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EXPERIMENTAL MEASUREMENT OF THE ACCUMULATED HEAT FROM THE OPERATION SYSTEM OF THE HEATING IN A BUILDING WITH A LIGHTWEIGHT ENVELOPE

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Abstract

The heating and cooling of buildings with large-scale ceiling systems nowadays is widely used in traditional as well as in new, low-energy buildings. This type of system is being employed in a building of the Civil Engineering Faculty (FCE), Slovak Technical University, in Bratislava. The building´s refurbishment in 2010 included the complete replacement of the building´s envelope. The replacement is a lightweight facade with a high percentage of transparent construction. Due to the differences between the type of envelope and the heating system, the operation of the heating system frequently causes thermal discomfort, especially during warm spring or autumn days. The aim of the measurements was to evaluate the control of the operation of the heating output, the appropriateness of the location of sensors measuring the outdoor temperature and possible improvement of the current control system to improve the heating system´s quality.

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Key words

- Heating,
- Control,
- Temperature,
- Thermal comfort.

1 INTRODUCTION

Low temperature heating via the Crittall system was used for the first time in the 1930s. It was considered a progressive system and was used in expensive houses, office buildings, and other major edifices. It was realized by the Skokan Company. These efforts lasted until the nationalization of the company in 1948. The first major applications were the Vinohrady hospital and the Biela labuť shopping center (1938) in Prague. In Bratislava, the Crittall heating system was used, for example, in prefabricated high rises on Ružová dolina, Miletičova Street, and in the Istropolis cultural house. Massive socialization of construction activities began in the 1950s and 1960s, and conditions began to develop which gradually destroyed radiant ceiling heating. This hidden system was a favorite of architects, especially when used in brick buildings, where it worked optimally. This was especially true in new, lightweight structures because of its thermal properties. At that time the system was used in universities (ČVUT Prague, e.g., the Faculty of Mechanical and Electrical Engineering, and Bratislava, e.g., the Faculty of Civil Engineering) in classrooms with big southern, eastern, and western window areas; the negative effects from glare were particularly intense. The basic property of Crittall, i.e., a high thermal inertia and a resulting difficulty in regulating it in relation to climatic conditions, was gradually forgotten. After 1970, this construction system was abandoned; it returned in the 1990s in new houses. Now it is being combined with renewable energy. It can be a part of energy systems known as “thermally active structures”. They accumulate heat or cold, which they can later use indoors (Babiak et al., 2013; Cihelka et al., 1985; Némethová et al., 2016).

The basic aim of a heating system is to provide thermal comfort in all possible conditions. Therefore it is important to properly design segments with an appropriate selection of thermal output and segment controls.

The building itself and its thermal-technical properties influences the control of a heating system and are supposed to be carefully considered by the building services engineer. In the case of differences between the dynamic behavior of a building and its heating system, even a high standard control system can have problems providing required the parameters of a control system.

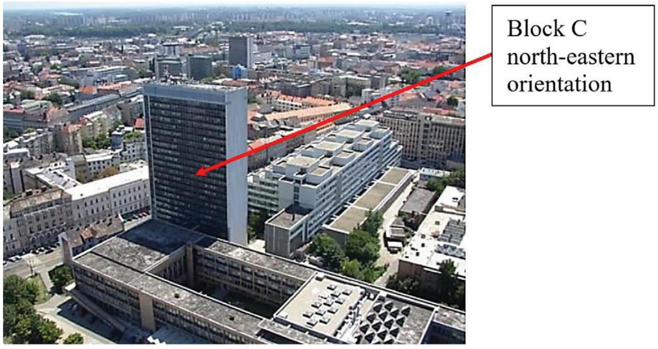

Fig. 1 *High-Rise Building of Civil Engineering Faculty, Block C*

2 BUILDING CHARACTERISTICS

The high-rise building that is the subject of this paper (C block of FCE SUT) has 23 floors and is partially used as an office building for administrative staff and teachers. It was renovated in 2010. Its new facade has excellent thermo-technical properties. The northeastern part of the building has a single facade and triple glazed windows. The southwestern side has a double facade with an air layer and windows that can be opened (Figure 1). The facade is lightweight with a high percentage of glazing (transparent construction).

