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A new methodology for the evaluation of the perceived air quality depending on the air pollution, caused by human bioeffluents, the temperature, the humidity as well as the air velocity

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ABSTRACT
Different researchers found an influence of the air temperature, the air humidity and the air velocity on the perceived air quality, which within the olf-decipol method of Fanger is not taken into account. It is possible, with the aid of the freshness of the air and the olf-decipol method of Fanger, to distract a methodology for the evaluation of the perceived air quality depending on the air temperature, the air humidity and the air pollution, caused by human bioeffluents. The aim of this study is to incorporate air velocity at neck height, as an extra parameter in this methodology, as well.

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Perceived air quality; human bioeffluents; olf; decipol; temperature; humidity; air velocity; freshness; percentage of dissatisfied; performance; fatigue

Introduction

Almost 30 years ago Fanger published for the first time a method to assess the perceived indoor air quality (Fanger 1988), on the basis of new concepts. This method uses the air quality assessed through the human nose by a group of people (panel) that is trained in observing the air quality (Bluyssen 1990). Fanger introduced two new concepts, namely the olf and the observed decipol respectively for air pollution and air quality.

Later on, other researchers noted the influence of air enthalpy on the perceived air quality that within the olf-decipol method of Fanger is not taken into account (Berglund and Cain 1989; Fang, Clausen, and Fanger 1998). Today, there is no generally applicable mathematical model with which the percentage of dissatisfied due to the perceived air quality as a function of the air temperature and the air humidity can be expressed and that takes into account all forms of air pollution (e.g. caused by humans, the interior, the ventilation system and the outdoor air) in practice, without making use of a group of trained people on observing the air quality. For the time being there is no handy and reliable electronical device in trade that, quickly, easily, used by one person and without much costs, measures the perceived indoor air quality, in accordance with the olf-decipol method of Fanger. This makes the applicability of the olf-decipol method in practice difficult.

Besides that, there is another problem with regard to the olf-decipol method which has to be solved. In the approach of the olf-decipol method the perceived air quality is modeled using one exposure–response relationship between ventilation rate and the perceived quality of air polluted by human bioeffluents, independently of the type of pollution source. But as shown in a research

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of Knudsen, Wargocki, and Vondruskova (2006) the relationship between the ventilation rate and the perceived quality of air polluted by human bioeffluents is different from the corresponding relationships for building materials. The slope of 0.25 ± 0.08 between the acceptability of the perceived air quality and the amount of fresh air [in Log L/s/person], in the case of human bioeffluents, is lower for the majority of the building materials. This implies that the effect on the perceived air quality of a change in ventilation rate will be underestimated when using the relationship for human bioeffluents rather than the actual relationship (Knudsen, Wargocki, and Vondruskova 2006). However, the olf-decipol method has been developed on the basis of the air pollution caused by humans, on which this study is limited.

As long as there is no handy and reliable electronically device in trade, to measure the perceived indoor air quality, it is obvious to consider to which extent, with relatively simple to determine indicators such as the CO and the CO_2 percentage, a right connection can be found with the latest insights (Roelofsen 1998, 2003). Following the aforesaid problems, Clements-Croome proposed the freshness of the air as a scale to determine the percentage of dissatisfied due to the perceived air quality as a function of the freshness instead of the decipol (2008). The aim of this research is to examine to what extent using the freshness of the air and the olf-decipol method of Fanger an in practice usable methodology for the evaluation of the perceived air quality is to derive, depending on the temperature and the humidity of the air and the air pollution caused by human bioeffluents; also in view of the current laws and regulations. After all most regulations for indoor air quality consider only the air pollution that people cause, since this source is unavoidable. Other air pollution sources affecting indoor air quality (such as indoor surface materials, installations, the building and the outdoor air) in laws and regulations are often disregarded and are the responsibility of the market parties (Roelofsen 2012).

The research of Berglund and Cain (1989) is the first, well documented, research (with full body exposure) in which the influence of the air temperature and the air humidity on the perceived air quality is demonstrated and where the subjects themselves are the only source of contamination. In the later research of Fang, Clausen, and Fanger (1998) certain building materials are the sources of pollution. Having regard to the objective it seems, therefore, to make sense at first to start off on the basis of the research of Berglund and Cain (1989). For the used models and an extended discussion of the influence of the air temperature and the humidity on the perceived air quality is referred to (Roelofsen 2016). An electronic version of this Ph.D Thesis (Roelofsen 2016) is available at https://repository.tudelft.nl/.

