HUMAN RESPONSE TO LOCAL HEATING FOR USE IN CONNECTION WITH LOW ENTHALPY VENTILATION

A. K. Melikov, G. Langkilde, L.W. Rasmussen

Centre for Indoor Environment and Energy
Department of Energy Engineering
Technical University of Denmark, Lyngby, DENMARK

ABSTRACT

This paper presents results on the human response to individually controlled radiant local heating of the body which can be used together with low enthalpy ventilation based on low room air temperature and humidity. Experiments were performed with 18 human subjects to identify the optimum combination and location of local radiant heating panels designed to compensate for cooling of the body at room air temperatures in the range 14-23 °C. The subjects were instructed to change the heating power of the panels and to select the optimum condition that would provide them with thermal comfort. Questionnaires were used to register subjects' satisfaction with the thermal environment. Most of the subjects were able to control the local heating panels and were able to achieve thermal comfort for the body at a room air temperature of 20 °C. Half of the subjects, however, complained of cold discomfort on one or more body parts at room air temperatures of 17 and 14 °C. The thermal comfort reported by the subjects for the whole body and for the different body parts was influenced significantly by the number and location of the heating panels. Recommendations for the design of local radiant heating are suggested in this paper.

KEYWORDS

Thermal comfort, Energy, Forced ventilation

INTRODUCTION

The design goal of conventional HVAC systems has been to provide an environment in the occupied zone of spaces that is as uniform as possible and that will satisfy the greatest number of occupants. An important requirement is that the HVAC systems are energy-efficient. The requirements for temperature and air movement in a space, as prescribed in the present standards (ISO 7730 1993, ASHRAE 55 1992), are based on average values for a large group of occupants. However, most often occupants' physiological and psychological responses to the indoor environment differ due to differences in clothing, activity, individual preferences to the air temperature and movement, time response of the body to changes of the room temperature, etc. The thermal insulation of the clothing of the occupants may vary from 0.4 clo to 1.2 clo and even more and the metabolic rate may range between 1 met and 2 met due to differences in occupants' physical and mental activities (ASHRAE Handbook of Fundamentals 1993). The individual differences in the preferred air temperature may be as great as 10 °C (Grivel and Candas 1991). The occupants' preferences to the air movement may differ more than four times (Melikov et al. 1993). Therefore it is not surprising that thermal discomfort is often reported from a large percentage of occupants in offices where the thermal environment complies with the recommendations in the standards(Schiller et al. 1988). Thermal environmental conditions most acceptable for the occupants may be achieved by providing each occupant with the means to heat or cool the body, i.e. to generate his/her own micro-environment.

Recent laboratory experiments reported by Fang et al. (1997) have shown that the perceived air quality, both for unpolluted and polluted air, improves when both air temperature and humidity decrease. Fanger (1997a,b) recommends designing HVAC systems for a modest enthalpy of the air in rooms, i.e. low air temperature and relative humidity. This new principle of ventilation, the Low Enthalpy Ventilation (LEV), has the potential to improve the perceived air quality, to decrease the rate of required ventilation air and also to achieve energy savings.

The potential for energy saving by lowering the room air temperature below the average comfort temperature and enhancing personal comfort by providing occupants with the means to generate their own micro-environment, especially local heating of the body, has been recognized earlier (Madsen and Saxhof 1979, Jones 1988, Nelson and Langness 1992, Sørlie et al. 1993, Wyon 1996)). The results of these studies show that it will be possible to lower the room air temperature below the comfort temperature recommended in the standards and maintain thermal comfort for the occupants by providing them with means for local heating of the body. In this way, the number of satisfied occupants may increase and the perceived air quality may improve. Energy savings may be gained as well.

In order to design local heating efficiently and to apply it in practice, there is a need to answer the following important questions that have not been addressed in previous studies: what is the optimum number and location of heating elements?; what is the lowest room air temperature to use for local heating without giving rise to complaints of local discomfort from occupants?; what is the extent of use and control of the local heating by the occupants under steady-state and transient conditions?; what will be the energy savings, if any?; how much will the occupants' perception of air quality improve?; what will be the impact of local heating on workers' productivity? Some of these questions have been studied and reported in this paper.

