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Acceptable air velocities using demand-controlled ventilation for individual cooling

Kari Thunshelle[1,*], *Henrik* S. Nordby[2], *Håkon* Rikoll Solberg[1], *Sverre* Holøs[1] and *Peter* G. Schild[1]

[1] SINTEF Community, Pb 124 Blindern, 0314 Oslo, Norway
[2] OsloMet, P.O Box 4 St. Olavs plass, 0130 Oslo, Norway

Abstract. One of the main challenges in highly insulated buildings is the increasing share of energy demand for cooling. New solutions for low energy cooling are needed. Individual cooling by demand-controlled ventilation and use of ceiling mounted nozzles for cooling by higher air velocities could be an alternative. A laboratory study was designed to investigate thermal comfort and thermal sensation for elevated indoor room temperatures relevant to Norwegian summer climate; 24°C, 26°C and 28°C with a relative humidity set point of 40 %. Air flow was set to give air velocities of 0.25 m/s, 0.50 m/s and 0.75 m/s. 21 test persons were exposed to different air velocities in a cross-over study. Questionnaires on thermal comfort and thermal sensation were answered repeatedly. Jets from ceiling mounted supply air nozzles was shown to improve thermal comfort at 24 °C, 26 °C and 28 °C. In general, most test persons preferred low air velocity (0.25 m/s) at 24 °C, while high (0.5 m/s) or extra high (0.75 m/s) air velocities were preferred at 26 °C. At 28 °C, extra high or even higher air velocities were preferred.

1. Introduction

For energy efficient buildings, energy demand for heating is becoming very low, even in cold climates. Energy demand for cooling, however, has become an increasingly important part of the total energy demand.

The most common approach for new, non-residential buildings in Norway is to install demand-controlled ventilation (DCV) systems. By carefully regulating indoor temperature and avoid elevated air velocities, good indoor air quality (IAQ) and thermal comfort are achieved.

It is established knowledge that increasing air velocity allows thermal comfort at higher temperatures, and this is implemented in standards such as ANSI/ ASHRAE 55 [1] and ISO 7730 [2]. Increasing air velocity normally demands much less energy than decreasing room temperature by cooling. There have been several studies on air flow characteristics and application to test persons [3-5]. Fluctuations in air speed simulating natural wind is regarded as preferable over constant mechanical air flow. However, more knowledge is needed with regards to how this knowledge best can be used to achieve high thermal comfort while reducing energy demand in buildings with DCV.

A prototype nozzle considering these aspects was developed. The use of ceiling mounted nozzles is regarded attractive by building owners to maintain flexibility to floor plan changes.

This paper describes laboratory experiments to examine how the use of air jets affected the thermal comfort of a test panel under different room temperatures. In the same experiments, effects on skin temperature were measured, of which the results are described by Solberg et al. [6].

2. Methods

2.1 Climate chamber setup

The climate chamber used for the experiments reflects a standard setup and size of an open plan office for four persons. Its dimensions are 6.0 m * 4.8 m * 2.7 m, corresponding to a floor area of 28.8 m². Four tables and chairs were placed in the chamber, representing office desks. As seen in figure 1, the tables were placed face to face as standard open plan office setup. Since the available tables were smaller than standard 1.0 m depth and 1.2 m length, spaces were provided between the tables and the positions marked.

A constant, balanced ventilation rate of 240 m³/h for both supply and extract air were applied to ensure satisfactory air quality for the four test subjects in the climate chamber. Two standard supply air diffusers each connected to a plenum box were mounted in the ceiling. Dampers can direct supply air from the plenum box to diffuser or project designed nozzles. Two nozzles were connected to each plenum box by small ducts and installed in the ceiling. The nozzles were placed above the counter desk and at a slightly angled direction, see figure 1.

Care was taken to avoid interference between different jets. General supply air placing was controlled to not influence the thermal comfort negatively.

