THERMAL PLUMES ABOVE A PERSON

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ABSTRACT

Comprehensive air velocity measurements were carried out above a thermal manikin to find the velocity distribution in the plume above the head. The thermal manikin was either standing or sitting in a climate room (6 x 8 x 4.6 m) in quiet, isothermal surroundings. The air velocities in the plume were measured at different heights above the top of the head. The manikin's heat effect was varied within a wide range. The measurements were made with both a breathing and a non-breathing manikin. The velocities were measured by means of a flow analyser equipped with 24 hot ball probes mounted on a measuring cross. The measurements were complemented with measurements made with a Laser-Doppler anemometer.

KEY WORDS

Person, plume, air velocity.

INTRODUCTION

When a person´s surface temperatures are higher than the temperatures of the surrounding air a convective upward flow along the body will be created. Above the head the flow transforms into a more or less normal plume depending on whether the person is standing or sitting. The air velocities in the plume depend on the person´s heat effect (size, activity level, clothes etc.) and on the height above the head.

In Computational Fluid Dynamics (CFD) calculations it is necessary to define the input loads including those that are person related. Mierzwinsky (1980) and other researchers have measured air velocities above living persons, but the use of a Breathing Thermal Manikin gives better possibilities of control and measuring of the person´s heat effect.

METHODS

In the test room which has a floor area of 6 x 8 m^2 and a ceiling height of 4.6 m the thermal manikin was placed in the centre of the floor either standing or sitting as shown in figure 1.

Figure 1. Air velocity measuring cross with hot ball probes above breathing thermal manikin.

The test room was unventilated. A large number of thermocouples were placed on a measuring column and on the various surfaces to control that the surroundings were almost isothermal. A measuring cross mounted with 24 hot ball probes, 12 pieces on each axis uniformly distributed by 10 cm was hung above the manikin's head. One axis was placed parallel to the shoulders, the other perpendicular to that. The measuring cross could be raised and lowered.

The breathing thermal manikin was developed at Technical University of Denmark. The manikin is shaped as a 1.7 m high average sized woman. The manikin consists of a fibre glass armed polyester shell wounded with nickel wire used sequentially to measure the surface temperature and to heat the manikin to a specified skin temperature in 16 individual zones. The skin temperature and the heat output correspond to a person in thermal comfort. An artificial lung can provide the respiration either through the mouth or through the nose. It is possible to control the respiration frequency (number of breaths per minute) and the pulmonary ventilation (litres per minute).

The measurements were difficult to perform. Although the surrounding air in the test room was very near to isothermal conditions and to zero velocity the plume above the manikin's head meandered slightly and the measured velocities varied both with time and place. Therefore, it was necessary to measure over a period of 10 minutes to get a representative mean value and to repeat each experiment several times to choose the best results.

The following measuring heights h above the top of the head were chosen: 0.5 m, 1 m, 1.5 m, 2 m and 2.5 m. In that way the highest measuring position above the manikin in standing position was 1.7 m +2.5 m = 4.2 m which was not so far from the ceiling height of 4.6 m. So the influence of the ceiling can be seen in the results for the highest values of h above a standing manikin. Therefore, some of those measurements were left out.

Partly to verify the measurements with ball probes which were carried out with the following three different heat effects to the manikin: 90 W, 115 W and 130 W, and partly to extend the measurements to other heat effects a Laser-Doppler anemometer was set up 1 m above the top of the head of the standing manikin as shown in figure 2. This fixed position was chosen because the highest velocities in the previous measurements were found here.

Figure 2. Laser-Doppler anemometer for measuring air velocity in one direction. The measuring point is placed 1 m above the top of the manikin's head.

RESULTS

The results with and without breathing were alike. As described by Hyldgaard (1994) the reason is that the exhaled flow from the nose penetrates the convective flow along the body and after that it acts alone as a warm "cloud" outside the measuring area. The inhaled air is taken from the upward convective flow along the chest. The measurements showed that breathing had hardly any effect on the velocities above the head. Therefore, the following results include both the cases with and without breathing. For the use in CFD calculations etc. the exhaled warm "clouds" must be treated alone.

Standing person

The convective flow is very quickly transformed into an axis symmetrical flow above a standing person. Already at the height h = 0.5 m above the top of the head the air velocities measured on the two axes were almost equal. Figure 3 shows the mean velocities measured along both axes and a Gauss approximation. The vertical axis is passing the centre of the top of the head.

