Temperature calibration and Annual performance of cooling for ceiling panels

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Abstract. In this paper, the annual energy usage and emission efficiency of ceiling panels for cooling were assessed with IDA ICE building performance simulation software. The models were calibrated against measurements carried out in the autumn of 2021 at the nZEB test facility in Tallinn University of Technology. Calibrated models were then used to investigate the energy performance of the systems with annual simulations with the Estonian test reference year and energy simulation input data for office buildings in EN 16798-1:2019.

The simulations were conducted on a room model with fixed geometry and boundary conditions. The goal of the control strategy was to maintain a specified operative temperature within the room. The annual cooling energy need of the test room was compared with the same value obtained using an ideal cooler with 100% convective heat emission. Additionally, a single-value performance indicator in the form of an air temperature set-point deviation was obtained for the device and each configuration, as the result of this research, to be used in further hourly, monthly, or annual cooling energy usage calculations. The imperfections in air stratification within the room (temperature gradient), the surface temperature of the panels, and additional temperature deviation from the set-point to achieve the desired operative temperature level are the effective parameters on the performance indicator. Further analysis is needed to determine if room temperature set-point deviation can be applied with varying room geometry, boundary conditions, and cooling control principles.

Keywords. Cooling, Cooling design, Cooling device performance, Cooling simulation, thermal comfort, ceiling panel, thermal stratification
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1. Introduction

The recent analysis and trends of climate change show a warmer pattern in Europe's climate, while the heatwaves are lasting longer, resulting in more cooling demand in the buildings. [1] This results in higher energy consumption for cooling and an increase in the importance of emission efficiency and accurate calculation and energy simulation of cooling devices. For cooling ceiling panels, there are three main aspects of accuracy measurement, vertical room temperature profile, cooling power output, and ceiling panel surface temperature. [2]

In this paper, the emission efficiency of the cooling ceiling panels is assessed. The European standard EN 15316 [3] presents a method for quantifying the influence of various system components, such as the effect of the emitter system on room air stratification and the effect of the system on thermal comfort (considering the operating temperature). This quantification takes the form of additional set-point increments to the initial room air temperature set-point to account for the energy difference necessary to overcome the effects of these components.

The purpose of this work is to compute such set-point increments using experimental data collected at the Tallinn University of Technology's nZEB test facility. These measurements are utilized to calibrate the IDA ICE 4.9.9 [4] model of the same nZEB facility room at Tallinn University of Technology. The necessary parameters are subsequently used in the model for yearly simulations. The set-point difference is then computed based on the energy need. This method was originally conducted in 2019 [5] as a contribution to the CEN TC 130 standardization technical committee's agenda for the determination of the experimental input and model calibration data required for dynamic simulations.

2. Methods

In this paper, the annual cooling energy need of ceiling panels was analyzed. For this purpose, these steps were followed:

1. The simulation model is created in IDA ICE

4.9.9 software package. The CFD-free zone model [6] is used to model the air temperature in horizontal 0.2 meter layers (total 15 layers). Models with low and high cooling capacity ceiling panels were created.

2. The modelled temperature at different heights were compared to measured values provided in [7] for model calibration.
3. The simulation model calibrated against the measurements by minimizing a mean square equation function using two main variables:
    a. Kfin, thermal resistance of the coolant which effects the rate of heat transfer between the surface and the environment and consequently influences the surface temperature of the ceiling panels
    b. Extra heat loss introduced as thermal bridge to correct the temperature magnitude.
4. Annual cooling energy is simulated with the calibrated model with pre-defined input data from EN16798-1 [8] using the Estonian test reference year climate file [9].
5. The cooling need dependency from room temperature setpoint is assessed with an identical model with an ideal cooler instead of ceiling panels. The cooling temperature set-point increment was identified so that the cooling needs of the models with ceiling panels and ideal cooler were equal.

2.1 Test room and conditions

Ceiling panels are installed in the largest room of the facility located on the East side of the building. The general view of the inside of the room is shown in **Fig. 2**. The room is 30 m^2 and has four windows, two on the East-facing external wall and one on each North and South facade. The test room has a false ceiling, and the whole building has a ventilated crawlspace.

The room temperature during experiments was free-floating and the temperature developed based on the the heat balance of internal heat gains, ventilation air flow, heat transfer from/to the outdoor environment and adjacent rooms and cooling capacity of ceiling panels. The exterior venetian blinds of South- and East-oriented windows were drawn to minimize the uncertainty due to solar heat gains. Chilled water with constant flow rate and supply temperature was supplied to the ceiling panels.

