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Publication Date
2015-07-01

DOI
10.1080/23744731.2015.1060104

Effects of Diffuser Airflow Minima on Occupant Comfort, Air Mixing, and Building Energy Use (RP-1515)

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Abstract

There is great energy-saving potential in reducing variable air volume (VAV) box minimum airflow setpoints to about 10% of maximum. Typical savings are on the order of 10-30% of total HVAC energy, remarkable for an inexpensive controls setpoint change that properly maintains outside air ventilation. However, there has long been concern whether comfort and room air mixing are maintained under low flows through diffusers, and this concern has prompted VAV minima to be typically set at 20-50% of maximum.

RP 1515 evaluated occupants' thermal comfort and air quality satisfaction in operating buildings under both conventional and reduced minimum VAV flow setpoints, and measured the air diffusion performance index and air change effectiveness for typical diffuser types in the laboratory. The hypotheses were that lowered flow operation would not significantly reduce comfort or air quality, and that HVAC energy savings would be substantial. The hypotheses were almost entirely confirmed for both warm and cool seasons. But beyond this, the reduction of excess airflow during low-load periods caused occupants' cold discomfort in the warm season to be halved, a surprising improvement. It appears that today's widespread overcooling of buildings can be corrected without risk of discomfort by lowering conventional VAV minimum flow setpoints.

http://dx.doi.org/10.1080/23744731.2015.1060104
www.escholarship.org/uc/item/6kj9t7cj

Introduction

Variable Air Volume (VAV) box minimum airflow setpoints have tremendous energy implications. Simulations have shown that lowering the minimum airflow setpoint to the levels needed for outside air ventilation (~10% of maximum flow) will reduce a conventional building's heating, ventilating, and air-conditioning (HVAC) energy on the order of 10-30% (Hoyt et al., 2014). This is a remarkable saving for a simple controls setpoint change that costs nothing in new construction and costs very little as a retrofit.

VAV minimum flow setpoints have traditionally been maintained at higher levels (30-50% of max) because of three concerns held by practitioners and manufacturers: (1) VAV boxes might be unable to sense or control low flows, (2) low flows might cause the occupants to perceive draft discomfort from insufficient mixing of diffuser discharge air, and (3) poor air quality might result from a combination of poor control and insufficient diffuser mixing.

To address these concerns, diffuser manufacturers and the ASHRAE Handbook of Fundamentals have suggested that minimum VAV airflows be limited to 30%-50% of design airflow. There has however been little or no published research validating these limits. It is worth examining them to see whether they are justified.

Recent research has addressed the stability and accuracy issue in (1) above. A study of VAV terminal unit control at low flows found that current VAV box technology controls stably to between 5% and 15% of design flow for typical VAV box selections (Dickerhoff and Stein, 2007). As a result of this work, California Title 24 energy code in 2008 mandated "dual-maximum" VAV control, in which cooling minimum flow is limited to 20% of maximum, but as temperature decreases into heating mode, the minimum ramps up to 50%. A similar requirement was added to the 2013 version of ASHRAE Standard 90.1. Taylor et al. (2012) provide a summary of dual maximum control and VAV box sizing. In 2012, ASHRAE Research Project RP-1353 (Liu et al. 2012), extended the 2007 research over a wider range of technologies and field conditions, corroborating the results of the previous project.

Given that VAV boxes appear to control stably at very low flows, the remaining questions then are: can occupant comfort and indoor air quality (IAQ) be maintained within the space under low flows through the diffusers?

It is common practice within the HVAC industry to focus attention on design load conditions, and overhead diffusers are typically selected to optimize performance at maximum airflow. Room airflow distribution changes when zone airflow is decreased at lower loads, and also during heating, so there is concern that inadequate air mixing will produce uncomfortable conditions, poor ventilation, or both. The comfort concerns are that insufficiently mixed cool air "dumping" on occupants from diffusers will cause cool draft sensations, or that temperature will stratify within the space causing cool feet or hot heads. The ventilation concern is that outside air entering the room through the diffusers may, if insufficiently mixed, bypass the occupants.

In cooling mode, diffuser discharge velocities at low airflows may not be high enough to create the Coanda effect necessary to overcome the negative buoyancy of the cold air being discharged, thereby causing cold supply air to drop into the space (Int-Hout 2004, 2012a, 2012b, John 2012). In heating mode, insufficient forced mixing out of the diffuser may cause high-temperature supply air to shortcut along the ceiling to the return outlet, resulting in undesirably stratified temperatures, poor air exchange effectiveness, and poor temperature control. Mixing of high-temperature supply air is entirely different from the Coanda mixing during cooling.

A number of research projects have examined air distribution and ventilation effectiveness under low-flow conditions. Bauman (1995) and Fisk (1997) using a test chamber and thermal manikin found that acceptable comfort conditions and ventilation effectiveness were maintained with overhead diffusers at 25% of cooling flow maximum. Persily and Dols 1991, Persily 1992, Offermann and Int-Hout, 1989, Bauman 1993, Fisk 1995 found that ventilation effectiveness was maintained at low flows in cooling and in low-temperature heating, often lower than the diffuser manufacturer's recommended ranges.

There are two indices for heat transfer and ventilation used by the diffuser industry, the air diffusion performance index (ADPI) and air change effectiveness (ACE). ADPI is a laboratory protocol to comparatively rate diffusers' abilities to uniformly mix the air in a test volume, following ASHRAE Standard 113 (2009). A low ADPI may indicate dumping within a space. ACE is a tracer gas test of ventilation effectiveness according to ASHRAE Standard 129. It is referenced in Std 62, de-rating ACE when you have poor mixing.

ASHRAE RP 1515 was designed to address questions (2) and (3) above. The project was a combined field and laboratory study carried out between 2011 and 2013. Office workers' thermal comfort and air quality satisfaction were evaluated in a set of buildings operating alternately under conventional and reduced-minimum VAV flow setpoints. In addition, the mixing performance of a range of typical diffuser types was measured in the laboratory. The hypothesis for the field study was that the low flow operation would not significantly degrade comfort. The hypothesis for the lab testing was that low flows would not degrade the air diffusion performance index (ADPI) of ASHRAE Standard 113, or the ventilation effectiveness of a well-mixed system. In parallel with the occupant tests, the HVAC energy savings from reducing flows in the field study buildings were evaluated under co-funding from the California Energy Commission. The project is reported in: https://escholarship.org/uc/item/3jn5m7kg#page-6.

Throughout this paper, we shall refer to "high-minimum" and "low-minimum" VAV control sequences. 'High minimum" represents conventional engineering practice, in which VAV minimums are in the range of 30-50% of maximum flow. In the field studies, we fixed VAV minimums at 30% to represent high-minimum control, unless there were ventilation requirements calling for more airflow (Higher minima were required for ventilation in 10% of zones where minima ranged from 35% - 45% of maximum). "Low minimum" represents the proposed retrofit, in which the VAV minimum setpoints are generally in the range of 10-20%, unless there were ventilation requirements exceeding this. The minimum setpoint for each VAV unit is taken to be the larger of: *(1)* the minimum outside air rate based on California Title 24 minimum ventilation requirements (the larger of 0.15 cfm/sf, or 15 cfm/person (7.1 l/s person)) or *(2)* lowest setpoint allowed by the VAV controller, or 6-10% depending on VAV box inlet size. This ensured that the minimum setpoint satisfied both the ventilation requirement and VAV unit controllability. Thus, the results can be interpreted as the savings between a benchmark case with 30% VAV minimums, and a retrofit case in which the generic strategy described above was applied. California Title-24 minimum ventilation rates were used to calculate minima in the field study buildings and previous analysis reported in Taylor et al. (2012) showed that the Title-24 rates meet or exceed ASHRAE Standard 62.1 ventilation requirements for multiple zone systems with recirculation.

Method

This study involved four steps:

1. VAV control systems were re-programmed in selected buildings to allow minimum VAV flow rates to be globally switched between high and low.

2. Occupants were surveyed to evaluate their responses to high and low minimum flows.

3. Energy use was monitored and analyzed for both high and low minimum flow rates.

4. A representative range of diffusers were tested in a laboratory to quantify ADPI and ACE under the two operation modes.

Building selection, instrumentation, and controls reprogramming

We searched for buildings that would allow us to (1) program a toggle function to switch between a conventional high minimum sequence to a low minimum sequence in all zones, (2) survey the buildings' occupants repeatedly for their satisfaction with the indoor environment during the high and low minimum operation modes, and (3) install energy meters to monitor the energy consumption of various HVAC equipment operating under high and low minimum operation modes.

The study sites were: six buildings on the Yahoo! campus, Sunnyvale, California, consisting mostly of open-plan offices; a county government legal office building in Martinez, CA consisting mostly of private offices; and a university office building at University of California Merced with mostly private offices that we surveyed but did not monitor or toggle. We learned that the Yahoo! campus and the UC Merced building had already operated for several years with generally low-minimum setting, but the Ferry Building had until the study been operated on a conventional 30-50% minimum.

1) Yahoo! buildings

The Yahoo! buildings were built in 2001, totaling 980,000 ft^2 (91,000 m^2) floor area. An overview of the campus including buildings A – G and a view of Building D from outside are shown in Figure **1**1. (Building C,the cafeteria, was not monitored.). The offices in Yahoo! are mostly cubicles in an open interior plan, with two types of partitions, high and low.

Figure 1 Yahoo Campus

In total, there were 3850 employees. The sizes of each building and the number of HVAC components are summarized in Table 1.

Building	Area (ft^2)	Stories	No. of packaged AC units	Design airflow of packaged AC units (total cfm)	No. of chillers	Air terminal units
Building A (w. data center)	180,700	4	2	184,000	3	186
Building B	180,700	4	2	184,000	2	188
Building D	180,400	5	2	184,000	1	225
Building E	212,600	5	3	212,840	3	243
Building F	91,000	3	2	90,000	1	92
Building G	79,700	3	2	80,000	1	83
Totals	925,100		13	934,840	11	1017

Table 1 Summary of campus buildings and HVAC units

http://dx.doi.org/10.1080/23744731.2015.1060104
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VAV box types. There are 1073 VAV zones on the campus, of which 254 are cooling only, 246 are fan powered, and 573 have reheat coils. A mixture of series and parallel fan-powered VAV units typically serve conference rooms, which are not the focus of this study. Cooling-only VAV units typically serve interior zones.

