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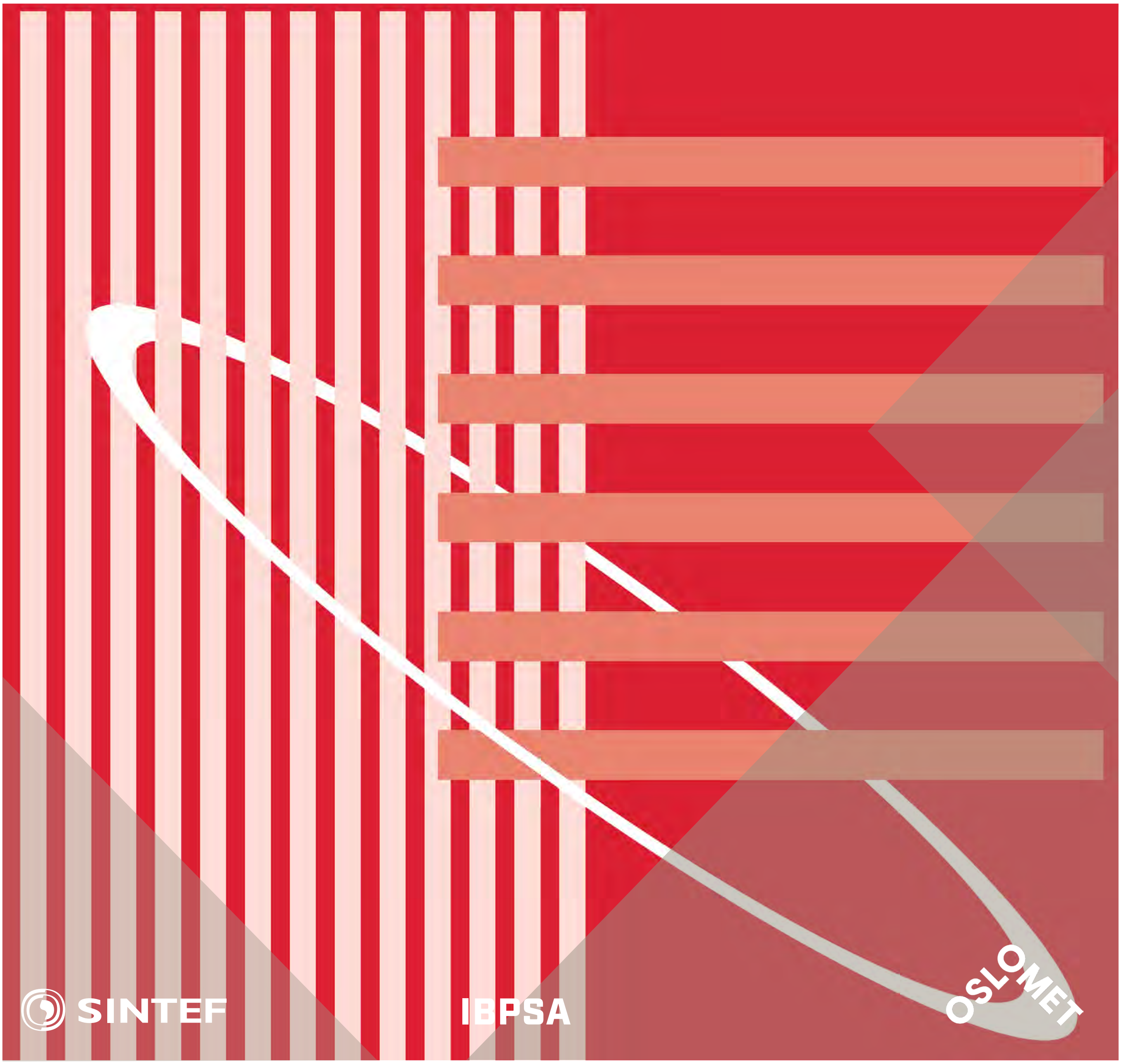

SINTEF Proceedings

Editors:
Laurent Georges, Matthias Haase, Vojislav Novakovic and Peter G. Schild

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Chilled water temperature control of self-regulating active chilled beams

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Abstract

The flow rate of chilled water in a self-regulating active chilled beam is constant without respect to the actual cooling load. The cooling capacity is instead determined by the room temperature, which gives rise to the self-regulating effect, and also by the centrally controlled chilled water temperature, which is the focus of this paper.

Previous studies have emphasized the benefit of avoiding room-level control equipment, but also highlighted the risk of overcooling with detrimental effects on thermal climate and energy demand. Overcooling may be avoided by supply temperature control, but strategies have not yet been studied in systems operating in cooling mode only.

