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Publication Date
2018-07-22

Reducing building over-cooling by adjusting HVAC supply airflow setpoints and providing personal comfort systems

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SUMMARY
Over-cooling happens commonly in air-conditioned buildings that costs energy and results in discomfort complaints. There are many reasons causing overcooling, and HVAC engineers and researchers have proposed several approaches to prevent it from happening. In this paper, we describe a field study to show how the overcooling and energy use were significantly reduced by lowering maximum and minimum supply air flowrate setpoints, while providing personal comfort systems for occupants. The study was conducted over 16 months in two office spaces of a campus building with high HVAC energy expenditure and frequent cold complaints. The initial visit and measurements showed that the spaces were over-ventilated, causing cold discomfort in several workstations. We provided personal comfort systems to 26 occupants (heated/cooled chair, footwarmer, legwarmer based on occupants' own choices) to maintain comfort, and gradually reduced the maximum and minimum supply air volume setpoints, to reduce the air-conditioning intensity and to let the office ambient temperature float. We increased occupants' satisfaction rate from 56% to over 80%, meanwhile lowered HVAC zone energy use by 60% in heating and 40% in cooling.

1 INTRODUCTION

Complaints on over-cooling are common in modern buildings, from shopping malls to office buildings to public transit, from U.S. (Mendell and Mirer, 2009) to Australia (Cena and de Dear, 2001) to tropical zones like Singapore and Hong Kong. The narrow temperature setpoint range of current practice is eliminating warm temperatures, often leaving indoor temperatures cooler in summer than in winter. Not surprisingly, news articles entitled "Enduring summer's deep freeze" (Murphy, 2015), "Air conditioning in your office is sexist" (Sanghani, 2015), "Why your office is freezing in the summer" (Ferro 2016), etc. grasped the public's attention (Fred – should we remove these sentences?). In fact, over-cooling is not just a thermal comfort problem but is also accompanied with excessive energy use and productivity performance loss. For example, a recent study reported that the energy waste related to over-cooling in U.S. commercial buildings could reach up to 8% of its total energy usage (Derrible and Reeder, 2015). Other productivity studies also showed that people worked less and made more mistakes when they were in cold or cool temperatures compared with a thermally neutral environment (Lan et al., 2011; Seppänen et al., 2006).

There are many reasons causing overcooling. Oversized HVAC systems, high maximum and minimum airflow rate, setpoints, and narrow temperature deadbands are among them. A large-scale field study conducted in several buildings by Arens et al. (2015) showed that when the minimum flowrates were reduced from 30% to 10%, the dissatisfaction rate found under high minimum operation was reduced by 47% in summer. Typical savings are on the order of 10-30% of total HVAC energy. Taylor et al. (2012) provided a summary of dual maximum control and VAV box sizing, to explain how to control the flowrate accuracy when it is

operated under low minimum flowrate. Kaam et al. (2017) proposed a time-averaged ventilation control strategy to maintain a low minimum flowrate. The objective of the present study is to evaluate comfort and energy saving results by reducing both maximum and minimum air flowrates and by providing PCS to maintain occupant thermal comfort. Full details of the field study are provided by Bauman et al. (2015).

2 METHODS

The investigated subjects are located in two floor areas of a modern building, approximately 180 m^2 each; 16 people on the second floor, among them 5 in private offices; 10 occupants on the second floor, all in private offices. When we first arrived, we found that the implemented control sequences in the zones were causing regular fluctuations between heating and cooling on a 2- to 3-hour cycle. When the system switched from heating to cooling, this coincided with an increase in supply airflow rate up to its maximum setpoint value. The combination of the coldest supply air temperature with the highest airflow rate is likely one of the primary causes for the cold discomfort reported by the occupants. Before re-setting the maximum and minimum airflow setpoints, PCSs were delivered to the 24 subjects to ensure their thermal comfort. Each subject was allowed to select a single piece of his or her favorite PCS equipment. In total, 18 heated and cooled chairs, 4 leg warmers, and 4 feet warmers were chosen.

