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Indoor Air Quality in the 21st Century: Search for Excellence

P. OLE FANGER

Abstract Field studies demonstrate that there are substantial numbers of dissatisfied people in many buildings, among them those suffering from sick building syndrome (SBS) symptoms, even though existing standards and guidelines are met. The reason is that the requirements specified in these standards are rather low, allowing a substantial group of people to become dissatisfied and to be adversely affected. A paradigm shift from rather mediocre to excellent indoor environments is foreseen in the 21st century. Based on existing information and on new research results, five principles are suggested as elements behind a new philosophy of excellence: 1) better indoor air quality increases productivity and decreases SBS symptoms; 2) unnecessary indoor pollution sources should be avoided; 3) the air should be served cool and dry to the occupants; 4) "personalized air", i.e. a small amount of clean air, should be served gently, close to the breathing zone of each individual; and 5) individual control of the thermal environment should be provided. These principles of excellence are compatible with energy efficiency and sustainability.

Key words Productivity; Pollution source control; Enthalpy; Personalized air; Individual thermal control.

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Introduction

The ambition for ventilation and indoor air quality in buildings is quite low. The philosophy since the 1930s has been to provide acceptable indoor air quality (IAQ), i.e. that a calculated substantial group of persons (e.g. 15, 20 or 30%) are foreseen to be dissatisfied, while the rest find the air quality barely acceptable. This thinking, reflected in many ventilation standards and guidelines (ASHRAE, 1999; CEN, 1998; ECA, 1992), has led in practice to quite a number of dissatisfied persons (as predicted), while there are usually only a few people who are ready to characterize indoor air quality as outstanding.

That substantial rates of dissatisfaction actually occur in many existing buildings is documented in numerous field studies (Fisk et al., 1993; Mendell, 1993; Sundell, 1994; Bluyssen et al., 1996). These field studies report also that many people suffer from SBS symptoms.

I think it is fair to say that the indoor air quality is quite mediocre in many buildings, even though existing standards may be met. We need a paradigm shift in the new century to search for excellence in the indoor environment. Our aim should be to provide indoor air that is perceived as fresh, pleasant and stimulating, with no negative effects on health, and a thermal environment perceived as comfortable by almost all occupants. In achieving this aim, due consideration must be given to energy efficiency and sustainability. Do we have the necessary information to implement this in practice? Yes, on thermal comfort we do have a comprehensive database, while our knowledge on indoor air quality is still rather incomplete. This reflects the complexity of the interaction between indoor air quality and human comfort and health. But we do have some information on indoor air quality, as well as important new research results that will have a significant impact on the design of future ventilated spaces for human occupants.

This article will discuss some principles and new research results believed to be essential for providing excellence in future indoor environments.

A Good Indoor Environment Pays

New research results document for the first time that the quality of indoor air has a significant and positive

Director, International Centre for Indoor Environment and Energy, Department of Energy Engineering, Bldg. 402, Technical University of Denmark, DK-2800 Lyngby, Denmark, www.ie.dtu.dk

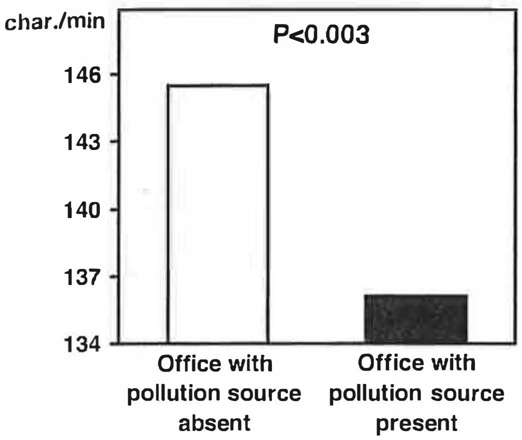

Fig. 1 Impact of indoor air pollution on productivity, i.e. number of characters typed on a PC (Wargocki et al., 1999)