The heat for the building is provided by a heat delivery plant with a water-water base. The distribution system for Block C is divided into two pressure zones (PZ). The first zone handles floors 1 to 10; the second one takes care of the 11th to 23rd floors. Each zone is subdivided into two branches, i.e., one for the northeastern offices and the other for the southwestern offices. Each branch has its own equitherm thermal control system for heating water in a basic composition (a controller, two sensors and a control valve). The delivery system is designed to be a large-scale Crittall warm water heating system (Figure 2) with a temperature gradient of 55/45 °C for sustaining the concrete core´s temperature; since the renovation, it has also been used as a cooling system during the summer months (Kačúr et al., 2010)

3 METHODOLOGY OF THE MEASUREMENTS

Large-scale heating with built-in piping for heating is considered to be sustainable as far as its dynamic properties are concerned. It

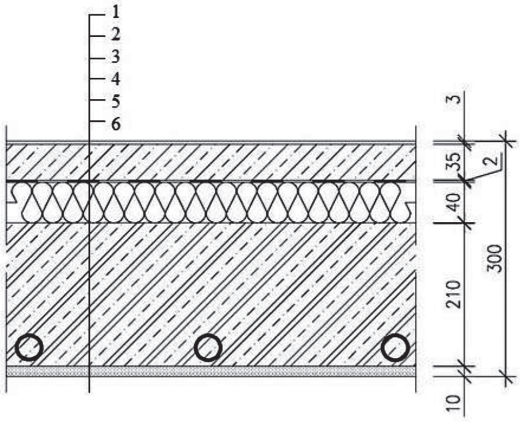

Fig. 2 *The heating structure of the ceiling (Crittall system) (Kačúr et al., 2010)*
1) PVC + glue 3 mm, 2) concrete screed 35 mm, 3) insulation against moisture, 4) thermal and sound insulation 40 mm, 5) reinforced concrete slab 210 mm, 6) lime-cement plaster 10 mm

can cause thermal discomfort, especially in the spring and autumn, as well as during sudden changes in the outdoor temperature that influence indoor temperatures so quickly that a sustainable heating system is not able to react fast enough to provide thermal comfort indoors. Therefore, it is important to check the control system, the heat output system, and the location of the thermal sensors to see if it is possible to add control elements to improve the operation of heating system or if it will be necessary to change the control strategy (Koudelková, 2015).

3.1 Methodology from the Point of View of Location

Two reference offices were selected for the measurements. Both are situated on the 6th floor of the 23 – storey building. Room 609 has a southerly orientation, white the other one, room 620, has a northerly/easterly orientation. Both offices are occupied by one person. The floor area is almost identical; i.e., both of them have one peripheral wall; the other walls are indoors. The air temperature during the heating season is identical as well. The heating area of the ceiling covers 45% of the total ceiling area.

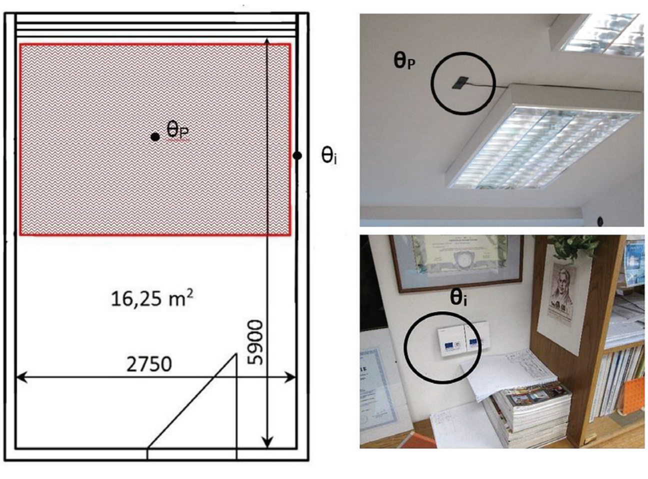

Fig. 3 *The layout of the reference office and the location of the sensors θi - indoor air temperature, θp - temperature of the heating surface of the ceiling*

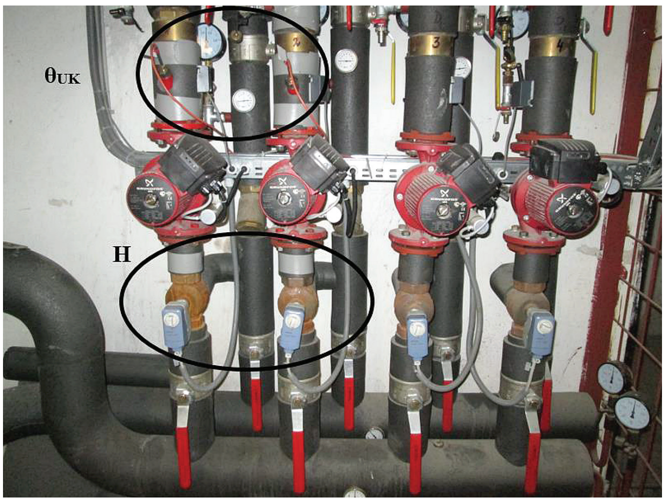

Fig. 4 *Location of heat sensors in the room with the heat source θ_{UK} – supply water temperature – branch V1 (north-eastern) and branch V2 (south-western), H stroke of three-way control valves*