Simulations are carried out with IDA ICE. The results show that overcooling is effectively avoided by proper control of the chilled water temperature. Desired thermal climate is achieved and the energy demand is in the same order of magnitude as in a system with individually and ideally PI-controlled active chilled beams.

Introduction

The International Energy Agency recently proclaimed the growth in global demand for space cooling as a blind spot of energy policy and one of the most critical energy issues of our time (IEA, 2018). While the global demand for other end-uses of energy in buildings (heating, lighting, cooking etc.) is expected to decline or plateau the coming decades, demand for cooling is expected to increase dramatically (IEA, 2017). Sustainable technologies of meeting this demand are consequently highly desirable.

Active chilled beams

Active chilled beams (ACB) are hydronic cooling equipment connected to the ventilation system and to a chilled water loop. The operation of a common type of ACB is illustrated in Figure 1. Primary air is provided from an air handling unit while chilled water is circulated through a cooling coil inside the ACB. The primary air enters the ACB via a pressure plenum and several nozzles along the beam. The high air velocity generated by the nozzles reduces the static pressure and induces room air (referred to as secondary air) which cools down as it passes the coil before it mixes with the primary air. The mixed air is then discharged into the room through slots along both long sides of the beam and attaches to the ceiling by means of the Coandă effect. The flow rate of secondary air divided by the flow rate of primary air is known as the induction ratio. The flow rate of chilled water is usually controlled as a function of the difference between the room air temperature and the cooling set-point temperature in order to match the cooling capacity with the actual cooling load. In addition, a dew-point control system is usually applied to make sure that the chilled water supply temperature is kept with a margin from the indoor air dew-point in order to avoid condensation forming on the coil surface.

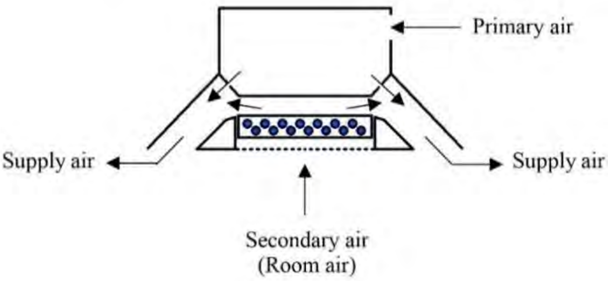

Figure 1: Schematic diagram of an active chilled beam

ACBs are suitable for using chilled water of relatively high temperature, henceforth referred to as high temperature cooling. This provides benefits such as increased use of free cooling, better performance of chillers, reduced risk of condensation (reduced latent load), reduced thermal losses in the chilled water distribution system and less need for individual room control. The latter is supported by a self-regulating effect originating from the fact that the cooling capacity is influenced by the room temperature. This is further discussed in the next section. Active beams may also be used for heating, either with a four-pipe system or a two-pipe system. Four-pipe systems allow versatile control of heating and cooling of each beam. Conventional two-pipe systems are operating either in cooling or heating mode, but innovative configurations with room air tempered water allow simultaneous heating and cooling also in two-pipe systems (Maccarini et al., 2017b).

Self-regulation

The cooling capacity of a comfort cooling system is affected by the room air temperature even if excluding the control system. As room air temperature increases, the driving temperature difference between room air and chilled water increases and consequently also the cooling capacity. As room air temperature decreases, the cooling capacity decreases and reach zero if the air temperature equals the chilled water temperature. In conventional systems, this effect is not enough to maintain the desired thermal climate and a control system is required. With ACBs, it is usually the flow rate of chilled water that is controlled. If designing for a very small temperature difference (i.e. high chilled water temperature), even small changes in air temperature will have large counteracting influence on the cooling capacity, and the conventional control system becomes redundant. The self-regulating effect is often referred to when studying thermally activated building systems (TABS) but has also been emphasized by several researchers investigating ACB systems (Brister, 1995; Henderson et al., 2003; Schultz, 2007; Ruponen et al., 2010; Kosonen & Penttinen, 2017; Maccarini et al., 2017b). The simplicity, robustness and cost-savings of avoiding thermostats, control valves and actuators are the main drivers for designing completely self-regulating systems. The drawbacks are the risk of overcooling, increased circulation pump work and less flexible regarding individual room temperature control.

