INFLUENCE OF HEAT ACCUMULATION OF THE OBJECT ON THE OPERATION OF THE COOLED CEILINGS COOLING SYSTEM

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The application of cooling systems is a relatively efficient way to ensure the required thermal comfort conditions. One option is the application of cooled ceilings, where the heat load is removed using a ceiling structure with integrated cooling panels. These systems allow for a suitable way remove the heat load, but at the same time, compared to conventional air conditioning systems, they are characterized by a certain time dependence. The presented article describes experimental measurements carried out on days with high exterior heat exposure. Measurements evaluating the effect of the phase shift of temperature oscillations on the operation of the system were carried out using two cooling operating modes. According to results, it can be concluded that cooling systems based on cooling ceilings can be used effectively even with high external heat gains.

KEYWORDS

cooling ceiling, reversible heat pump, energy storage, thermal attenuation, phase shift of temperature fluctuations

1 INTRODUCTION

In addition to legislative requirements, energy-efficient buildings must also meet the requirement of thermal comfort. Thermal comfort represents a state in which the subject achieves suitable conditions of thermal well-being. Thermal comfort is understood as a highly subjective state and is directly dependent on several parameters such as environmental temperature, air humidity, air flow speed, indoor air quality, building physics as well as human physiology [Micallef 2016, Driss 2016, Hao 2007]. According to the ANSI/ASHRAE 55-2010 standard, thermal comfort is defined as "a state of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation." As stated by [Kalliomaki 2016, Zhang 2017], measuring thermal comfort is very challenging because the physiology of the person depends on the person's metabolism, the person's current clothing, that means it depends on the subjective feelings of well-being and physiology of a specific person.

People's satisfaction with indoor temperature conditions is therefore one of the factors that must be taken into account when designing the working environment or conditions in buildings. If this condition is not met, there is a risk that the building will not be perceived as efficient by the residents. The relationship between the thermal comfort conditions of residents of residential buildings, workspaces and the energy efficiency of systems is evaluated by [Salata 2018].

In summer, it is possible to ensure thermal comfort with various cooling systems. Operation of cooling systems to ensure the required thermal comfort represents the removal of heat gains in interiors.

The generation of heat load in modern office spaces is currently generated not only by people and the increasing number of computing and other technology, but also by the action of solar radiation and outside temperature [Fredriksson 2001]. The heat load is removed by various technical methods, for example with cooled air adjusted to the required temperature, or by using cooling panels, cooling convector systems or cooling ceilings.

Solar radiation and the outside temperature affect the external envelope of the building and thereby also change the internal heat gains [Pivarciova 2019]. Such action can be defined as cyclical with a 24-hour period and manifests itself as the thermal inertia of the structure. In this case, solar radiation and temperature behave as a harmonic function, while the temperature exhibits a phase shift. This point of view must be understood as simplistic, considering the various aspects affecting the ideal course for a specific day. The influencing factors are mainly the speed and direction of wind flow, atmospheric pressure, cloud cover and, in the case of solar radiation, atmospheric pollution defined by the turbidity coefficient [Bochen 2009].

According to [Chmurny 2003], the harmonic fluctuation of the outside air temperature can be expressed by the relation (1) for a fluctuation period of τ=24 hours

$$t_{e,\tau} = t_{e,av} + A_e cos(\omega\tau - \varphi) \tag{1}$$

Where $t_{e,av}$ – average temperature [°C], A_e - amplitude of temperature change within a 24-hour period [°C], ω – circular frequency [h^{-1}] $\omega_{\tau24}$=(2π/24), φ - phase angle, represents the time of maximum amplitude A_e [rad]

$$A_e = t_{e,max} - t_{e,av} = t_{e,av} - t_{e,min} \tag{2}$$

Where $t_{e,max}$ maximum temperature [°C] for τ=24, $t_{e,min}$ minimum temperature [°C] pre τ=24.