* Corresponding author: kari.thunshelle@sintef.no

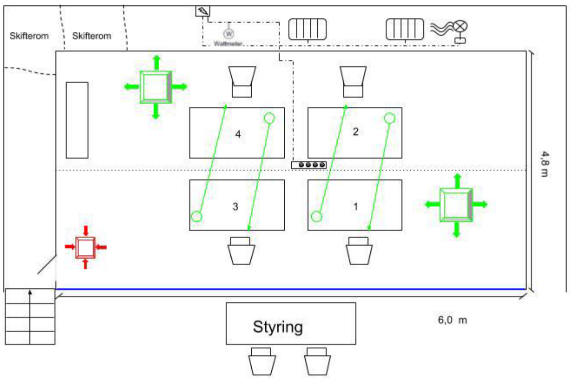

Figure 1. Climate chamber setup. Four nozzles placed above desks and two supply air diffusors (green). Extract (red)

2.2 Climate chamber regulation

In addition to controlling heating and humidification of the supply air, the space surrounding floor and walls were also heated. During the three weeks of experiments, the room air temperature was kept at 24.0 ± 0.1 °C during the first week, at 26.0 ± 0.2 °C during the second week and at 27.9 ± 0.1 °C during the third week.

Supply air temperature (21.9 ± 0.5 °C) and relative humidity (39.8 ± 0.5%) were kept constant throughout the entire duration of the experiments.

2.3 Preliminary experiments Determination of nozzle angle and test air velocity level.

Preliminary experiments were done to determine suitable nozzle directions and angles towards the body. Based on subjective evaluations as well as measurements of skin temperature described in [6], head and chest position were selected for the experiments. Two nozzles were pointed at a person's head, while the two others were pointed at the person's chest while seated, at a distance of 1.5 m, see figure 1.

2.4 Air velocity measurements

Design air velocity levels were set to 0.25 m/s ("low"), 0.5 m/s ("high") or 0.75 ("extra high") at the position of the test persons. Measurements of air velocity were done by hotwire anemometer SwemaAir 300 with Swa03 (± 0.04 m/s at 0.05-1.0 m/s and ± 0.5 at 10-40 °C) with a time constant of 0.25 s. The instruments were mounted on a movable rig. The rig was controlled by a positioning system and measuring position for each of the workplaces could be precisely repeated. All measurements were logged at 0.65 s interval for 8 minutes for each of the air flows

Preliminary experiments were done to decide the optimal position and height of the measurements. The air velocities at five heights above floor are provided in table 1.

Table 1. Measured air velocity at the test person's position.

Height [m]	Air flow/Required air velocity		
	Low	High	Extra high
	12 [m^3/h] /0.25 [m/s]	21 [m^3/h] /0.50 [m/s]	30 [m^3/h] /0.75 [m/s]
	Average air velocity [m/s]	Average air velocity [m/s]	Average air velocity [m/s]
1.3	0.25	0.45	0.78
1.2	0.26	0.48	0.73
1.1	0.22	0.48	0.67
1.0	0.22	0.47	0.58
0.8	0.18	0.35	0.35

The air flow in each nozzle was controlled by a DCV-damper. Control measurements were done to find the optimal air flows that would provide values closest to the designed air velocities at the test person's position. Reasonable distribution of air velocities at positions above desk height was controlled, and measurements at height 1.2 m was emphasised. The results of the measurements with the chosen air flows are shown in table 1. The measured velocities were fluctuating, more at low air flow than at high and extra high.

During the actual experiments, control measurements of air velocities were done for each of the studied room temperatures without persons present.

2.5 Experimental design

Four test persons were present each test day, in total 20 persons for each room temperature.

The study was conducted as a repeated measure with cross over design where each person represents his/her own reference. Position for person A, B, C and D as well as air velocity were varied according to the schedule given in table 2 for each test day.

The experiments were conducted in March, which is still a cold month in Norway. The test persons were given instructions in a 10-15 min period before starting the experiments. Before each session of experiments, the test persons were acclimated to the climate chamber room temperature in a conjunction room. Lunch was served outside the climate chamber in slightly colder indoor temperature (~ 21-22 °C).

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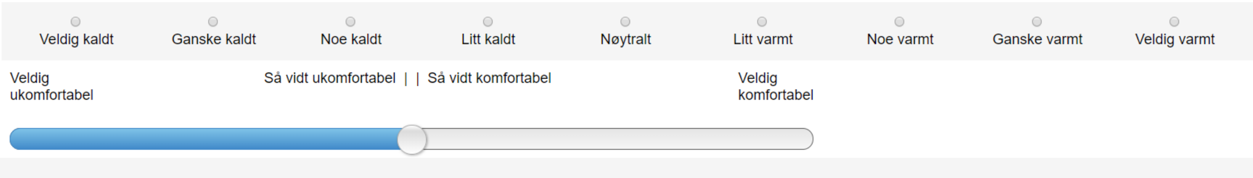

Figure 2. Screenshot of the thermal sensation scale (upper part) and thermal comfort scale (lower part) as presented in the online questionnaire.