Figure 1. Participants with PCS equipment installed

After delivering PCSs, the minimum and maximum airflows of VAV terminals were reduced sequentially. We first reduced the third floor minimum flowrate setpoint, then reduced the maximum airflows in two steps, and eventually it equaled to the minimum airflow rate level (Figure 2). After reducing the supply airflows on the third floor, the room temperatures were actively monitored to see whether comfort conditions could be maintained. When comfort conditions were guaranteed, the air volumes on the second floor were also reduced. The airflow reduction sequences are presented in Figure 2. At the end, the minimum airflow rate was reduced to about 60% of the original values on the 3rd floor, and 50% on the 2nd floor. The maximum airflow rate was reduced to about 40% of the original values on both floors.

In addition to airflow reduction, the room set-point temperatures were also lowered in cold season (Nov. 2014 to Jan. 2015) to examine the PCS's improvements on thermal comfort and heating energy savings potential. The temperature decreased 0.56°C (1°F) each two weeks until they were 2.78°C (5°F) lower than the initial condition over a two-month period (Figure 2).

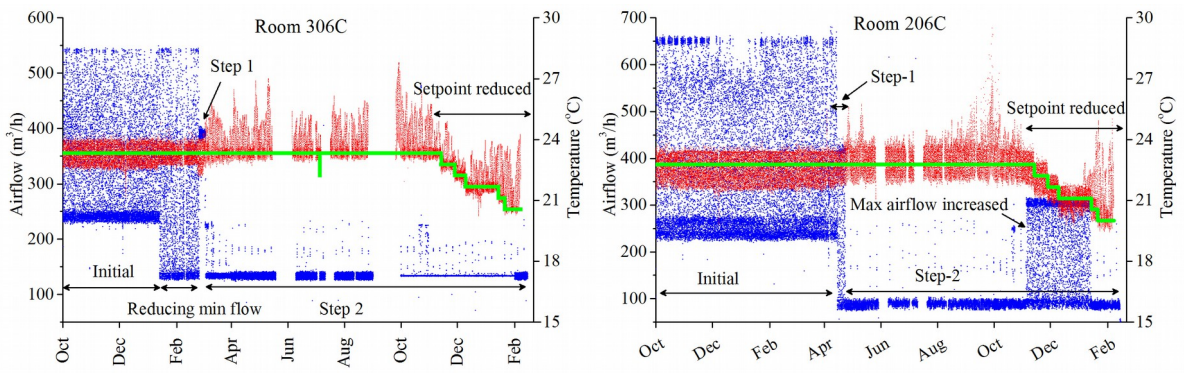

Figure 2. Airflow and temperature changes in two rooms of the two floors. X-axis represents the date, and Y-axis represents the flowrate (primary) and air temperature (secondary). Blue lines: the maximum and minimum flowrate reduction; Green lines: temperature setpoint reduction in winter; Red lines: actual ambient temperature. It fluctuates more after the flowrate reductions, and became warmer on the third floor, where the cold complaints are the highest.

We surveyed the occupants' thermal comfort during each of the phases when the ventilation rates and temperature setpoints were changed, including a reference case before any changes were made for the flow rate and before PCSs were delivered. The power use of plug load equipment including PCS was measured by wireless power monitors. The supply air temperature and airflow rates from ceiling air diffusers were also recorded.

3 RESULTS

Thermal comfort satisfaction. Figure shows occupants' subjective perceptions for each survey period. The first two boxes compared situations with and without PCS with nothing else changed: the pink box represents the initial condition without PCS and was regarded as the baseline (marked "Pre" in the figure), the yellow one is with PCS (marked "Post" in the figure). The PCS increased the baseline acceptability (middle figure) rate from 56% to 77%. Occupants' thermal sensation was between neutral and slightly cool, and the PCS raised the thermal sensation toward warm, but the averages were similar (top figure). The 5 green boxes represent warm condition surveys in summer season after reducing VAV airflows. As temperature increased due to reduced ventilation rate, occupants' thermal sensation shifted from the cool side towards neutral and the warm side. The thermal acceptance lifted from 56% to around 80%. The overcooling discomfort was reduced. The 5 blue boxes show the survey results in winter season when the ambient temperature was reduced by 0.56°C to 2.8°C. As the ambient temperature became cooler, occupants' thermal sensation lowered again to the cool side. The levels of cool sensation were similar to or lower than the level under the baseline condition, close to "slightly cool", however, the acceptability (with the PCS in place) was much higher than the baseline condition.

