Air heating of passive house office buildings in cold climates – how high supply temperature is acceptable?

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ABSTRACT

The impact of over-tempered air on the perceived indoor climate was evaluated by questionnaires filled in by the users of the first office building with passive house standard in Norway. In this building, the heating demand is covered entirely by warm air supplied into the rooms through the ventilation system.

On the coldest days of January 2014, warm ventilation air was supplied into the rooms at a constant temperature during half an hour. Each user of the building was exposed to 3 different supply temperatures (around 21.5°C, 24°C and 26°C) under the minimum ventilation rate according to the Norwegian standards (17 l/s). Questions related to both perceived thermal comfort and Sick Building Syndrome-symptoms (SBS; feeling tired, headache, etc.) were answered by all the occupants on a scale of 0 (unsatisfied) to 10 (satisfied). The data from the questionnaires were then analyzed using a random effect linear regression model.

The regression analysis did not report any significant relationship between the supply air temperature, and perceived thermal comfort and SBS. It enables to document with a 95% certainty that increasing the difference between supply air and room temperature by 1°C would cause a maximum reduction of the SBS score of 1.02 points on a scale of 190. The impact of an increase of the supply temperature on the perceived SBS seems therefore very limited.

Using air heating to completely cover the heating demand therefore appears to be a relevant solution for office buildings in cold climate with passive house standard.

KEYWORDS

Ventilation, air heating, passive house, questionnaires, indoor climate

1 INTRODUCTION

The GK environmental house is the first office building with passive house standard in Norway (see Figure 1a). It is located in Oslo, and was taken into use in August 2012. In this building, the heating demand is covered entirely by warm air supplied into the rooms through the ventilation system. Active air supply diffusers are then used to control the ventilation rate according to room temperature and occupancy (Demand-Controlled Ventilation).

While this solution sounds appealing, it is not clear whether air heating alone can ensure an acceptable indoor climate in the cold climate of Norway. In fact, short-circuiting of the warm ventilation air may occur if the temperature difference between supply and room temperature is high, which may be the case during the coldest days.

This can be responsible for a poor perceived indoor air quality and impact the well-being and productivity of the occupants (Sundell, 2011).

In this context, the research and development project Forklima is carried out in the building (http://www.sintef.no/Projectweb/For-Klima/). The aim of this project is to assess whether it is possible to cover the heating demand with warm ventilation air exclusively in office buildings with passive house standard, while maintaining an acceptable thermal comfort and indoor air quality. In the present paper, the impact of over-tempered air on the perceived indoor climate was evaluated by questionnaires filled in by the employees located in the open plan offices of the building, see Figure 1b.

Evaluating the perceived indoor climate in buildings satisfying the passive house standard (NS3701, 2012) is crucial to validate their use in countries with cold climate. The aim of this study is to do so with occupants carrying out their daily tasks in real conditions, and therefore to provide a valuable addition to studies of the perceived indoor climate in controlled conditions.

Figure 1: a) GK environmental building, Oslo. b) View of the open plan offices.

2 METHODOLOGIES

The experiments were carried out on January 23 and January 24, 2014 which were among the coldest days of January 2014 in Oslo. In order to assess the impact of air heating on the perceived indoor climate, over-tempered ventilation air was supplied into the open plan offices through mixing ventilation diffusers located at ceiling height.

An active supply diffuser is located above each desk, covering 2 to 4 persons, and continuously recording the supply airflow rate, supply temperature, as well the air temperature in the room. The control and monitoring were carried out from a distance through the Building Management System, see Figure 2.