Dynamic periodic changes in the outside air temperature described by equation (1) also affect the contact surface of the building structure. The dynamics of changes are transferred to the structure itself, while oscillations are dampened, i.e. the decrease in the amplitude of Aw (walls) and the phase shift of temperature fluctuations. Thus, the phase shift of the temperature oscillation expresses the time during which the amplitude of the temperature oscillation passes from one side of the structure to the other. The result is a gradual damping of the temperature ν in the wall. As further stated by [Chmurny 2003], this shift is also manifested on the inside of the structure and is manifested by fluctuations in the internal surface temperature of the structure.

$$t_{w,\tau} = t_{w,av} + \frac{A_e}{\nu} cos(\omega\tau - \varphi - \psi) \tag{3}$$

Where ν – temperature attenuation, ψ – phase shift of temperature fluctuations [rad]

$$\psi = \tau_{Ai} - \tau_{Ae} \tag{4}$$

Where τ_{Ai} – reach time $t_{i,max}$, τ_{Ae} – reach time $t_{e,max}$

Thermal attenuation according to [Katunsky 2013] indicates how many times the temperature amplitude on the inner surface of the wall structure is smaller than the temperature amplitude of the outside air.

$$\nu = \frac{A_e}{A_w} \quad (5)$$

Where A_w – temperature amplitude on the inner surface [°C]

As reported by [Katunsky 2013, Lendelova 2015], the calculation of temperature attenuation for a multi-layer construction according to Sklover applies the empirical relation (6)

$$\nu = 0{,}7exp\left(\frac{D}{\sqrt{2}}\right)\frac{s_i+h_i}{s_1+U_1}\cdot\frac{s_2+U_1}{s_2+U_2}\cdots\frac{s_n+U_{n-1}}{s_n+U_n}\cdot\frac{h_e+U_n}{h_e} \quad (6)$$

Where D - thermal inertia, h_i – heat transfer coefficient on the inside of the wall structure [$Wm^{-2}K^{-1}$], h_e – heat transfer coefficient on the outside of the wall structure [$Wm^{-2}K^{-1}$], U_j – heat absorption of the outer wall surface [$Wm^{-2}K^{-1}$].

The thermal inertia for a multilayer structure can be determined as (7)

$$D = \sum D_j\ ;\ \ D_j = R_j s_j \quad (7)$$

Where s_j – thermal absorption of the layer [$Wm^{-2}K^{-1}$] , R_j - thermal resistances of layers (wall structures) [m^2KW^{-1}],

thermal absorption of the layer according to [Katunsky 2013, Lendelova]

$$s_j = \sqrt{\frac{2\pi}{\tau} b_j} \quad (8)$$

Where b_i - thermal receptivity of the layer

$$b_j = \lambda_j c_j \rho_j \quad (9)$$

According to [Chmurny] if $D_j \geq 1$ then the layer absorption is

$$U_j = s_j \quad (10)$$

If $D_j < 1$ then j = 1,2,...n

$$U_j = \frac{R_j s_j^2 + U_{j-1}}{1 + R_j U_{j-1}} \quad (11)$$

For j = 1

$$U_j = \frac{R_1 s_1^2 + h_i}{1 + R_1 h_i} \quad (12)$$

Figure 1 shows the principle of phase shift of temperature fluctuations in the wall structure. The phase shift represents the time difference between the maximum value of the amplitude of the outdoor air temperature and the maximum value of the amplitude on the internal surface of the structure.

Due to the fact that when using ceiling cooling, in most cases the prepared cooled water is subsequently accumulated with the help of a heat pump, it is possible to use different time periods of the day for the accumulation of the glycol. The removal of the thermal load using the ceiling cooling system thus makes it possible to use the inertia of the systems compared to conventional systems. The presented article deals with the issue of optimizing the operation of the system with cooled ceilings in relation to achieving the required interior conditions of thermal comfort. The aim of the implemented experiment was to monitor the influence of the phase shift of temperature fluctuations in the summer season on the operation of the cooling system using cooled radiant ceilings. Attention is paid to the possibilities of optimizing the use of accumulated energy while eliminating the influence of the phase shift of temperature fluctuations in the circuit construction. At the same time, an evaluation of the activation of the heat pump within a 24-hour cycle is carried out in relation to the optimal energy efficiency during the accumulation of the heat-carrying medium.