The airflow rate of the room was 45 l/s (approximately 1.46 l/(s·m^2)), and the air handling unit supply air temperature is measured every 10 seconds for the period of the tests with an average of 20.2°C.

Fig. 1 – Tallinn University of Technology nZEB test facility

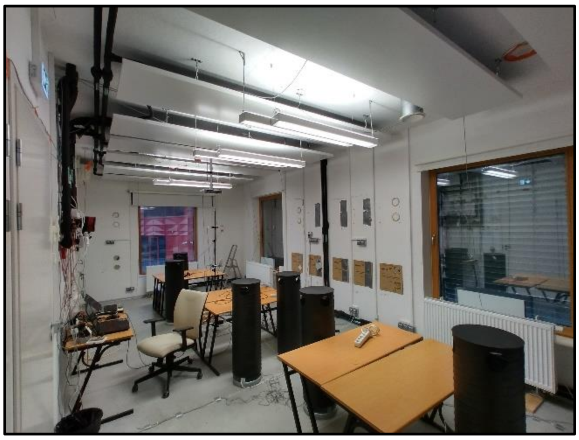

Fig. 2 – General view of the testing premises.

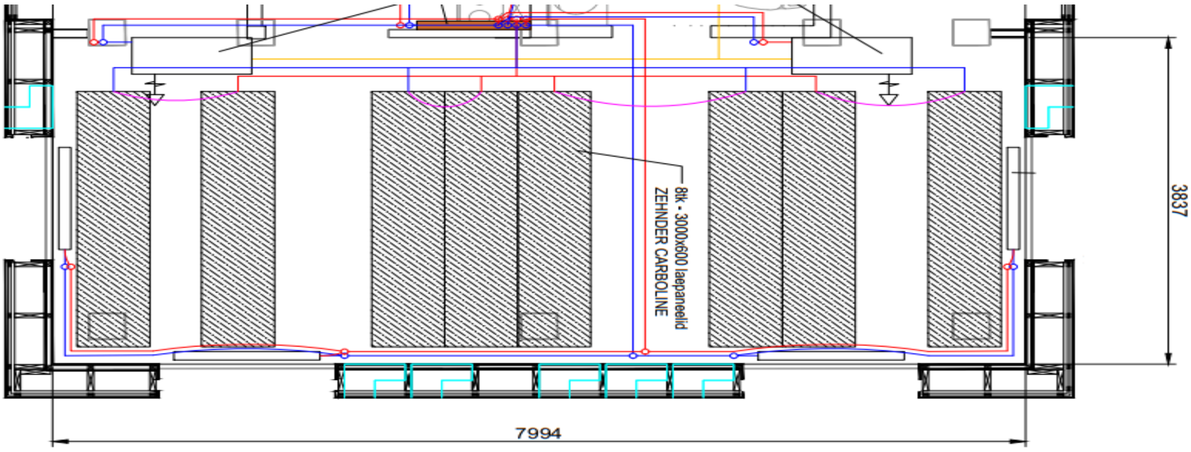

Fig. 3 – Positioning of ceiling panels and supply (blue) and return (red) pipes.