METHOD

Experimental facilities

The experiments were conducted in an environmental chamber with dimensions 6x5x2.4 m^3. The chamber is described in detail by Kjerluf-Jensen et al. (1975). The air velocity field in the chamber is uniform with a mean velocity below 0.06 m/s. The mean radiant temperature in the chamber is equal to the air temperature. The air temperature in the chamber can be controlled between 5 and 50 °C with an accuracy of ±0.2 °C. The vertical and horizontal air temperature gradients are less than 0.2 °C. The time constant of the chamber is relatively small: it takes 15 minutes to change the air temperature by 3 °C and to achieve a mean radiant temperature that differs from the air temperature by less than ±0.5 °C.

An office workplace was simulated in the chamber by adding a small desk and an office chair. The subjects participating in the experiments were provided with local radiant heating from four panels positioned as shown in Figure 1. One panel (0.60x0.99 m) was attached to the back of the chair to provide heating at the back of the subjects; a second panel (0.33x0.41 m) was attached to the chair below the seat to provide local heating at the back of the legs as well as to generate upward convective air movement around the subject's body; a third panel (0.42x0.66 m) was attached horizontally below the table to provide local heating at the knees and the thighs; and the last, a fourth panel (0.33x0.66 m), was attached on a downward slant below the desk to provide local heating at the front of the lower legs and the feet.

The panels had different sizes but were of identical design, consisting of a 50 mm thick plate with high insulation, one side of which was covered by electrically heated foil. The surface temperature of the panels could be changed continuously and independently, ranging

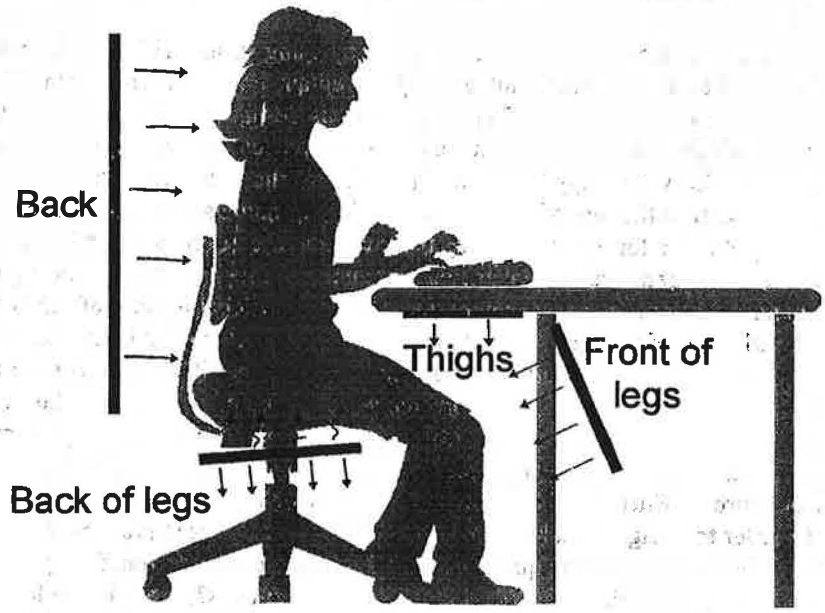

Figure 1. Number and positioning of the radiant panels used for local heating of the subjects during the experiments.

from equal to the room air temperature up to 60 °C by 4-5 °C per minute. For this purpose, the electric current through the heated foil of the panels was changed independently by four transformers. The surface temperature of the heating panels was measured continuously during the experiments.

Experimental conditions and procedure

Eighteen persons, 6 females and 12 males, most of them students, between 20 and 27 years of age (one, however was 44 years old), participated in the experiments. Each subject participated in three experiments. During the first experiment the subjects could use only the heating panel for the back; during the second experiment the subjects could heat their body locally by the panels for the back and for the thighs; and during the third experiment, the subjects could receive local heating of the body from the four heating panels.