influence on the productivity of office workers (Wargocki et al., 1999). In a well-controlled normal office, two different air qualities were established by including or excluding an extra pollution source, invisible to the occupants. The two cases corresponded to a low-polluting and a non-low-polluting building as specified in the new European guidelines for the design of indoor environments (CEN, 1998).The same subjects worked for 4.5 hours on simulated office work in each of the two air qualities. The ventilation rate and all other environmental factors were the same under the two conditions. The productivity of the subjects was found to be 6.5% higher ($P<0.003$) in good air quality (Figure 1) and they also made fewer errors and experienced fewer SBS symptoms (Wargocki et al., 1999). This study performed in Denmark has later been repeated in Sweden with similar results (Lagercrantz et al., 2000). The results from these blind studies show that improved air quality increases productivity significantly. This increase should be compared with the cost of conditioning the indoor environment, which for office buildings in the developed countries is typically less than 1% of the labour cost. There is therefore a strong economic incentive to improve the indoor air quality.

Fisk and Rosenfeld (1997), on the basis of a literature survey, estimated the economic losses caused by poor IAQ due to illness, absenteeism and lost production in the US, and Seppänen (1999) has made similar estimates for northern European conditions. The conclusion in both cases is that the estimated losses are high compared to the cost of running the HVAC systems. While information on the negative impact of poor IAQ on productivity is new, there is more data available on the negative influence of warm discomfort on productivity. Wyon (1996) has given an excellent review of the literature on thermal discomfort and productivity.

Pollution Source Control and Ventilation

Avoiding unnecessary indoor air pollution sources is the most obvious way to improve indoor air quality. Its effect on productivity and SBS symptoms has been demonstrated in the study discussed above (Wargocki et al., 1999). Source control has also been used with great success outdoors and is the reason why the outdoor air quality in many cities in the developed world is much better today than it was 20 or 50 years ago.

In the new European guidelines for the indoor environment (CR 1752) (CEN, 1998), there is strong encouragement to design low-polluting buildings and recommendations on low-polluting building materials are given. Systematic selection of materials to avoid the well-known cases of SBS caused by polluting materials is common practice in several countries, e.g. in Scandinavia. Pollution sources in the HVAC system are a serious fault, degrading the quality of the air even before it is supplied to the conditioned space (Fanger et al., 1988a). The selection of materials, development of components and processes, as well as maintenance of the HVAC system, should be given high priority in future.

Source control is the obvious way to provide good indoor air quality with a simultaneous decrease in the consumption of energy. But increased ventilation also improves the indoor air quality and decreases SBS symptoms as demonstrated by Sundell's classic studies (Sundell, 1994) (Figure 2). The energy cost of increased ventilation may be minimized by efficient heat recovery.

Serve the Air Cool and Dry

In ventilation standards, indoor air humidity has for decades been overlooked. It has been generally accepted that the relative humidity was rather unimportant for human beings as long as it was kept between

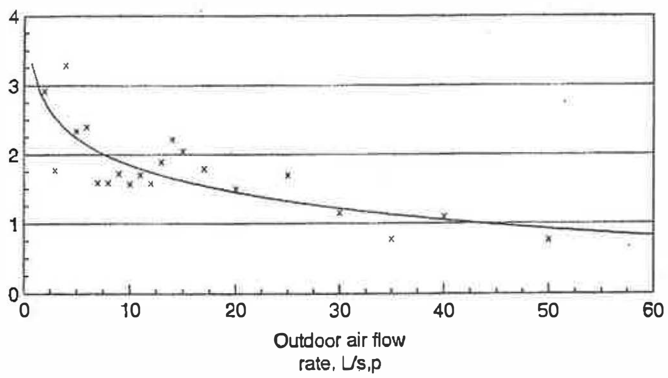

Fig. 2 The risk of SBS symptoms as a function of ventilation rate in 160 office buildings in Sweden (Sundell, 1994)

approximately 30% and 70% (ASHRAE, 1999; CEN, 1998; ECA, 1992). This consensus stems from the fact that the humidity in the comfort range of temperatures has a minor impact on the thermal sensation of the entire human body (Fanger, 1970; ASHRAE, 1992; ISO, 1993).