Table 2. Daily time schedule, showing alternation of test persons (A-D) between desk 1-4 (D1-D4).

Time	Nr.	Air velocity	Head		Chest	
			D1	D2	D3	D4
9:10-9:30		Acclimatisation				
9:30-9:40	0	No air	A	B	C	D
9:45-10:15	1	Low	A	B	C	D
10:20-11:50	2	High	A	B	C	D
11:55-11:25	3	Low	C	D	A	B
11:30-12:00	4	High	C	D	A	B
LUNCH						
12:30-12-50		Acclimatisation				
12:50-13:20	5	High	C	D	A	B
13:25-13:55	6	Low	C	D	A	B
14:00-14:30	7	High	A	B	C	D
14:35-15:05	8	Low	A	B	C	D
15:10-15:40	9	Extra high	A	B	C	D

2.6 Test persons

Four test persons participated each day. The test persons were employees or students at the project partners' organisations, each person volunteering to 3 days of lab experiments. Test persons were chosen to represent the variety of office workers. In total, 21 (13 male and 8 female) persons participated in the experiments. Table 3 shows the age distribution of the participants.

Table 3. Age distribution of the participants.

Age category	[%]
20-29	47.6
30-39	14.3
40-49	47.6
50-59	14.3
60+	19.0

Test persons were instructed to dress in jeans, t-shirt (or similar) and light shoes, corresponding to 0.7 clo. During the tests, they were instructed to perform light office work sitting at the table, using a laptop computer. The activity level was estimated to correspond to 1-1.2 met.

2.7 Questionnaires

For each session, the test persons were asked to answer an online questionnaire three times during each session; at the start, after 10 minutes and after 25 minutes.

The questionnaire consisted of two parts. The first part included questions about personal details and were only answered at the start of each test day.

The second part consisted of questions related to thermal sensation and perceived thermal comfort for the whole body and different parts of the body. For thermal sensation, the test persons were asked "*How do you experience the skin temperature?*" The extended 9-point scale, also known as the UCB model, as described in [7, 8] was used to range thermal sensation from -4 to +4 (see figure 2). The scale was coded as following: -4 = "*very cold*", -3 = "*cold*", -2 = "*cool*", -1 = "*slightly cool*", 0 = "*neutral*", +1 = "*slightly warm*", +2 = "*warm*", +3 = "*hot*" and +4 = "*very hot*". This is an extension of 7-point scale from ASHRAE 55 [1] and ISO 7730 [2].

Perceived thermal comfort scale is divided in two parts and rated on a continual scale from 0 = "*very uncomfortable*" to 4.99 = "*just uncomfortable*" and from 5.01 = "*just comfortable*" to 10 = "*very comfortable*". It was not possible to rate at the midpoint (see figure 2).

Only the answers for the whole body are reported here. We received in total 1607 responses from the test persons.

3. Results

3.1 Overall thermal sensation

Thermal sensation is evaluated at different air velocities and room temperatures. Figure 3 shows the distribution of the answers on thermal sensation. At a room temperature of 24 °C, the majority of the responses were neutral and slightly cool, while at 26 °C the responses were neutral and slightly warm. However, at 28 °C, the responses ranged from neutral to warm.

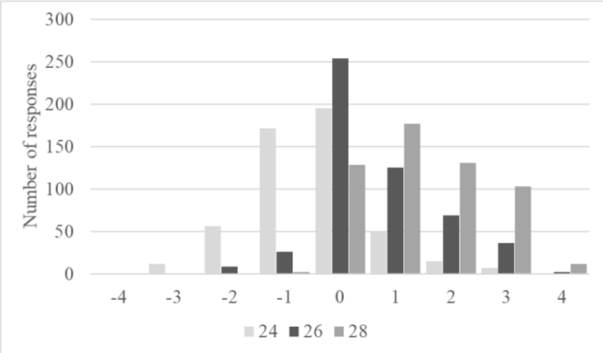

Figure 3. Distribution of thermal sensation scores (-4 =Very cold, 4 = very hot) for the whole body at different room temperatures.

