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NATURAL CONVECTION AROUND THE HUMAN HEAD

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SUMMARY

Natural convection around the human head

1. Factors determining the convective flow patterns around the human head in 'still' conditions are discussed in relation to body posture.

2. These flow patterns have been visualized using a schlieren optical system which reveals that the head has a thicker 'insulating' layer of convecting air in the erect posture than in the supine position.

3. Local convective and radiative heat transfer measurements from the head have been made using surface calorimeters. These results are seen to be closely related to the thickness of the convective boundary layer flows.

4. The total convective and radiative heat loss from the head of a subject in the erect and supine position has been evaluated from the local measurements. For the head of the supine subject the heat loss was found to be 30% more than when the subject was standing.

INTRODUCTION

The natural convection boundary layer which forms part of the human micro-environment allows the body to exchange heat with the surroundings by free convection. This boundary layer has been visualized and measurements of the velocity and temperature profiles within the flow have been described in detail elsewhere (Lewis, Foster, Mullan, Cox & Clark, 1969, and Clark, 1973).

The mathematical expression governing the flow parameters of velocity and thickness is the Grashof Number, $Gr = g(H^3/\nu^2)\,(T_s - T_a)/T_a$ where g is the acceleration due to gravity H, the vertical height on the body surface, ν the kinematic air viscosity and T_s and T_a the skin and ambient

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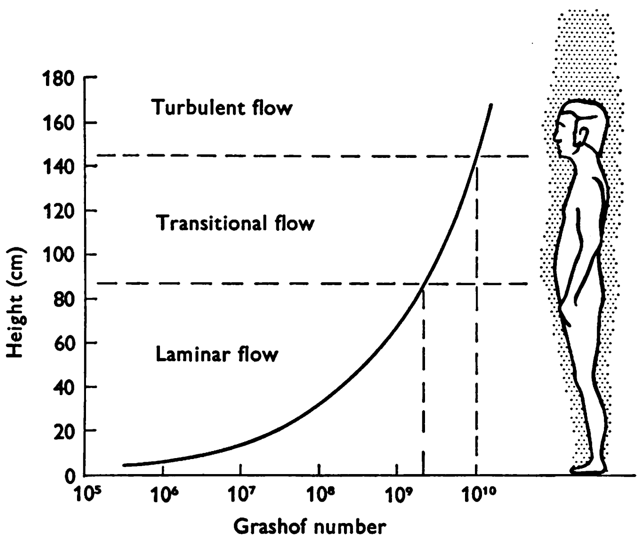
temperatures respectively (° K). When the Grashof number is less than 2×10^9 the flow is laminar and closely follows the contours of the body. If the Grashof number exceeds 10^{10} the flow is fully turbulent; the region between these two values of the Grashof number is subject to transitional flow with the fluid having characteristics of both laminar and turbulent flow. For a naked standing man in an air temperature of 20° C the flow remains laminar to a height of about 90 cm and only becomes fully turbulent after 150 cm.



Text-fig. 1. Variation of Grashof number with vertical height over the body surface for a skin temperature of 33° C and an ambient air temperature of 20° C showing the regions of laminar, transitional and turbulent flow. The dotted area around the outline of the human figure indicates the convective boundary layer flow.

Text-fig. 1 shows the variation of the Grashof number with height and indicates the state of the flow at various positions on the body. The free convective heat loss per unit area is directly dependent on the slope of the temperature profile within the boundary layer flow and may be expressed by $q = k\mathrm{d}T/\mathrm{d}X$, where k is the thermal conductivity of the air, and $\mathrm{d}T/\mathrm{d}X$ is the slope of the temperature profile at the skin surface, with X the horizontal distance from the body surface.

In areas where the boundary layer is thin, the temperature gradient is steep and there is a consequent high heat loss. Where the layer is thicker, the temperature has a greater horizontal distance in which to drop from that of the skin to the surroundings, the gradient is, therefore, shallower and the heat loss lower.

In the case of the standing man the boundary layer affords a degree of thermal protection since the flow has been increasing in thickness over the body. Consequently the temperature gradients over the head are shallow and the convective heat loss is limited.