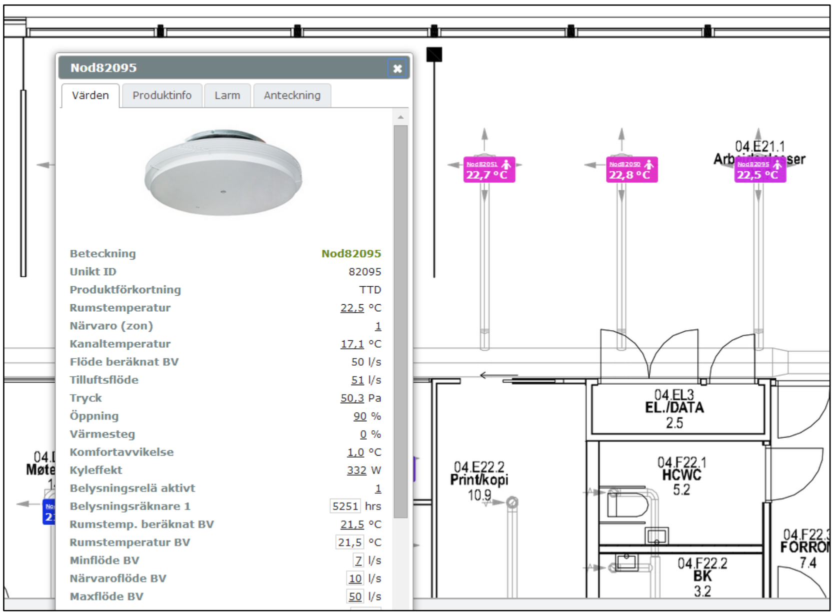

Figure 2: Remote control and monitoring of the supply airflow rate, supply temperature and room temperature for each diffuser of the building.

Interventions on the supply temperature were carried out from 10:00 to 10:30 and from 14:00 to 14:30, on both January 23 and 24. On January 23 from 10:00 to 10:30 am, the plan for the interventions were to have a supply temperature for the south and north part of the building of 24°C and 21°C, respectively (see Table 1). On January 23 2:00 – 2:30 pm, the supply temperatures were switched for the two parts of the building. On January 24, the interventions were carried out in the same way as the previous day, except that the high supply temperature was changed from 24°C to 26°C, see Table 2. In such a cross-over experiment, each user in the building was exposed to all three supply temperatures. In addition, the minimum ventilation rate according to the Norwegian standards was used (17 l/s).

A consequence of the high performance of the envelope of the building is that there is no need for a too high supply air temperature to maintain an acceptable indoor temperature. Therefore, the length of the interventions was reduced to half an hour in order to not cause a rise of the indoor temperature, and therefore study the impact of over-tempered air of the perceived indoor climate, and not the impact of the temperature level.

Table 1: Plan for the cross-over experiment on January 23

Date	**23rd January 10:00-10:30**		**23rd January 14:00-14:30**	
Part of building	South	North	South	North
Supply temperature T_s	21,5°C	24°C	24°C	21,5°C
Ventilation rate	17 l/s	17 l/s	17 l/s	17 l/s

Table 2: Plan for the cross-over experiment on January 24

Date	**24th January 10:00-10:30**		**24th January 14:00-14:30**	
Part of building	South	North	South	North
Supply temperature T_s	21,5°C	26°C	26°C	21,5°C
Ventilation rate	17 l/s	17 l/s	17 l/s	17 l/s

A questionnaire was answered by the users at the end of each of the four interventions in order to measure the users' perceived health and well-being. The questions included in the questionnaire are shown in Table 6, and the questionnaire was handled to the occupants through a web-based application. On each question, the users gave a value between one and ten ranging from very uncomfortable to very comfortable. The sum, *S*, of all the scores for a given user, represents the overall health and well-being for this user. The questionnaire also included health question like whether a used suffered from asthma or cold.

Data from the questionnaires were analyzed using a random effect linear regression model with *S* as the dependent variable. The supply air temperature was included in the model as a continuous independent variable. The effect of supply temperature on *S* was controlled for differences in gender and whether a user suffered from asthma or cold by including these variables in the model. Furthermore, we expect that repeated measures from the same user is correlated, *ie.* some users are always too cold and some users are always tired, and this was taken into account by including a random effect on the user level in the regression model. Statistical analyses were performed using the program R (R development team, 2013) and the R package lme4 (Bates, 2013).

In addition, the results obtained during both days were compared to the results obtained from a questionnaire run on November 19, 2013 under normal operating conditions for the building. That corresponds to a supply temperature and a ventilation rate varying according to the demand measured in each room, *ie.* Demand-Controlled Ventilation.

The numbers of participants answering the questionnaire for the four interventions were 34, 31, 24 and 25. On November 19, 46 persons answered.

3 RESULTS AND DISCUSSION

3.1 Actual conditions during the experiments

The measured conditions (supply and average room temperature for each part of the building) during the experiments are reported in Table 3 for January 23, and in Table 4 for January 24. The reported supply temperatures correspond to the average of the temperature at the exit of the Air Handling Unit over the 30 minutes of each intervention. The average room temperature corresponds to the average of the temperature measured by all the active diffusers in the buildings.

