The effect of body motion on convective heat transfer from a nude man

by U. C. GALIMIDI*, B.Sc. (Mech. Eng.),
J. M. STEWART†, M.Sc. (Mech. Eng.), and
A. J. VAN RENSBURG†, M.Sc. (Phys.) (Visitors)

SYNOPSIS

The effect of body movement on convective heat transfer from a man performing a block-stepping task was investigated experimentally by direct measurements of convective heat transfer. A series of experiments was conducted in which a nude man was required to stand at rest or to block step at 12 and 24 steps per minute. Wind speed, which was kept constant during each experiment, spanned the range 0,5 to 3,5 m/s. Air temperature was kept constant at 43 °C in all the experiments.

The results showed conclusively that the convective heat-transfer coefficient depends on the stepping rate. The effect of body motion can be regarded as being equivalent to an increase in the velocity of the free stream. The equivalent increase in air speed was found to be 0,36 and 0,77 m/s for 12 and 24 steps per minute respectively.

Data from various sources, including the present study, indicate that wind speed should be increased by about 0,30, 0,55, and 0,80 m/s to account for low, moderate, and vigorous body movements respectively. These findings are of direct relevance to the practical assessment of heat stress.

SAMEVATTING

Die uitwerking van liggaamsbeweging op konvektiewe hitteoordrag van 'n man wat 'n blokklimtaak uitvoer, is eksperimenteel ondersoek deur regstreekse metings van konvektiewe hitteoordrag. Daar is 'n reeks eksperimente uitgevoer waarin 'n naakte man gevra is om op die plek te rus of teen 12 en 24 treë per minuut op 'n blok en weer af te klim. Die windsnelheid wat gedurende elke eksperiment konstant gehou is, het 'n bestek van 0,5 tot 3,5 m/s gehad. Die lugtemperatuur is in al die eksperimente konstant op 43 °C gehou.

Die resultate het onweerlegbaar bewys dat die koëffisiënt van konvektiewe hitteoordrag van die treetempo afhang. Die uitwerking van liggaamsbeweging kan beskou word as gelyk aan 'n toename in die snelheid van die vrye stroom. Daar is gevind dat die ekwivalente toename vir 12 en 24 treë per minuut onderskeidelik 0,36 en 0,77 m/s is.

Data uit verskillende bronne, insluitende die huidige studie, toon dat die windsnelheid vir lae, matige en strawwe liggaamsbewegings onderskeidelik met 0,30, 0,55 en 0,80 m/s verhoog behoort te word. Hierdie bevindings is van regstreekse belang vir die praktiese evaluering van hittespanning.

Introduction

The study of heat exchange between a wet surface and air has shown convective and evaporative heat transfer to depend significantly on the velocity of the free stream[1]. In addition to the velocity of the free stream, other flow parameters, as shown by recent studies, can have an appreciable effect on these avenues of heat transfer. For example, an increase in air turbulence can, in certain conditions, increase the heat-transfer coefficient by as much as 50 per cent[2]. In any investigation of heat transfer from a working man, consideration must be given to the possible effects of body motion, since such motion must necessarily modify the flow conditions in various ways. Turbulence, relative air-to-surface velocities, and angles of orientation are among the factors that are affected.

Nishi and Gagge[3], using the naphthalene sublimation technique, have shown that body movements in nominally still air can be accounted for by an effective wind speed, V_{eff}, which depends on the type of body activity. However, when Mitchell and Hatze[4] applied this technique to men performing a block-stepping task, they found the effective wind speed to be independent of the rate of stepping provided that the velocity of the free stream exceeded 0,5 m/s. As the air velocity decreased below 0,5 m/s, the effect of stepping rate became progressively more apparent.

In view of the importance of wind speed in the assessment of heat stress, and of the unexpected and unexplained results obtained by Mitchell and Hatze, the aim of this study was to determine, by direct calorimetry, the convective heat-transfer coefficient for a nude man at rest and at two rates of block stepping.

A list of the symbols used is given at the end of this paper.

Experimental Procedure

The convective heat-transfer coefficient, h_c, is defined by the following equation:

$$J_c = A_c h_c (t_{sk} - t_a) \quad \ldots \ldots \quad (1)$$

The convective heat exchange, J_c, between the subject's skin surface and the air stream was measured directly by means of the differential thermometer developed by Carroll and Visser[5]. The measurement of convective heat transfer in the calorimetric wind tunnel of the Chamber of Mines has been described in detail by Stewart *et al.*[6].