3.2 Overall thermal comfort

As seen in figure 4, the test persons were mostly satisfied with the thermal comfort for the whole body at all three room temperatures. The highest average score for thermal comfort is seen at a room temperature of 26 °C (mean ± sd:7.0 ± 2.1), and the lowest at 28 °C (mean ± sd: 5.8 ± 2.6).

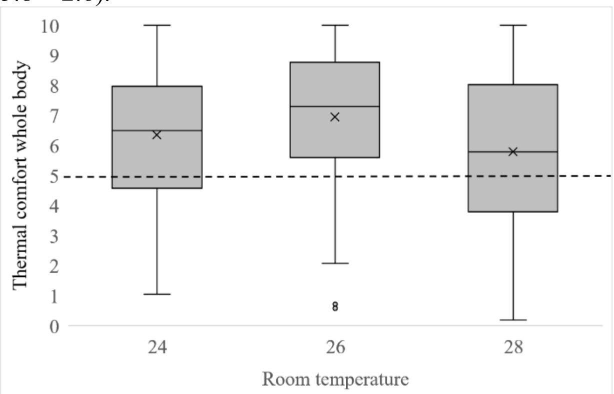

Figure 4. Boxplots of the scores for thermal comfort for the whole body at different room temperatures. The line inside the boxplot indicates the median value and x is the mean.

3.3 Air velocity

Figure 5 shows the scores of thermal comfort given at different time periods with different air velocities (0.25 = low, 0.50 = high, 0.75 = extra high) and different room temperatures during the test sessions.

For all room temperatures, there is no temporal variation of thermal comfort at low and high air velocities during a test session. There is, however, a slight variation of thermal comfort at extra high air velocities with a drop 10 minutes after the test session starts.

As indicated by the dotted line, the distributions of the boxplots show that at the test persons were comfortable at all air velocities when the room temperature was 26 °C. However, at 24 °C the majority of the test persons were comfortable at low air velocity, whereas at 28 °C, higher air velocity was regarded as more comfortable than low.

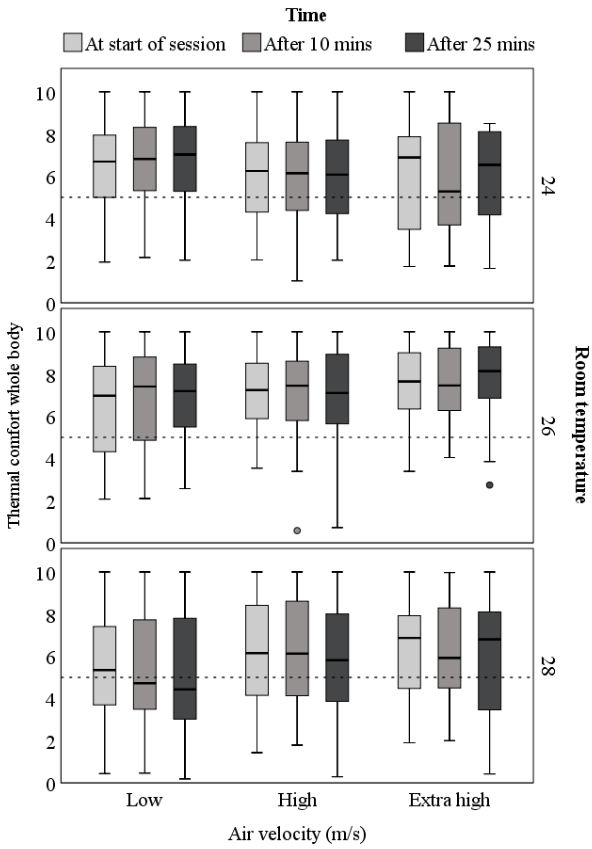

Figure 5. Boxplots of the scores for thermal comfort for the whole body by room temperature and air flow (at different questionnaire rounds. The dotted line indicates “just comfortable/just uncomfortable”. The line in the middles of the boxplots is the median value.