Table 3: Measured conditions during the test on January 23, 2014

Date	**January 23 10:00-10:30**		**January 23 14:00-14:30**	
Part of building	South	North	South	North
Supply temperature T_s [ºC]	24.5	21.0	21.2	24.1
Average room temperature [ºC]	22.3	22.0	22.4	22.4
Outdoor temperature [ºC]	-6.2		-4.9	
Outdoor conditions	Cloudy		Cloudy	

Table 4: Measured conditions during the test on January 24, 2014

Date	**January 24 10:00-10:30**		**January 24 14:00-14:30**	
Part of building	South	North	South	North
Supply temperature T_s [ºC]	26.7	21.3	21.4	26.3
Average room temperature [ºC]	22.0	22.1	22.2	22.3
Outdoor temperature [ºC]	-6.3		-4.5	
Outdoor conditions	Cloudy		Cloudy	

We can see that the measured supply air temperature during the tests on January 23 and 24 in both parts of the building are in good agreement with the plan for the cross-over experiments presented in Table 1 and Table 2. In addition, the outdoor conditions were similar on both days. Futhermore, the average room temperature during the experiments is similar during all experiments, ranging from 22.0°C to 22.4°C. This enables to say that the evaluated parameter is indeed the use of over-tempered air, and not the temperature level. In fact, the temperature rose only slightly during the interventions by about 0.5 ºC.

The measured conditions inside of the building during the intervention on November 19 under normal operating conditions are presented in Table 5. We can see that the conditions on that day corresponds to the use of a supply air temperature below room temperature in order to compensate for the internal heat gains, and maintain an acceptable indoor temperature. There again, the average room temperature was similar to the average room temperature during the interventions on January 23 and 24.

Table 5: Measured conditions during the test on November 19, 2013

Date	**November 19 06:00-14:00**	
Part of building	South	North
Supply temperature T_s [ºC]	15.9	15.6
Average room temperature [ºC]	22.3	22.0
Outdoor temperature [ºC]	4.1	
Outdoor conditions	Slightly cloudy	

3.2 Perceived indoor climate on January 23 and 24

The questionnaire handled to each occupant of the building is presented in Table 6, as well as the average score for each question of the questionnaire, describing the well-being on a scale of 1 (uncomfortable) to 10 (comfortable), for the different supply temperatures.

Table 6: Questionnaire with average score corresponding to the different ventilation strategies.

Questions	November 19	T_s=21°C	T_s=24°C	T_s=26°C
Are you tired?	6.43	7.67	7.16	8.08
Does your head feel heavy?	6.83	8.29	7.46	8.48
Do you have a headache?	8.07	8.73	8.16	8.92
Do you feel faint or dizzy?	8.26	8.79	8.65	8.60
Do you have problems concentrating?	6.87	7.52	7.46	8.20
Do your eyes feel itchy or burning?	8.39	8.65	8.46	8.64
Do you feel hoarse or does your throat feel dry?	8.17	8.90	8.43	9.24
Does your face or your hands fell itchy or burning?	9.20	8.77	8.57	9.16
Do you feel nauseous or otherwise unwell?	9.37	9.62	9.49	9.16
Is it too warm?	7.76	8.37	7.86	8.48
Is there bothersome warmth because of sunshine?	8.26	9.15	9.05	9.60
Is it too cold?	8.00	8.27	8.54	9.12
Do you feel a draught around your feet or your neck?	9.37	8.71	8.86	9.32
Are there bothersome variations of temperature?	8.85	8.19	8.59	8.56
Does the air feel heavy?	7.80	8.48	7.62	8.04
Does the air feel dry?	8.02	8.29	8.00	8.84
Is there any unpleasant smell?	9.48	9.54	9.49	9.80
Do you have a stuffy or runny nose?	9.30	9.33	8.95	9.80
Do you cough?	8.96	9.04	8.84	9.12

The users feel quite well overall, with almost all average scores above eight. Furthermore, the average scores appears to be relatively close to each other.

Table 7 shows the results from the regression analysis. All answered questionnaires (34+31+ 24+25=114) were included in the analysis.

Table 7: Results from the linear regression

Parameter	Estimate	St. err.	df	t value	p value
Supply temperature	-0.16	0.52	59.55	-0.31	0.755
Gender male (reference: female)	19.42	7.82	51.01	2.48	0.016 *
Asthma (reference: No asthma)	17.29	16.83	50.42	1.03	0.309
Has a cold (reference: No cold)	4.98	5.37	72.07	0.93	0.357

*Signif. codes: p-value < 0.01:**, p-value < 0.05:**

This regression analysis did not report any significant relationship between the supply air temperature, and perceived thermal comfort and SBS (*S*). On the other hand, the regression analysis documents with a 95% certainty that increasing the difference between supply air and room temperature by 1°C will cause a maximum reduction of the SBS score (*S*) of 1.02 point (-0.16 - quantile_studT(0.95, 59.55)*0.52 = -0.16 -1.67*0.52 = -1.02). This reduction is minimal, since a typical score for *S* is between 100 and 160 for the users on the questionnaire. We also observe that the perceived indoor climate is better for male users, but that there is no significant difference in the perceived indoor climate for users with asthma or cold.