The perceived air quality was all significantly improved compared with the baseline condition, especially when the temperature setpoint was lowered in winter season (blue boxes in bottom figure).

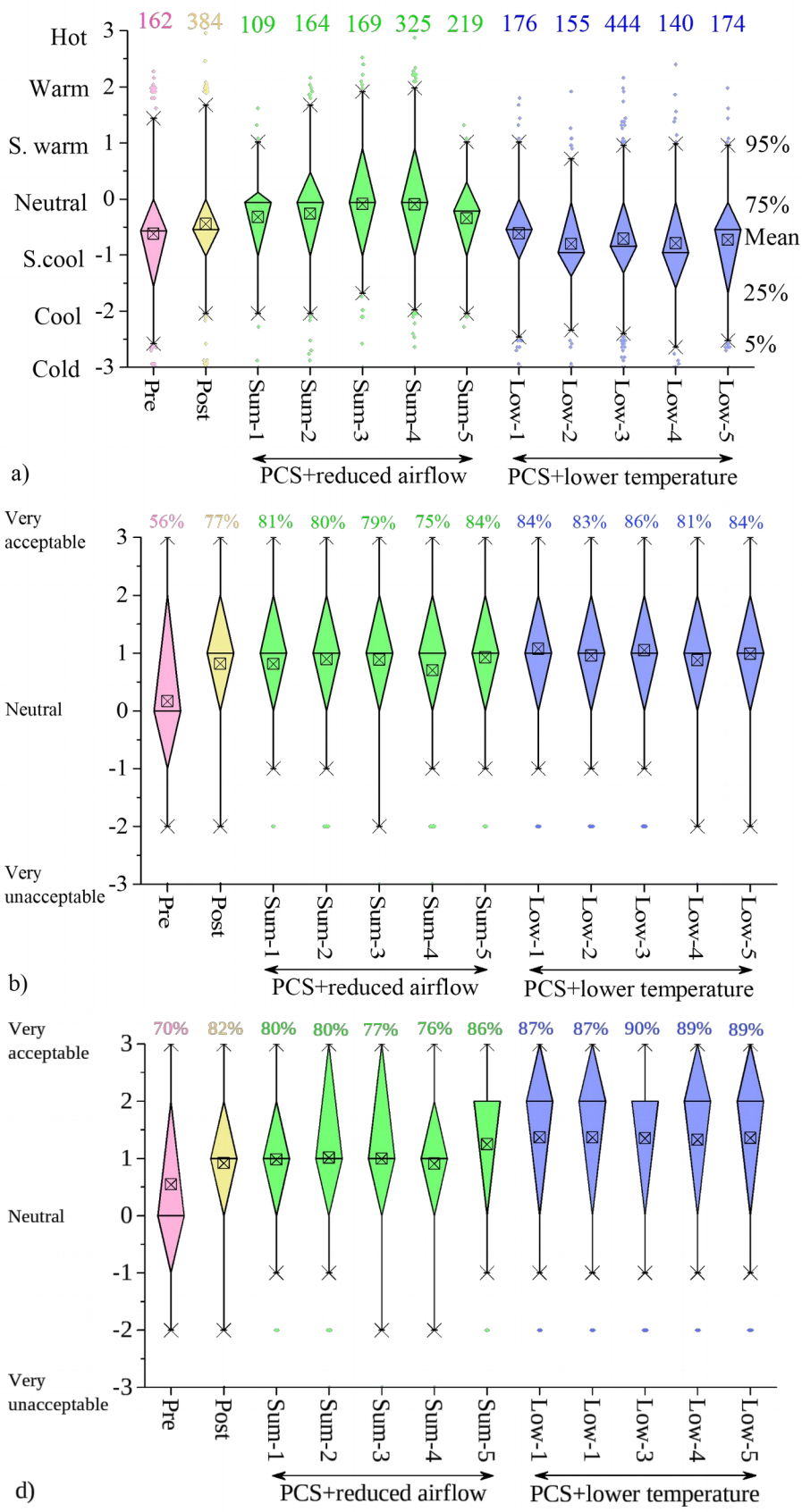

Figure 3. Occupants' satisfaction surveys - thermal sensation (top), acceptance (middle), perceived air quality (bottom)