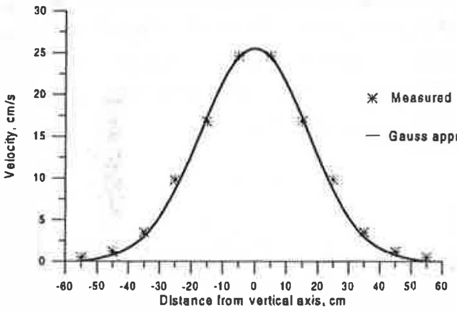

Figure 3. Air velocities measured 0.5 m above the standing manikin's head compared with a Gauss approximation. Heat effect = 90 W.

At higher values of h the measured velocities fitted even better to Gauss curves. Therefore, only the Gauss approximations are presented in the following sections. Figure 4 includes the curve from figure 3.

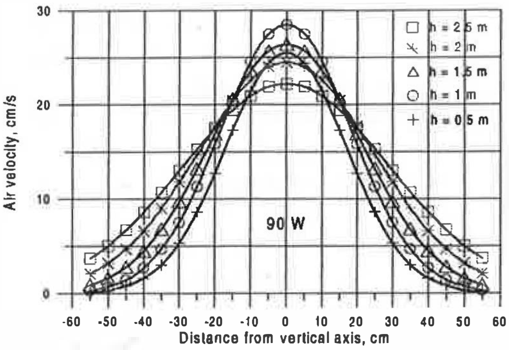

Figure 4. Vertical air velocities at different heights h above the standing manikin's head. The manikin's heat effect = 90 W.

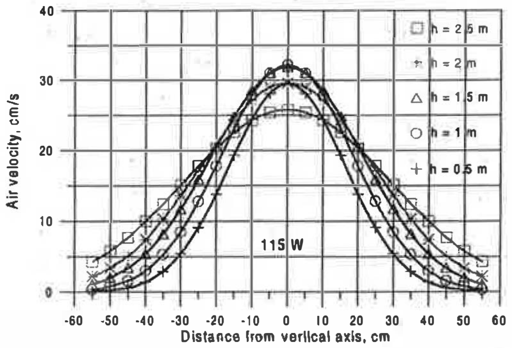

Figure 5. Vertical air velocities at different heights h above the standing manikin's head. The manikin's heat effect = 115 W.

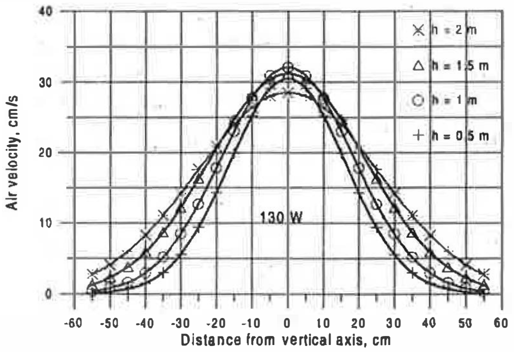

Figure 6. Vertical air velocities at different heights h above the standing manikin's head. The manikin's heat effect = 130 W.

A comparison between the figures 4 to 6 discloses that the central velocities in the plumes for 115 W and 130 W are nearly equal but different from the central velocities in the plume for 90 W. In order to enclose the reason and also to enlarge the examination area to other heat effects additional measurements with a Laser-Doppler anemometer were performed. Only one measuring point positioned on the vertical axis 1 m above the top of the head was chosen.

Because of the plume axis meandering it was necessary to find an appropriate measuring period and to repeat each measurement several times. A measuring period of 3 minutes was chosen and the best results were selected. The mean velocities of 107 selected measurements are shown in figure 7.

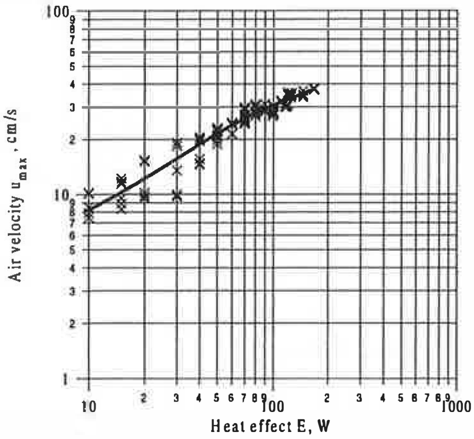

Figure 7. Central velocities u_{max} in the plume 1 m above the standing manikin's head measured with a Laser-Doppler anemometer.