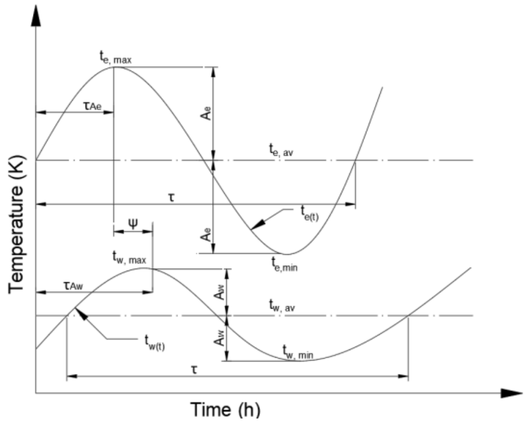


Figure 1. Phase shift of temperature oscillations

2 METHODS AND MATERIALS

The aim of the experimental measurement was to monitor the course of the characteristic values during the application of the ceiling cooling system in the period of high external heat load. The experimental measurements for the needs of the study were carried out in the laboratory of the Department of Process Technology. The RES laboratory represents a complex multivalent system enabling the creation of selected combinations of heat and cold sources. For the given experimental measurements, the conditions were monitored in the office room, which is part of the RES laboratory. The dimensions of the room are length 6.7m x width 2.8m x height 3.0m. The exterior wall is fitted with a plastic window measuring 2.2m x 2.3m. The window is equipped with an external screen with a sunscreen allowing the elimination of excessive solar gains in the summer. Contact with the interior is represented by the floor, 3x inner wall and a building opening into the interior is represented by a door. The properties of the individual constructions of the outer shell and the roof are listed in table (1). The external structures are a beam structure (Wall A) made of 365 mm thick CDM brick insulated with 8 mm polystyrene foam. The window space (Wall B) is made of 250 mm thick CDM brick and insulated with 8 mm polystyrene foam. The ceiling structure is represented by reinforced concrete beam with a plaster thickness of 150 mm. Cinder embankment with an average layer thickness of 220 mm, gas silicate boards and hardened insulation based on stone wool with a thickness of 120 mm.

To ensure the required conditions of thermal comfort, the room is provided with a system of ceiling cooling panels placed in the plasterboard soffit. In the room, the interior temperature, relative humidity and dew point value are monitored using integrated sensors using a dew point sensor located in the ceiling. The source of cooled water circulating in the system is a double-compressor reversible air-water heat pump WBAN 162. The total cooling capacity of the heat pump is 22.78 kW. The experimental system also consists of a pump group, safety devices, storage tank, three-way mixing valve with drive. The output temperature of the working medium from the heat pump ranges from 4.5°C to 10°C.

