the temperatures in these parts and in other parts of the clerestory lights. The thermal imager which was used in this case covers a wide temperature range which also enabled measurement of the temperature below zero, which were recorded several times during February 2011. As for the fluxmeter, it works in even better conditions when it comes to temperature measurements, which was also a reliable tool this research where the use of the fluxmeter showed the values of heat flux very clearly.

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