Research Berglund & Cain

The research was conducted in a test chamber using a group of 20 persons, consisting of 10 men and 10 women aged from 18 to 62 years, which were divided into groups of 5 people. The temperature and relative humidity in the test room were adjustable. The ventilation amounted 267 ± 31 m^3/h. Subjects responses were measured at three metabolisms, namely: 0.94 met (sitting), 1.95 met (five-minute walk, stand for five minutes) and 2.82 met (continuous walking). The average clothing resistance was 0.56 ± 0.04 clo. All test subjects took part in 27 different tests of 1 hour, defined by the combination of 3 air temperatures, 3 relative humidities and 3 metabolisms.

Of five people the body temperature, the skin temperature, the heart rate and the skin humidity were continuously measured, while two times each test the oxygen consumption was measured. From this, the actual metabolism could accurately be calculated. The subjects gave immediately after entering the test room and every 15 minutes after that their judgement on the indoor air quality on the basis of a questionnaire. Three questions were directly related to the air quality (freshness, stuffiness, acceptability) and four indirectly (skin moisture, humidity, air motion and thermal sensation).

The research showed, in addition to the influence of the enthalpy of the air on the perceived air quality, also that the air temperature had a somewhat more potent influence on perceived air quality than did humidity. The chamber contained essentially no active odor sources, except for the occupants themselves, and had the relatively high ventilation rate of at least 15 l/s per person of clean air. The perceived air quality and the freshness of the air turned out to be almost independent of the time within the experiment. This was not due to adaptation since the maximum exposure time was 1 hour and research shows that adaptation occurs only after approximately 1-hour exposure (Fang et al. 2004). A person's olfactory system adapts to odor in a short time so odor intensity decreases with exposure, but in this case the staleness perception did not diminish with time, implying that the chamber air was odorless.

It was concluded that the temperature and the humidity of the air in certain cases might be of larger affect on the perceived air quality than the air pollution itself. Which supports the proposal by Clements-Croome to use the freshness of the air as a scale to evaluate the perceived air quality. In this regard, the freshness of the air is the perception of the air quality, depending on the temperature, humidity, pollution and the velocity of the air.

Freshness of air

One of the aims of the research in Roelofsen (2016) was the mathematical relationship between the freshness of the air, the air pollution caused by human bioeffluents, the air temperature and the air humidity. For that, use was made of the research results of Berglund and Cain (1989).

By means of multiple regression analysis, the relationship was established with the freshness of the air as a function of the ratio of the rate of air pollution generation to the rate of fresh air inlet flow as well as the dry and the latent heat transfer on the surface of the nasal mucosa. The heat transfer in the nose was taken because the nose is the primary sensory surface where the freshness of the air is observed. In Roelofsen (2016) analysis by multiple regression obtained an equation for the freshness of the air, on the basis of an air pollution load balance and a heat and moisture balance of the nasal mucosa:

$$F = a + b*(t_{\text{nasalmucosa}} - \text{ta}) + c*(\text{pa}_{\text{nasalmucosa}} - 0.01*\text{pa}) + d*10*G/(V*\varepsilon), \{R^2 = 0.918; \sigma = 0.239\}.$$

Herein is:

- F : freshness of the air, according to a seven-point scale (0–6)
- ta : air temperature (°C)
- $t_{\text{nasal mucosa}}$: mean temperature of the nasal mucosa surface (°C)
- $\text{pa}_{\text{nasal mucosa}}$: mean vapor pressure at the nasal mucosa surface (Pa)
- pa : vapor pressure of the air (Pa)
- G : air pollution load (olf)
- V : fresh air quantity (l/s)
- ε : ventilation-effectiveness, according to NPR-CR-1752 (1999)
- a–d : regression coefficients (–).

In Figure 1 the observed values (Berglund and Cain 1989) and the predicted values for the freshness of the air (see equation above) are compared with each other.