Site Control System and Trending Capability. An Automated Logic Controls system provides zone-level control throughout the campus. The research project upgraded the trending functions of the system to create a relational database of all VAV zone control points trended on one-minute time intervals. Two years of data were obtained for analysis.

Controls re-programming. A controls contractor was hired to reprogram all 1,017 VAV units in the six Yahoo! buildings so that they could be operated at different minimum flow rates. A diagram of the new dual-maximum flow control sequences is shown in Figure 2 below. Minimum flow setpoints for the experiment were calculated according to the procedures recommended in in the Energy Design Resources Advanced VAV Design Guide (EDR 2010) and (Taylor & Stein 2004, Taylor et al., 2012). In these, the minimum flow rate that a VAV box can operate is limited by the code-required minimum ventilation rate and by the limitations of controllers that become unstable or inaccurate at very low flow. Ventilation rates are prescribed in the California Title 24 Building Code and for office buildings are determined by the maximum of 15 CFM/person or 0.15 CFM/ft^2.

Figure 2 shows three VAV reheat zone control sequences; (a) conventional single maximum sequences that is used as the baseline in this study, (b) dual-maximum sequence with discharge temperature control, (c) a “simultaneous” dual-maximum sequence that was used in this study. Control system memory limitations at both study sites prevented implementing the full dual-maximum sequence including discharge temperature control. As a result more reheat energy was used, and the overall energy savings potential reduced.

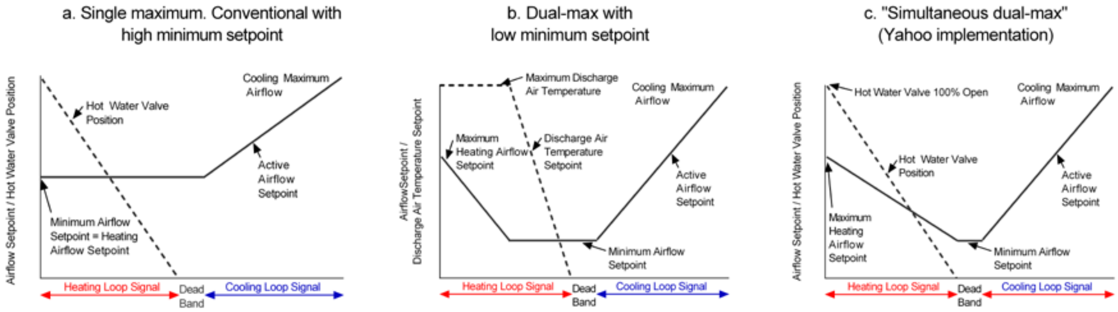


Figure 2. VAV reheat-zone-terminal-unit control sequences.

Figure 3 shows the distribution of minimum flow fractions implemented in Yahoo zones for both the high- and low-minimum test conditions. The differences come from zonal differences in ventilation requirements. It can be seen that 10-15% is the dominant mode under the low condition.

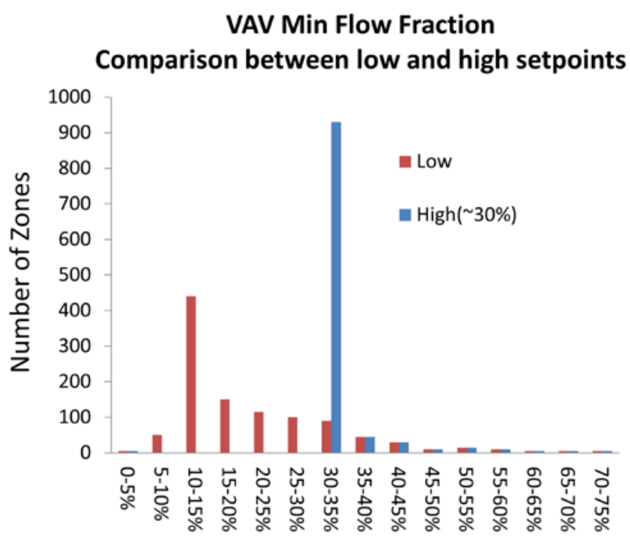
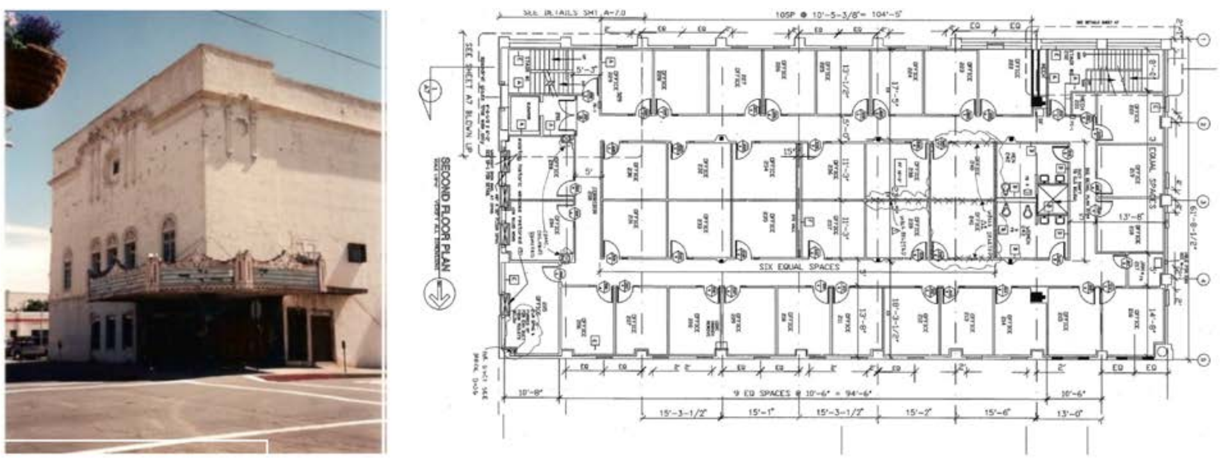


Figure 3 Yahoo! minimum flow fraction setpoints used in the high and low minimum test conditions

Metering. Power and gas meters were installed for each building. Heating (and reheat), cooling, and fan energy were sub-metered. The metering provided the capability to measure the magnitude of savings from changing VAV minimums for each of these end-uses.

2) Ferry Building: A county government office building

The Contra Costa County legal office is located at 800 Ferry Street, and it is referred to in this report as "Ferry Building" (Figure 4). It is a 20,000 ft^2 (2,100 m^2) historical theater building renovated into an office building in 1997. Private offices comprise 60% of the floor space with the remaining space consisting of conference rooms, open plan offices, and other support spaces. The building has 22 VAV zones of which 4 are cooling-only VAV and the rest are VAV with hot water reheat. The diffusers are perforated with blades in face.The controls system is Alerton BacTalk.



Ferry Building **Floor plan**

Figure 4. Ferry Building.

A controls contractor connected energy meters to the control system for trending. Separate meters were installed for the Ferry Building's supply fan, return fan, and four AC units. The original minimum flow rates were high, ranging from 30 – 50%. The building engineer made the changes to the VAV minimums at the switch-over times. The minimums in all the 22 VAV units were reduced by approximately 75% (Figure 5). The small number of zones made manual changes feasible, unlike the huge Yahoo! study site where automated switch-over was required.

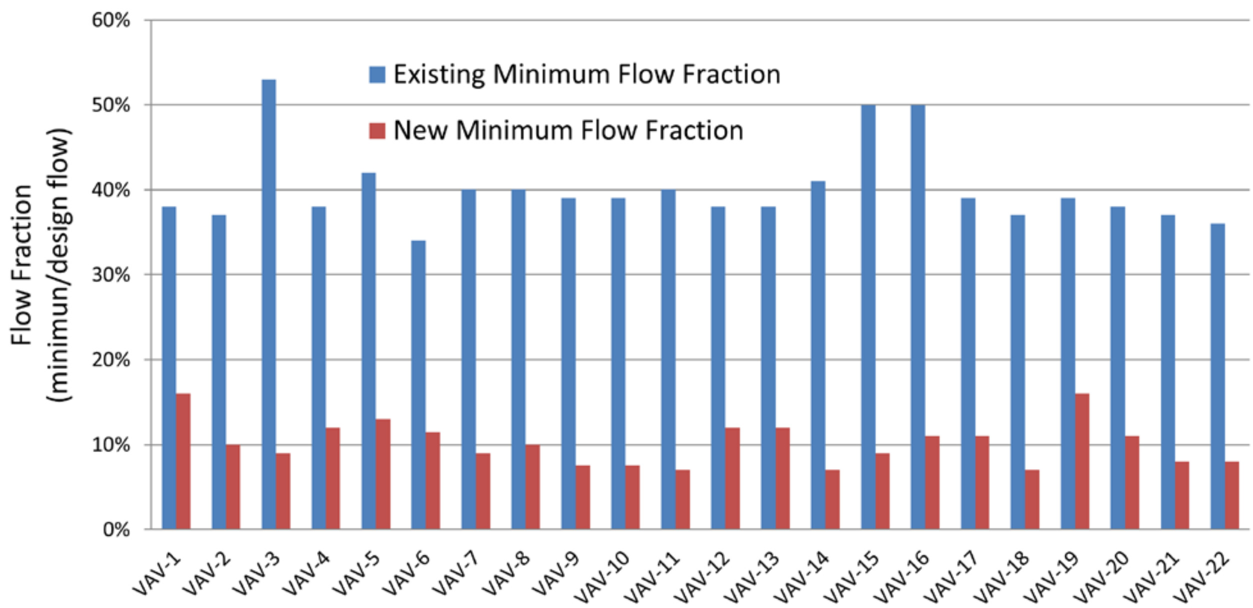


Figure 5 Distribution of zone minimum flow setpoints in Ferry Building

Testing schedule

VAV minima were switched several times between high and low during the one-and-a-half-year study. Although the survey periods took place during short intervals within this period, the whole period was used for measuring energy consumption. The following timelines (Figures 6 and 7) show when these changes occurred for the Yahoo! buildings and Ferry Building.