If the subject is lying down the flow pattern over the head is substantially different. In this posture there is no flow over the head from below, there is only the boundary layer which has been generated over the head itself.

Because of these differences in flow fields it is to be expected that the local and total heat losses from the head may vary with changing body posture.

When the subject is lying down the convective flow pattern established around the head may be considered as being similar to that around a heated horizontal cylinder. For the standing subject the head may be represented by the same cylinder placed vertically on top of a second cylinder that generates a boundary layer to simulate the convective flow from the lower parts of the body.

This paper reports the results of experiments to measure these variations of heat loss from the human head with posture in free convection, and compares the results with calculated values for the cylindrical models.

METHODS

The convective flow patterns over the head of a subject in various postures were observed and photographed using a schlieren device, developed at this Institute (Lewis, 1967). From these observations diagrammatic illustrations were prepared to show the essential differences in the flow fields.

Small surface plate calorimeters which were a development of those previously described (Toy & Cox, 1973, 1974) were used to measure the local heat transfer from regions of the head. These calorimeters measured some 1·2 cm × 0·8 cm × 0·02 cm thick and were attached to the skin surface using double-sided adhesive tape with the insulation against the skin. This thickness of these calorimeters and their associated wiring was such as not to interfere with the convective flow patterns, as shown by the schlieren observations.

Electric power could be applied to the heating element until the temperatures registered by the two thermocouple junctions were equal. In this state there was no conductive heat flow across the calorimeter, and the power supplied to the heater was equivalent to the heat loss from the surface of the skin by radiation and convection. Before each series of tests the subject would remain in the posture to be tested for some time until a thermal equilibrium was attained as indicated by the steadiness of the calorimeter and thermocouple readings.

All of the experiments were performed in a climatic chamber at 22 ± 1° C in 'still air' conditions (horizontal air movement less than 30 cm/sec). The walls, ceiling and floor were lined with similar material so that in all postures the radiation to these surfaces was substantially similar. Any changes in the measured heat output were therefore due to convective heat transfer differences.

Preliminary heat transfer measurements were made from a heated horizontal cylinder (7 cm diameter and 60 cm long) and the results compared with established data (Schmidt, 1932). The convective flow pattern around the cylinder was also visualized in the schlieren system. Heat transfer measurements were taken from the forehead of a subject in the standing, sitting and lying positions, and their time dependency noted.

Two subjects were used in these experiments; one with a full head of hair and one who was nearly bald. Calorimeters were attached to the faces of both subjects and additionally, along the median line of the head of the bald subject.

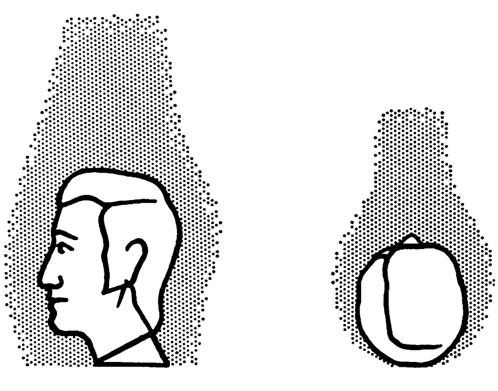
In the experiments where the subject was supine or prone, the head was supported in a small sling so that the convective flow could develop all round the head; this was not possible if the subject lay on a board or bed. The total convective and radiative heat loss was determined from the local heat transfer rates measured at several positions over the head. The head was considered as being divided into small areas and the heat loss from each of these areas was determined from the local heat transfer measurements. Summation of the heat loss from each area gave the total heat output by convection and radiation from the head.

RESULTS

Local heat transfer measurements

Text-fig. 2 shows diagrammatically the differences in the convective flow over the head of a standing and lying subject as observed using the schlieren optical system.