The developed model in Roelofsen (2016) is valid for:
$21°\text{C} \leq \text{ta} \leq 27°\text{C}$
$717 \text{ Pa} \leq \text{pa} \leq 2339 \text{ Pa}$
$3.9 \text{ l/(s.olf)} \leq V/G \leq 16.3 \text{ l/(s.olf)}$
$0.94 \text{ met} \leq \text{metabolism} \leq 2.82 \text{ met}$
$18 \leq \text{age} \leq 62$ years.

Figure 1 shows that the predicted freshness of the air well matches with the observed freshness of the air.

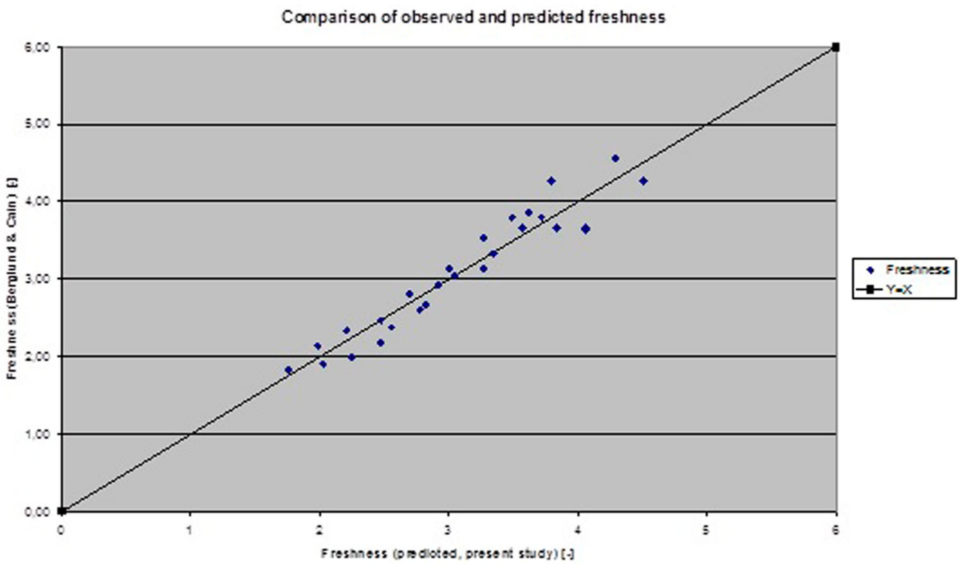

Figure 1. Comparison of observed and predicted freshness (Roelofsen 2016).

The percentage of dissatisfied

In the research of Berglund & Cain, the subjects were not explicitly asked about the dissatisfaction but if the observed air quality was sufficiently unacceptable for them to make a change as in leave the place, open a window, turn on a fan, etc. For the research in Roelofsen (2016), it was assumed that the number of dissatisfied is determined by the subjects who find the observed air quality sufficiently unacceptable to make a change. With this premise, based on the research results of Berglund & Cain, a function for the percentage of dissatisfied was derived (Roelofsen 2016).

Influence of air velocity on the freshness of the air

The influence of air movement on the freshness of the air was examined for warm environments by Zhai et al. (2015). In a climate chamber controlled at 3 temperatures (26°C, 28°C and 30°C) and 2 relative humidity levels (60% and 80%), 16 subjects (8 males and 8 females) dressed in summer clothing (0.5 clo) were exposed to 7 levels of air speed ranging from 0.05 to 1.8 m/s. The subjects were asked to rate their thermal sensation, comfort, perceived air quality, air movement acceptability, humidity sensation and eye-dryness during the 2-hour-and-15-minute-long tests. Air movement significantly improved the subjects thermal comfort, perceived air quality and humidity sensation without causing dry eye discomfort. Without air movement the 80% acceptable limit established by the ASHRAE standard 55 was reached at 26°C/RH 60%, 26°C/RH 80% and 28°C/RH 60%. With air movement, more than 80% of the subjects perceived the environments acceptable at 28°C/RH 80%, 30°C/RH 60% and 30°C/RH 80%. The preferred air speeds for ceiling fans were in many cases higher than the limit specified in the ASHRAE standard, which is 0.8 m/s when users have no control over the fan (Zhai et al. 2015). A study of Huang et al. (2014) showed that the differences in cooling between ceiling fans, ceiling jets and desk fans are small.