3.3 Comparison with the perceived indoor climate on November 19

In a second time, the perceived indoor climate on November 19 during normal operating conditions in the building is compared to the perceived indoor climate with a supply temperature of 24°C and 26°C; see Table 8 and Table 9 for the results from the regression analysis. All answered questionnaires (34+31+ 24+25+46=160) were included in the analysis.

Table 8: Comparison of the perceived indoor climate with Ts=24°C with control Ts=21°C and control November 19 (normal operating conditions).

Parameter	**Estimate**	**St. err.**	**df**	**t value**	**p value**
T_s=24°C (reference: T_s=21°C)	2.836	2.361	60.640	1.201	0.2343
November 19 (reference: T_s=21°C)	-2.151	2.686	65.150	-0.801	0.4262
Gender male (reference: female)	17.996	6.818	71.520	2.640	0.0102 *
Asthma (reference: No asthma)	19.442	11.422	73.540	1.702	0.0929
Has a cold (reference: No cold)	10.005	4.427	72.080	2.260	0.0268 *

*Signif. codes: p-value < 0.01:**, p-value < 0.05:**

Table 9: Comparison of the perceived indoor climate with T_s=26°C with control T_s=21°C and control November 19 (normal operating conditions).

Parameter	**Estimate**	**St. err.**	**df**	**t value**	**p value**
T_s=26°C (reference: T_s=21°C)	-0.3305	2.9678	52.3600	-0.111	0.91174
November 19 (reference: T_s=21°C)	-6.9514	3.3516	57.9300	-2.074	0.04253 *
Gender male (reference: female)	20.8096	6.6642	66.8900	3.123	0.00265 **
Asthma (reference: No asthma)	20.0683	10.9914	68.3500	1.826	0.07225
Has a cold (reference: No cold)	9.6786	4.9827	70.1200	1.942	0.05610

*Signif. codes: p-value < 0.01:**, p-value < 0.05:**

The regression analysis documents with a 95% certainty that:

- the mean score *S* with supply temperature 24°C is with 95% certainty less than –2.836 + 1.67*2.361 = 1.11 worse than the mean score *S* with supply temperature 21°C, and a supply temperature of 26°C is with 95% certainty less than 5.3 worse than 21°C.

- the mean score *S* with supply temperature 24°C is less than 1.67 worse than the mean score *S* on November 19 under normal operating conditions.

- The score *S* with supply temperature 26°C is significantly better (higher score) then compared to November 19 with p-value 0.043.

The results indicate that the perceived indoor climate was better for short periods with supply temperature of 24°C and 26°C compared to November 19. This result may be due to the fact that the supply temperature on November 19 was of on average of 15.6°C and 15.9°C, see Table 5, which is quite low. Indeed, the scores in Table 6 indicate that the users find the environment slightly cold (with a score of 8.00 for the question "Is it too cold?"). There is however no indication that the users suffered from discomfort by draught, with a score of 9.37 to the related question. Furthermore, it can be noticed that the users were feeling more tired and had more trouble to concentrate on November 19 than on January 23 and 24. It could be possible that we observe the fact that November is a month were many people are typically feeling tired in Norway (transition to winter, poor weather, many have worked all autumn without vacations etc.).

4 CONCLUSIONS

This study enabled to document that the supply of over-tempered air as high as 4°C above room temperature over short time periods provided a good perceived indoor climate in the open plan offices of the building. Using air heating to completely cover the heating demand therefore appears to be a relevant solution for buildings in cold climate with very low heating demand.

This confirms the results presented in a previous paper (Cablé, 2014) concerning field measurements of the thermal comfort and ventilation efficiency in a cubicle office of the same building. The latter reported a good ventilation efficiency and thermal comfort even under unfavourable conditions (*ie.* high supply air temperature and low ventilation rate), provided that heat sources were present in the room.

However, winter 2013/2014 was particularly mild in the Norwegian context. The study will therefore be repeated during winter 2014/2015 in order to confirm the obtained results and conclusions.

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