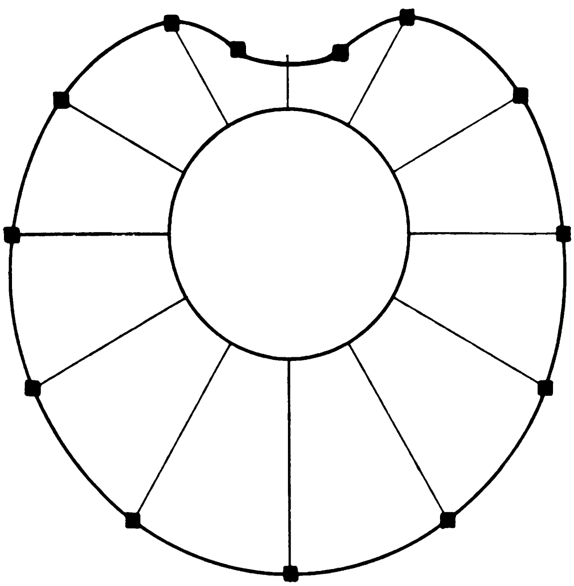
Natural convective flow patterns over the head in two postures



Text-fig. 2. The dotted area indicates the extent and shape of the convective boundary layer for the two postures.

The flow over the head of a standing subject is some 15–20 cm thick and the velocities in the flow exceed 30 cm/sec.

By contrast the flow over the horizontal head reaches only some 5 cm/sec with a maximum thickness of about 1 cm on the side of the head. The hot air streams break away to form a gently moving plume leaving the head from the top of the face. The flow patterns over the heated horizontal cylinder were very similar to those observed over the horizontal head. For the case of the seated subject, the flow pattern is more complicated. The boundary layer begins to form from the lower abdomen and interacts with the air streams that break away from the horizontal surfaces of the knees and thighs. The result is that the flow over the face differs little from that in the standing posture and the heat transfer rates are also substantially similar for these two postures.



Text-fig. 3. Local convective heat loss distribution around a horizontal heated cylinder. The greatest heat loss is seen over the lower part of the cylinder where the boundary layer is thinnest and the temperature gradient steepest.

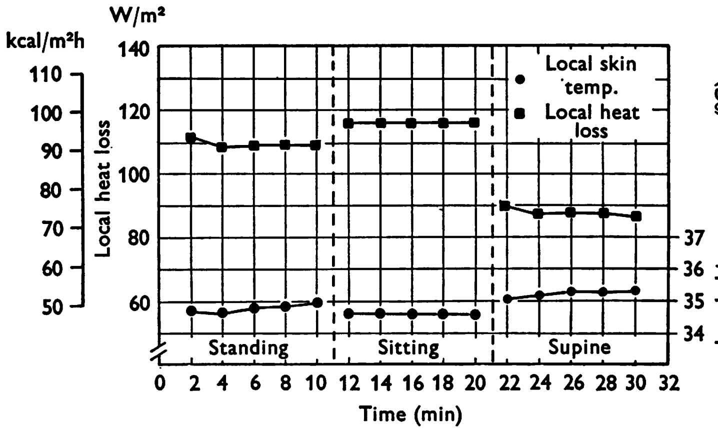
Calorimeters attached to the circumference of a heated horizontal cylinder produced the result shown in Text-fig. 3 for the heat transfer distribution around the cylinder.

The convective heat output is seen to be related to the schlieren observation of the flow patterns. Where the boundary layer is thin, at the bottom of the cylinder, the temperature gradient is steep and the heat transfer is high. As the flow speeds up and thickens, the heat transfer decreases until in the plume, where the thermal gradients are least, the heat transfer is lowest.

When the heat loss is measured from the forehead of a subject in the three postures of standing, sitting and lying the result is as seen in

Text-fig. 4, where the heat loss and local skin temperature is plotted with time to indicate the thermal stability in each position.

The heat losses and local skin temperatures are seen to be little different in the standing and sitting postures as might be expected from the similarity in flow fields noted earlier. However, when the subject is lying down with his face upwards, the heat transfer falls by some 30 % even though the skin temperature rises slightly. This heat transfer reduction is in accord with the heat transfer measured around the cylinder shown in Text-fig. 3