A comparison between figure 7 and the figures 4 and 5 shows good agreement while there is less agreement between the figures 7 and 6. This indicates that the measured velocities presented in figure 6 are too low. The reason can be seen in figure 7, namely that the scattering is so large that it might explain the results in figure 6. It must be recommended to avoid use of figure 6 because the velocities differ from the mean value although they are within the scattering.

Curiosity was the reason for measuring at heat effects so small that it is of no interest for living persons, but the results complete the picture. Figure 7 shows the largest scattering at lower heat effects and this indicates a transition area between laminar and turbulent flow. The polynomial regression suggests a change of the slope in the area 0.25-0.30 m/s which corresponds to a change into a chiefly turbulent flow. The slope above 0.3 m/s, corresponding to 98 W, seems to be about 0.4.

Sitting person

Above a sitting person the plume is not axis symmetrical. The air velocities above the legs are higher than those behind the back. However, the plume above the head transforms into an axis symmetrical Gauss plume, so it is almost similar to that form already 1.5 m above the head. Therefore, the following figures 8-10 show Gauss approximations for the velocities at the heights of 1.5 m to 2.5 m.

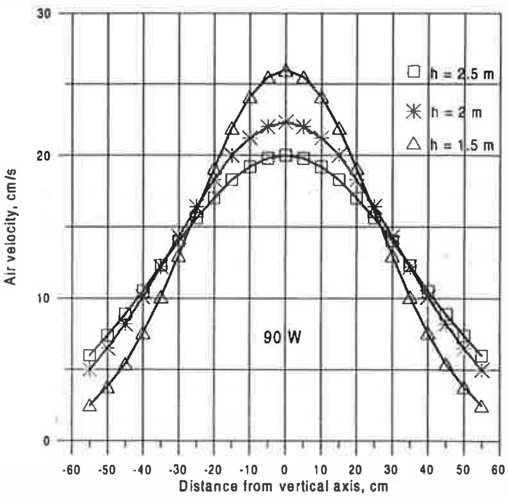

Figure 8. Vertical air velocities at different heights h above the sitting manikin's head. The manikin's heat effect = 90 W.

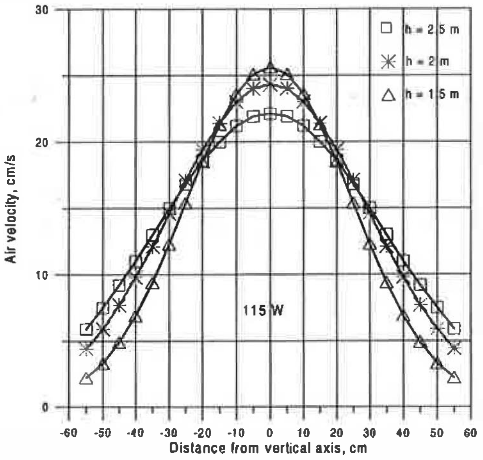

Figure 9. Vertical air velocities at different heights h above the sitting manikin's head. The manikin's heat effect = 115 W.

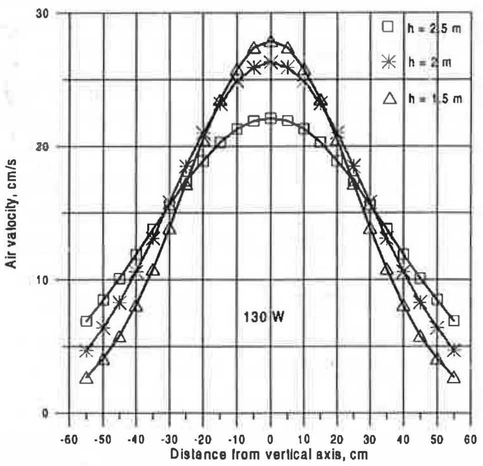

Figure 10. Vertical air velocities at different heights h above the sitting manikin's head. The manikin's heat effect = 130 W.