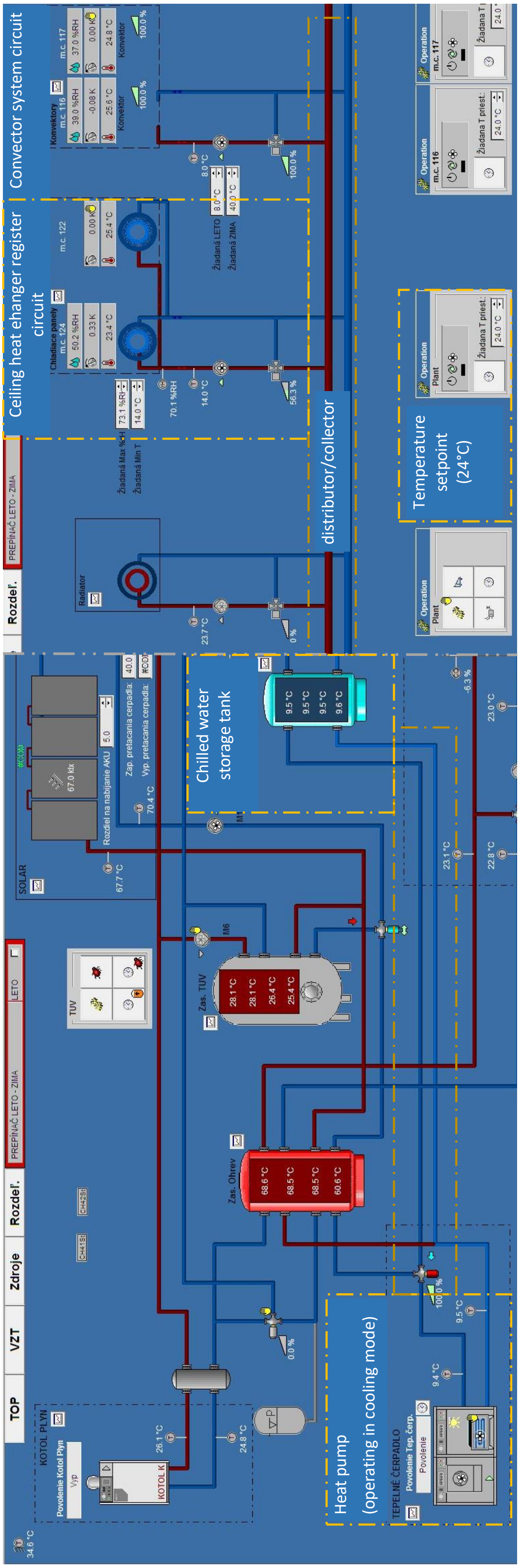


Figure 2. The applied scheme of the system in multivalent laboratory

The cooled heat transfer substance is accumulated in a cooling water tank with a volume of 800 l. The process level of control as well as the provision of recording of read data from individual measuring nodes is provided by the software system Desigo Insight designed based on Siemens Desigo Insight (Fig. 2).

2.1 Conditions of the experiment

The measurements were carried out in the period with high exterior temperatures from 26.6 to 30.6. 2022. For the given period, the maximum exposure to the exterior temperature in the shade above 36°C was assumed. Courses of own outdoor temperature measurements are described in the results section. The chosen period allows experiments to be carried out to evaluate the elimination of the effects of the phase shift of temperature fluctuations by changing the activation of the ceiling cooling system over time. The work cycle of the ceiling cooling system consists of the work cycle of the heat pump and the work cycle of the circulation pump of the ceiling panels, which are by default activated simultaneously from 6:00 a.m. and deactivated at 4:00 p.m. Outside of working days, the system is deactivated. To ensure thermal comfort in the experimental room, the desired interior temperature was set at 24 °C. This temperature was chosen due to the maximum load of the ceiling panel system under the given climatic conditions.

3 RESULTS

The results of the analysis of the object constructions are shown in Tab. 1. As can be seen from the results, the ceiling shows the greatest thermal inertia, wall B represents a structure with 60.87% inertia compared to the ceiling and 74.44% compared to wall A. In terms of surfaces in contact with the exterior, the ceiling is dominant, with an area share of 84.89% and a phase shift of 17.3 h. Wall A represents 8.15% of the total area in contact with the exterior and with a phase shift of 14.1 h and wall B represents 6.97% and a phase shift of 10.5 hours. As it follows from the evaluation, the ceiling structure has the most significant effect. The weighted average value of the phase shift is 16.57 hours. The result is the fact that daytime temperature exposures are carried over into the night period, where they cover the entire length of time during the night.