Existing ventilation standards and guidelines are based on the following thinking: there are certain pollution sources in a space and ventilation is required in order to dilute the chemical pollutants to a level where they are perceived as acceptable to humans. The thinking is that air is perceived exclusively by the olfactory and chemical senses in the nose and that the perception depends only on the chemical composition of the air. The implied conclusion is that the required ventilation is independent of temperature and humidity. However, a paper by Berglund and Cain (1989) indicated that temperature and humidity have an impact on the perception of clean air in a climate chamber.

New comprehensive studies at the Technical University of Denmark have demonstrated that perceived air quality is strongly influenced by the humidity and temperature of the air we inhale. People prefer rather dry and cool air. The strong effect of humidity and temperature on perceived air quality was proven in experiments where 36 subjects judged the acceptability of air polluted by different typical building materials in a climate chamber (Fang et al., 1998a).

It is the effect of humidity and temperature combined in the enthalpy of the air that is essential for the perceived air quality as shown in Figure 3. The enthalpy was changed in the room while the chemical composition of the air was constant. The thermal sensation for the entire body was kept neutral (neither too warm nor too cool) by modification of the subjects' clothing. The acceptability did not change with time, i.e. no adaptation took place.

The impact of enthalpy on acceptability or on perceived air quality expressed in percent dissatisfied or decipol is strong. Two other independent studies at the Technical University of Denmark where approximately 70 subjects were exposed to numerous combinations of humidity and temperature on the face also showed an excellent correlation between enthalpy and acceptability (Fang et al., 1998b; Toftum et al., 1998) with an even stronger impact of enthalpy.

Humans obviously like a sensation of cooling of the respiratory tract each time air is inhaled. This causes a sensation of freshness which is felt pleasant. If proper cooling does not occur, the air may be felt stale, stuffy and unacceptable. A high enthalpy means a low cooling power of the inhaled air and therefore an insufficient convective and evaporative cooling of the wet

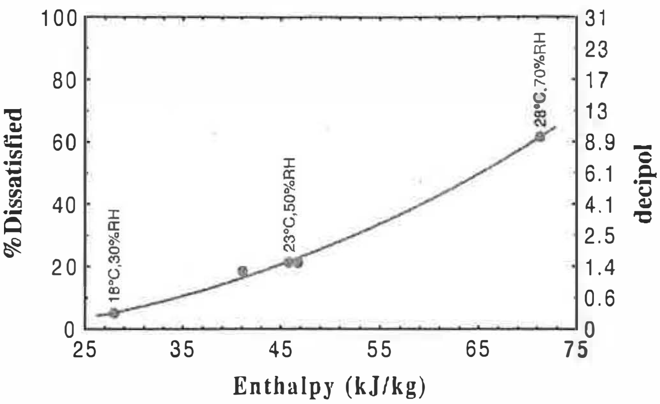

Fig. 3 Perception of clean air during whole-body exposure of persons to different levels of indoor air enthalpy (Fang et al., 1998a)

mucous membranes in the respiratory tract, and in particular the nose. This lack of proper cooling is closely related to poorly perceived air quality. The phenomenon is analogous to the well-known strong impact of temperature on perceived quality during intake of drinks, e.g. water or wine.

Heat loss through respiration is only around 10% of the total heat loss from the body and humidity and temperature of the inhaled air has therefore only a small impact on the thermal sensation for the human body as a whole. This is presumably why humidity has previously been overlooked. The new studies show that the local effect of air temperature and humidity on the respiratory tract and therefore on perceived air quality is one order of magnitude higher than for whole body thermal sensations. This new evidence has quite dramatic practical consequences. It is obvious that the enthalpy has a strong impact on ventilation requirements and therefore on energy consumption. Fang et al. (1999) showed thus in their most recent study that people perceive the indoor air quality better at 20°C and 40% RH and a small ventilation rate of 3.5 l/s · person than at 23°C and 50% RH at a ventilation rate of 10 l/s · person.