Each experiment started with a 30-min acclimatization period during which the air temperature in the chamber was 23 °C and all heating panels were switched off. During this period the subjects were encouraged to modify their clothing in order to reach thermal comfort. Additional clothing was available in the chamber. After the first 30 min the air temperature in the chamber was decreased to 20 °C. From this moment until the end of the experiment, the subjects were not allowed to modify their clothing but were instructed to use the radiant heating panels to compensate for the lower temperature and to keep their body thermally comfortable. The air temperature was kept at 20 °C for 45 min and then decreased to 17 °C and kept at this temperature for another 45 min. This procedure was followed during the three experiments. Only during the last experiment, when the subjects were allowed to heat their body by the four heating panels, was the air temperature in the chamber decreased further and kept for 45 min at 14 °C. The temperature goal in the chamber was achieved during the

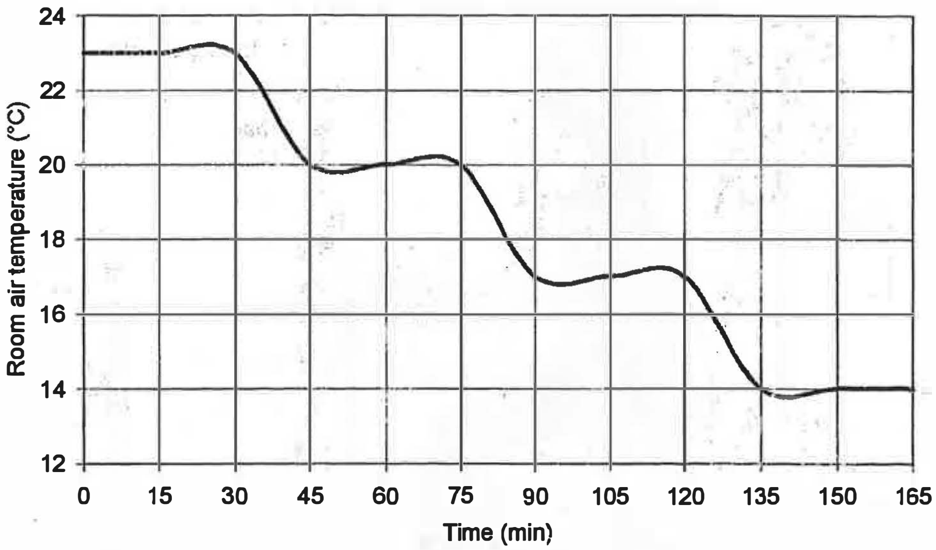

Figure 2. Air temperature in the climate chamber during the experiment.

first 15 minutes of each 45-minute period. The air temperature in the climate chamber was recorded during the experiment as shown in Figure 2. The subjects were not informed about the air temperature in the chamber or about the surface temperature of the panels. However, before commencement, they were informed about the purpose of the experiment and were instructed on how to use the heating panels.

During the experiments, the subjects voted every 15 min on a questionnaire. After that they had to stand up and put the questionnaires in a box located at the opposite end of the chamber. This activity increased their metabolism to simulate office-t pe work. The subjects had to answer questions regarding: body posture, activity, thermal environment (acceptable/unacceptable, pleasant/unpleasant, stimulating/sleepy) , how the air was felt (humid/dry, fresh/stuffy), thermal sensation for the entire body and local thermal sensation of several body parts (ASHRAE's seven-point scale) as well as whether the sensation was comfortable or uncomfortable due to warmth or cold. At the end of the experiment the subjects listed the clothing garments worn as well as their personal data.

RESULTS

Figure 3 shows the percent of subjects that assessed the thermal environment as acceptable for the body as a whole at 23, 20, 17 and 14 °C. Results from the three experiments, with a heating panel at the back, with heating panels at the back and the thighs, and with all four heating panels are compared in the figure. It should be remembered that at a room air temperature of 23 °C the subjects were not allowed to use the local heating but instead were encouraged to modify their clothing in order to achieve thermal comfort. As expected, the number of subjects who felt the environment acceptable for the whole body decreased when the room temperature decreased. At a room air temperature of 17 °C, 50% of the subjects were not able to achieve an acceptable thermal condition by local heating of the back and the thighs. At this air temperature, local heating by the four panels was needed in order to compensate for the cooling of the body and to provide acceptable thermal conditions for 88% of the participants in the experiment.