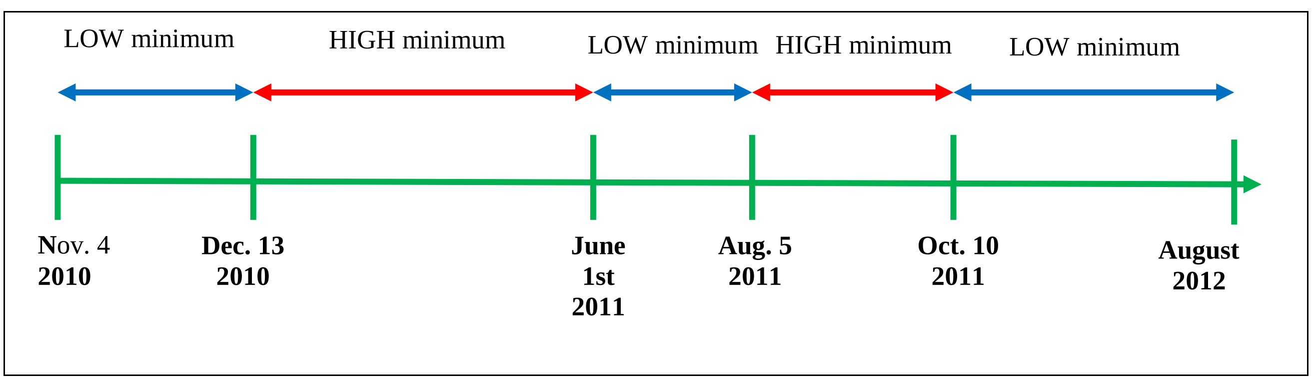


Figure 6 Yahoo! entire study period

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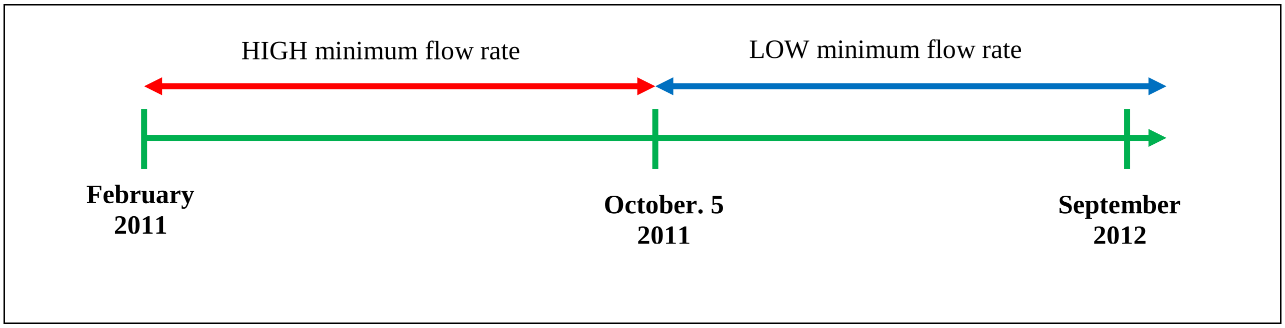

Figure 7 Ferry Building entire study period

Occupant surveys

Two types of occupant surveys were administered to the buildings' occupants: '*right-now*' and '*background*'. A right-now survey asks people's subjective perceptions of indoor environmental quality (IEQ) issues at the time of the survey, and is done with concurrent physical measurements that allow causal effects to be determined. A background survey allows inter-building comparison of IEQ satisfaction as perceived by occupants over time. In this study the IEQ scores of a large set of conventional buildings could be compared with those of a few atypical buildings that had been operated over time in low-minimum mode.

The ***right-now*** survey. The web-based survey measures occupants' responses to thermal comfort, local body part discomfort, air movement perception, perceived indoor air quality, acoustical quality, and other indoor environment related questions. The right-now survey was administered repetitively throughout both high- and low-minimum periods of operation, allowing the comparison of occupant perceptions in the two operation modes. The survey also included branching questions that appear whenever occupants enter a dissatisfied response to a survey question, to help identify the source of the dissatisfaction. The branching questions asked about diffuser dumping, drafts, cold feet, and other issues that pertain to low VAV airflows.

The right-now survey was administered in the six office buildings on the Yahoo! Campus during the cool season from Dec. 2 – Dec. 23, 2010, and during the warm season from Sept. 29 – Oct. 26, 2011. About 7330 individual responses were received from 432 occupants during the cool season, and 2100 responses from 83 occupants during the warm season.

In the Ferry Building, surveys were conducted only during the warm season (Sept. 22 – Oct. 21 2011), since we were unable to access the building before March 2011. After installing the control toggles and power meters, only the warm season was available for the occupants' satisfaction survey. This survey received 996 individual votes from 61 occupants. (Table 2)

The survey questionnaire was conducted three times per day, normally around 10 AM, 2 PM, and 4 PM. About the middle of each survey period, the low minimum flow rate was switched between high and low minimum operation, using the toggle function described above. The schedules of the high/low minimum flow rate during the occupant survey period, together with the number of participants and number of responses, are shown in Table 2 .

	Low minimum flow rate	High minimum flow rate	Number of responses	Number of participants
Yahoo! cool season	Dec. 2 – 13, 2010, 2 PM	Dec. 13 2 PM – Dec 23, 2011	7330	432
Yahoo! warm season	Oct. 10 5 PM – Oct. 26, 2011	Sep. 29 - Oct. 10, 2011, 5 PM	2100	83
Ferry Building warm season	Oct. 6, 6 AM – Oct. 21, 2011	Sept. 22 – Oct. 5, 2011, 6 AM	996	61

Table 2 Survey periods under high/low minimum flow rates

The ***background*** survey is also web-based, measuring occupants' long-term satisfaction with their work environments in terms of thermal comfort and other IEQ-related questions. Results are compared to the existing Center for the Built Environment (CBE) Background Survey database, which is considered large enough (65,000 respondents in 600 buildings) to serve as a de-facto benchmark of conventional building comfort performance. This provides the opportunity to compare the comfort performance of buildings that have historically been operated under low flows with that of conventionally operated buildings.

The Yahoo! buildings and a single office building at University of California Merced are unusual in that they have been historically operated under unusually low minimum flow rate setpoints. The CBE Background Survey was conducted in all six Yahoo! office buildings and in the UC Merced building. The Ferry Building had historically been operated conventionally with high minimums, so no background survey was administered.

Results

Flow rate, loads, and temperature under high and low minimum VAV flow rate operations

Observed flow rates

For the Yahoo! campus, it was possible to analyze approximately one year's trend data from before Oct 2010 when the study started. Roughly 870 zones had been trended with usable data. The airflow that had occurred during all heating and cooling hours was evaluated for each type of air terminal: cooling-only, reheat, and fan-powered terminals. As seen above in Figure 3, the minimum airflow settings varied quite widely: 35% of Yahoo! zones had minimum flow rate below 10%, and 68% of zones had minimum flow rates below 20%. However virtually all were lower than the conventional minimum of 30%.

Figure 8 characterizes the distribution of actual flow fractions in the Yahoo! buildings and the Ferry Building, during all hours of high- and low-minimum operation. The values may be compared to the corresponding setpoint values given in Figures 3 and 5.

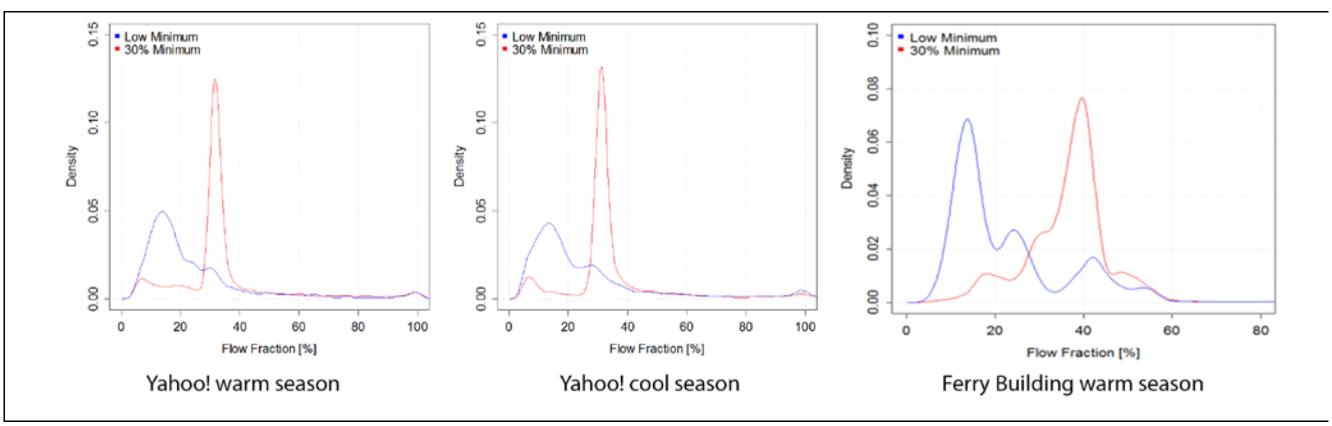

Figure 8 Flow rate distributions during occupied hours

Table 3 shows the average flow fractions for the test periods given in Table 2, all measured at the time a survey response was obtained. These low minimum values are higher than those measured over all occupied hours (Figure 8). This is due to most surveys being obtained in the afternoon when loads are generally higher (surveys were solicited at 10am, 2pm, and 4pm). The low flow fractions in the morning are underrepresented in Table 3, but do appear in Figure 8. Some of the lowest values in Figure 8 undoubtedly represent the conditioning of relatively unoccupied space, and illustrate the importance of the ability to reduce flow at low-occupancy times to reduce energy use and overcooling.