During operation, the flow rate of chilled water in a self-regulating system is constant. The chilled water supply temperature is equal throughout the system, but may be controlled centrally. Accordingly, pure spatial differences (between locations) in cooling load may be taken care of by having different design cooling capacities while pure temporal variations (over time) may be taken care of by controlling the supply chilled water temperature centrally. The remaining obstacle, the combination of both types (spatiotemporal variations), are up to the self-regulating effect of the system to control. As a consequence, indoor temperature variability is an inherent feature of self-regulating systems. This is in contrast with conventionally controlled systems, which are theoretically able to keep the indoor temperature constant in multiple rooms with different heat gain profiles.

Self-regulating ACB systems have notable similarities as well as differences with TABS. Both systems operate with a small driving temperature difference, implying a strong self-regulating effect and high sensitivity to changes in the chilled water supply temperature. However, the main challenge of control of TABS is the integration with the thermal mass of the building and the associated slow response time. This challenge has attracted a lot of research on developing control strategies of TABS. A comprehensive review of this was presented by Romani et al. (2016). In TABS control strategies, the controlled variables are the supply temperature and the flow rate of chilled water. The most common controlling parameter is the outdoor air temperature and sometimes also with indoor air temperature feedback. In most cases, the instantaneous outdoor air temperature is used. In other cases, the average of the previous hours or the average of the predicted hours is used as input to the controller (Romani et al., 2016).

Previous work on self-regulating active chilled beams

Previous research on self-regulating active beams includes both studies based on simulations and studies based on measurements. Furthermore, it includes active beams for both heating and cooling as well as for cooling only. Kosonen & Penttinen (2017) presented a simulation based study investigating the energy consumption of active beam systems in cold climate. The active beams were used for both heating and cooling, the supply temperature was controlled between 20 °C (cooling mode) and 22 °C (heating mode) in order to keep the indoor air temperature within 21-25 °C. Too low indoor air temperatures during low occupancy outside of the summer season were observed. The authors suggested that this could be avoided by compromising the simplicity of self-regulation by the use of zonal-level control valves. Ruponen et al. (2010) presented simulations comparing a conventional low temperature ACB system with a high temperature ACB system and a self-regulating high temperature ACB system. The main reason for using a high temperature system was to reduce the need for dehumidification of supply air without risk of condensation. The main reason for self-regulation was the simplicity, reliability and reduced need for maintenance. A constant chilled water supply temperature of 20 °C was used in the high temperature systems. This caused excessive cooling which was compensated for by also using more heating. As a solution, the authors called for future research on control of the chilled water supply temperature. Maccarini et al. (2017a) compared different control strategies for active beam systems used for both heating and cooling. With all strategies, the water supply temperature was controlled within 20-23 °C and kept the indoor air temperatures within 20-24 °C. Following four strategies of controlling the supply temperatures were investigated. First, as a function of the outdoor air temperature. Second, as a function of the exhaust air temperature. Third, with respect to the maximum and minimum room air temperatures. As long as these were within the cooling/heating set-points, the supply water temperature equaled the return water temperature. The fourth and final strategy was as a function of the outdoor air temperature (as in the first strategy). In addition, the flow rate was reduced on system level (proportional in each beam) with respect to the maximum and minimum room air temperatures (as in the third strategy). Regarding energy performance, no significant difference was noticed neither between the first and second nor between the third and the fourth strategy. Strategy three and four required 7-10 % less energy than strategy one and two, but on the other hand, they also required measurements of air temperature in each room of the building as input to the controller.

Controlling the supply water temperature as a function of the outdoor air temperature has also been included in studies of measurements in real buildings. Maccarini et al. (2019) investigated a self-regulating active beam system used for both heating and cooling. Supply water temperature was controlled within 20-23 °C, indoor air temperatures were measured at two positions during a summer day and a winter day and it was concluded that the system was able to provide good thermal conditions (21.0-23.2 °C). Filipsson et al. (2020a) presented the operation and performance of a self-regulating ACB system where heating was provided from a separate radiator system. The ACBs were supplied chilled water of 20.0-21.5 °C controlled as a function of the outdoor air temperature. Indoor air temperatures in the open-plan offices were measured all the year round in 37 positions. It was concluded that the indoor air temperatures were both uniform and stable. The average was 22.3 °C annually and 22.6 °C during summer. The authors called for adjusted control of the chilled water temperature as a way to obtain larger differences between summer and winter, which is suggested by applicable standards and guidelines (CEN, 2019).

Objective

The objective of the work presented in this paper is to compare different strategies of controlling the chilled water supply temperature of a self-regulating active chilled beam system. These are compared with respect to energy use and indoor operative temperature.

Method

The work presented in this paper is based on simulations carried out in the building performance simulation software IDA ICE (EQUA Simulation AB, 2018). IDA ICE has been validated in several research projects, both by measurements (Loutzenhiser et al., 2007) and by inter-model comparison through ANSI/ASHRAE Standard 140-2004 (EQUA Simulation AB, 2010).