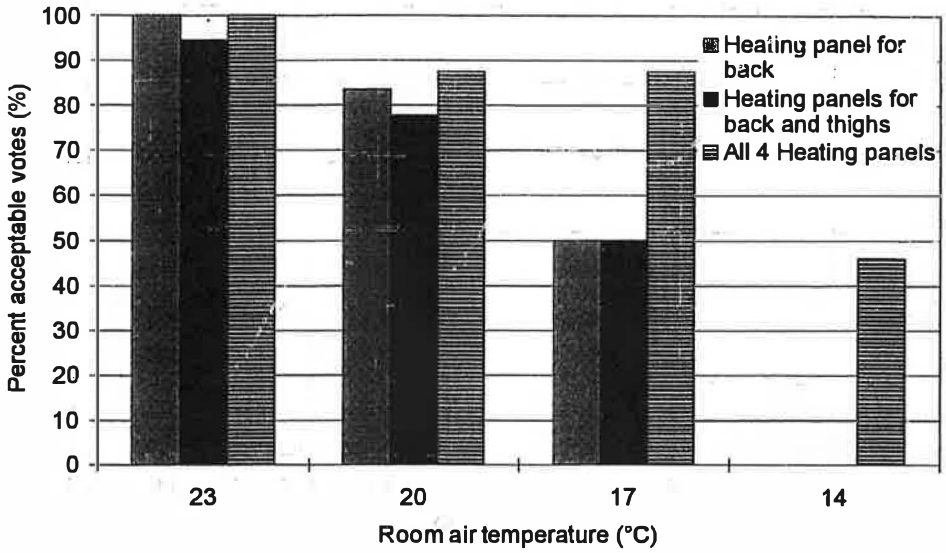

Figure 3. Percent of subjects who could achieve acceptable thermal comfort for the whole body by different combinations of local heating panels at room air temperatures of 23, 20, 17 and 14 °C.

Regardless of the local heating provided, the subjects felt cooler when the room air temperature decreased. Subjects' thermal sensation for the whole body was almost neutral at room a air temperature of 20 °C and slightly below neutral at 17 °C when the four heating panels were used. Subjects were able to achieve a steady-state thermal sensation for the body at each room air temperature. However, it should be borne in mind that the exposure at each room air temperature was relatively short and this may not always be the case in practice.

Figure 4 compares the percent of subjects who felt local thermal discomfort on one or more parts of the body at 23, 20, 17 and 14 °C during the three experiments. The use of local heating helped to decrease the local discomfort. The subjects benefited most by using all four panels. At 20 °C, only 12% of the subjects reported local thermal discomfort when using all four panels for local heating. Only one subject reported thermal discomfort for the entire body. The hands and the arms were the body parts which were felt cold at 20, 17 and 14 °C room air temperature.

Less than 50% of the subjects used the maximum power of one or more of the heating panels although they reported cold thermal discomfort, local or for the whole body. The number of subjects who assessed the thermal environment as unacceptable and did not use the maximum power of the heating panels was greater than the number of subjects reporting an unacceptable thermal environment and using the maximum power of the heating panels. Two subjects could not achieve an acceptable thermal condition by using the maximum power of the heating panels. The analyses of the results did not indicate that the reason for not using the maximum power of the heating elements was local warm discomfort or high thermal asymmetry.

The panel most used was that for the back. The panel below the chair was least used although often complaints of local cooling were reported for the back of the legs. The convective flow from the panel below the chair was not very effective in warming the body seated on the chair.