	Low minimum flow fraction (%)	High minimum flow fraction (%)
Yahoo! warm season	25.9	35.8
Yahoo! cool season	27.5	35.4
Ferry Building	23.1	36.7

Table 3 Average of the flow fractions coincident with each right-now survey response

Zone air temperatures

Lowering the minimum flow setpoints increased the room temperature. In the warm season, the average air temperatures increased 0.2ºC (0.4ºF) in Yahoo! buildings and 0.6ºC (1.2ºF) in the Ferry Building in the mornings, and increased 0.3ºC (0.6ºF) in Yahoo! buildings and 1.5ºC (2.7) ºF in the Ferry Building in afternoons. In cool season, the average air temperatures increased 0.3ºC (0.6ºF) in mornings and 0.5ºC (0.9ºF) in afternoons in the Yahoo! buildings. Relative humidities throughout the entire study were moderate, below 50%.

In addition, the discharge air temperature under currently examined ranges (12-24ºC, 55 – 75ºF) did not have strong influence on sensation and comfort. Details are presented in Appendix C of the RP1515 report.

Survey Results 1: Repetitive 'right-now' surveys, administered before and after the intervention

Temperature satisfaction

Figure 9 compares the temperature satisfaction between high and low minimum operation for the three surveys (Yahoo! warm season, Yahoo! cool season, and the Ferry Building warm season).. The data comes from 3 days before and after the switch between high and low. The temperature dissatisfaction during these periods is summarized in Table 4.

When the minimum flow setpoint was reduced from high to low, the warm-season dissatisfaction rates were reduced by 47%, both in the six Yahoo! buildings and in the Ferry Building,. Among the three surveys, the dissatisfaction rate was highest in the Ferry Building. During the cool season, the six Yahoo! buildings all show unchanged dissatisfaction rates between the two minimum flow rate operation modes.

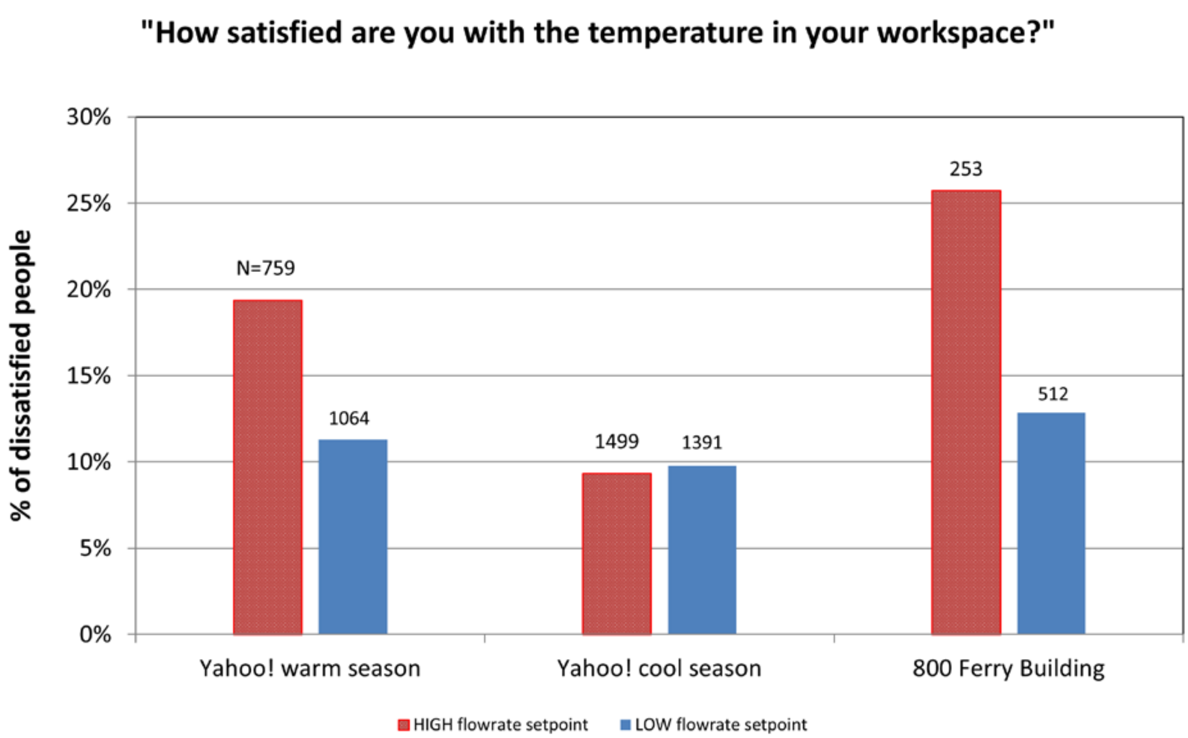

Figure 9 Comparison of temperature dissatisfaction rates under high and low minimum operation modes for the three surveys

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Survey	HIGH min flow rate	LOW min flow rate
Yahoo! warm season	19.8%	10.5%
Yahoo! cool season	9.3%	9.4%
Ferry Building	21.7%	11.5%

Table 4 Summary of dissatisfaction rates for temperature satisfaction under high and low minimum flow rate setpoints for the three surveys

Thermal sensation distribution

The higher rate of dissatisfaction under high minimum flow rate operation during the warm season may be a result of summer over-cooling of the buildings. Figure 10–12 show thermal sensation distributions in the three surveys (Yahoo! warm and cool seasons and Ferry Building warm season).

The sensation ranges within the data are defined as follows: ‘cold’ (sensation scale less than -2.5), ‘cool’ (sensation scale -2.5 to – 1.5), ‘slightly cool’ (sensation scale -1.5 to -0.5), ‘neutral’ (sensation scale -0.5 to 0.5), ‘slightly warm’ (sensation scale 0.1 to 1.5), ‘warm’ (sensation scale 1.5 to 2.5), and ‘hot’ (sensation scale above 2.5).

In the Yahoo! warm season survey, 21.5% felt slightly cool under high minimum flow operation, 10.4% felt ‘cool’, and 5.5% felt ‘cold’, a total of 37.4% of the population feeling ‘slightly cool’ to ‘cold’. In comparison, only 16.7% felt ‘slightly warm’, 4.3% ‘warm’, and no one felt ‘hot’; a total of 21.1% of the population feeling ‘slightly warm’ to ‘warm’. When the VAV operation was changed from high to low minimum, over-cooling was reduced and 13.2% of the population switched from the ‘cool’ and ‘cold’ categories to the ‘neutral’ category. This corresponds to the 47% reduction in the dissatisfied population measured with the satisfaction scale (Figure 9).

In the Yahoo! cool season survey, there is no significant difference between thermal sensation distributions between high and low minimum operation (Figure 11).

Under high minimum operation, summer over-cooling in the Ferry Building is stronger than in the Yahoo! buildings (Figure 12). Although the portion of the population feeling 'slightly cool' to 'cold' (37.6%) is similar to the Yahoo! buildings (37.4%), 10.6% feel 'cold' in the Ferry Building, almost twice the 'cold' population in the Yahoo! buildings (5.5%, Figure 10). 20.7% feel 'slightly cool', and 6.4% feel 'cool'. When the VAV operation was switched from high to low minimum, the population feeling 'cool' and 'cold' reduced from 37.4% to 15.8%, 8.5% moved to the 'neutral' category, and 13.3% moved to the 'slightly warm', 'warm', and 'hot' category. As in Yahoo!, the shift on sensation towards warmth reduced the size of the dissatisfied population by 47%.

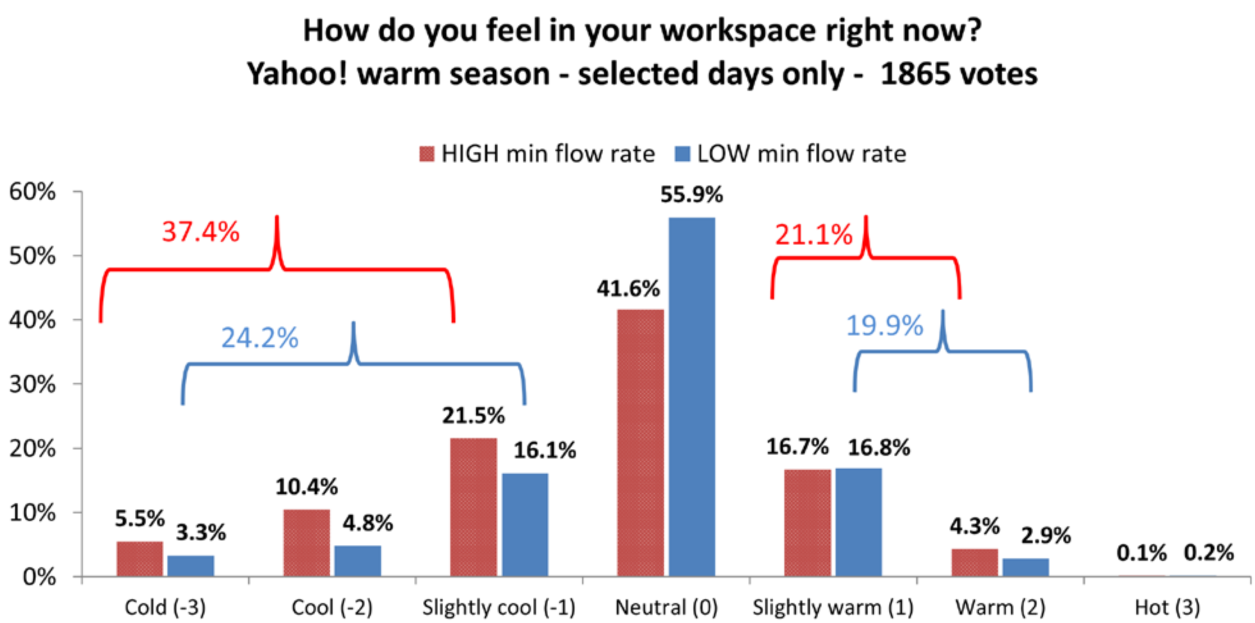

Figure 10 Thermal sensation distribution (Yahoo! warm season survey)