Skin temperature was measured continuously with four copper–Constantan thermocouples located at four sites on the skin surface (arm, chest, thigh, and calf). Mean skin temperature was calculated by the use of four area-based weighting factors[7]. In addition, measurements of skin temperature were made at 15 sites, and an arithmetic average was used in the calculation of mean skin temperature. The four- and fifteen-point mean skin temperatures were found not to differ significantly.

Air temperature was measured continuously, also with copper–Constantan thermocouples. These were

*Formerly of the Chamber of Mines Research Organisation, Johannesburg; now at Everite Limited, Johannesburg.
†Chamber of Mines Research Organisation, Johannesburg.

positioned in a vertical plane about 1,5 m upstream from the subject.

The subject's surface area was measured by the photometric technique developed by Halliday and Hugo[8].

Before each experiment, the wind velocity was measured with a calibrated hot-wire anemometer.

A young acclimatized man acted as subject. His physical characteristics were as follows:

height 1,68 m, mass 70 kg, surface area 2,025 m^2.

Three rates of body movement were used, namely rest and stepping on and off blocks at 12 and 24 steps per minute. The blocks were 0,110 m and 0,195 m in height. These stepping heights cause the metabolic rates associated with these tasks to be approximately 100 and 200 W/m^2 respectively, which were requirements related to other aims of the experiment[9]. The block-stepping routine has been described in detail by Mitchell and Hatze[4]. The subject stepped in time with a metronome that provided 48 pulses per minute.

Although the environments used in the present study were selected primarily to produce high levels of skin wettedness[9], the air temperature of 43 °C that was used throughout was sufficiently high for h_c to be calculated with acceptable accuracy. In all the experiments, the mean radiant temperature was kept approximately equal to the air temperature. Wind velocities of 0,51 m/s, 0,75 m/s, 1,14 m/s, 1,74 m/s, 2,61 m/s, and 3,56 m/s were examined.

The duration of each test was 90 minutes, during which time the subject, dressed in underpants only, stood or stepped as required by the experimental programme.

Convective heat transfer and mean skin temperature (four points) were measured continuously. The four-point measurements of skin temperature were checked against measurements of skin temperature at 15 points on three occasions: at 10, 45, and 93 minutes. On these occasions the subject stood still.

During each test, other parameters were also measured, but these measurements are not relevant to this paper.

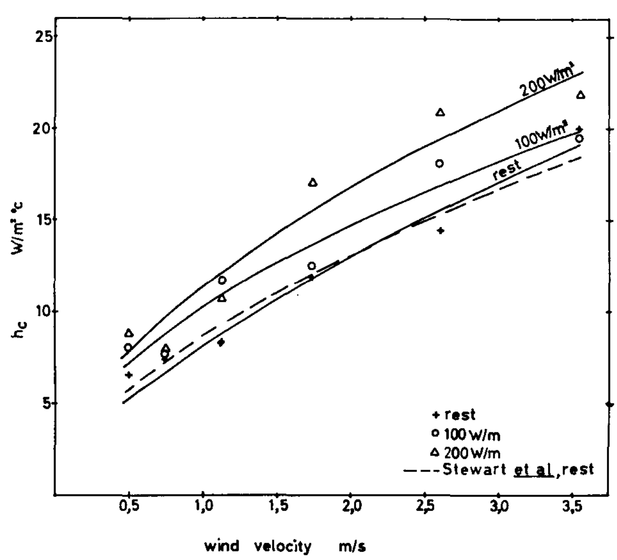

Fig. 1—Convective heat-transfer coefficient for rest and for metabolic rates of 100 W/m² and 200 W/m²

TABLE I

RESULTS OF THE REGRESSION ANALYSIS

Work rate	a	b	*RSD*	*r*
Rest	8,21	0,66	1,11	0,983
100 W/m^2	10,25	0,52	1,31	0,979
200 W/m^2	11,43	0,55	1,87	0,971

Results

To avoid inaccuracy in the measurement of convective heat transfer from the subject's skin surface due to possible adiabatic evaporation of dripped sweat from the floor, the analysis was confined to data collected only during the first 30 to 40 minutes of each exposure.

The convective heat-transfer coefficient has been plotted against wind speed in Fig. 1 for each of the three rates of metabolism. A regression analysis, based on the assumption that h_c can be described by the equation[10]

$$h_c = aV^b, \quad \quad (2)$$

yielded the values listed in Table I.

Also shown in Fig. 1 is the curve established by Stewart *et al.*[6] for nude men standing in hot environments.