It must be realized that the heat effect illustrated in the figures 4-6 and 8-10 is only the heat emitted by convection and radiation and not the heat emitted by evaporation and breathing. For office work the activity level could be 1.2 met corresponding to 70 W/m^2. A person with a surface area of 1.9 m^2 would have a total heat emission of 133 W out of which only about 90 W would be emitted by convection and radiation. In this case the figures 4 and 8 can be used. In cases with lower effects figure 7 can be used to adjust the read velocities because they vary almost proportionally to the central velocity at different heat effects.

For the results approximated to Gaussian curves it is easy to calculate the integral properties of the plumes (Kofoed 1991). If r_v [m] is the distance from the vertical axis where 1/e of the maximum velocity u_{max} is found the following equations apply:

The volume flux V:

$$V = \pi \cdot u_{max} r_v^2 \qquad (1)$$

where V = volume flux [m^3/s]
u_{max} = the central velocity [m/s]

The vertical momentum flux M:

$$M = \frac{\pi}{2} \rho u_{max}^2 r_v^2 \qquad (2)$$

where ρ = the density [kg/m^3]

The kinetic energy flux E:

$$E = \frac{\pi}{3} \rho u_{max}^3 r_v^2 \qquad (3)$$

DISCUSSION

Mierzwinsky (1980) has measured temperatures and velocities in plumes above living persons. Two rooms with the ceiling heights 3.5 m and 2.66 m respectively were used. The measuring heights above the top of the head were mainly in the range of 5-95 cm. He found maximum central velocities about 60 cm above the head which, however, could be affected by the ceiling height. Of course, it also must have been difficult to control the activity level for the living persons who were sitting or standing still.

In the present work the measurements are carried out in a room with a greater ceiling height (4.6 m) to be able to measure at greater heights above the head (0.5-2.5 m) and still avoid measuring near the ceiling where the plume is braked. Moreover, the person´s heat effect corresponding to the activity level is varied within a large area.

Because a person is a low temperature heat source the surplus temperatures in the plumes above the person will be very low and difficult to measure with reasonable accuracy at great heights above the head. Therefore, it was chosen not to use the measured temperature distributions in the plumes.

The accuracy of the velocity measurements is approximately ±2 cm/s. All velocity probes were calibrated in vertical upstream from a pivotally open jet wind tunnel. The scattering caused by the plume meandering was minimized by adjusting the plume centre and selecting the best measuring series. However, the scattering caused by the movement variations with the time is included in the results. This is the main reason for the incongruity in the results at different heat effects.

Earlier results (Mierzwinsky and Popiolek 1982; Kofoed 1991) confirmed that the central velocities above concentrated heat sources decrease with the height above the source in the power -1/3. However, the human body is a low temperature heat source with a great surface area. Figure 11 shows the central velocities above the standing manikin.

Figure 11 shows a completed transformation of the plume approximately 1.5 m above the head. At increasing heights the velocities decrease with a slope about -1/3. For a sitting person the plume will develop like that but at a lower velocity level.

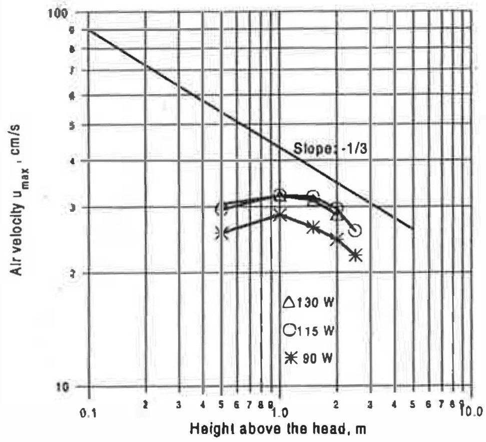

Figure 11. Measured central velocities u_{max} at different heights above the standing manikin's head. The heat effect is the parameter.

Figure 7 shows the relationship between the central velocity and the heat effect. A slope about 0.4 was found at higher heat effects. A slope of 1/3 was earlier found above concentrated heat sources. It is not impossible that the slope would approach that value at even higher heat effects of a person.

It was expected that a well-controlled room with a great ceiling height and an almost isothermal, quiet indoor climate in combination with well-calibrated, advanced measuring equipment would give results with a good mutual agreement. However, this expectation was not fulfilled. Even above a totally sedentary or standing manikin without breathing there will be a plume axis meandering, and in addition to that all velocities in the plume are varying with the time. This makes the measurements very difficult to carry out. Hopefully, the present work will in spite of that give an essential contribution to the knowledge about a person's influence on the surrounding air.

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