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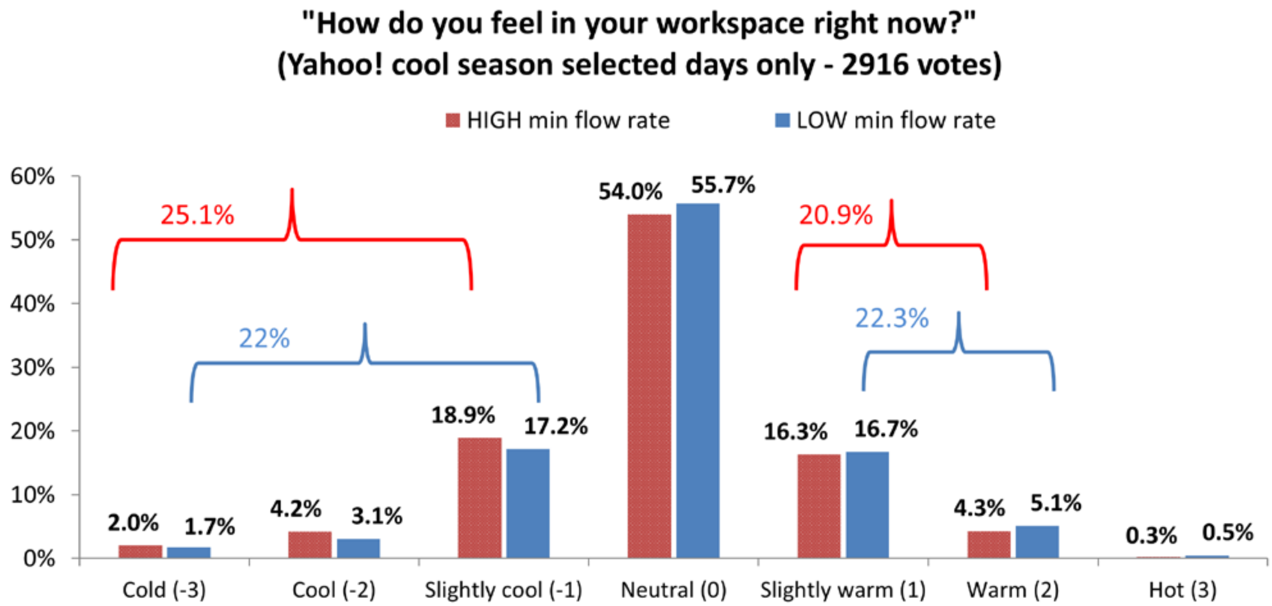

Figure 11 Thermal sensation distribution (Yahoo! cool season survey)

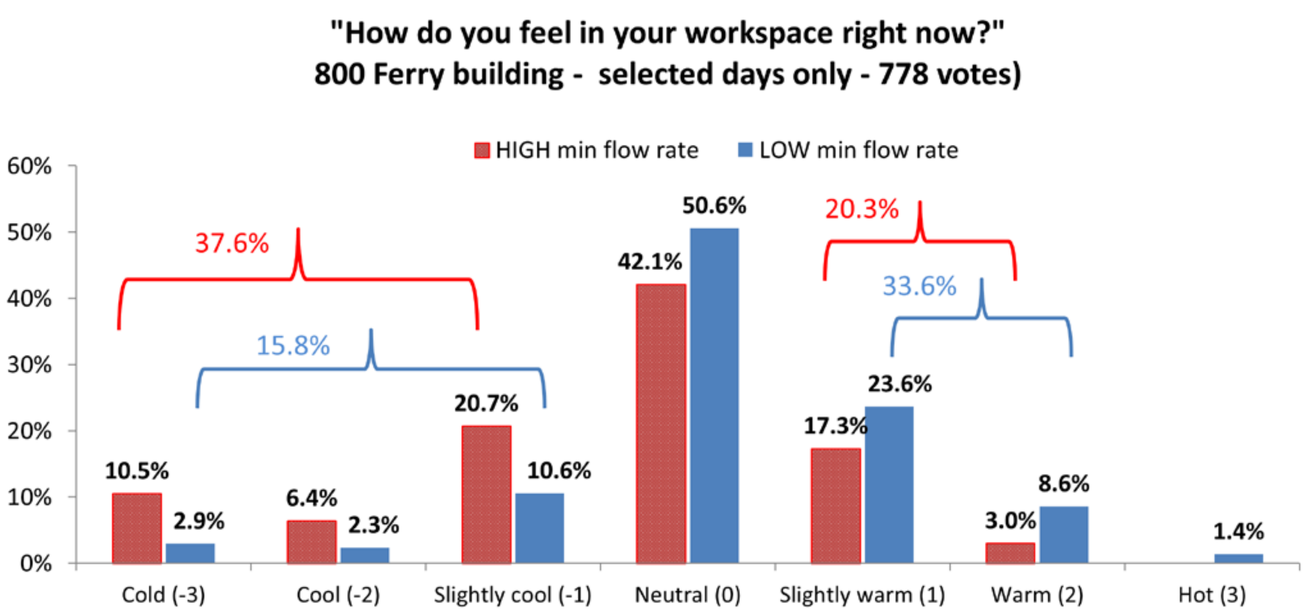

Figure 12 Thermal sensation distribution (Ferry Building warm season survey)

Satisfaction with perceived air quality

When the minimum flow rate setpoints are reduced from high to low, the volume of outside air entering the air handler unit (AHU) is not changed. Only the volume of recirculated air is decreased, resulting in a higher fraction of outdoor air in the primary air stream. Therefore, there is very little change in actual indoor air quality as measured by the fresh air volume delivered to the occupants.

If diffusers at low flows do not deliver air appropriately, the air quality may diminish and occupants perceive it. The right-now survey includes occupants' perception of perceived air quality. Analyzing the same set of data used for determining temperature satisfaction in Figure 9, Figure 13 shows satisfaction with perceived air quality. Closely following the temperature satisfaction results, perceived air quality was significantly improved in the warm season surveys (Yahoo! buildings and the Ferry Building) when the minimum flow setpoint was reduced, and unchanged for the two modes of operations in the Yahoo! cool season.

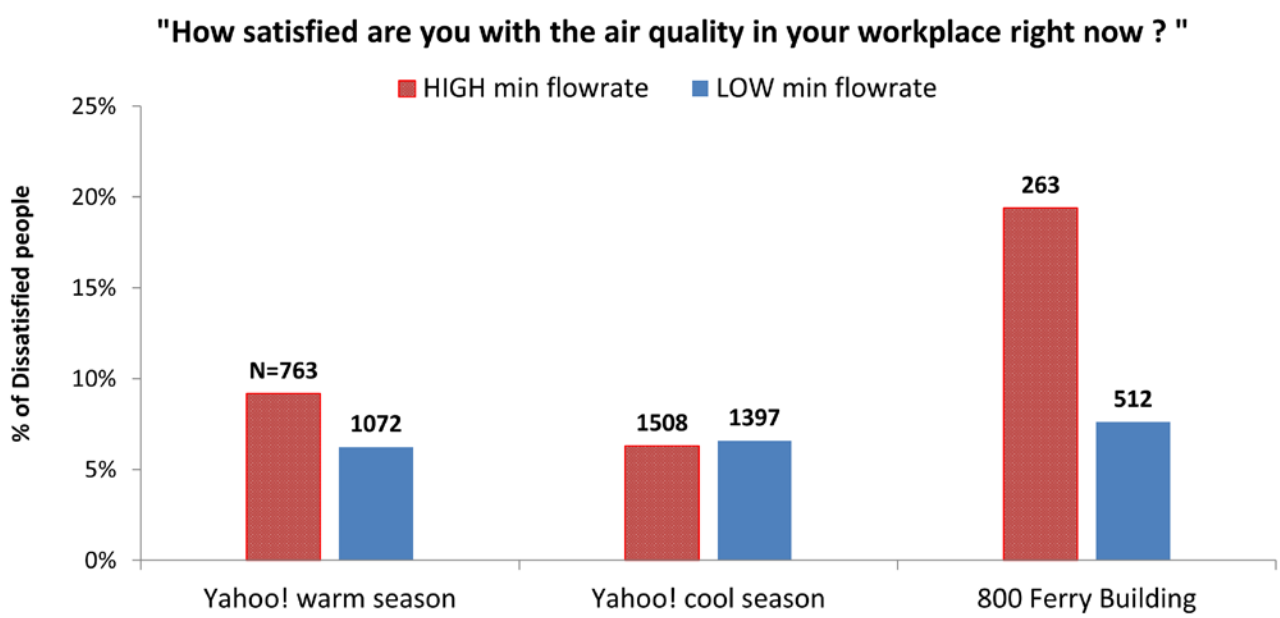

Figure 13 Comparison of perceived air quality dissatisfaction rates under high and low minimum operations for the three surveys

Sense of air movement

Another concern about the consequences of low minimum operation is that people near diffusers may sense 'draft' (unwanted air movement). The assumption is that under low flows the Coanda effect may cease to function, and that cool supply air would drop down unmixed onto the occupants below. To address this concern, we grouped people by flow rate (<30%, 30-40%, and >90%) and surveyed their sense of air movement. Four choices were presented in the survey: (1) no air movement, (2) little air movement, (3) moderate, and (4) strong. In the Yahoo! buildings there was little or no difference when the flow rate was at <30% and 30-40%. It was under high flow rate (>90%) that the population perceiving the air movement as "moderate" and "strong" nearly doubled. In the Ferry Building, the sense of air movement is higher (16%) when the flow rate is 30-40% than when the flow rate is <30% (there was no data for flow rate >90%). These results contradict the original concern — that when the flow rate is as low as 10%, there could be flow dumping causing air movement problems.

Physical evidence of dumping could not be detected for low flow rates in an intensive measurement session in one Yahoo! building during a weekend. Velocity and temperature measurements show that supply air mixes within a very short distance of the diffuser rim when flow rates are low. This can be seen in a IR image that was taken during low minimum (10%) operation (Figure 14). The cold air jet from the diffuser travels only 10cm (4 inches) across the ceiling before warmer air entraining from below has mixed across its full depth. At higher flows, the cold air travels many feet across the ceiling before reaching the same level of mixing.