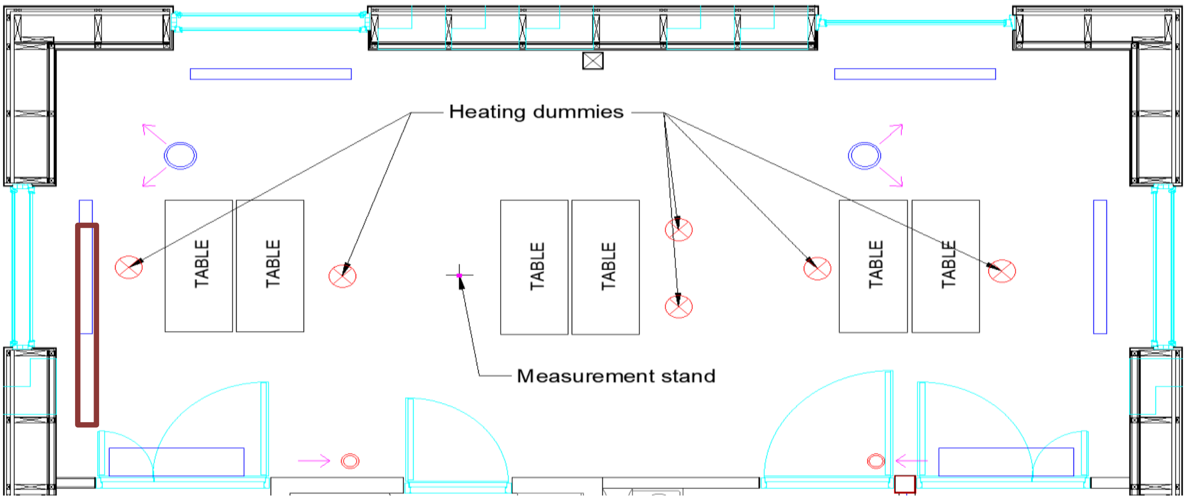

Fig. 4 - Room setup and positioning of heating dummies.

Necessary temperature sensors were installed in the room to measure the temperatures needed for the calibration. For supply and return temperature, ceiling and floor temperature, ceiling panels surface temperature, and the air stratification in the room.

Internal heat gains in the form of 6 thermal dummies were placed in the test room consisting of 3 incandescent lamps with a rated output of 3x60 W per dummy. There was no specific profile, and all heating dummies were always on to the full power. As an extra heat source, one radiator was also working with a rated power of 1000W. Positioning of the dummies and the room radiators can be seen in **Fig. 4**, while the only working radiator is the one with red color.

2.2 Ceiling Panels

The specifications for testing are briefly provided here. detailed information regarding the tests is available in the experimental study. [7]

Eight ceiling panels with a size of 600 x 3000 mm and a nominal cooling output of 172 W at 8°C logarithmic temperature difference installed under the ceiling using suspension cables at the height of 2.85 m from the floor and the upper side of the ceiling panels which can emit toward the ceiling is insulated by the manufacturer using mineral wool. Ceiling panels are installed in four pairs, and each pair of panels are connected in series. The detailed geometry and positioning of the panels are indicated in **Fig. 3**. The tests have been done at two nominal outputs named High and Low in this paper. The detailed specifications of each test are listed in **Tab. 1**. For each case, 1 hour of consecutive data has been measured with time steps of 10 seconds. Such data is then imported to the calibration models for boundary conditions and supply air temperature for the air handling unit.

Tab. 1 - Ceiling panels test specifications.

Parameter	Value	
	Low	High
Supply temperature, °C	18.50	15.09
Return temperature, °C	20.64	17.96
Chilled water flow rate, l/h	337	335
Cooling output per pair, W	205	282

2.3 Measured air temperature and surface temperatures

Surface temperatures were measured at several locations, and the average temperatures for the duration of the tests are written in **Tab. 2**. 1st series refers to the ceiling panels that had chilled water inlet connected to them, and 2nd in series refers to the ones with returned water pipe connected to them.

Tab. 2 – Measured surface temperatures.

Device	Sensor	Temp., °C
Ceiling panels HIGH	1st in series	16.30
	2nd in series	17.75
Ceiling panels LOW	1st in series	19.36
	2nd in series	20.38

The air stratification profile is measured at some data points, and the temperature in the other heights is interpolated. Measured air temperatures in different heights are used to compute vertical temperature gradients inside the zone.

$$G = \frac{t_2 - t_1}{h}, \tag{1}$$

Where t_2 and t_1 are temperatures from the two consecutive temperatures from the measured layers, and *h* is the height difference between the two layers.

2.4 Model Calibration

For the calibration, a variable is defined based on the root mean square errors (RMSE) method in order to achieve the lowest possible error between measured temperatures and simulation results. Such minimization will lead to calibrated simulation models. The objective function is written as:

$$f(x) = \sum_{m=1}^{M} \sqrt{(\frac{\sum_n(\hat{t}_n^{air} - t_n^{air})^2}{N})} + \sqrt{(\frac{\sum_n(\hat{t}_n^{surf} - t_n^{surf})^2}{N})} \tag{2}$$

Where $\hat{t}_n^{air}$ and t_n^{air} are the simulated and measured air temperatures in layer *m* (m defines the number of the layer in gradient, e.g., *m*=1 for the temperature at the height of 3m) and $\hat{t}_n^{surf}$ and t_n^{surf} are the surface temperatures of the ceiling panels from simulated and measured results.