The test persons were also asked if they wanted more or less air or if the situation is suitable and they want no change in air velocity. Table 4 shows the preferences of the test persons. At 24 °C the majority of the test persons preferred low air velocity (62%), and 68.5% wanted less air at extra high air velocity. At 26 °C, most test persons (55.1%) wanted more air at low air velocity, and high (56.3%) or extra high (70.2%) air velocity were preferred

Moreover, at room temperature 28 °C, 57.6% preferred extra high air velocity. Most test persons wanted more air at both low (83.9%) and high (60.7%) air velocity

As shown in table 4, we see small differences in air velocity preferences between chest and head, but when the air jet is directed to the head, there is slight tendency to desire more air, particularly at room temperatures higher than 24ºC.

Table 4. Air velocity preferences for different jet air velocities.

T [ºC]	Air velocity	Position	Air jet velocity		
			Extra high [%]	**High [%]**	**Low [%]**
24ºC	More	Chest	1.8	0.5	11.1
		Head	1.8	2.3	9.7
		Overall	**3.7**	**2.8**	**28.8**
	OK	Chest	18.5	25.0	30.5
		Head	9.3	26.8	31.5
		Overall	**27.8**	**51.8**	**62.0**
	Less	Chest	35.2	24.1	8.3
		Head	33.3	21.3	8.8
		Overall	**68.5**	**45.4**	**17.1**
26ºC	More	Chest	0.0	9.7	26.7
		Head	7.0	17.6	28.4
		Overall	**7.0**	**27.3**	**55.1**
	OK	Chest	31.6	30.7	20.7
		Head	38.6	25.6	19.1
		Overall	**70.2**	**56.3**	**39.8**
	Less	Chest	15.8	9.2	2.5
		Head	7.0	7.1	2.5
		Overall	**22.8**	**16.4**	**5.1**
28ºC	More	Chest	15.3	30.4	39.8
		Head	22.0	30.4	44.1
		Overall	**37.3**	**60.8**	**83.9**
	OK	Chest	32.2	18.1	8.9
		Head	25.4	17.7	6.4
		Overall	**57.6**	**35.9**	**15.3**
	Less	Chest	3.4	2.1	0.9
		Head	1.7	1.3	0
		Overall	**5.1**	**3.4**	**0.9**

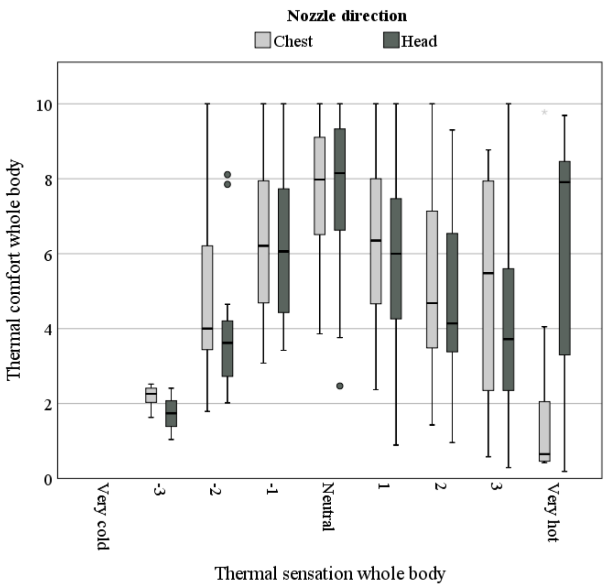

Figure 6. Relationship between thermal comfort and thermal sensation evaluation with nozzle pointing at the chest or the head.

Figure 6 shows that when the test persons are on the warm side of thermal sensation scale, the thermal comfort scores are slightly better when the nozzle is pointing at the chest than to the head. However, nozzle pointed at head is preferred when the test persons feel very hot.

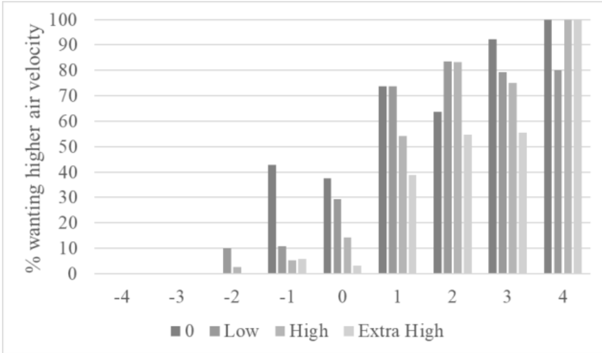

Figure 7. Higher air velocity (0 = reference session) demand according to thermal sensation (-4 to 4).