The systematic difference between the curves for rest and those for metabolic rates of 100 W/m^2 and 200 W/m^2 (see Fig. 1) indicate the extent to which body movements can increase the convective heat-transfer coefficient. The observed increases in h_c can be explained by

(a) an increase in the relative velocity between the body and the air stream;

(b) an increase in turbulence of the boundary layer, and

(c) a cyclic change in the orientation of the various body segments relative to the air stream.

For practical reasons, the effect of these factors can be combined into an equivalent wind speed, which depends on the rate of body motion and which is added to the measured air velocity. If this equivalent wind speed is independent of the velocity of the free stream, the convective heat-transfer coefficient then becomes

$$h_c = a(V+\delta)^b, \quad \quad (3)$$

where δ is the equivalent increment in wind speed for each particular rate of body movement and the sum $(V+\delta)$ can be interpreted as an effective wind speed. The constants a and b relate to the data for a resting man, and δ is the average velocity difference (by integration) between the curves for rest and for each of the two work rates (see Fig. 1).

The values derived for δ are given in Table II, and are demonstrated graphically in Fig. 2.

Discussion

The Naphthalene Sublimation Technique

The effect of body movement on the convective heat-transfer coefficient was investigated previously[3, 4] by the naphthalene sublimation technique developed by Nishi and Gagge[3]. Balls of naphthalene are attached to the skin surface at various sites, and their rate of loss in mass by sublimation is used to determine the velocity of the free stream at the site of attachment. So that the balls will be located within the free stream, they are positioned outside the boundary layer, approximately 4 cm from the skin surface. Since the balls are firmly attached to the body, their rate of sublimation is an indirect measure of the air speed relative to the skin surface. As such, the technique would appear to provide a convenient means for measuring the effective wind speed of a physically active man.

However, when the effect of body movement on heat transfer is considered, it is a considerable oversimplification for this effective wind speed to be interpreted as being equivalent to immobilization of the man with an increase in the velocity of the free stream. For instance, the convection from a cylindrical body segment will be affected by changes in its angle relative to that of the air flow, a factor that will not affect the sublimation rate from the ball. Furthermore, since the naphthalene balls are positioned outside the boudary layer, they will not be affected by changes in the rate of heat loss due to changes in the thickness or turbulence of the boundary layer. These arguments lead to the conclusion that the technique of naphthalene sublimation has a doubtful interpretation in terms of the effects of body motion on heat transfer.

In view of this conclusion, it is apparent that the effects of body motion on heat transfer are best investigated by measurement of the heat transfer actually experienced by the body, as was done in the present study.

The results presented in Fig. 1 show that an increase

TABLE II

INCREMENTS IN WIND SPEED

Stepping rate	Stepping height	δ
step/min	m	m/s
12	0,110	0,360
24	0,195	0,767

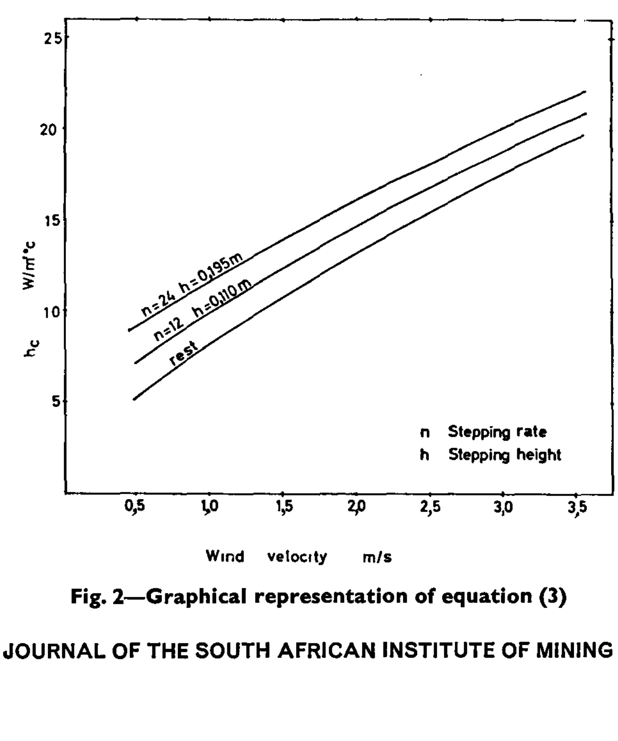

Fig. 2—Graphical representation of equation (3)