The calibration process is written in the steps below:

- The temperature gradients generated, and then plotted together with the temperature gradients from the measurements to create a visual comparative chart.

- The temperature profiles from simulations then compared to the measured profiles. Using RMSE method, two variables are adjusted for calibration.

- The variables *Kfins* and the extra loss factor are adjusted in to minimize the RMSE formula. *Kfins* parameter has impact on surface temperature of the ceiling panels and by adjusting the *Kfins* parameter using RMSE method, the gap between simulated and measured temperature is reduced.

- The profiles with the minimum RMSE are called calibrated models in which *Kfins* and extra loss factor are closer to the real values in experiments.

- Those values then used in annual energy simulations

The cooling capacity parameters are calculated based on the power formula. The formula that is used for power calculations is as follow:

$$P = Kc \times LMTD^N \tag{3}$$

Where P is cooling power, Kc is power law coefficient for cooling, LMTD is the logarithmic mean temperature difference between the air temperature at the height of the panels, supply and return water temperature, and *N* is power law exponent.

- In the formula, the parameter N is used as the constant provided by the manufacturer, LMTD calculated based on the measured temperatures and cooling power is the average of Kc in LOW and HIGH cases calculated using the power formula based on measured values during the experiments.

In **Fig. 5** and **Fig. 6 t**here are temperature differences between different layers of the air temperature gradients when we compared the measured data to the simulation data, specifically on the layers close to the ceiling. That is due to the fact that IDA ICE 4.9.9 gradient temperature calculations are all based on horizontal layers using the so-called transient zonal model. [10] while the temperature sensors during the tests were in specific point that could have a different temperature than the average of the whole layer in that height.

2.5 Annual Energy Simulation

The parameters used in the simulations are according to EN 16798-1:2019 [8] that are listed below:

- The number of occupants sitting and working in the office is 1.81 (17 m^2/person), the equipment and lighting power are 12 W/m^2 and 6 W/m^2, respectively,

- Air Handling Unit (AHU) supplies air with a constant temperature of 20 °C,

- The office has a Constant Air Volume flow of 2 Litre per second per square meter during office hours (workdays 6 a.m. to 7 p.m.)

- There is no shading for the simulations,

- Windows will never open,

- The operative temperature set-point at the location of the occupant is 26°C, and since such set-points usually results in oversized cooling systems, 3% deviation from this during the cooling period was acceptable for the annual energy calculation.

The resulted cooling energy need from annual energy simulation using the ceiling panels then compared to the energy simulation using an ideal cooler with the same requirements (26°C operative temperature with 3% deviation) in order to identify what air temperature set point using ideal coolers should be used for the annual energy simulations instead of modelling the ceiling panels in details and such difference will be reported as a temperature increment. The emission efficiency of the ceiling panels then calculated by simulating the model with the same parameters using ceiling panels and ideal cooler. The resulted cooling energy usage using Ideal cooler then divided by energy usage of ceiling panels, to provide the emission efficiency of the ceiling panels.

The formula that is used for emission efficiency calculations is as follow:

$$\text{Efficiency} = \frac{E_{Ic}}{E_C} \tag{3}$$

Where E_C is the annual energy usage of the ceiling panels and E_{Ic} is the annual energy usage of the ideal cooler.

3. Results and discussion

3.1 Model Calibration

The temperature gradients from simulation results and test results for two LOW and HIGH cases are presented in **Fig. 5**. Qualitatively, the absolute values for the LOW case temperature profile is closer to the measurements compared to the HIGH case, while the main temperature difference in the upper layer has offset from the measured values in both cases. However, the shape of the temperature profiles was more similar to the measurements for the HIGH case, but there was an offset of 1.8°C. The absolute temperature of the lower layers fits quite well in the LOW case compared to the HIGH case. The reason for such difference in the upper layer between test measurements and the simulation results in both cases is the fact that the temperature sensors were located in the middle of the two coupled panels in the test, but in the simulation model, such location does not exist. The temperature of the surrounding area of the ceiling panels is lower than points further, resulting in lower temperatures measured in the real test, while IDA ICE 4.9.9 gradient temperature calculations are all based on horizontal layers using the so-called transient zonal model. [7]