In this study analysis of the previously mentioned experimental results of Zhai et al. (2015) by multiple regression obtained a mathematical model for the freshness difference of the air, if the air velocity at neck height (seated: 1.1 m above floor) is larger than 0.05 m/s and reads:

$$\Delta F = a + b*(t_{nasalmucosa} - ta) + c*(pa_{nasalmucosa} - 0.01*pa) + d*.(v_{air} - 0.05), \{R^2 = 0.955; \sigma = 0.058\}.$$

Herein is:

- ΔF : freshness difference (–)
- $t_{nasal\ mucosa}$: mean temperature of the nasal mucosa surface (°C)
- $pa_{nasal\ mucosa}$: mean vapor pressure at the nasal mucosa surface (Pa)
- v_{air} : mean air velocity at neck height (m/s)
- ta : air temperature (°C)
- pa : vapor pressure of the air (Pa)
- a–d : regression coefficients (–).

The model is valid for:

- Activity level: 1 met
- Air temperature: ≥26°C
- Relative humidity: ≥60%
- Air velocity: $0.05 < v_{air} \leq 1.8$ (m/s).

To get an impression of the influence of air movement on the perceived air freshness for air, the model predictions for the freshness differences of the air are graphically displayed in Figure 2. The comfort area, according to air quality category C, is shaded green in the chart. The horizontal line in the green shaded area is the evaluation, on the basis of the CO_2-concentration, according to NPR-CR-1752 (1999).

In Figure 3 the influence of the air movement on the performance change, with regard of a category B air quality are shown, based on the research of Wargocki, Wyon, and Fanger (2000).

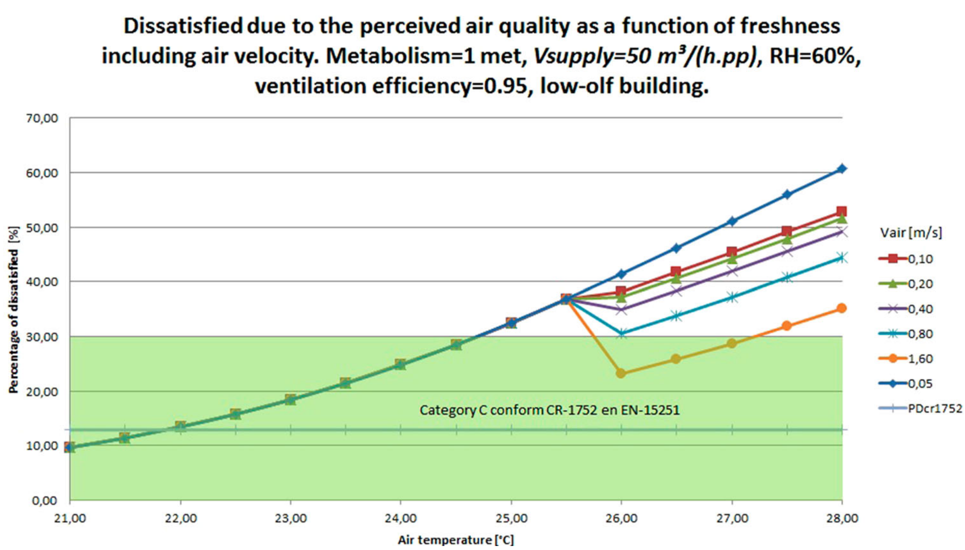

Figure 2. Dissatisfied due to the perceived air quality.