3.2 Methodology of the Measurements and the Parameters Measured

The following parameters were measured:

a) in the reference offices (Figure 3):
   - the indoor air temperature
   - the heating surface temperature

b) in the room with the heat source (Figure 4):
   - the hot water temperature in branches V1 (north-eastern) and V2 (south-western orientation)
   - stroke of three-way control valves

c) outdoors:
   - outdoor temperature of northern facade
   - outdoor temperature of south-western facade

The values were monitored at 5 and 15-minute intervals in the central monitoring system.

3.3 Measurement from the Point of View of Time

In the period of time between 13 – 18 February, 2015, selected parameters measured were monitored. The parameters measured and the heating conditions were as follows:

- during a reduction and subsequent increase in the heating system´s performance in the time period from February 13 – 15, 2015,
- during the ordinary operation of the heating system, from February 16 – 18, 2015 (Koudelková, 2015).

4 RESULTS

From February 13 (Friday) to February 15 (Sunday), 2015, the reduced mode was applied. The three-way valves in the V1 and V2 branches were closed on 14.2. from 0:00 till 11:00 a.m., and on 15.2. from 0:00 till 12:00 a.m., with only a very small amount of the mixing of the supply water being used (Koudelková, 2015).

Figure 7 represents the outdoor temperature measured on the northern and south-western sides of the facade.

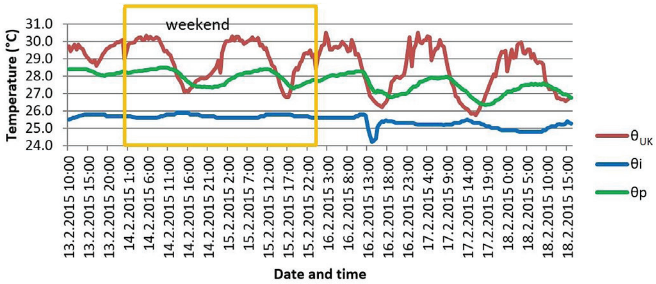

Fig. 5 *Temperature – office 620 (north-eastern orientation)*
θ_{UK} – supply water temperature, θ_i – indoor air temperature, θ_p – heating surface temperature

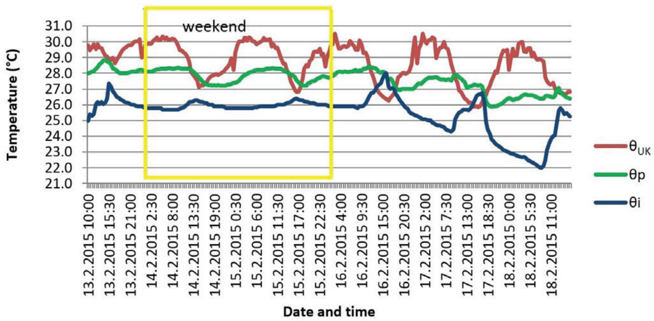

Fig. 6 *Temperature – office 609 (south-western orientation)*
θ_{UK} – supply water temperature, θ_i – indoor air temperature, θ_p – heating surface temperature

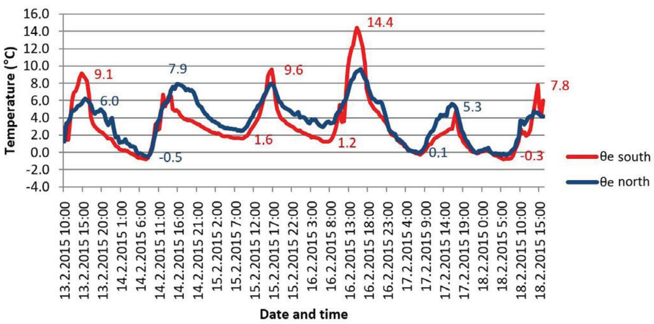

Fig. 7 *Outdoor air temperature*
$\theta_{e\ south}$ – outdoor temperature of south-western facade,
$\theta_{e\ north}$ – outdoor temperature of northern facade