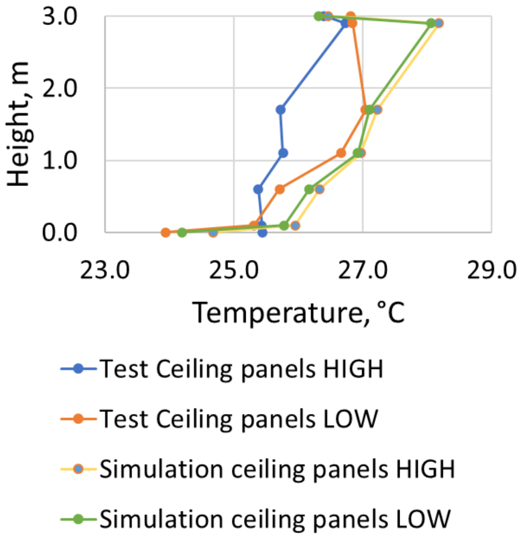

Fig. 5 - The temperature gradient in the test room from sensors measurements and simulation before calibration using MSE method.

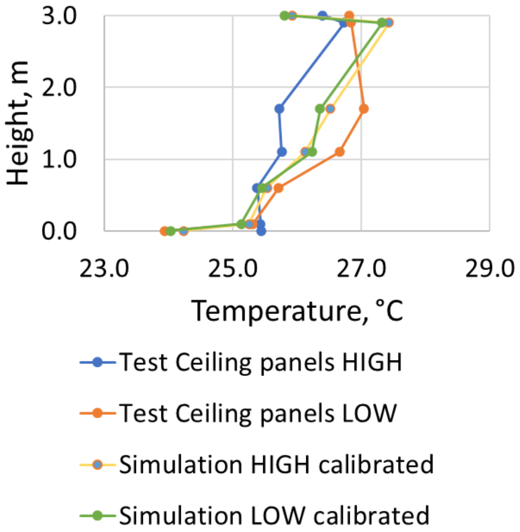

Fig. 6 - The temperature gradient in the test room from sensors measurements and simulation after calibration.

The calibration process using MSE resulted in extra heat loss from room boundary. The result of optimization process and the added heat loss is presented in **Fig. 7**. The temperature gradient profiles after calibration using RMSE method are presented in **Fig. 5** and **Fig. 6.** The calibration is done by minimizing the sum of the squared differences between each of the temperature data points in every height. The surface temperatures of the ceiling panels after calibration are also shown in **Fig. 9** . The surface temperature of the ceiling panel, which is connected to the chilled water input in the coupled system, is lower than the second panel. The measured values are from a point on the ceiling panels, while the simulation results are an average of the temperature on the whole panel. The thermal image of the panels **Fig. 8** shows that the temperature is different at different points of the panels, and such difference can be up to 1 degree.

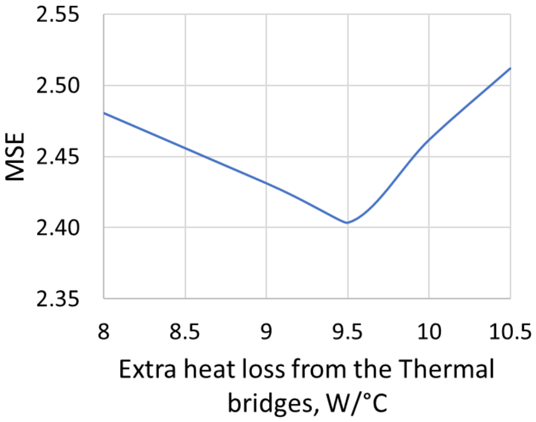

Fig. 7 - The Extra heat loss from thermal bridges resulted from optimization process using MSE.

The surface temperatures and resulting temperature in the height of 2.9m, which is important for cooling capacity and surface temperature calibration, can be summarized in **Fig. 9**. The temperature difference between the surface temperature and air temperature are close for both simulation and test results, while as it is demonstrated, the temperatures of the upper layer from the simulations are higher.

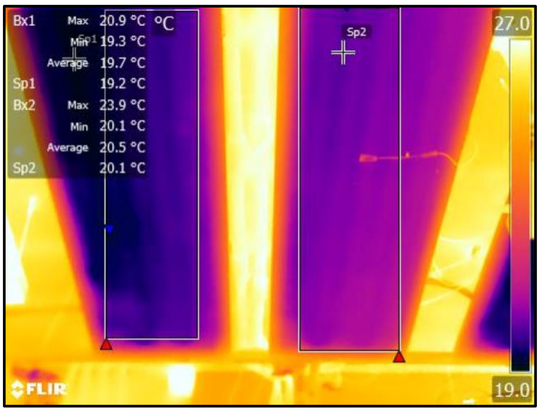

Fig. 8 - Thermal image of the ceiling panels, LOW case.