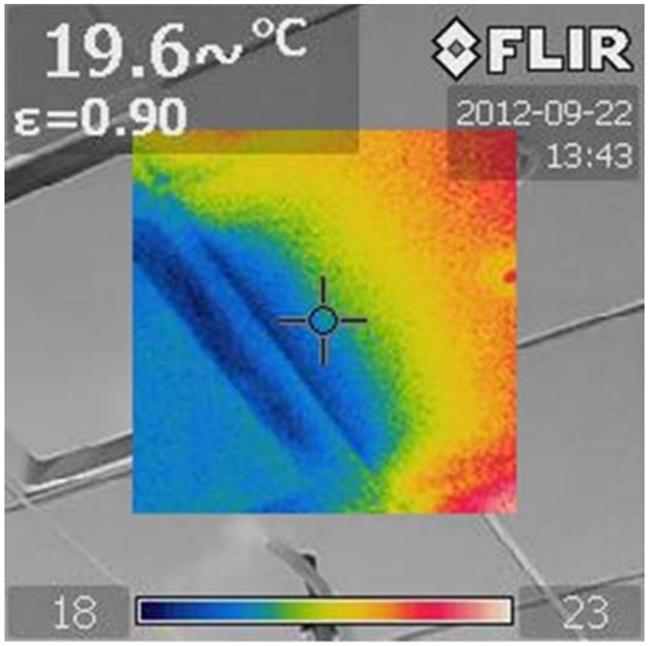

Figure 14. IR image during low minimum (10%) operation

Survey Results 2: Background survey of occupant satisfaction in low-minimum flow buildings

A background survey was conducted in the six Yahoo! buildings, and the small office building at UC Merced, using the web-based CBE occupant satisfaction survey. Each of these buildings had been controlled for several years to low VAV flow minima based on required outside air ventilation (in practice approximately 10% of VAVmax). If there were problems with thermal comfort and perceived air quality due to reduced mixing in the room air, they should appear in this survey of performance over time.

1279 people at Yahoo! (33% of the Yahoo! population) and 44 out of 85 in UC Merced (52% response rate) participated in the background survey. Figure 15 compares the mean values of the nine categories from the surveys at Yahoo!, UC Merced, and the 372 office buildings from the entire CBE database. The blue diamonds represent the CBE benchmark data. The 7 low-flow-minimum buildings can be seen to be indistinguishable from the CBE database in their occupants' satisfaction with the building, workspace, and other IEQ categories unaffected by the low flow rates. The two categories that *are* affected by flow rate--thermal comfort and perceived air quality—are highlighted by the blue box. These can be seen to be significantly better than the database averages. The six Yahoo! buildings rank in the 89th percentile for temperature satisfaction, the 76th percentile for perceived air quality, and the 60th percentile for general building satisfaction (Figure 16, 17). The UC Merced building ranks in the 75th percentile for temperature satisfaction, the 75th percentile for perceived air quality, and the 40th percentile for general building satisfaction.

This not only supports the hypothesis that low flows would not degrade comfort and occupants' perception of air quality in the workplace, but goes well beyond in suggesting that the low flows actually improved the comfort and perceived air quality.

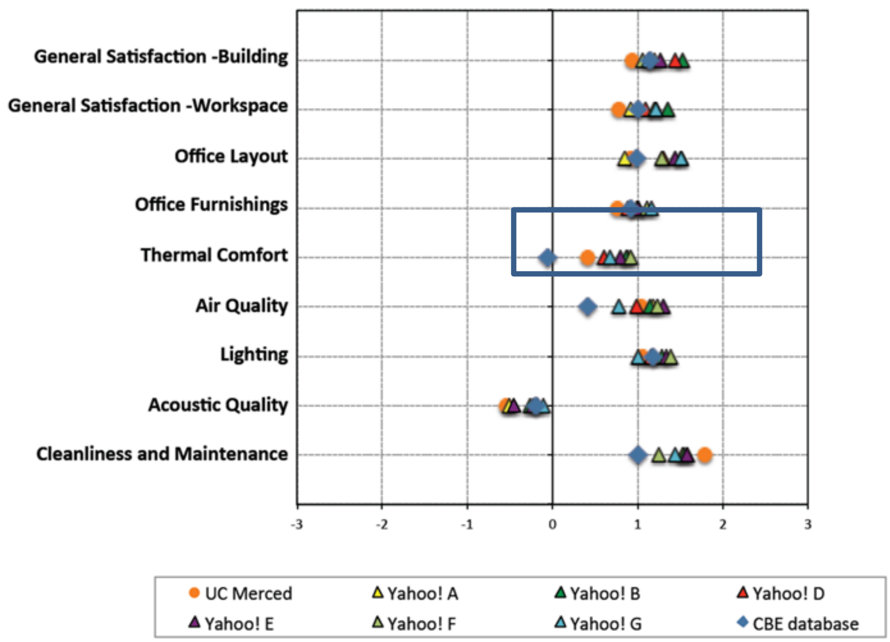

Figure 15. CBE background survey comparison for the 7 buildings from the current study with the 372 office building from the entire CBE database

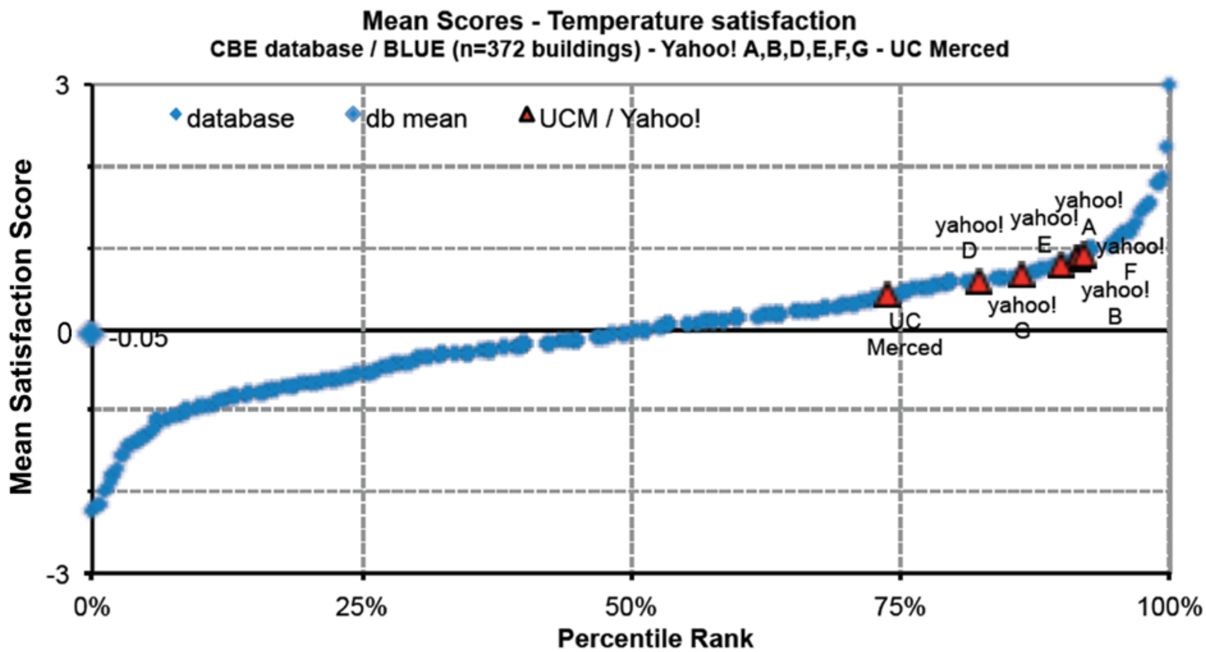

Figure 16. Ranks of the 7 buildings from the current study with the entire CBE database for temperature satisfaction

http://dx.doi.org/10.1080/23744731.2015.1060104
www.escholarship.org/uc/item/6kj9t7cj

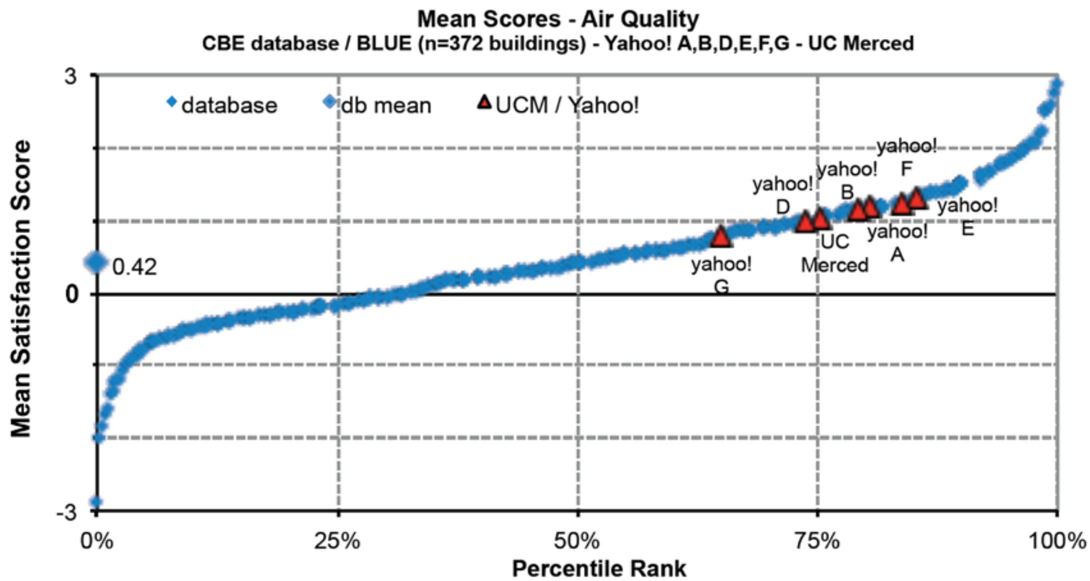

Figure 17 Ranks of the 7 buildings from the current study with the entire CBE database for perceived air quality

In the survey, occupants were also asked whether the thermal comfort in their workspaces enhances or interferes with their ability to get their job done. 79% of the surveyed population (including the neutral votes) from the 6 Yahoo! buildings, and 64% of population in the UC Merced building indicated that the thermal comfort in their workspaces enhanced their ability to get their job done. Considering that the thermal comfort category is normally rated second lowest among the 9 categories surveyed (Figure 15), for 79% of the population to respond that their thermal comfort is "enhancing" their work performance can be considered a very high value.