5 ANALYSIS OF THE PARAMETERS MEASURED

In Tables 1 and 3, the supply water, the surface heating area, and the indoor air temperatures in rooms 620 and 602 are presented. The following time intervals were evaluated/analyzed:

- 14.2. from 0:00 till 11:00 a.m., when the three-way valves in branches V1 and V2 were closed or a small amount of water was mixed;
- the temperature of the heating system was falling,
- 14.2. from 11:00 a.m. to midnight, the valves were open and the water was heating,
- 16.2. – 18.2., conditions of the usual operations.

Office 620 (north-eastern orientation):

<u>*Cooling (Figure 8, Table 1)*</u>

- the supply water temperature was falling at 8:30 a.m., which was caused by the postponed transport of the supply water and was also due to a small difference between the supply water and return water caused by the accumulation of heat on the heating surface. Also, the self-control effect of the ceiling heating area was due to the small difference in temperature between the ceiling´s surface and the indoor air temperature (Table 1). The water temperature started to rise at 4 p.m.
- the temperature of the ceiling´s heating surface started to fall at 11 a.m., after closing the segments, but actually while opening the three-way valve. The drop in temperature lasted for 13 hours, until the time when the armatures were closed again on 15.2. at midnight. The drop in temperature was 1.1 K.
- the indoor air temperature was stable again without any great changes noticeable.

<u>*Heating (Figure 8, Table 1)*</u>

- the water was heating on 14.2. at 11 a.m. till midnight or for 13 hours; the control valve was open; after midnight it was closed. It took a longer time until the temperatures of the surface and water arrived at the values that had been set up

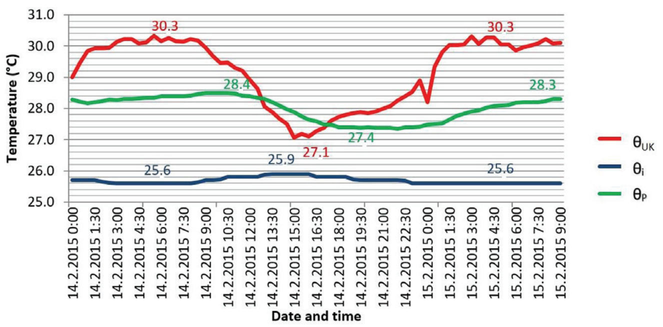

Fig. 8 *Temperature measured: part of Picture 5 – office 620 (north-eastern orientation)*
θ_{UK} – supply water temperature, θ_i – indoor air temperature, θ_p – heating surface temperature

compared to the time needed for cooling. The time when the valve was open again till the reaction of the heating system took place was postponed. The indoor air temperature was sustained and did not fall.

Tab. 1 *Temperatures during heating and cooling – Office 620 (north-eastern orientation)*

		Cooling	Heating
V1	Date, time	14.2. 0:00h 14.2. 11:00h Closed: 11 h	14.2. 11:00h 15.2. 0:00h Open: 13 h
θ_{UK}	Date, time	14.2. 8:30h 14.2. 16:00h Total 7:30h	14.2. 16:00h 15.2. 2:30h Total 10:30 h
	Temperature	30.2 °C 27.1 °C→**3.1K**	27.1 °C 30.1 °C→**3K**
θ_p	Date, time	14.2. 11:00h 15.2. 0:00h Total 13:00h	15.2. 0:00h 15.2. 11:30h Total 11:30h
	Temperature	28.5 °C 27.4°C→**1.1K**	27.4°C 28.3 °C→**1.1K**
θ_i	14.2.: average: 25.7 °C maximum: 25.9 °C minimum: 25.6 °C 15.2.: average: 25.7 °C maximum: 25.8 °C minimum: 25.6 °C		

θ_{UK} – supply water temperature in the branch V1, θ_i – indoor air temperature, θ_p – heating surface temperature

In Table 2 the averages of the ceiling surface and indoor air temperature are given as well as the daily maximum and minimum temperature values. The assessment of the indoor air temperature is shown in Tables 2 and 4. It was performed in accordance with the relevant documents:

1. the Slovak and European standard STN EN 12831, where the requirements on thermal comfort are defined by the design room temperature. In STN EN 12831 the design room temperature is defined as the operative temperature in the centre of the conditioned space, at the height of 0.6 to 1.6 m. According to the standard this temperature should serve for the calculation of design heat losses when designing a heating system (STN EN 12831, 2012).
2. the Decree of the Ministry of Health no. 259/2008 Coll., where the requirements on thermal comfort are defined by the operative temperature (Regulation of the Ministry of Health, 2008).