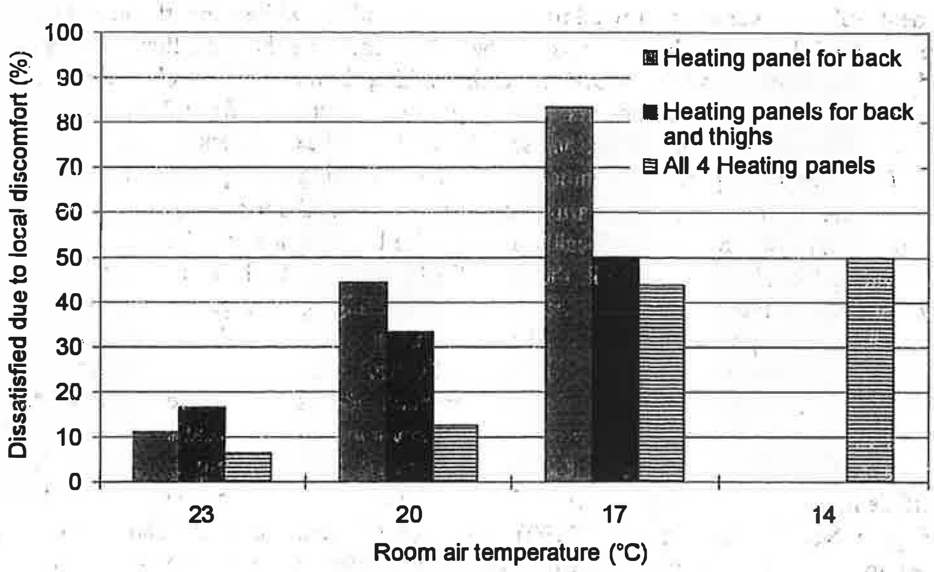

Figure 4. Percent of subjects feeling local thermal discomfort at one or more body locations. Results with three different combinations of local heating panels used at room air temperatures of 23, 20, 17 and 14 °C are compared.

The analyses of the continuous records of the surface temperature of the panels during the experiments showed that more than 70% of the subjects participating in the experiment regulated the panels in small steps in order to compensate for the low room air temperature and to achieve thermal comfort. With each experiment, and with time, the subjects improved their performance.

DISCUSSION

The results of this and previous studies show that a decrease of the room air temperature can be compensated for by local heating so that occupants remain in thermal comfort. The present study indicates that local heating, if well designed, can provide most occupants in a space with thermal comfort at a room air temperature as low as 20 °C. Nelson and Langness (1992) suggested that a decrease of the room air temperature to 19.5 °C is possible by providing occupants with a heating panel mounted below the desk. Madsen and Saxhof (1979) concluded that the room temperature can be decreased by 3 °C if occupants are provided with a local radiant panel heating at the back. It should be remembered that the time of the experiments of this study was relativity short. It may be expected that during a long exposure in practice, 20 °C may be the lowest acceptable air temperature for the most sensitive occupants. However, in rooms where the occupants' activity is higher than a typical office activity of 1.2-1.3 met, an air temperature lower than 20 °C may be accepted. Therefore, the activity and the working pattern of the occupants play an important role for the lowest design air temperature that can be kept in a room with local heating of the occupants. The lowest air temperature will depend also on the body area provided with local heating, as well as its size. There is a limit to the compromise people will make between the heat balance of the body as a whole and the body's thermal asymmetry. This has been studied before (Fanger et al. 1985).

Clothing is another important factor when local heating is applied. Local cold discomfort will be experienced at body parts tightly covered by clothing and less at body parts where a layer of insulating air between the skin surface and the clothing exists. During this experiment, subjects were not allowed to modify their clothing while using the local heating. It may be expected, however, that subjects will be able to improve the local thermal sensation of the body parts to some extent by modifying their clothing. In fact this was observed during the present study: the number of subjects with long sleeves increased from 33% from the first experiment to more than 75% during the second and the third experiment.

The present experiments indicate that local heating can provide occupants with thermal comfort at a room air temperature as low as 20 °C, without causing unacceptable local cooling or heating of the body. A local heating of the body by a large, half-egg-shaped back panel providing local heat to the neck, the back, the lower legs and the ankles, combined with a heating panel below the desk which provides heat to the thighs, the legs and the feet and at the same time heats the upper surface of the desk and thus the arms and the hands in contact with it, may be a good design solution. As suggested by Sørlie et al. (1993) an important design condition is that the desk should be closed at the back, thus shielding the space for the legs below the desk as much as possible from the room environment and creating their own micro-environment. This will make the use of the heat generated by the heating panel below the desk more efficient. The surface temperature of the top of the desk has not been studied in detail but according to Nelson and Langness (1992), a surface temperature of 34 and 36 °C may be expected to provide comfort for the occupants. For safety reasons, the maximum surface temperature of the heating panels should not exceed 60 °C and the electric current should not be more than 24 V. A cable from the ceiling for the electricity supply to the panel at the back of the chair seems most appropriate convenience and for the ergonomics of the workplace.