Figure 4 binned the thermal sensation (top figure) and acceptance (bottom figure) based on the indoor ambient temperatures across the entire study period. In the top figure, the black filled circles represent the initial condition without PCS (pre), which had colder thermal sensation, and accompanied by low acceptance ratio (50%-68%) in temperature range from 21.9ºC to 24ºC. The other dots show the cases with PCS (post, open circle), summer condition (green triangles) after the flowrates were reduced, and the winter condition with both flowrate and ambient temperature setpoints (purple * lowered room temperature). Once PCS was introduced, occupants' thermal sensation was closer to thermally neutral. The comfort acceptance rate was significantly higher with PCS (open circle) than without (filled circle), at the same indoor ambient temperature (bottom figure). When the indoor temperature exceeded 25ºC, the acceptance rate with PCS also reduced lower than 80%. It seems that the PCS can provide 80% occupant satisfaction between 20°C and 25°C as measured. No room temperatures below 20°C occurred during the study.

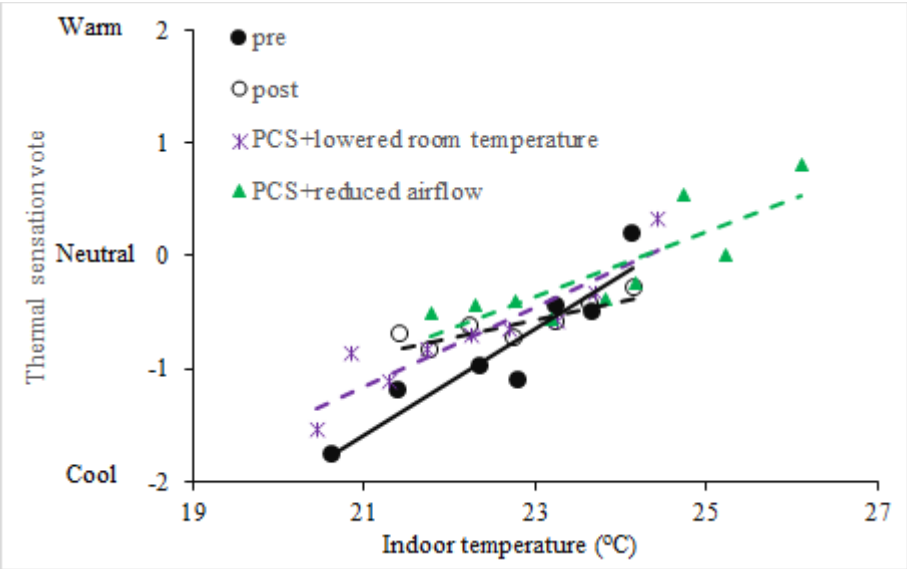

Figure 4. PCS's effects on subjective perception: a) thermal sensation, b) thermal acceptance

Figure shows how people used PCS (top figure) and their preferences for ambient temperatures (bottom figure) throughout the study. The diversity of individual differences is clearly seen by the two figures that show during all study periods, there were people using heating or cooling features of the PCSs, and there were people who preferred different ambient temperatures (warmer, cooler, or no change). The diversity of the responses makes it clear that giving people some control over their own thermal settings (such as PCSs) can lead to much higher satisfaction, even in ambient conditions which would normally be considered less acceptable.