The building

The model consisted of one floor of an office building with location and climate representing Stockholm, Sweden. The total area of the simulated office floor was 600 m^2 (20 x 30 m) whereof 500 m^2 was open-plan offices, two meeting rooms of 25 m^2 each and one larger meeting room of 50 m^2. During working hours, the doors to the meeting rooms were open for 15 minutes every two hours. During nights and weekends, they were open at all times. The open-plan office was divided into five separate zones in order to model spatial differences in this area. The eight zones in total are illustrated in Figure 2.

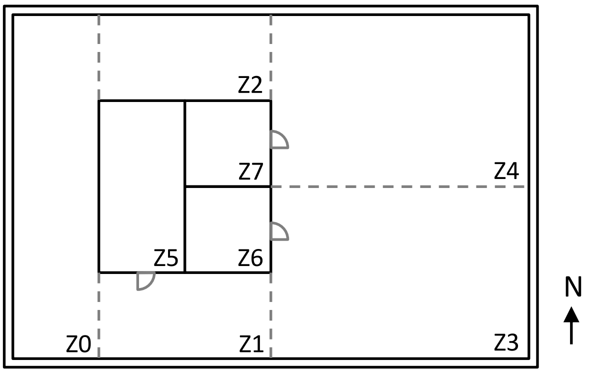

Figure 2: Plan view of the modelled office floor.

Exterior walls consisted of 20 cm light insulation covered by concrete, 22 cm on the inside and 7.5 cm on the outside. Interior walls consisted of 3 cm light insulation between air gaps of 3.2 cm and plasterboards of 2.6 cm on each side. Windows with a g-value of 0.5 and a U-value of 1.2 W/m^{2}K covered 32 % of each façade. Internal blinds, reducing the g-value by 35 %, were drawn when solar radiation exceeded 100 W/m^2. Horizontal shading was represented by surrounding buildings of the same height as the modelled building at a distance of 10 m.

The floor consisted of 0.5 cm floor coating on top of 2 cm lightweight concrete and 15 cm concrete. A suspended ceiling of 3 cm light insulation material was located 50 cm beneath the concrete roof. The volume between the suspended ceiling and the concrete roof was modelled as separate zones.

Surface area of furniture was 1.8 m^2 per m^2 floor area. Material properties of furniture were in accordance to what Johra et al. (2017) specifies as equivalent indoor content material. The furniture was interacting with the energy balance only by convection while its influence on radiation was not taken into account.

The internal heat gain

Levels and schedules of internal heat gain were modelled as declared in Figure 3. Heat gain represented by the white area was included when sizing the ACB system but not when simulating the full-year operation. The reason was to take into account that the actual use of a building differs from the design conditions.

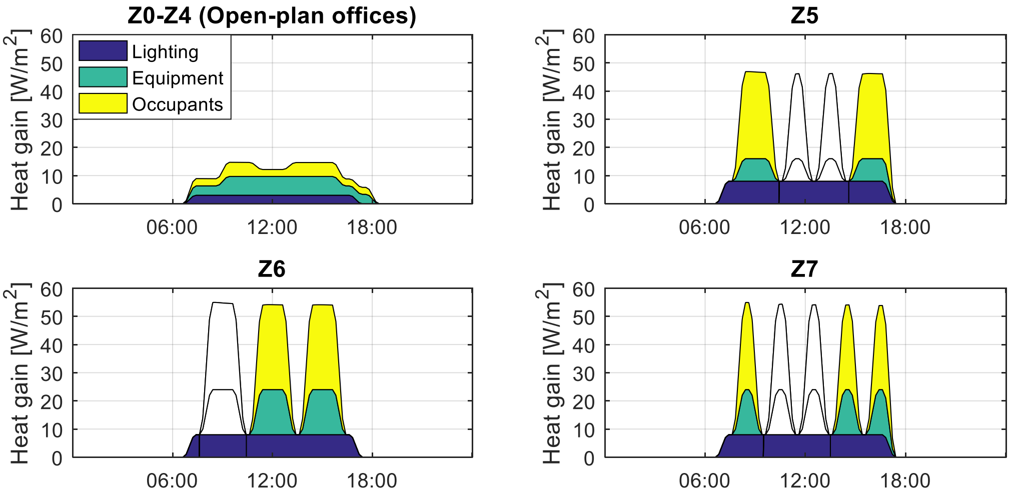

Figure 3: Internal heat gain (white area was included only when sizing the ACBs and not in subsequent simulations).