Sunrise for the Presov region and the given period is at 4:32 a.m. and sunset is at 8:43 p.m., which means that the average length of daylight is 16 hours and 11 minutes. The curves of the external temperature are shown in Fig. 4. The average daily outdoor temperature for the period of daylight represents $\bar{t}^{S}_{26.6}$= 28.99 °C, $\bar{t}^{S}_{27.6}$= 28.13°C, $\bar{t}^{S}_{28.6}$= 28.21°C, $\bar{t}^{S}_{29.6}$= 30.51°C, $\bar{t}^{S}_{30.6}$= 32.85°C. The average daily outdoor temperature for the work period (from 8:00 a.m. to 4:00 p.m.) then $\bar{t}^{W}_{26.6}$= 30.74°C, $\bar{t}^{W}_{27.6}$= 30.40°C, $\bar{t}^{W}_{28.6}$= 32.94°C, $\bar{t}^{W}_{29.6}$= 33.02°C, $\bar{t}^{W}_{30.6}$= 35.14°C. The average night-time outdoor temperatures are $\bar{t}^{N}_{26.6}$= 19.49°C, $\bar{t}^{N}_{27.6}$= 22.34°C, $\bar{t}^{N}_{28.6}$= 21.08°C, $\bar{t}^{N}_{29.6}$= 21.84°C, $\bar{t}^{N}_{30.6}$= 23.53°C. During all days, the night temperature is lower than the required daytime temperature in the rooms. This means that the night temperature does not affect the temperature in the room by increasing it. Based on the performed analysis, the work cycles of the heat pump and circulation pump were determined according to the schedule shown in Fig. 3.

The circulation pump of the ceiling panel system is deactivated according to the set schedule at time t+1 hour. after the end of the heat pump operation due to the use of the remaining accumulated energy from the work cycle. This energy enables the removal of part of the heat gains in the room that occur after 4:00 p.m. And they would be manifested by an increase in the temperature in the room. Activation of the circulation pump is carried out for two possible modes, (A) simultaneously with the heat pump, (B) at time t-1 hour before the activation of the heat pump.

	Construction	Thickness m	ρ kg/m³	λ W/(m K)	c J/(kg K)	R m² K/W	s W/(m² K)	D_j -	D -	ψ
Wall A	Polystyrene foam -PPS	0.08	40	0.037	1270	2.1622	0.3698	0.7995	5.2301	14.1
	CDm hr. 365	0.365	1450	0.690	960	0.5230	8.3597	4.4306		
Wall B	Polystyrene foam -PPS	0.08	40	0.037	1270	2.1622	0.3698	0.7995	3.8934	10.5
	CDm hr. 250	0.250	1450	0.720	960	0.3623	8.5395	3.0939		
Ceiling	ISOVER T	0.120	160	0.039	1020	3.0769	0.6805	2.0939	6.396	17.3
	Slag	ø 0.22	750	0.270	750	0.8148	3.324	2.7084		
	Reinforced concrete	0.150	2400	1.580	1020	0.0949	16.776	1.5937		

Table 1. Properties of constructions

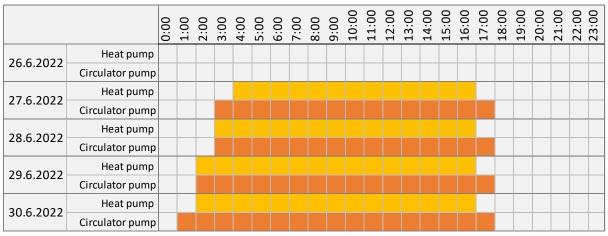


Figure 3. Work cycle of the ceiling cooling system

The course of the temperature in the monitored room at the time the system is deactivated, i.e. during the weekend is shown in Fig. 4. The internal temperature gradually increases and reaches 25.9°C. At 9:50 p.m., the outside temperature dropped below room temperature and at 11:59 p.m. it reached 23°C.