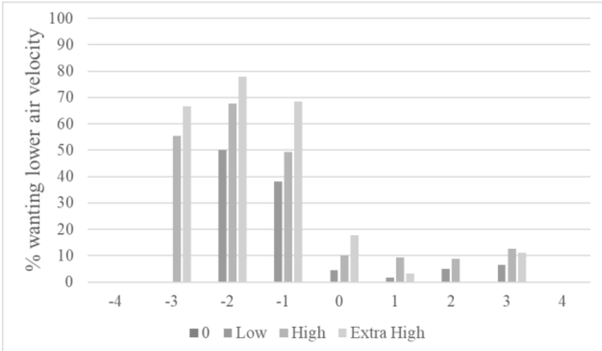

Figure 8. Lower air velocity (0 = reference session) demand according to thermal sensation (-4 to 4).

Figures 7 and 8 show that test persons scoring on the warm side of the thermal sensation scale wanted increasingly higher air velocity, while test persons being on the cold side wanted decreasingly lower air velocity.

3.4 Individual variations

The distribution of overall thermal comfort by room temperature and thermal sensation is showed in figure 9. The test persons are more comfortable with being slightly cool at room temperature 26 °C and 28 °C than at 24 °C. Moreover, they are also more comfortable being slightly warm at 24 °C than at 28 °C.

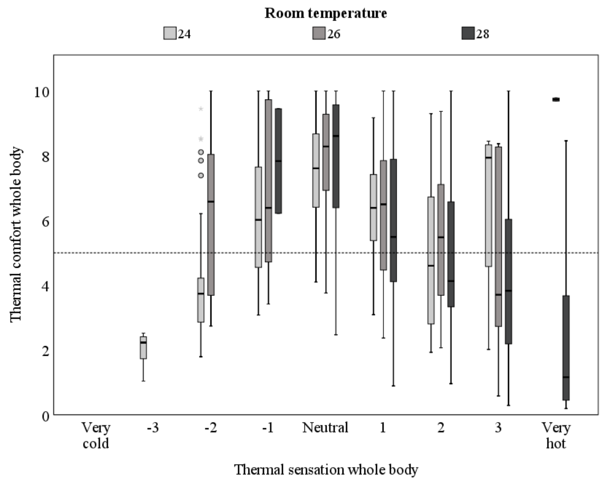

Figure 9. Relationship between overall thermal comfort and thermal sensation at different room temperatures.

Table 5. Overview of acceptable thermal score by test persons at different conditions. X denotes no data. **Gray square: lowest thermal score > 5.** PD = percentage dissatisfied. Each square represents 1-12 individual questionnaire answers.

	24 °C				26 °C				28 °C				
ID	**0**	**Low**	**High**	**Extra high**	**0**	**Low**	**High**	**Extra high**	**0**	**Low**	**High**	**Extra high**	**%PD**
1	■			■	■		■	■					**37**
2	■	■	■	■	■	■	■	■	■	■	■	■	**0**
3	■	■	■	■	■	■	■	■	■	■	■	■	**0**
4								■				■	**48**
5	■	■	■	■	■	■	■	■	■		■	■	**1**
6	■	■			■	■	■		■	■	■	■	**6**
7	■			■	■				■				**30**
8	■	■			■	■	■	■	■			■	**14**
9	■							x	■				**79**
10	■	■	■	■	x	x	x	x				■	**36**
11	■	■	■	■	■	■	■	■	x	x	x	X	**0**
12	x	x	x	x				■					**50**
13	■				■	■	■	■					**31**
14					■			■					**34**
15	x	x	x	x				■				■	**54**
16					■	■			■	■	■	■	**20**
17	■				■	■						■	**45**
18	■				■	■	■	■		■	■	■	**31**
19													**76**
20								■				■	**60**
21	x	x	x	x	■			■	■		■	■	**18**
%	**26**	**24**	**37**	**44**	**30**	**26**	**18**	**14**	**57**	**52**	**35**	**29**	

Table 5 shows an overview of the conditions where each test persons always gave an acceptable thermal score (> 5, dark squares). We see individual variations as some are always satisfied while others are always dissatisfied, regardless of room temperature or air velocity. The lowest percentage dissatisfied were seen for 26 °C (14-30%), while the highest percentage dissatisfied were seen 28 °C with 0 (57%) and low (52%) air velocities.