The HVAC system

Two modifications were made to the default ACB model in IDA ICE. First, the induction ratio of the ACBs was taken into account when determining internal convective heat transfer in the zones. An induction ratio of five was used. Second, the convective heat transfer at the ceiling was determined by the supply air temperature, in contrast to the other surfaces where it was determined by the zone/exhaust air temperature. These modifications were supported by the results presented in a previous paper (Filipsson et al., 2020b).

Ventilation air flow rate of 1.50 l/sm^2 was in operation between 06:00 and 19:00. The primary air temperature was 20.0 °C when outdoor air temperature exceeded 10 °C, 21.0 °C when outdoor air temperature was below -10 °C and linearly interpolated in between. During June-August, the ventilation was turned on at 4:00 on Mondays in order to purge excess heat accumulated during the weekend. Chilled water flow and ventilation were interlocked, hence no cooling from the ACB system when the ventilation was not in operation. For reasons of indoor air quality, meeting rooms were supplied additional ventilation air flow when occupied. This additional air flow was 1.65 l/sm^2 and supplied through a separate supply air device by-passing the ACBs.

The relatively high temperature of chilled water allowed using the chilled water loop to preheat the incoming outdoor air. This was utilized as long as there was a heating demand of supply air, a cooling demand in the chilled water loop and the outdoor air temperature was at least 3 °C lower than the chilled water supply set-point. Henceforth, this is referred to as free cooling from AHU. Due to the constant flow of chilled water close to room air temperature, some ACBs occasionally provided heating instead of cooling. This implied an internal transfer of heat between zones and is henceforth referred to as free internal cooling.

Heating was supplied through hydronic radiators. These were P-controlled with respect to the indoor air temperature with a proportional band of 1.0 °C (20.5-21.5 °C). The temperature transfer efficiency of the exhaust air recovery unit was 80 %, both in heating and cooling mode. A schematic illustration of the HVAC system is presented in Figure 4.

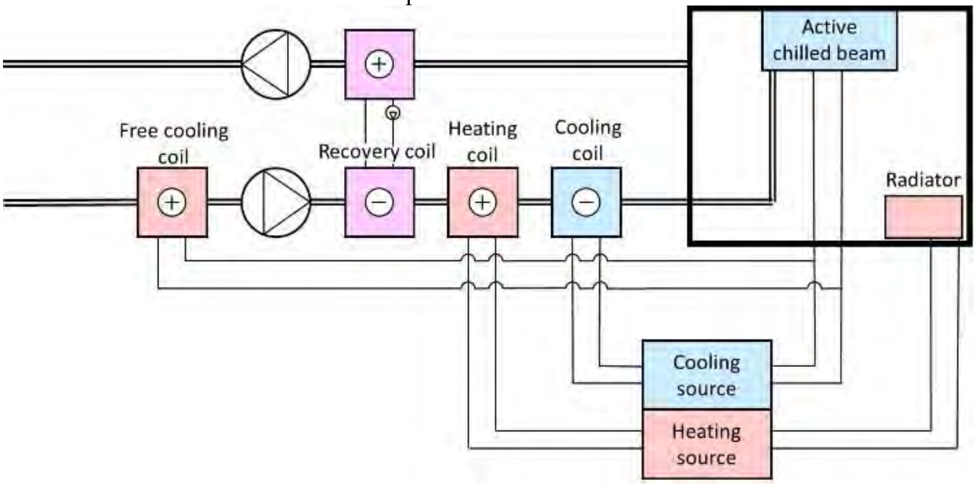

Figure 4: Schematic illustration of the HVAC system

The sources of heating and cooling are generic in this study. In reality, they could be district heating/cooling, heat pump/chiller etc.

The control strategies

The investigated control strategies are listed in Table 1. Regardless of strategy, the chilled water supply temperature was limited to be as least 20 °C.

Table 1: List of included control strategies.

Name	Chilled water supply temperature	Chilled water flow rate
CON20	20 °C	Constant
OA1021	$f(t_{oa})$	Constant
OA1522	$f(t_{oa})$	Constant
EA24	$f(t_{ea})$	Constant
TOP25	$f(\max(t_{op,z}))$	Constant
PI23	20 °C	$f(t_{a,z})$
PI24	20 °C	$f(t_{a,z})$

In Table 1, t_{oa} is the outdoor air temperature, t_{ea} is the exhaust air temperature, $t_{op,z}$ and $t_{a,z}$ is the operative temperature and air temperature in each zone. In strategy CON20, the chilled water supply temperature was constant at 20 °C which means that it provided as much cooling as possible. In contrast, strategy TOP25 aimed at keeping the maximum operative temperature at 25.0 °C, which can be seen as keeping the provided cooling to a minimum. Strategies OA1021 and OA1522 controlled the chilled water supply temperatures as functions of the outdoor air temperature. These functions are presented in Figure 5.