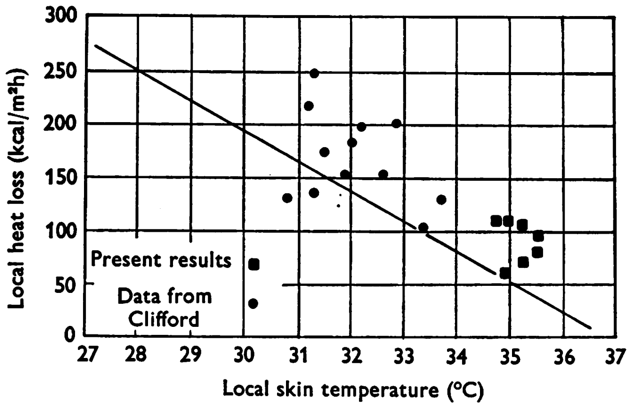


Text-fig. 4. The variation of local heat loss by radiation and convection with posture from a single position on the forehead in an ambient air temperature of 23° C.

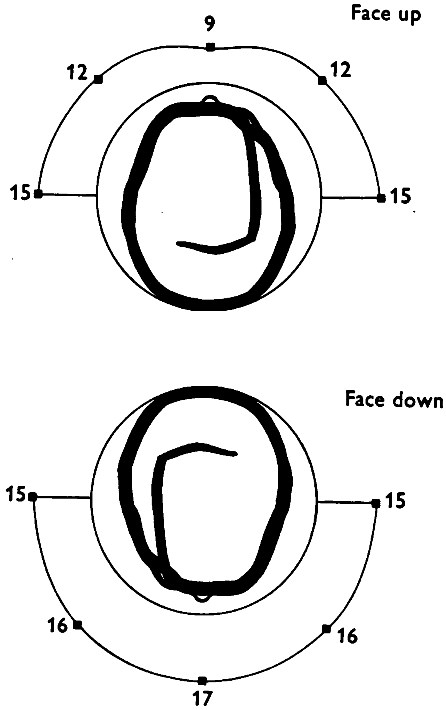
since the forehead lies within the convective plume where the temperature gradients and heat transfer rates are lowest.

Three calorimeters attached to the face are shown in Pl. 1 and the heat losses with the subject seated are shown in Text-fig. 5, where they are compared to results from Clifford (1966). The heat losses with the subject face-up and then face-down are shown in Text-fig. 6. These results are plotted around the head as convective heat loss coefficients and the similarity with the heat transfer around the heated cylinder is clearly seen. The greatest change in the heat transfer occurs on the forehead where there is nearly twice as much heat lost face-down compared to face-up.

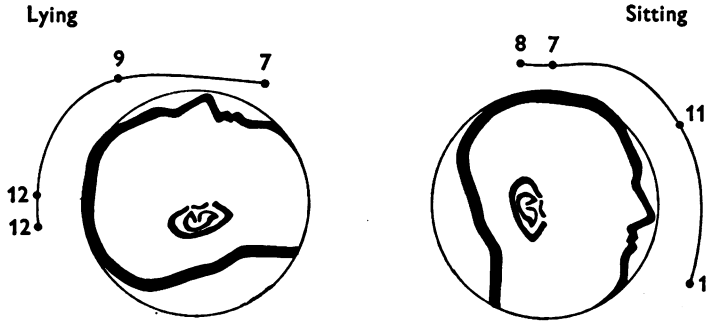
Text-fig. 7 shows the heat loss coefficients along the median line on the head of the balding subject in the sitting and lying postures; in this case it is again seen that the heat transfer is lowest at upward facing horizontal surfaces, and at any of these measuring sites on the head a change of posture results in a change in heat transfer.



Text-fig. 5. Local heat loss by radiation and convection from the face of a sitting subject. Present results compared with those of Clifford (1966), the continuous line being the regression line given by Clifford.



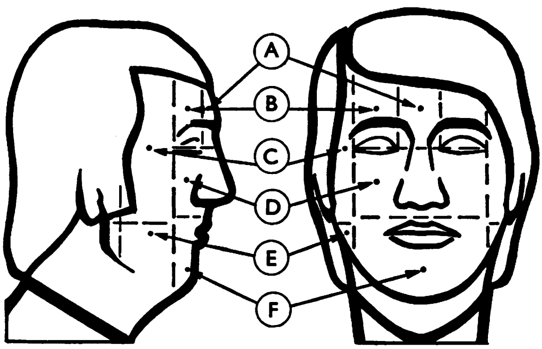
Text-fig. 6. Local convection plus radiation coefficients (W/m^2 ° C) from the face of a supine and prone subject with a full head of hair. Skin temperature 33° C, ambient temperature 23° C.