Both relevant documents refer to the operative temperature. The operative temperature is defined as the arithmetic mean of the indoor air temperature and the mean radiant temperature providing that the difference between the indoor air temperature and the mean radiant temperature is less than 4 K.

During the monitored period, the operating temperature was also monitored, the values were recorded manually at given time intervals. These values were then compared to the measured indoor air temperature data. The deviation between them was ± 0.1 to ± 0.3 K, so it can be said that the indoor air temperature and the operating temperature are approximately equal.

The evaluation of the indoor air temperature according to Regulation 259/2008, work classification 1a (offices) – operating temperature requirements (Regulation of the Ministry of Health, 2008):

– during ordinary operations, the indoor air temperature during the days monitored exceeded the maximum value of the operating temperature on average by 1 to 1.7 K. This value was also exceeded during the weekend, when the heating temperature fell. The interval of the limited operating temperature was not exceeded.

According to STN EN 12 831, the requirement for calculating the indoor air temperature of dwellings and offices is $\theta_i = 20°C$:

– the indoor air temperature was higher on average by 5 to 5.7 K.

Room 609 (south-western orientation):

<u>*Cooling (Figure 9, Table 3)*</u>

– during the cooling of the system, the temperature of the heating water and time shift was identical with the temperature of the heating water in branch V1.
– the fall in the heating surface´s temperature started at 12:20 a.m., which was 1:20 hours later than in office 620. It was caused by a higher outdoor temperature on the south-western side compared

Tab. 2 *Average, minimum and maximum daily air temperatures and comparison with Regulation 259/2008 – room 620 (north-eastern orientation)*

	Temperature (°C)	Date 14.2.	15.2.	16.2.	17.2.	18.2.
Measured values	Average heating surface temperature θ_p	28.0	27.9	27.6	27.2	27.3
	Average daily temperature θ_i	25.7	25.7	24.4	25.2	25.0
	Maximum daily temperature $\theta_{i,\ max}$	25.9	25.8	25.8	2.5	25.4
	Minimum daily temperature $\theta_{i,\ min}$	25.6	25.6	24.2	24.9	24.8
Comp. 259/2008	Optimal operating temperature $\theta_{o,\ opt.}$	20 - 24				
	Limited operating temperature $\theta_{o,\ prip.}$	18 - 26				
STN EN 12 831	Indoor design temperature θ_i	20				

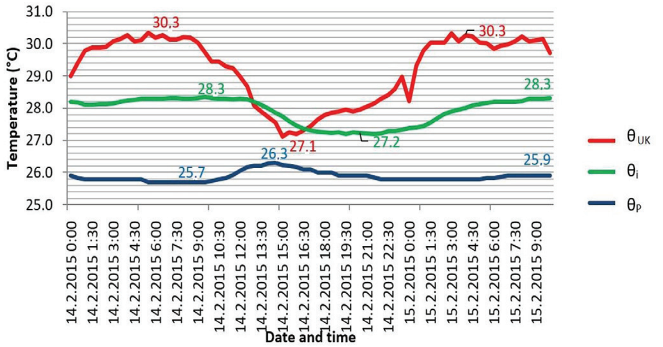

Fig. 9 *Temperature: part of graph in Figure 6 – room 609 (south-eastern orientation)*
θ_{UK} – supply water temperature, θ_i – indoor air temperature, θ_p – heating surface temperature

to the north-eastern facade (Figure 7). The temperature fell by 1 K and lasted for 11:15 hours, which was 1:45 hours shorter than in room 620. It was not influenced by the indoor air temperature, which was stable and did not undergo any great changes.

Heating (Table 3):
– during the heating time the temperature and time were similar to room 620.
– the indoor air temperature was stable and again experienced no great changes.

In Table 4 the average surface temperatures are given, as well as the indoor air temperature together with the maximum and minimum temperature values.

The evaluation of the indoor air temperature according to Regulation 259/2008, for the work class of 1a – operating temperature requirements:
– during ordinary operations the indoor air exceeded the limited value of the optimum operating temperature by 0.9 to 2.3 K. This value was also exceeded during the weekend, when the heating fell.
– the interval of the operating temperature was not provided on 16.2., when the maximum value was exceeded by 0.3 K (Figure 6), which followed the rise in the outdoor temperature caused by the sun. Also, the indoor air temperature was oscillating during the following two days, which was caused by solar gains, ventilation and cold weather (Figure 7).