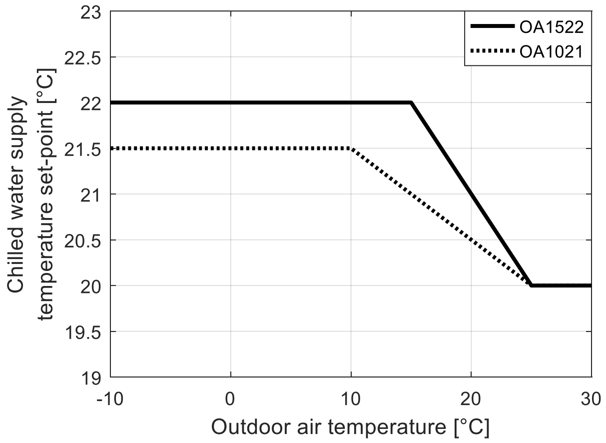

Figure 5: Chilled water supply temperatures as functions of the outdoor air temperature.

In strategy EA24, the chilled water supply temperature was controlled with respect to the exhaust air temperature. The control was aiming for a constant exhaust air temperature of 24 °C.

Strategies PI23 and PI24 were not self-regulating. These had ACBs individually controlled in each zone and the chilled water flow rates were PI-controlled with room air temperature set-points of 23.0 °C and 24.0 °C respectively.

The design cooling capacity of the ACBs was equal in all investigated control strategies. They were sized to obtain a maximum operative temperature of 25.0 °C when using the strategy of a constant supply chilled water temperature at 20 °C (CON20) and design heat gain schedule according to Figure 3.

Results

The results are divided into two parts. The first part is about the energy demand and the second part is about the thermal climate.

Energy

The annual amounts of energy delivered from the cooling and heating sources (see Figure 4) are presented in Figure 6. Energy required for coil cooling is relatively small and very similar in all strategies. The cooling recovery system is the reason why they are not totally equal, since strategies causing low indoor air temperatures require less coil cooling thanks to the recovery coil. Energy required by the heating coil differs slightly more between the strategies. Differences are partly explained by the heat recovery system but to a larger extent by the operation of the free cooling coil. Strategies better able to utilize the free cooling require less energy for the heating coil. This applies to strategies with low chilled water temperature coinciding with low outdoor air temperature (especially CON20). On the other hand, these strategies require more energy for radiator heating since this causes simultaneous and opposing radiator heating and ACB cooling. This unfortunate situation is especially obvious when looking at the radiator heat demand. It also requires excessive use of ACB cooling, but due to utilization of the free cooling coil, this is less detrimental.

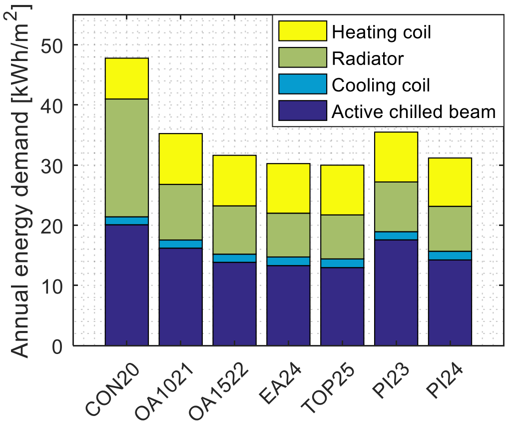

Figure 6: Demand for heating and cooling with each control strategy.

In Figure 6, the cooling energy required by the ACB system included only the part delivered from the cooling source. In Figure 7, the part delivered from the free cooling coil and from cold to warm zones is presented.

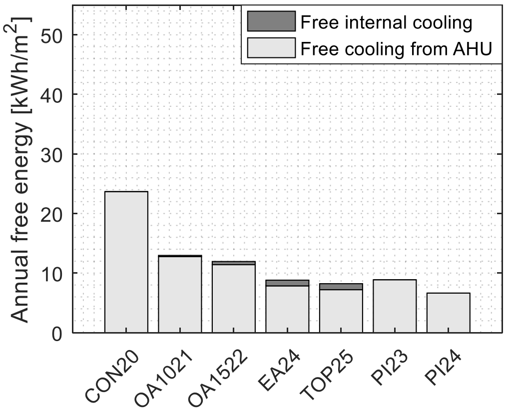

Figure 7: Cooling from cold zones (free internal cooling) and from the supply air (free AHU cooling).