Text-fig. 7. Local convection plus radiation coefficients (W/m² ° C) from the head of the balding subject for two postures. Skin temperature 34° C, ambient temperature 22° C.

Regional heat transfer measurements

Local heat transfer measurements were recorded from six positions on the right side of a subject's face in the standing, and in the horizontal face-up and face-down positions.



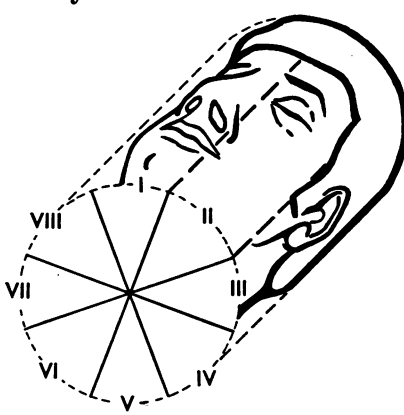
Position	A	B	C	D	E	F
Local heat loss (W/m²)	130	103	79	116	88	132

Text-fig. 8. Convective and radiative heat loss from the face of the standing subject with a full head of hair. Skin temperature 33° C, ambient temperature 23° C.

Since the convective flow pattern has been shown to be different in these postures, the heat loss from these positions is analysed in a separate way for each posture.

For the standing subject, the facial region is divided into the areas shown on Text-fig. 8. The total convective and radiative heat loss from the head of the subject is determined by summing the heat loss from each area to give a value of 10 W (some 4 W is due to free convection).

As a theoretical comparison, the total heat loss from a heated cylinder 23 cm long and 17 cm diameter was evaluated. These cylinder dimensions were those for the head of heated models of the human form used by Newling (1954). This was considered to be mounted above a second cylinder which simulated the convective flow from the lower part of the body. In the case of the vertical cylinder the theoretical calculation was based on the laminar boundary layer analysis for the flow over a heated flat plate (Ostrach, 1952) which was extended to the cylinder (Sparrow & Gregg, 1956). For the horizontal cylinder the analysis was similar to that developed by Schmidt (1932). The heat loss from the flat surfaces of the cylinders was found to be some 10 % of the total in the two configurations. The total heat loss from the 'head' cylinder was found from boundary layer theory to be 12·5 W.



Facial region	Local surface heat loss (W/m²)
I	81
II	110
III	135
IV	145
V	155
VI	145
VII	135
VIII	110

Text-fig. 9. Convective and radiative heat loss from the subject with a full head of hair in the supine position. Skin temperature 33° C, ambient temperature 23° C.

In the case of the supine subject, the surface of the head was divided into the strips shown in Text-fig. 9 which also shows the local heat loss for each strip. The total heat loss from the head in this posture, found by summing the heat loss for each horizontal cylinder representing the head, gave a value of 13 W. A theoretical result for the heat loss from the horizontal cylinder representing the head gave a value of 15·3 W.

DISCUSSION

The experiments reported in this paper show that the convective flow patterns, and consequently the local convective heat output rates around the human head, vary markedly with body posture. Local heat transfer measurements have been shown to be generally in accord with those which would be expected by considering the human head as either a heated horizontal or vertical cylinder.

The local heat transfer rates have been used to evaluate the heat output from the head and these results indicate that the head loses about 23% more heat in the supine posture than in the standing position. Thus the convective boundary layer provides some degree of thermal protection for the whole head in the standing case, but for the supine subject only those parts of the face within the convective plume are protected. The measurements from the face shown in Fig. 6 are compared with those of Clifford, who used Hatfield-Turner disks to measure heat loss from the face at various skin temperatures. Although the latter results were obtained at lower ambient temperatures, the present data are seen to be in line with those of Clifford (1966).