The *Kc* for each case calculated using the *N* parameter provided in manufacturers handbook (using the power calculation formula provided in the Methods part). The cooling power output of the eight ceiling panels from both LOW and HIGH cases is shown in **Fig. 10**. The *Kc* used in the simulations is the average of *Kc* from LOW and HIGH cases, together with *N* provided by the manufacturer. They both used to generate the Energy simulation results.

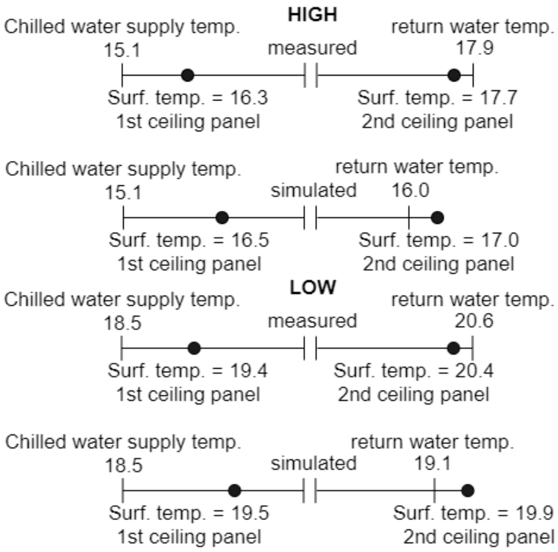

Fig. 9 – The graphical comparison for ceiling panels temperature and resulting air temperature between test results and simulation results.

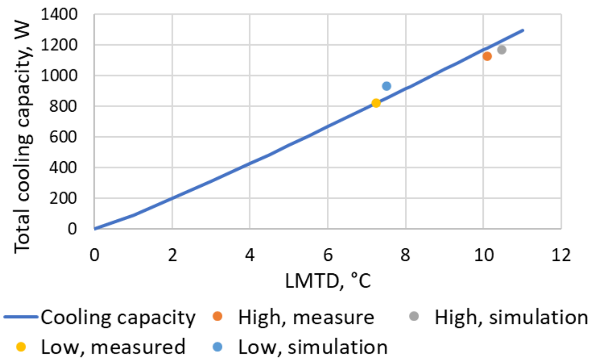

Fig. 10 – The average total cooling power for 8 ceiling panels measured from experiments and calculated in the simulations measured or expected average temperature difference between coolant and room air.

3.2 Annual Energy Simulation

The annual cooling energy use was simulated using two types of controls, PI controller and On/Off controller. The set-point has been adjusted for each type of controller. The adjusted set-points are shown in **Fig. 11**. The duration curves for temperatures from annual energy simulations are indicated in **Fig. 12** for each control strategy.

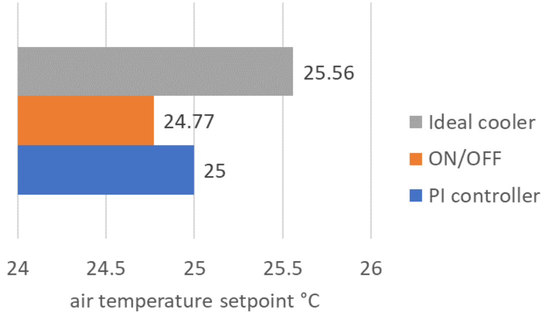

Fig. 11 – air temperature set-points to keep the operative temperature lower than 26 °C during 97% of the cooling period.

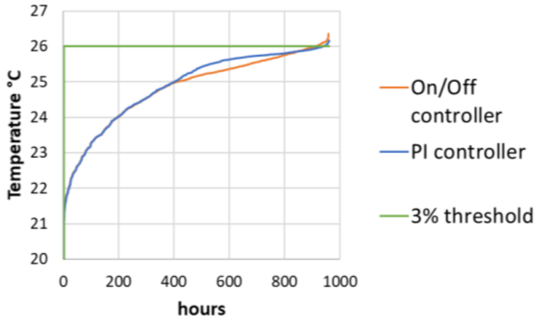

Fig. 12 – Duration curve for occupied hours during cooling months. PI controller and ON/OFF controller

The annual energy usage for each type of control system and their corresponding set-points in the chart of annual energy consumptions using the ideal cooler are shown in **Fig. 13**. As a result, the Total set point increment for the cooling ceiling panel with two different control systems are -0.79 for the ON/OFF controller and -0.56 for the PI controller.