It is advantageous to maintain a moderately low humidity and a temperature that is at the lower end of the range required for thermal neutrality for the body as a whole. This will improve the perceived air quality and decrease the required ventilation. It is surprising to note that even in air-conditioned buildings in warm and humid climates, energy may be saved by maintaining a moderate indoor air temperature and humidity. Of course it requires more energy per m^3 to cool and dehumidify the outdoor air further, but this will be compensated for by fewer m^3 of outdoor air required for ventilation.

Field studies (Andersson et al., 1975; Krogstad et al.,

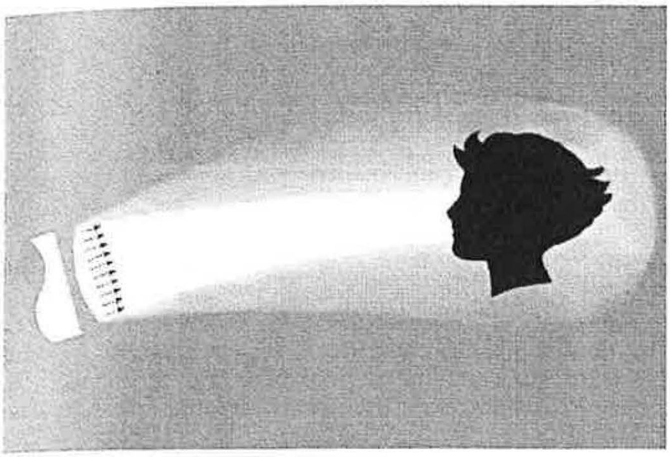

Fig. 4 The principle of personalized air (PA): small amounts of clean air supplied directly and gently to a person's breathing zone

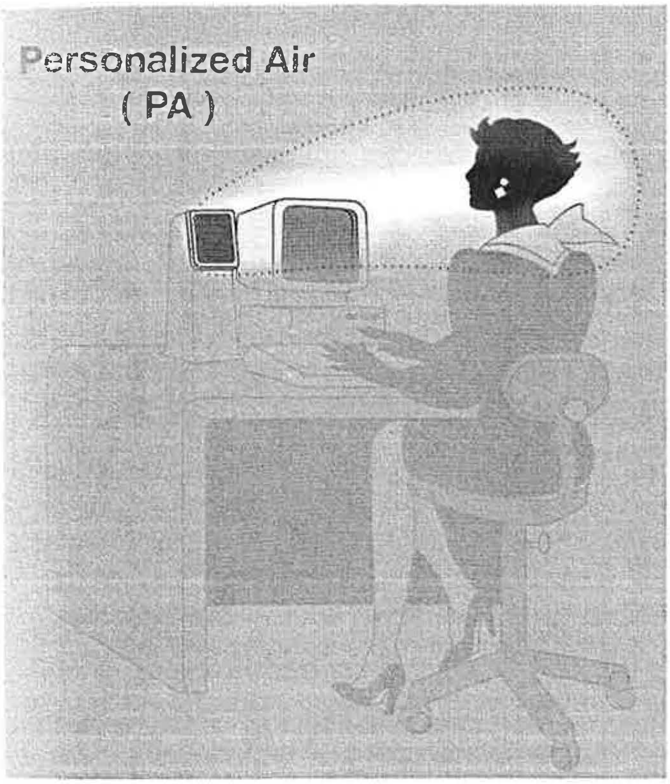

Fig. 5 Example of PA supplied from an outlet next to a PC at a workstation in an office

1991) show that moderate air temperatures and humidities also decrease SBS symptoms. There are therefore several good reasons to follow this advice: serve the air cool and dry for people.