Froese & Burton (1957) determined the heat output from the head by completely enclosing it in a calorimeter. They found that the average non-evaporative heat loss from the heads of three subjects in an ambient air temperature of 23° C (similar to that used in the present experiments) was some 78 kcal/m^{2}h (90 W/m^2 ° C). If the radiative and convective heat losses from the head in the present experiments are expressed in these units the values are 67·8 kcal/m^{2}h (79 W/m^2 ° C) and 88·1 kcal/m^2 (102 W/m^2 ° C) for the standing and lying postures respectively. These values are in reasonable agreement with those of Froese & Burton. However, in their experiments the head was protected from the convective flow over the lower part of the body and the air was circulated by a small electric fan, and these two factors would modify the convective flow patterns that determine the heat transfer from the head.

The authors wish to thank Mr J. E. Pipkin for the drawings of the human form incorporated in Text-figs. 1, 2, 6, 7, 8 and 9.

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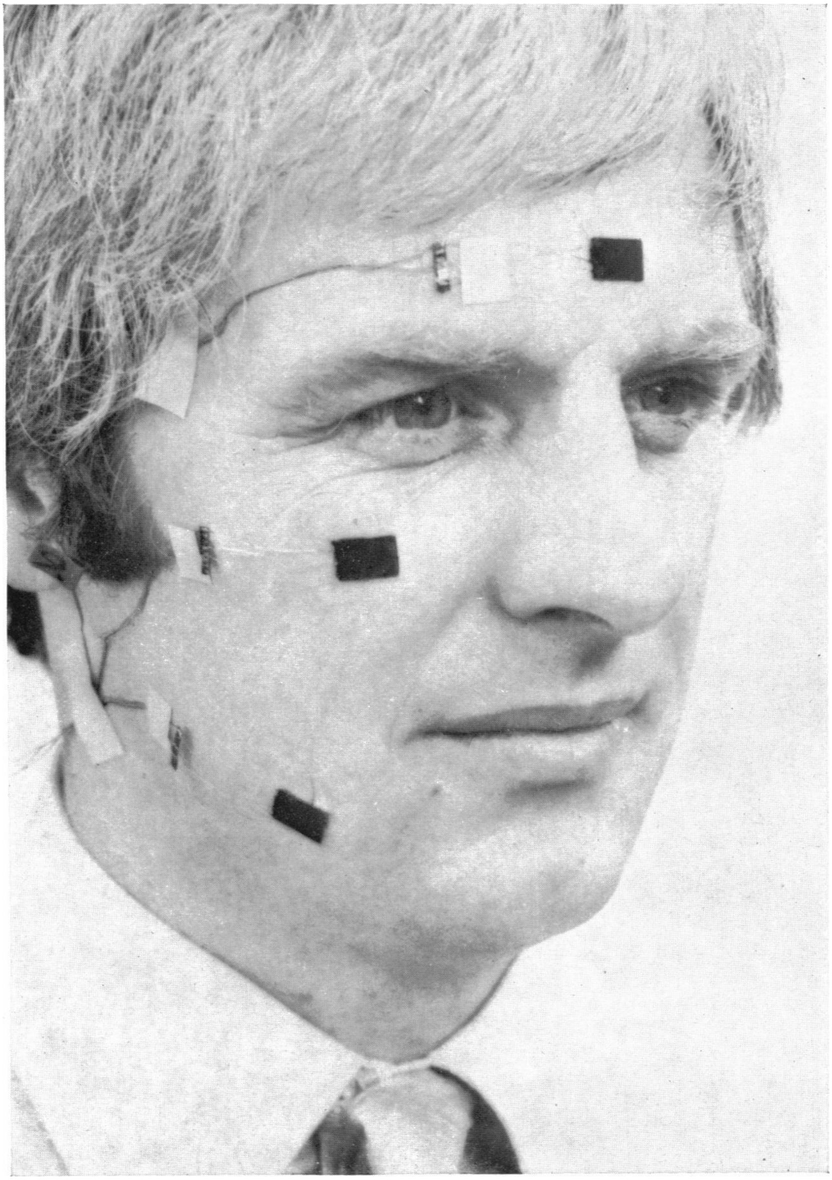

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EXPLANATION OF PLATE

Three surface plate calorimeters shown attached to the face of a subject.