Tab. 3 *Temperature during cooling and heating – room 609 (south-western orientation)*

		Cooling	Heating
V2	Date, time	14.2. 0:00h 14.2. 11:00h Closed: 11 h	14.2. 11:00h 15.2. 0:00h Open: 13 h
θ_{UK}	Date, time	14.2. 8:30h 14.2. 16:00h Total 7:30h	14.2. 16:00h 15.2. 2:30h Total 10:30 h
	Temperature	30.2 °C 27.2 °C→**3K**	27.2 °C 30.0 °C→**2.8K**
θ_p	Date, time	14.2. 12:20h 14.2. 23:35h Total 11:15h	14.2. 23:40 h 15.2. 12:25h Total 12:45h
	Temperature	28.3 °C 27.3 °C→**1K**	27.4 °C 28.3°C→**0.9K**
θ_i	14.2.: average: 25.9 °C maximum: 26.3 °C minimum: 25.7 °C 15.2.: average: 26.0 °C maximum: 26.4 °C minimum: 25.8 °C		

θ_{UK} – supply water temperature in branch V2, θ_i – indoor air temperature, θ_p – heating surface temperature

According to STN EN 12 831, the requirement for calculating the indoor air temperature of dwellings and offices, is θ_i = 20°C (STN EN 12831, 2012):
– the indoor air temperature exceeded this value on average by 3.8 to 6.3 K.

Nevertheless, the heating system was zoned according to the cardinal points, and each zone has its own equithermal control, which is based on the measured values of the supply water in branches V1 and V2 as seen in the graphs in Figures 5 and 6. It is possible to say that in both cases, the temperatures are identical and that the control is based on the values monitored in the sensors located on the northern facade.

6 CONCLUSION

Based on the experimental measurements, it is possible to say that in offices 609 and 620, the indoor air temperature exceeded the recommended intervals given in the Slovak regulations but that their progress was stable. However, when the sun was shining, the temperature in room 609 had a significant rise in temperature. After the closing of the control valves, the output of the heating areas dropped for quite some time, which was caused by a small difference between the supply and return heating water temperatures. It is also necessary

Tab. 4 *Average, minimum and maximum daily air temperatures, as well as the required values given in Regulation 259/2008 for room 609 are given*

	Temperature (°C)	Date				
		14.2.	**15.2.**	**16.2.**	**17.2.**	**18.2.**
Measured values	Average heating surface temperature θ_p	27.9	27.9	27.8	27.1	26.4
	Average daily temperature θ_i	25.9	26.0	26.3	24.9	23.8
	Maximum daily temperature $\theta_{i, max}$	26.3	26.4	28.0	26.7	25.8
	Minimum daily temperature $\theta_{i, min}$	25.7	25.8	25.4	23.1	22.8
Comp. 259/2008	Optimal operating temperature $\theta_{o, opt.}$	20 - 24				
	Limited operating temperature $\theta_{o, prip}$	18 - 26				
STN EN 12 831	Indoor design temperature θ_i	20				

to consider the thermal accumulation of heating surfaces, so the control of the system must be done in advance (Némethová et al., 2017; Valter, 2010; Ehrenwald and Kurčová, 2010).

It is possible to say that the strategy used for the existing control system is suitable only for the north-eastern heating zone; however it is necessary to set up a more suitable heating curve so that the indoor air temperature could be within the optimum values that would protect the system from overheating and so help reduce energy consumption. The control circuit of the south-eastern zone should be separate and utilize separate, functional, and appropriately located sensors of the outdoor air temperature.

To provide thermal comfort via the control system for the zones with a south-western orientation is quite complicated due to the different dynamic behavior of a building with a lightweight envelope and a heating system with high thermal accumulation. Due to the long thermal response of the heating system, control of the heating output based on, e.g., the indoor air temperature would not be appropriate. Although the control system would receive the information about the current indoor air temperature, the controller´s intervention would be reflected in the actual indoor air temperature with a long delay because of the long thermal response of the heating system.

Due to this fact, the appropriate control system should consider the weather forecast and reduce or increase the heating system´s output in advance according to the hydrometeorological weather forecast (Kovářová, 2016; Široký and Kubeček, 2010).

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