The free internal cooling relies on spatial variability in indoor air temperatures. The free internal cooling happens primarily during winter when the meeting rooms are cooled by the chilled water at the same time as the open-plan offices are heated by the chilled water. Since the cooling source it unable to provide heating, the chilled water temperature do not always reach its set-point. In Figure 8, both set-point and the actual chilled water supply temperature of strategy OA1522 is presented. As seen, during times of low outdoor air temperature, the water is chilled by the indoor air, hence are actual values lower than the set-point.

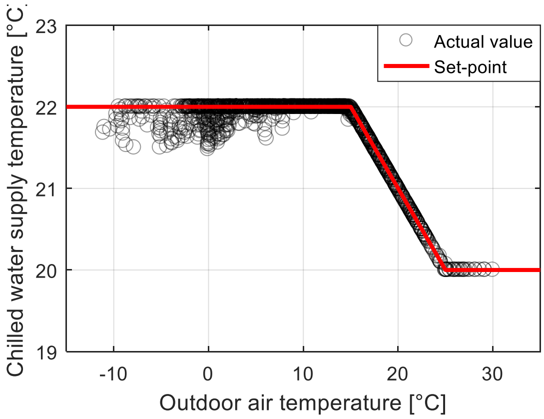

Figure 8: Chilled water supply temperature in OA1522

Thermal climate

The operative temperatures of all zones in the open-plan offices during weekdays 08:00-17:00 in a winter week, a spring week and a summer week are presented in Figure 9. The boxplot illustrates the minimum, maximum, median and the interquartile range. During operation of the HVAC-system in the summer week, the outdoor air temperature varied between 12 and 31 °C. Corresponding range was between 6 and 18 °C during the spring week and between -11 and -4 °C during the winter week. The green lines in the figure refer to the default indoor temperature ranges (for buildings with a normal level of expectation) suggested by standard EN 16798-1:2019 (CEN, 2019) to be used for energy calculations. These are based on the concept of predicted mean vote and correspond to an activity level of 1.2 met, winter clothing of 1.0 clo and summer clothing of 0.5 clo. The standard does not suggest temperature ranges to be used during spring and autumn.

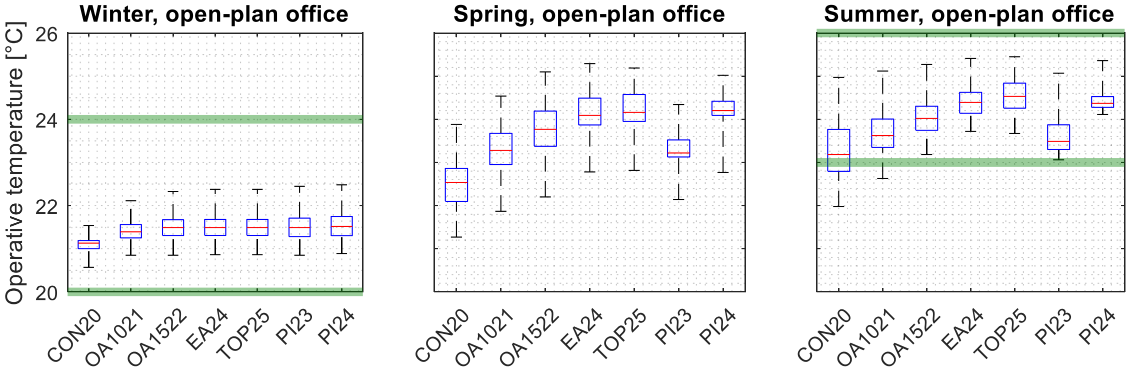

Figure 9: Operative temperature in the open-plan offices during a winter/spring/summer week.

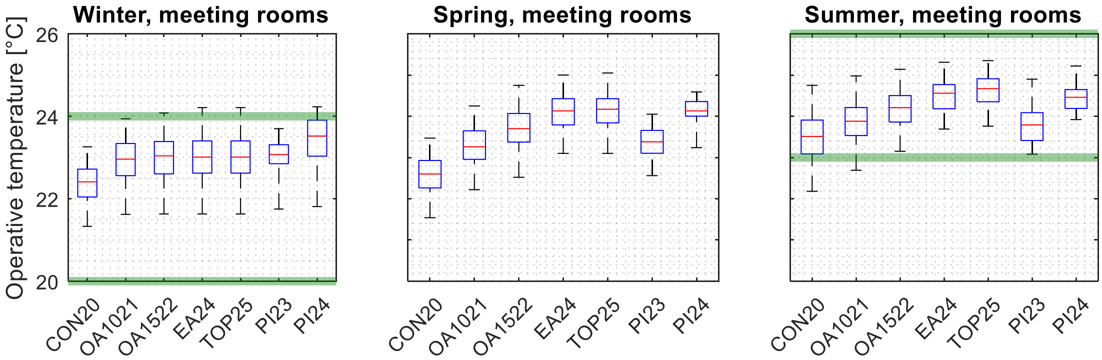

Figure 10: Operative temperature in the meeting rooms during a winter/spring/summer week.