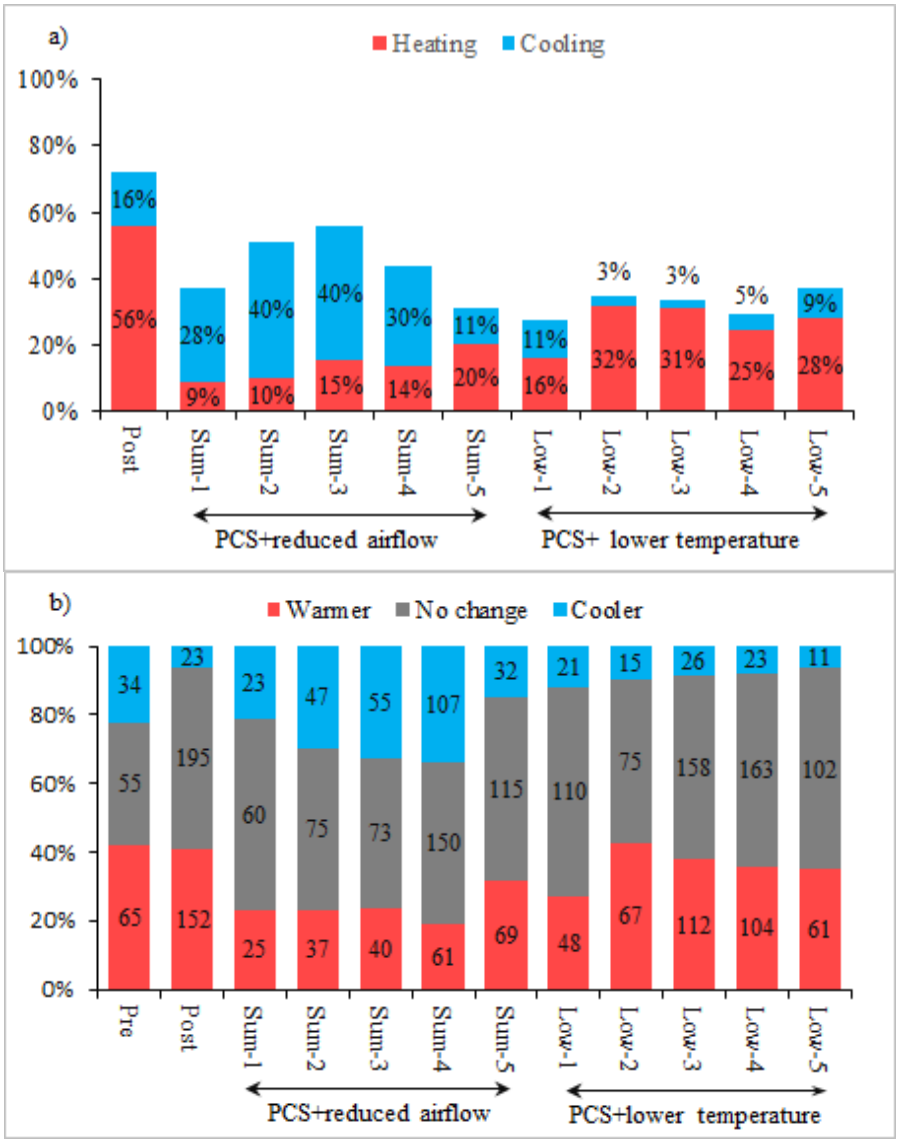

Figure 5. Occupants' behavior throughout the study period: a) the use of PCS, b) thermal preference. Numbers indicate the counts of the surveys

Energy savings. Error: Reference source not found illustrates how cooling and heating energy in office 306 (on the third floor) and 206 (on the second floor) responded to the airflow changes as a function of outside air temperature. The cooling energy climbed up when outdoor temperature increased, heating energy went up when outdoor temperature decreased. In warm season (e.g., > 26°C outdoor temperature), when the VAV airflow volume was reduced, the energy used in cooling was less than 50% of what had been in the baseline. Similarly, in cold outdoor temperatures (e.g., < 10°C), the lower airflow rates saved as much

as 65% of heating energy. For these two spaces, we observe that energy use for both cooling and heating were reduced by a larger amount by lowering the maximum airflow setpoint, compared to lowering the minimum airflow setpoint.