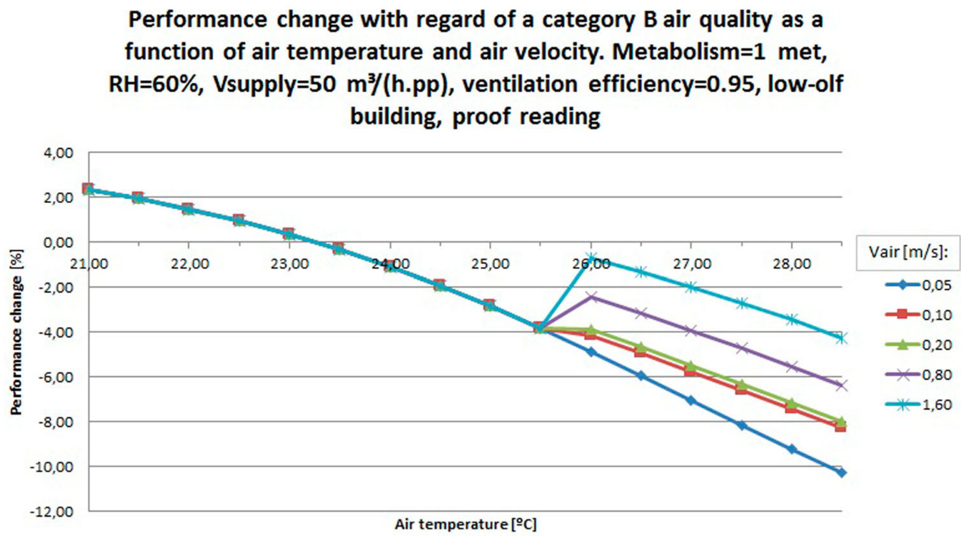

Figure 3. Performance change with regard to a category B air quality.

Conclusion

On the basis of this study and the research in (Roelofsen 2016), the following is concluded:

- The freshness of the air, polluted by people, is quite accurately calculated on the basis of the temperature, the humidity and the velocity of the air as well as the quotient of the amount of air pollution and the fresh air supplied
- As proposed by Clements-Croome (2008) it turns out to make sense to involve the freshness of the air in the evaluation of the perceived air quality, so the influence of air temperature and air humidity is taken into account
- The freshness of the air and the acceptance of the air quality are determined by the air temperature, the vapor pressure and the air pollution; and in terms of influence, in particular, in that order. This is also apparent from the examination of Fang, Clausen, and Fanger (1998, 2004)
- The calculated percentage of dissatisfied due to the perceived air quality, on the basis of the olf-decipol method of Fanger, without the influence of the temperature and humidity of the air, is about the average of the percentages calculated on the basis of the method as shown in this study
- The calculation results show that with an increase in metabolism and at rising air volumes (with a constant CO_2-concentration difference) also increases the percentage of dissatisfied and is larger than one would expect on the basis of the CO_2 concentration difference. This corresponds to one of the conclusions from the research by Rasmussen (1985) and Roelofsen (2003)
- In general one prefers indoor air with an average score for the freshness lower than 2.6 (i.e. 15% dissatisfied), according to the seven-point scale used here (0–6)
- Depending on the desired level of air quality the percentage of dissatisfied due to the perceived air quality as well as the (learning) performance, especially at an air temperature higher than ca. 23–24°C is significantly negative affected by the freshness of the air
- The need for fresh air implies a preference for radiant heating and cool designing above convective heating, which will result in a more pleasant indoor air quality and reduce the use of energy
- If a climate control system is deliberately designed on the basis of temperature transgressions, one needs to realize that the temperature transgressions strongly affect the freshness of the air and thus the percentage of dissatisfied due to the perceived air quality. The evaluation of the thermal indoor climate and the perceived air quality are in that situation not to be considered independently of each other

- If a climate control system is designed on the basis of temperature transgressions one should execute, in the design stage, not only temperature transgression calculations but also transgression calculations of the percentage of dissatisfied due to the perceived air quality to evaluate the indoor environment correctly. Ergo, this means another way of designing than is usual in the current professional practice
- The method described here lends itself to examine the perceived air pollution (in olf) by persons, based on a few relatively simple measurements of environmental parameters without having to use a group of trained people on air quality (so-called odor panels) (Roelofsen 2003)
- This method leads to a simplification of an in practice to perform air quality research, as long as there is no handy and reliable measuring device available for the measurement of the perceived air quality (Roelofsen 2003)
- With indoor temperatures above 25.5°C, an increased air speed at facial height will have a positive and profitable impact on the perceived air quality of employees in an organization
- The extent to which the air velocity and air flow direction at face height possibly affect the freshness of the air needs to be further examined.

Disclosure statement

No potential conflict of interest was reported by the author.

Notes on contributor

Paul Roelofsen studied Architecture, Urban Planning and Housing at the Eindhoven University of Technology specialising in the Physical Aspects of the Built Environment. The IFMA Award of Excellence for outstanding contributions to the Facility Management profession was presented to Paul in the USA in 2004 as well as an Award for Building Services Innovation in the Netherlands in 2007. In 2016 Paul received his Ph.D degree at the Delft University of Technology. Paul is a senior consultant at BAM Energy Systems, a visiting lecturer and a part time research fellow at the Delft University of Technology.

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