Energy Savings Results

A probabilistic model of energy use versus outside air temperature was created based on measured data and extrapolated to annual savings using TMY data. The model is described in the RP1515 final report (Arens et al 2012) and will be described in a separate paper. Tables 4 and 5 illustrate typical power consumption behavior under the two modes, for both cooling and heating.

On the Yahoo! campus, the low VAV minimum setpoints reduced gas consumption by an average of 12.2% (0.0225 therms/sf-year), and AC unit (fan + cooling) electricity consumption by an average of 13.5% (0.45 kWh/sf-year). In the Ferry Building, the low VAV minimum setpoints reduced gas use by 6.1% (0.011 therms/sf-year), cooling electricity by 28.8% (0.34 kWh/sf-year), and supply fan electricity by 42.6% (0.86 kWh/sf-year). Annual trends show that zone loads are generally very low which results in most zones spending most of the time at their minimum airflow setpoint.

Annual gas consumption	**Actual consumption 2011-2 [therms]**	**High minimum extrapolated annual consumption [therms]**	**Low minimum extrapolated annual consumption [therms]**	**Extrapolated annual savings [%]**	**Extrapolated annual savings [therm/sf-year]**
Yahoo!	98266	108320	94920	**12.2**	**0.0225**
Ferry Bldg	3665	3711	3486	**6.1**	**0.011**

Table 4 Extrapolated annual gas energy savings in Yahoo! and Ferry buildings

Cooling and fan electricity consumption	**Actual consumption 2011 [kWh]**	**High minimum extrapolated annual consumption**	**Low minimum extrapolated annual consumption**	**Extrapolated annual savings [%]**	**Extrapolated annual savings [kWh/sf-year]**

		[kWh]	[kWh]		
Yahoo! total	1801248	1828700	1562650	**14.55**	**0.482**
Ferry fan	30419	40520	23270	**42.6**	**0.86**
Ferry chillers	21561	23501	16722	**28.8**	**0.34**
Ferry total	51980	64021	39992	**37.5**	**1.2**

Table 5 Extrapolated annual electricity savings in Yahoo! and Ferry buildings

For all buildings, annual energy use data was compared to typical building use in the CEUS benchmark database. All metered data was within typical ranges.

It should be noted that these Yahoo! observed energy savings are less than the maximum possible because of the limitations in Yahoo!'s control system memory. Higher savings could be achieved on similar projects whose control sequences had the ability to minimize reheat through control of the discharge air temperature.

Laboratory test results: comfort and air exchange under a range of temperatures, flow rates, and diffuser types

Air distribution test setup

The Air Diffusion Performance Index (ADPI) was evaluated for 6 different diffusers following ASHRAE Std 113 (2009): Square Plaque Diffuser (SPD), Perforated Face Ceiling Diffuser with the pattern controller inside the face (PDF), Perforated Face Ceiling Diffuser With pattern controller inside the neck (PDN), Linear Slot Diffuser with plenum (SDB), High Side Wall Grille (520 Grille), and Round Cone Diffuser (RCD). (see Figure 18).

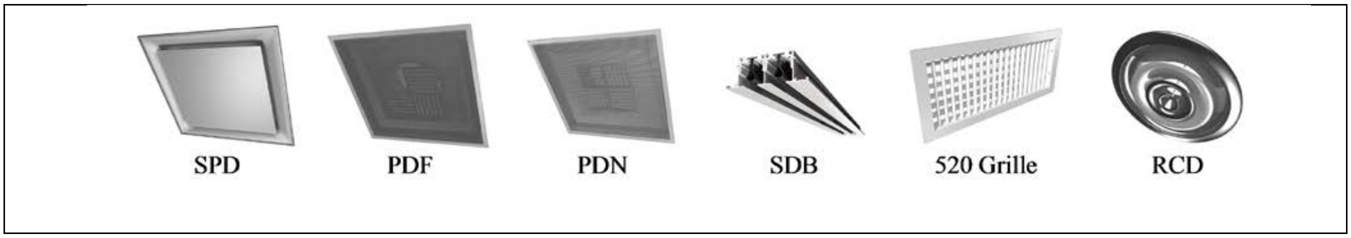

Figure 18. Six tested diffuser types

Figure 19 shows the test configuration, in accordance with ASHRAE Standard 70 (2006). Load simulators were deployed in strategic positions to represent the loads in a conditioned work space. They were added or removed to create the load to be met by each specific air flow test. A coordinate system covered all cardinal points in two planes. Controllers were set to test five different airflows (80%, 49%, 33%, 26%, 18%) at 2 different supplied temperatures 55ºF and 65ºF. Equipment was placed on each coordinate manually and software run to obtain data. Measurements were taken at four different heights; 4in, 24in, 42in and 66in. The ranges and accuracy of sensors are described in Table 3.6.1. Temperature and velocity readings were averaged over 3 minutes to provide accurate values for comfort measurements.

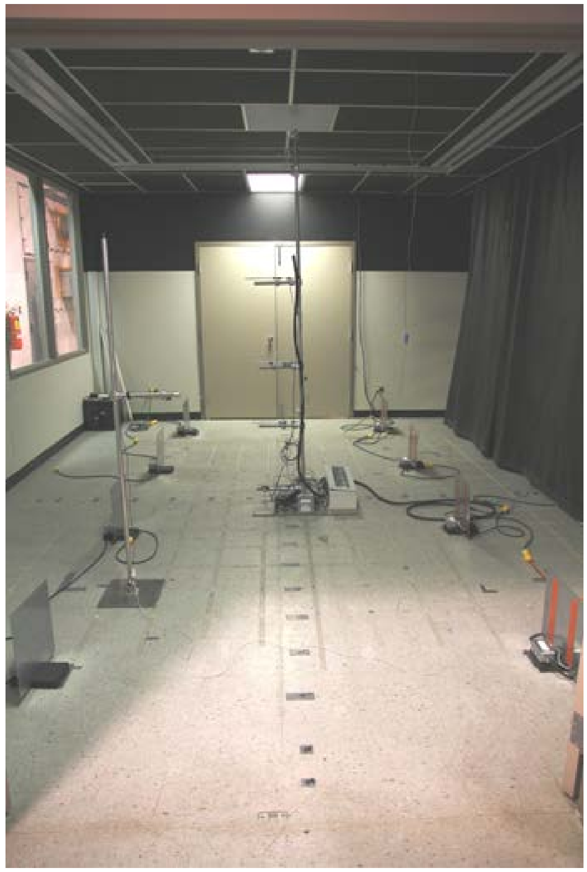

Figure 19. Diffuser testing chamber

Ventilation effectiveness test setup

The air change effectiveness testing was conducted to measure age of air and air change effectiveness. Once the test space had achieved a thermal equilibrium for a minimum of 30 minutes, the gas label, CO_2, was introduced to the air supply stream at a concentration of 4000 ppm. The concentration data collected during the step up and decay procedure was analyzed in accordance with ASHRAE Standard 129 to evaluate the age of air at all measurement locations. Tests were performed at airflow fractions of 26%, 18%, and 10%.

Air distribution test results

Figure 20 shows results for perforated diffusers with pattern controller inside the neck (PDN). These are typical of ceiling diffusers. The tests show more uniform temperature in the chamber at lower flow rates, and consistently lower air speeds in the occupied region at lower flow rates.

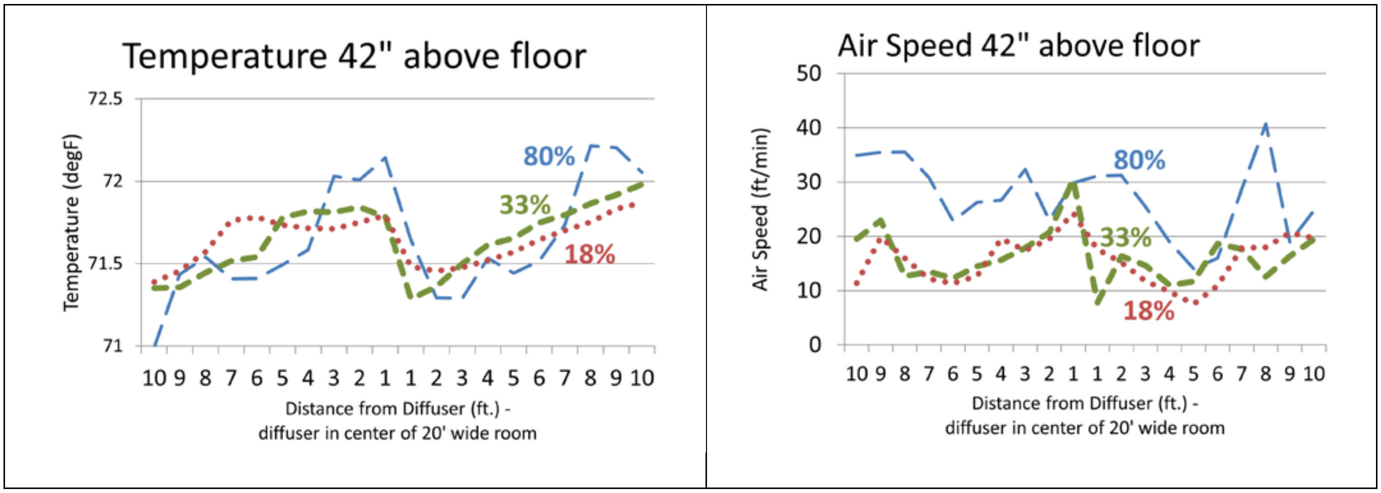

Figure 20. Air speed and temperature variations in a room transect 42" above the floor with PDN type diffusers at flow fractions of 18%, 33%, and 80%. These results are typical of ceiling diffusers.