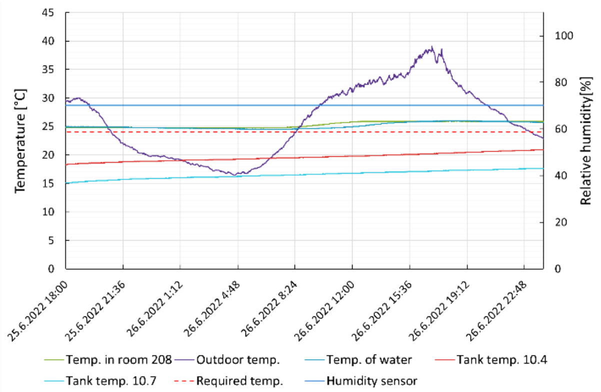
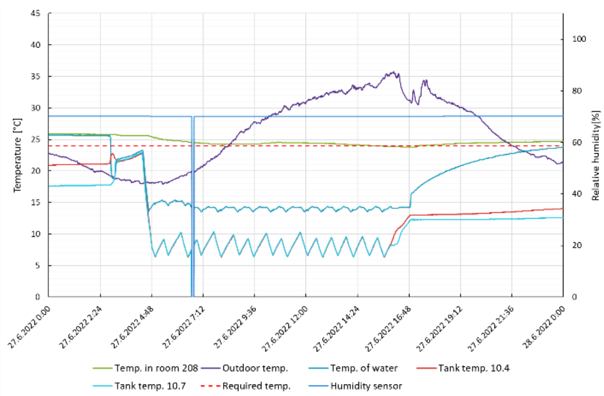
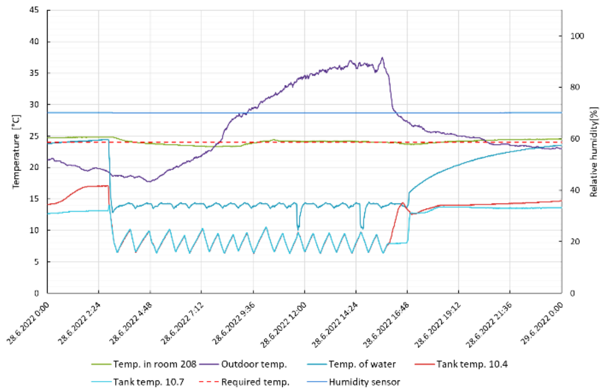
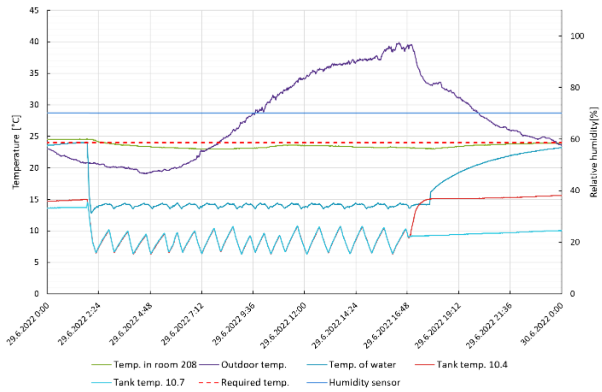


Figure 4. Evaluated quantities monitored during cooling - deactivated system (26.6.2022)

Figure 5 shows the temperature trends after activation of the cooling system, while the heat pump and system circulation is activated according to the selected schedule for the period 27.6. to 30.6.2022.







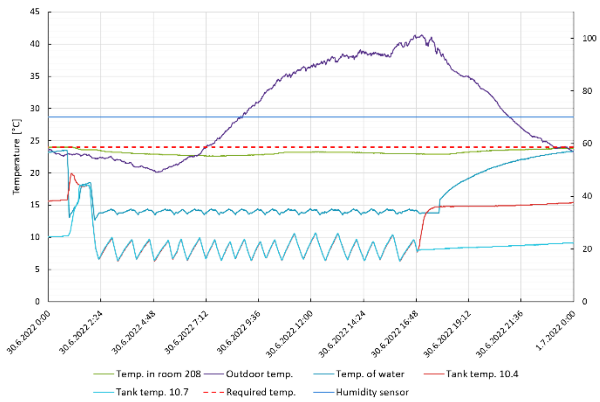


Figure 5. Evaluated variables monitored during cooling – activated system (June 27- June 30, 2022)