4. Discussions

We found that with higher room temperatures, the test persons also wanted higher air velocities. At 28 °C, some test persons also wanted even higher air velocity than what was provided by the air jets.

Simone and Olesen [9], who studied preferred local air velocities by desk fans, found that Scandinavians' preferred air velocities were 0.7 m/s at 26 °C and 0.8 m/s at 28 °C at 1.2 met and 0.5-0.6 clo. Our test persons, at 0.7 clo, show similar preferences. Thermal comfort was reported also at lower air velocities.

A review article comparing 14 studies of frontal air jets observed that at 26-27 °C air velocities between 0.36-0.6 m/s created a corrective power of -1K to -3K. "Power" here refers to temperature-correcting capability [10]. At 28 °C similar air speeds created a corrective power of -2K to -3K. Cooling by ceiling fan is found to be stronger, with a corrective power of -3K for air speeds between 0.25-0.6 m/s at 26 °C and as strong as -4K at 28 °C. The neutral temperature for persons at 1.2 met is 23 °C according to ASHRAE standard 55 [1]. A corrective power of -3K is then needed at 26 °C and of -5 at 28 °C.

The corrective power of the individual air velocities cannot be precisely determined from our experiments, but as the lowest PD % in all experimental condition was at 26 °C and high/extra high speed, a corrective power of -3K at 0.5-0.75 m/s is not unreasonable.

Airflow characteristics should also be considered. This is studied by Zhou et al. [4], Zhu et al. [5] and Huang et al. [3]. According to Huang et al. [3] airflow fluctuations can offset the temperature, and 0.6 m/s at 28 °C can be enough to make test persons feel thermal neutral and almost comfortable. Fluctuations were recorded in our experiment but will be analysed in another paper.

The results for the overall thermal comfort indicated that being slightly cool in a room temperature of 28 °C is clearly more comfortable than at 24 °C. Similarly, it is more comfortable to be slightly warm at room temperature 24 °C than at 28 °C. This could be due to the phenomenon alliesthesia, a physiological basis for thermal pleasure or delight in non-steady-state thermal environment [11,12]. When a person is slightly warm, increased air movement is associated with positive perceptual response. The air movement will chill the body towards neutral state, resulting in even higher thermal comfort than no air movement at neutral state. Our results show that cooling by air jet in higher room temperature is regarded as comfortable even if the person is feeling slightly cool.

Our results could possibly be affected by *temporal* alliesthesia, an instant pleasure of thermal influence when not being at neutral state. However, the results indicate that the temporal effect was minor, as thermal comfort and sensation was reasonably stable throughout each experiment.

In our experiments, we find only minor differences in thermal comfort or wanting more or less air for test persons with nozzle pointing the towards the head compared to chest. A possible explanation is that when the air jet reached the test persons, it was not a narrow and concentrated air stream. The head position was also influencing neck and upper chest, whereas chest position was also influencing neck and chin. This lowered the effect of variation.

We found that the higher air velocities bring the test persons to a state below neutral at 24 °C, but generally leaves them neutral to hot at room temperature 28 °C. This confirms the need of higher air velocity at the highest room temperature. Furthermore, some persons wanted more air already when feeling slightly cold. Higher air velocities can be not only acceptable but also desirable.

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Our results show that higher air velocities from ceiling mounted air nozzles can be used as an energy efficient solution for cooling.

5. Conclusions

Ceiling mounted supply air nozzles providing small jets with higher air velocity can improve thermal comfort for people performing office work in room temperature 24 °C, 26 °C and 28 °C. At a room temperature of 26 °C and above, extra high or even higher air velocities were seen to yield better thermal comfort. Individual differences indicate that individual control allows more optimized thermal comfort. Moreover, a position with jet-centre around the persons nose/chin would chill both head and chest.

For the future laboratory experiments, the effect of different supply air temperature and higher maximum air velocity should be investigated.

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