The complete test results are in Arens et al. (2012). Summarizing: for all the ceiling diffusers flush to ceilings, ADPI remains at 98-100% regardless of flow rate and discharge temperature. ADPI and air speed results show that diffusers mounted flush with the ceiling (PDF, PDN, SDB, SPD) have excellent air distribution performance down to 10% flow fraction. Discharge air temperature appears to have very little effect on ADPI or average air speeds when diffusers are mounted close to the ceiling and average air speeds decrease at lower flow fractions.

Ceiling (RCD) or side-wall/duct diffusers (520 grille) mounted below the ceiling plane produced a significant decrease in ADPI when flow fraction and discharge temperature were both at their lowest values (10% flow, 55ºF). This requires further examination, as the low flow condition may not create an appreciable comfort effect, and the ADPI may be improved by adjusting the diffuser's horizontal louvers upward. There was insufficient time to examine this.

Ventilation effectiveness test results

ACE results were similar to ADPI results in that ceiling mounted diffusers maintained consistent ventilation performance down to 10% flow. ACE is always greater than 0.96 for all tests of PDN and SDB diffusers. No ACE tests were performed on diffusers without ceilings.

Discussion

1) This project focused on the comfort and energy effects of reducing VAV minimum setpoints. The significant findings are that reduced flow minima not only save energy (as expected), but significantly reduce occupant discomfort from summer over-cooling (this was unexpected, though it might seem obvious in retrospect). The prevalence of low space loads such as observed in this project's buildings is not uncommon. They provide the reason that low minimums are necessary and would save energy. They may also be the general explanation for the summer over-cooling that is now endemic in the US (Mendell and Mirer 2009). From the load analysis in the studied buildings, one can see that the lowest minimum flows based on meeting minimum ventilation rates are still higher than what is needed to meet loads for significant amounts of time in the cooling season.

   Figure 21 shows an example load distribution observed in two Yahoo! buildings during the hottest month. The most frequent load is around 5-6 Btu/sf which is very low. Equivalent flows are indicated for a 20ºF deltaT between the supply air and the space. 1 cfm/sq.ft. is a typical design load, which is reached a small fraction of the time. The most frequent condition is 0.2 cfm/sq.ft. which is close to the cooling supplied by the system at the minimum required ventilation flow. The lowest loads are actually below the required ventilation load at a 12C (55ºF) supply air temperature, and a 11K (20ºF) deltaT.

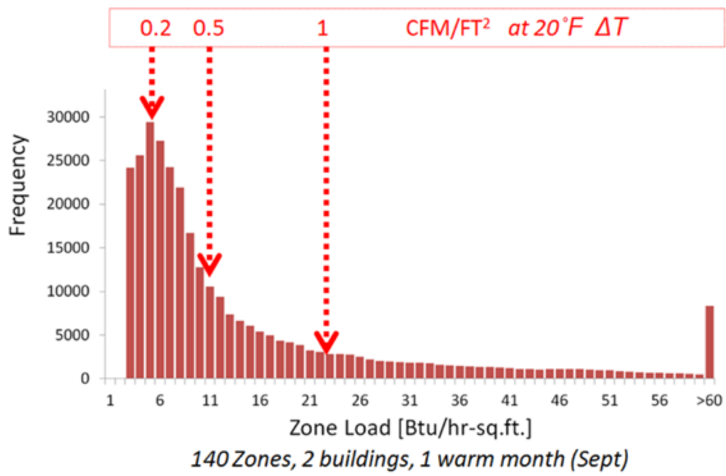

Figure 21 Load distribution in Yahoo building

2) Regarding draft, field measurements in Yahoo showed that the highest air movement in the occupied zone occurs during high flows, rather than low flows. This is consistent with the occupants' comments, where cool sensations were frequently noted in summer afternoons even though temperatures tended to be lower in the mornings. An example survey comment: "..starting to get cooler. My hands will start getting cold pretty soon. This usually means it's warming up outside." This suggests that draft sensation is occurring at the time of high loads and maximum flows.

3) The thermal sensation vote thresholds at which people found their environments acceptable were -2 to 2 in the Yahoo! buildings and -1.6 to 2.4 in the Ferry building. These results are similar to the results by

Zhang et al. (2009) in a laboratory study that showed the acceptable range of thermal sensations to be -1.5 to 2.

4) In this study, the baseline ambient condition during the two summer surveys was a state of uncomfortable overcooling, and the perceived air quality satisfaction improved as the zone air temperature became warmer with the low VAV minimum. This result contradicts a commonly cited assertion that perceived air quality is a monotonic function of room air temperature (Fang et al., 1998), and supports the view that perceived air quality is instead related to occupant thermal comfort (Humphreys et al., 2002), (Arens et al., 2008), (Zhang et al., 2010), (Zhang et al. 2011), (Kaczmarczyk et al., 2010), (Melikov and Kaczmarczyk, 2012).

5) The temperature and velocity profiles measured in the Price Industries test chamber show that diffusers mounted flush with the ceiling have high ADPI down to 10% flow fractions and average room air speeds that decrease with lower flow fractions. These results explain why occupants in the field study did not experience draft discomfort. Diffusers mounted on a sidewall or without a ceiling, thus absent the Coanda effect, provided reduced ADPI at the combined lowest flow and temperature. None of the buildings in this study had these diffuser configurations.

6) In the laboratory tests, diffusers flush with the ceiling (PDF, PDN, SDB, SPD) provided:

a. 98-100% ADPI regardless of flow or temperature
b. Lower air speeds at lower flow
c. Average air speed below the ASHRAE 55 draft limit
d. Lower air speed at 65ºF discharge temp compared to 55ºF

7) In the laboratory tests, diffusers with no nearby ceiling plane (RCD, 520 grille) provided:

a. 87-100% ADPI at 65ºF

b. Lower air speeds at low flow
c. Average air speed below ASHRAE 55 still air limit
d. ~60 ADPI, ~40 fpm air speed at 55ºF and lowest flow—the lowest performing condition

8) Since the adoption of Title 24-2008 and ASHRAE 90.1-2013, VAV zone minimum flow fractions in new construction have been required to be no higher than 20% or the ventilation rate if higher. This research shows that much lower minimums, as low as the minimum ventilation rate (often 5-15%), do not have negative impacts on occupants. These results, along with results from research into VAV box controllability and stability at low flow. suggest that energy codes and standards could adopt even more stringent VAV minimum criteria. However, the large proportion of existing buildings are typically operating at higher minima, up to 50%

9) Research on minimum flows could have far-reaching implications in support of changes to the ASHRAE Handbook, to manufacturers' literature, to the way engineers calculate minimum flow rates, and to proposed changes in Standards 90.1, 62.1 and 55. There is a need for generalizable guidance to designers and standards developers who are considering the use of low minimum airflows.

Conclusions

Six Yahoo! buildings and the Ferry Building were tested to determine comfort and energy use when the minimum flow rate setpoints were reduced from high (conventional level: 30-50%) to low (minimum ventilation rate or controllable minimum: ~10-20%).

Occupant surveys in the Yahoo! buildings and Ferry Building supported the hypothesis that there would be no degradation in occupant comfort. In winter, there was no appreciable difference between the two modes of operation. In summer, however, there was significantly improved thermal comfort ($p<0.001$) under low minimum operation. The dissatisfaction rate found under high minimum operation was reduced by 47% in both summer studies in Yahoo! buildings and in Ferry Building. The comfort improvements appear to be due to a reduction in summer over-cooling, as the zones have more capability to turn down at low load conditions. We encountered no evidence of draft sensation at low flow rates. In fact, upending the hypothesis, occupants perceived the most air movement when the flow rate was high, not low.

The perceived air quality was also improved in the summer when the high minimum operation was switched to low operation. The proportion of respondents dissatisfied with the air quality dropped by 32% in the Yahoo! buildings and by 62% in Ferry Building. Perceived air quality satisfaction correlates well with temperature satisfaction, so this improvement may come from improved thermal comfort. It might also suggest that the amount of mixing at low flows is sufficient to avoid actual air quality problems.

The background surveys from seven buildings which are normally operated under low minimum setpoints show that satisfaction with temperature and perceived air quality was the highest of all of the nine survey categories, and high when benchmarked against the entire CBE survey database. This is significant in that the satisfaction rankings for the buildings themselves was average.

On the Yahoo! campus, the low minimum setpoints reduced high-minimum gas use by an average of 12.2% (0.0225 therms/sf-year), and AC unit energy (including fan and cooling consumption) by an average of 13.5% (0.45 kWh/sf-year). In the Ferry Building, the low minimum setpoints reduced high-minimum gas use by 6.1% (0.011 therms/sf-year), cooling energy by 28.8% (0.34 kWh/sf-year), and supply fan energy by 42.6% (0.86 kWh/sf-year). Annual trends show that zone loads are generally low with many zones spending most of the time at their minimum airflow setpoint.

The temperature and velocity profiles measured in the Price Industries chamber show that diffusers mounted flush with the ceiling have high ADPI down to 10% flow fractions, and average air speeds in the occupied zone that decrease at lower flow fractions. This explains why occupants in the field study did not experience draft discomfort.

Reducing the minimum flow rate setpoints can be done simply by modifying parameters in the building control system that are often readily accessible. It is a very low-cost retrofit option that can often be carried out with no modification to the building hardware.

Acknowledgements

This study was jointly funded by ASHRAE (award number 030341-003), California Energy Commission (CEC contract number 500-99-013, work authorization number BOA-POB-244-B65), and the Center for the Built Environment (CBE) at the University of California, Berkeley. We are also very grateful to the buildings staff at Yahoo!, Ferry Building, and UC Merced for the substantial help in arranging access and helping with the collection of environmental, energy, and occupant survey data.

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