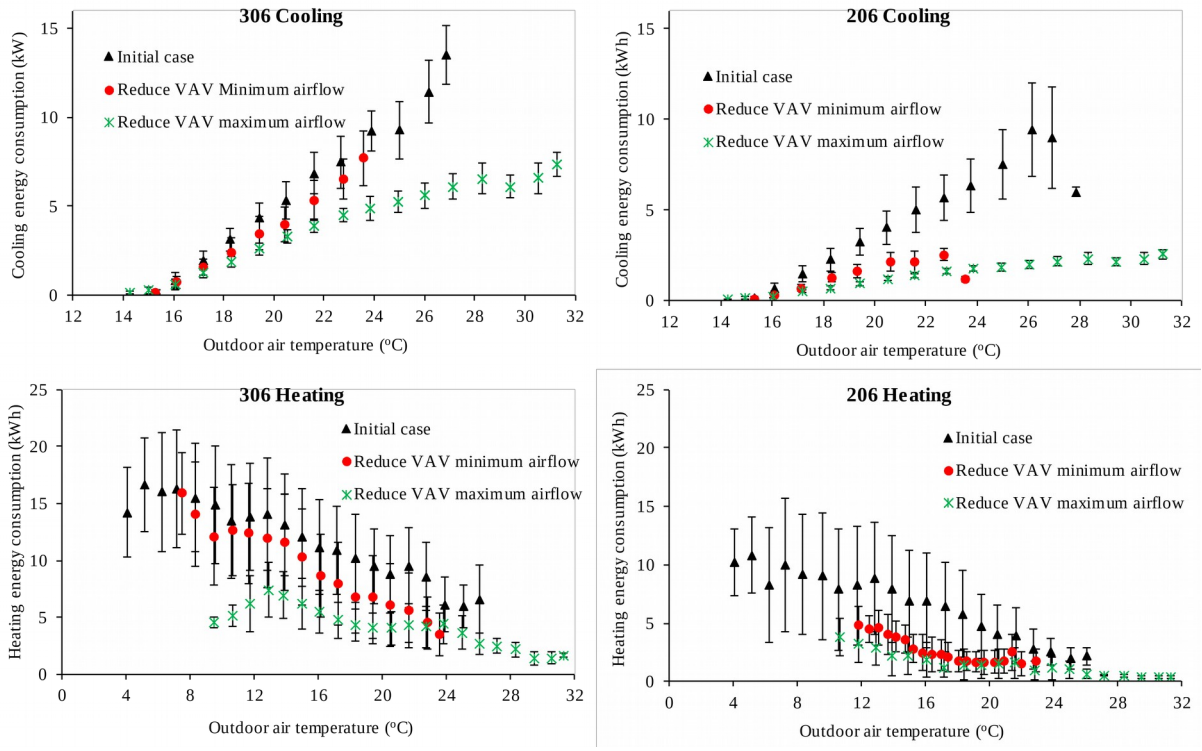

Figure 6. Energy saving effects of airflow adjustment

4 CONCLUSIONS

The study spaces had overcooling complaints. The study showed that the overcooling was caused by over ventilation and unstable controls settings. By reducing the maximum and minimum airflow setpoints, and by providing personal comfort systems, the thermal acceptance was enhanced from 56% to around 80%. The energy savings potential reached as high as 60% in heating and 50% in cooling without reducing occupants' thermal comfort and air quality perception. The detailed description of the study is provided by Bauman et al. (2015).

ACKNOWLEDGMENTS

This work was supported by the California Energy Commission Public Interest Energy Research (PIER) Buildings Program under Contract 500-08-044-01. We would like to express our sincere appreciation to Heather Bird, Energy Commission Specialist, who expertly served as our Commission Project Manager for this project. The work was also partially supported by the SPEED program which is supported by the California Energy Commission and managed through the California Institute for Energy and Environment (CIEE). We would like to thank Karl Brown for his involvement in the study. We would also like to thank David Rogers and Harry Stark (UC Berkeley) for their interest and support by coordinating access to the offices in the field study building.

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