In **Fig. 11**, we showed the resultant set-point rise in air temperature to keep the room at the appropriate operating temperature. This difference in temperature indicates the less energy necessary to overcome inaccurate indoor air stratification and the additional air temperature rise required to attain the desired operating temperature inside the space. This temperature increment is intended to be used in estimations and simulations of cooling energy use with ceiling panels on a monthly, annual, and hourly basis.

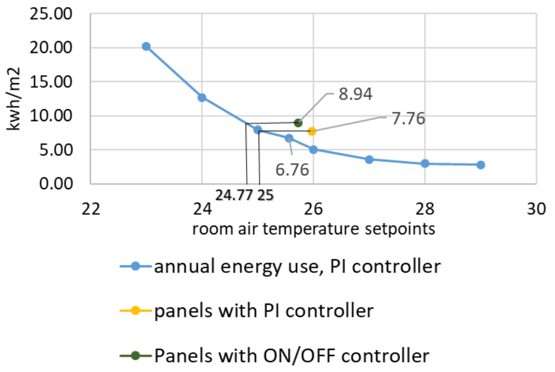

Fig. 13 – annual cooling energy usage curves resulted from simulations with ideal coolers and annual cooling energy usage points resulted from ceiling panels with different control systems.

The emission efficiency of the ceiling panels can be calculated from the annual cooling energy simulations using the ceiling panels and the ideal cooler. The annual energy results are derived from simulation and the emission efficiency can be calculated as follow:

$$\text{Efficiency, PI controller} = \frac{6.76}{7.76} = 87\%$$

$$\text{Efficiency, ON/OFF controller} = \frac{6.76}{8.94} = 76\%$$

3.3 Limitation and future work

The measurements conducted during autumn months between September and November, which are not the main cooling seasons in Estonia, but this timing helped us to reduce the impact of uncontrollable boundary conditions, e.g. solar gains. The internal heat gains were virtually applied using heating dummies and an electric radiator to simulate the real case scenario in summer. These loads are static, while the real internal heat gains vary by time, and therefore the system's inertia and the dynamic cooling loads' effects on the control parameters are not compared with simulation results. Further studies can be conducted to evaluate the possibility of using the room temperature set-point deviation for varying geometry, boundary conditions and control strategies.

In the future, such study can be conducted for other types of cooling systems. Furthermore, the measurements points can be increased to give us a better overview of the temperature gradients and average surface temperatures.

4. Conclusions

Annual energy usage and emission efficiency of ceiling panels for cooling using PI and ON/OFF controllers were assessed with IDA ICE building performance simulation software. The models were then compared to measurements carried out in the autumn of 2021 at the nZEB test facility at Tallinn University of Technology to reflect the accuracy of the building simulation model. The cooling capacity of the ceiling panels was then calibrated in models using actual values from the experiments, which were then used to investigate the energy performance of the systems with annual simulations with the Estonian test reference year and energy simulation input data for office buildings in EN 16798-1:2019.

During the calibration process the unknown values of Kfin and heat loss from the room's boundary were changed in order to have the minimum RMSE value for the temperature profiles measure from tests and calculated in the simulations. The IDA-ICE 4.9.9 [4] zonal model well reproduced the measured air temperatures at different heights in the test room.

The annual cooling energy need of the test room was compared with the same value obtained using an ideal cooler with 100% convective heat emission. Additionally, a single-value performance indicator in the form of an air temperature set-point deviation was obtained for the device and each configuration, as the result of this research, to be used in further hourly, monthly, or annual cooling energy usage calculations. Such increments for the ceiling panels are -0.79 for the ON/OFF controller and -0.56 for the PI controller. The imperfections in air stratification within the room (temperature gradient), the surface temperature of the panels, and additional temperature deviation from the set-point to achieve the desired operative temperature level are the effective parameters on the performance indicator.

Further analysis is needed to determine if room temperature set-point deviation can be applied for different cooling system devices and with varying room geometry, boundary conditions, and cooling control principles.

5. Acknowledgment

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