As seen in Figure 9, CON20 is always keeping temperatures lower than any other strategy. Higher operative temperatures (during spring and summer) are associated with lower energy use (see Figure 6). Compared to TOP25, OA1021 implies around 0.9 °C lower operative temperatures during spring and summer, and requires 17 % more energy for heating and cooling. The results of EA24 are very similar to TOP25. EA24 gives slightly lower operative temperatures during spring and summer, and also slightly higher energy use. The non-self-regulating strategies, PI23 and PI24, generally keep the temperature within a narrower range than the self-regulating strategies, especially PI24 during the summer week.

The operative temperatures in the meeting rooms during weekdays 08:00-17:00 in the winter week, the spring week and the summer week are presented in *Figure 10*.

The main difference from the open-plan offices is that the seasonal variations are much less pronounced in the meeting rooms, as a consequence of not being exposed to the exterior walls. Furthermore, during the winter week, the operative temperature is both considerably higher and more variable in the meeting rooms.

Discussion

Self-regulation implies that the flow rate of chilled water is constant without respect to the actual cooling load. Inherent features of such operation are indoor temperature variability and a risk of overcooling. Overcooling and too low room temperatures have been reported in previous studies of self-regulating ACBs (Ruponen et al., 2010) and also of self-regulating active beams used for both heating and cooling (Kosonen & Penttinen, 2017). Indicated by the results of the present study, excessive use of energy may effectively be avoided by controlling the chilled water supply temperature. Most importantly, the chilled water supply temperature should exceed the heating set-point during the heating season. Even though free cooling is supplied to the ACBs, simultaneous operation of radiators and ACBs causes excessive use of energy for heating.

In the investigated strategies in general, there was a trade-off between low energy demand and low temperatures during summer, spring and autumn. Regarding the energy demand, differences between self-regulating and non-self-regulating strategies were not larger than the difference between having a cooling set-point of 24 °C and 23 °C in a conventionally controlled system.

Strategy TOP25 requires measurements of the operative temperature in each zone as input to the controller and is therefore not a very practical option. The non-self-regulating strategies PI23 and PI24 require the indoor air temperature to be measured in each zone plus thermostats, control valves and actuators for the control of flow of chilled water in each ACB. On the other hand, these require slightly less electricity for the circulation pump. It shall be noted that PI23 and PI24 were ideal controllers modulating the flow rate of chilled water. In conventional systems in reality, simple on/off-control is much more common, hence less able to keep the indoor temperature within such a tight range.

Strategy OA1522 and EA24 both implied low energy use and acceptable thermal climate. EA24 required less energy, but on the other hand, also slightly high temperature in the meeting rooms during the winter week. This may be avoided by decreasing the exhaust air temperature set-point during winter. However, this increases the risk of simultaneous heating and cooling in the open-plan office.

Control of the heating system was made with P-control with respect to the room air temperature and a proportional band of 1.0 °C (20.5-21.5 °C). A wider band or a higher heating set-point would increase the occurrence of simultaneous heating and cooling.

For reasons of indoor air quality, the meeting rooms were supplied additional air flow during occupancy. Since the primary air temperature is lower than the room air temperature, this provides cooling and supports the stability of the indoor temperatures. Absence of this additional air flow would require larger ACBs in order to meet the design criterion. These ACBs would to a larger extent provide cooling also when the meeting rooms were unoccupied, hence causing larger temperature variability. Another factor that helps the self-regulation is the openings of doors to the meeting rooms. Less door openings would cause larger differences between the open-plan offices and the meeting rooms which would cause uncomfortably high temperature in the meeting rooms during the winter week.

All results presented are valid under the specific conditions of this study and should not be generalized without caution.

Conclusions

Under the conditions and assumptions made in this study, self-regulating active chilled beams are able to provide desired thermal climate without using more energy for cooling and heating than a conventional system with individually controlled active chilled beams. Controlling the chilled water supply temperature as a function of the temperature of outdoor air or exhaust air are two feasible options with similar results. Although associated with higher variability, self-regulating active chilled beams are able to keep the operative temperature within comfortable limits.

Acknowledgement

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