System starts-up is in (A) mode. At the time of system activation, the initial temperature in the monitored room was $t_{3:00}^{27.6} = 25.6°C$, the temperature reduction is recorded at 4:40. At 7:30, the temperature reached the value $t_{7:30}^{27.6} = 24.4°C$. The system reached the required temperature of 24°C only at 2:50 p.m. After deactivating the heat pump, the circulation pump continues to operate and the temperature in the room is maintained. After the end of the circulation operation, the temperature in the reservoir reaches a temperature of 13°C in the upper part of the reservoir and a temperature of 12.3°C in the lower quarter of the reservoir. The given temperatures indicate a sufficient supply of chilled water for further operation. The temperature of the circulating water in the system oscillates around the desired value of 14°C, while the lowest values are 13.6°C and the highest at 14.4°C. At this temperature, no increase in relative humidity is recorded by the dew sensor. The measured value is at the level of 70.1%. The limit value of dew point is set at 73.1%. The manifestation of thermal inertia can be observed by the gradual increase of the interior temperature at night. Measurements 28.6 and 29.6 were carried out for circulation pump mode (B). The temperature in the room at the time of system activation was equal $t_{3:00}^{28.6} = 24.7°C$, which represents a difference of 0.9°C compared to the previous day. The outdoor temperature for the given time has a similar character. From the above, it follows that the cooling of the space will ensure a drop in temperature, which will only increase due to the inertia of the outer shell. The required temperature of 28.6 is reached, but subsequently with the increase in outside temperature it is slightly exceeded by 0.2°C. This increase is due to the maximum possible energy load of the ceiling panels. They can no longer eliminate the increasing heat load. A possibility to ensure the required temperature at the maximum heat load is to shift the start of the system. The measurement from 29.09 records a temperature drop in the room with higher dynamics, which is associated with a higher temperature difference in the room and the outside temperature. Throughout the day, the maintained temperature in the room is lower than the required temperature. And even at a time with a significant increase in the outside temperature from 10:30 am. A slight increase in the internal temperature by 0.5°C is recorded and was maintained. On 30.06 the system was activated in mode (A) with the circulation pump activated at time t-1 h. comparing to the start of the heat pump. The remaining cooling capacity from the previous cycle was used. The temperature in the room after activating the circulation decreased by 0.6°C. After the start of the heat pump, the temperature drops further, and at 7:30 a.m. its value is 22.7°C, which is significantly below the required value. From the course of the daily temperature, we can observe the high thermal load of the object, but it is conveniently eliminated by shifting the activation of the system to the time of the phase shift of the object's shell. This eliminates the increase in temperature in the room during the night. At the same time, the accumulated energy in the water storage tank from the previous work cycle is used to reduce the temperature.

4 CONCLUSIONS

Due to the fact that the cooling ceiling system reaches its maximum capacity, timing optimization is a suitable tool for maintaining the desired interior temperature. At maximum outdoor temperatures well above 36°C, the effect of phase shift and heat capacity during cooling is significant, as it does not allow the temperature in the interior to be reduced by cooling from the outside environment. Thus, gradual overheating of the object occurs. When the cooling system is activated when the outside temperature rises, it may not ensure sufficient removal of the heat load through the cooling registers of the ceiling cooling. As shown by the obtained results, the optimal use of the water tank allows cooling of the building in the afternoon hours, when the sun exposure is still significant. And at the same time in the morning before starting the heat pump itself. The results show that this way the system is able to reduce the interior temperature by approx. 0.6°C. At the same time, even with maximum heat load, the system enables the temperature to be maintained significantly below the desired temperature value of 24°C by 1.3°C. The use of system activation optimization with consideration of the influence of thermal inertia makes it possible to operate cooling systems with cooling panels without the need to increase their cooling capacity.

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