Serve the Air where it is Consumed

In many ventilated rooms the outdoor air supplied is of the order of magnitude of 10 l/s · person. Of this air, only 0.1 l/s · person, or 1%, is inhaled. The rest, i.e. 99% of the supplied air, is not used. What a huge waste! And the 1% of the ventilation air being inhaled by human occupants is not even clean. It is polluted in the space by bioeffluents, emissions from building materials and sometimes even by environmental tobacco smoke before it is inhaled.

According to normal engineering practice, full mixing of clean air and pollutants seems to be an ideal. With displacement ventilation systems, one may be proud of reaching a slightly higher ventilation effectiveness of maybe 1.2. What I foresee in the future are systems that supply rather small quantities of clean air close to the breathing zone of each individual. The idea would be to serve to each occupant, clean air that is unpolluted by the pollution sources in the space. We would hesitate to drink water from a swimming pool polluted by human bioeffluents. Still we accept consuming indoor air that has previously been in the lungs of other persons and is polluted by human bioeffluents and other contaminants generated in the space. Why not serve small quantities of high-quality air direct to each individual rather than serving plenty of mediocre air throughout the space? Such "personalized air" (PA) should be provided so that the person inhales clean, cool and dry air from the core of the jet where the air is unmixed with polluted room air (Figure 4). In an office, the PA may come from an outlet next to the PC on the desk (Figure 5). It is essential that the air is served "gently", i.e. has a low velocity and turbulence which do not cause draught (Fanger et al., 1988b).

Please note that personalized air has nothing to do with individual thermal control for the entire body, which should be provided by other means (see below).

Individual Thermal Control

In buildings where many people occupy the same space it is difficult to provide thermal comfort for everyone at the same time. There exist well-known differences in preferred temperature between people. The traditional way of handling this is to aim for a compromise at an "optimal temperature" where as few persons as possible are dissatisfied (Fanger, 1970). It is obvious that it would be more advantageous if each individual could control his/her own local environment. Such a system with individual thermal control would allow all persons in a space to be satisfied.

In a space with traditional mixing of the ventilation air, it is beneficial that the air be kept at a moderately low temperature, corresponding to the coolest temperature preferred by any of the occupants. In an office this may for instance be 20°C or 21°C to provide appropriate cool inhaled air. All other subjects will require small amounts of additional moderate local heating which they can control to reach their own preferred operative temperature. It is essential that these small heating flows be provided by radiation or conduction, so that the air is still kept cool and pleasant to inhale. Individual thermal control by air movement should be avoided due to the risk of draught (Fanger, 1988b).

If the principle of personalized air is used, it is essential that a separate system be established for individual thermal control. It should be remembered that the idea of the personalized air system is to provide clean air to inhale, while the task of the individual thermal control system is to provide thermal neutrality for the entire human body. The individual thermal control system may also in this case function by radiation or conduction, and it is essential that it does not interfere with the highly sensitive flow of clean air to the breathing zone in the personalized air system.

An innovative combination of the two principles poses an exciting future challenge to HVAC engineering in the search for indoor environmental excellence.

Conclusions

The indoor environment in many buildings existing today is rather mediocre and gives rise to frequent complaints, even though present standards are met. A paradigm shift is foreseen with a search for excellence of indoor environments rather than the present effort to limit and reduce dissatisfaction and complaints.

The following principles may be useful steps in realizing such a new philosophy of excellence.

- Better air quality pays as it results in higher productivity and causes fewer SBS symptoms.
- The air should be served cool and dry for people.
- Small amounts of clean air should be served where it is consumed, i.e. as "personalized air" close to the breathing zone of each person
- Unnecessary pollution sources should be avoided.
- Individual thermal control should be established to handle personal differences in thermal preference.

The above principles of excellence are compatible with energy efficiency and sustainability.

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