Local heating may be used in open offices as well as in other offices where a high air quality of the indoor environment is required. An appropriate application of local heating may be in large spaces where very few occupants perform work at a low activity level, such as in large halls (airports, exhibitions, closed shopping centres), supermarkets, information centres, etc.

CONCLUSIONS

Local heating, combined with clothing modification, can provide occupants with thermal comfort without local cold or warm discomfort of the body when the room air temperature is kept as low as 20 °C.

Regulation of the local cooling will not be a problem for most of the occupants.

A good design solution can be a local heating of the body by a large, half-egg- shaped back panel providing local heat to the neck, the back, the lower legs and the ankles, combined with a heating panel below a desk (closed at the back) which provides heat to the thighs, the legs and the feet and to the upper surface of the desk, thus heating also the arms and the hands. An important design condition is that desk is closed at the back.

A cable for the electricity supply from the ceiling to the panel at the back of the chair seems most appropriate convenience and for the ergonomics of the workplace.

REFERENCES

ASHRAE (1992) ANSI/ASHRAE Standard 55-1992, *Thermal environmental conditions for human occupancy*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE Handbook of Fundamentals, 1993. *American Society of Heating, Refrigerating and Air-Conditioning* Engineers, Atlanta.

ISO 7730 (1993) "Moderate Thermal Environments-Determination of the PMV and PPD Indices and Specification of the Conditions for Thermal Comfort", (Geneva:ISO), 1993.

Fang, L., Clausen, G. and Fanger, P.O. (1997) Impact of temperature and humidity on acceptability of indoor air quality during immediate and longer whole-body exposures. *Proceedings of Healthy Buildings/IAQ'97: Global Issues and Regional Solutions,* Washington D.C., U.S.A., 2, 231-236.

Fanger, P.O., Ipsen, B.M., Langkilde, G., Olesen, B.W., Christensen, N.K. and Tanabe, S. 1985. Comfort limits for asymmetric thermal radiation. *Energy and Buildings*, 8 (3), 225-236.

Fanger, P.O. (1997a) Global issues related to offices and public assembly halls from a building perspective. *Proceedings of Healthy Buildings/IAQ'97: Global Issues and Regional Solutions*, Washington D.C., U.S.A., 2, 19-24.

Fanger, P.O. (1997b): Air humidity and perceived air quality. *Proceedings of Deutsche Kälte-Klima-Tagung, Hamburg*.

Grivel, F. and Candas, V. (1991) Ambient temperatures preferred by young European males and females at rest. *Ergonomics*, 34 (3), 365-378.

Jones, B.W. (1988) User interactive microclimate control. A new frontier: Environment for innovation, *Proceeding of International Symposium on Advanced Comfort Systems for the Work Environment*, Troy, NY: Rensselaer Polytechnic Institute, pp. 222-229.

Kjerulf-Jensen, P., Nishi, Y., Graichen, H. (1975) A test chamber design for investigating man's thermal comfort and physiological response. *ASHRAE Transactions, 81(1), 73-79.*

Madsen, T.L. and Saxhof, B. (1979) An unconventional method for reduction of the energy consumption for heating of buildings. *Proceedings of XVth International Congress of Refrigeration*, IV, 623-633.

Melikov, A.K., Arakelian, R. S., Halkjaer, L. and Fanger, P.O. (1993) Spot cooling - part 2: Recommendations for design of spot cooling systems. *ASHRAE Trans.*, 100 (2), 500-510.

Nelson, T.M. and Langness, T.B. (1992) Supplemental individual heating in offices: the oasis heating solution. *Enhancing industrial performance: Experiences of integrating the human factor*, Herman Kragt, London/ Washington D.C., 205-301.

Schiller, G.E., Arens, E.A., Bauman, F.S., Benton, C., Fountain, M. and Doherty, T. (1988) A field study of thermal environments and comfort in office buildings. *ASHRAE Transactions*, 94 (2), 280-308.

Sørlie, R., Langnes, T.B. and Hanssen, S.O. (1993) Maintaining acceptable thermal comfort with a low air temperature, by means of local heating. *Proceedings of Indoor Air '93*, Helsinki, Finland, 5, 377-382.

Wyon, D.P. (1996) Individual microclimate control: required range, probable benefits and current feasibility. *Proceedings of Indoor Air '96*, Nagoya, Japan, 1, 1067-1072.