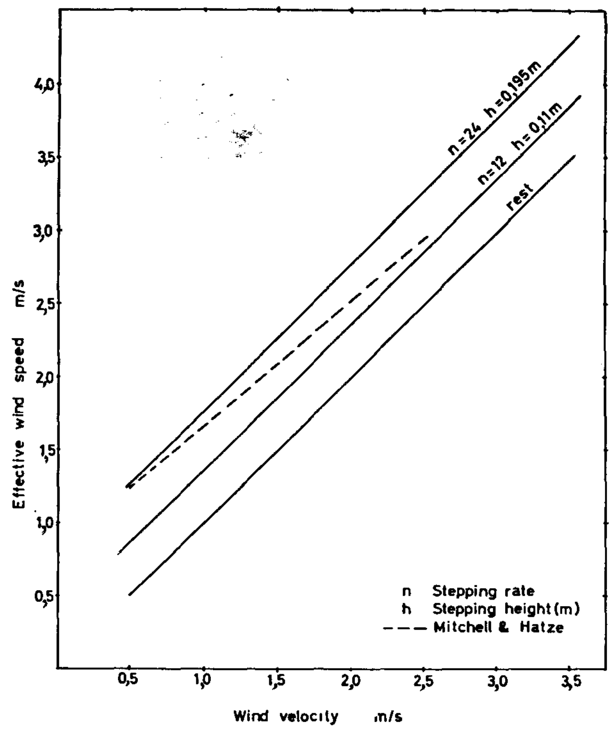

Fig. 3—Effective wind speed versus velocity

in the rate of body movement causes an increase in the heat-transfer coefficient. Computationally, this increase in h_c can be regarded as being equivalent to an increase in the velocity of the free stream. Fig. 1 can thus be used to define an equivalent increment in wind speed for each rate of body movement. These findings contradict the work of Mitchell and Hatze[4], who found the increase in relative wind speed due to block stepping to be independent of stepping rate for wind speed in the range 0,5 to 2,5 m/s. Unfortunately, they did not obtain data for a stationary man, and the meaning of their unexpected result is therefore doubtful. Their result is compared graphically with those of the present study in Fig. 3. It is worth noting that an extrapolation of Mitchell and Hatze's result to a wind speed of 4 m/s causes the effective wind speed to be lower than the actual wind speed.

The Assessment of Heat Stress

Since many studies of heat stress in the mining industry involve block stepping in simulated underground environments, it is essential to draw attention to the magnitude of the effect of different rates of body movement on the heat stress actually experienced by the human body. For example, stepping at 12 steps/min (h=0,110 m) and 24 steps/min (h=0,195 m) would have the effect of increasing the effective wind speed by 0,36 and 0,77 m/s respectively. In typical mining conditions (33 °C D.B., 31 °C W.B., and 0,5 m/s), this would increase the cooling power of the environment by about 63 W/m^2 and 125 W/m^2 respectively for a man with a fully wet skin and a mean skin temperature of 35 °C.

This observation has an important implication for the assessment of heat stress in underground situations. Very few mining activities involve body movement as

TABLE III

AIR SPEED CORRECTION FOR BODY MOTION IN VARIOUS LABORATORY TASKS

Category	Ref.	Task	Room air velocity m/s	Additional air velocity m/s	Method used
	3	Treadmill walking 0,89 m/s	0,15 to 0,20	0,25	Naph. sublimation
Light	13	B. Ergometer 30 r/min	0 to 0,23	0,3 to 0,4	Part. calorimetry
	3	B. Ergometer 50 r/min	0,15 to 0,20	0,3	Naph. sublimation
	*	Block stepping 12 step/min	0,5 to 3,5	0,33	Direct calorimetry
Moderate	11	B. Ergometer 60 r/min	0,5 to 3,5	0,35	Direct calorimetry
	3	B. Ergometer 60 r/min	0,15 to 0,20	0,50	Naph. sublimation
	3	Treadmill walking 1,34 m/s	0,15 to 0,20	0,59	Naph. sublimation
	12	Treadmill walking 1,34 m/s	0,15 to 3,0	0,75	Part. calorimetry
Vigorous	*	Block stepping 24 steps/min	0,5 to 3,5	0,66	Direct calorimetry
	3	Treadmill walking 1,78 m/s	0,15 to 0,20	0,83	Naph. sublimation

*This study

Note: In spite of the arguments to the contrary, the consistency between the data for naphthalene sublimation and calorimetric methods demonstrated in this table suggests that the sublimation technique gives acceptable results in nominally still air (0,15 to 0,2 m/s), i.e. in the region of free convection.

great as that involved in block stepping. Consequently, for the same free-stream velocity, the effective wind speed of a man engaged in underground work will usually be lower than that for a man performing a block-stepping routine. Direct application of laboratory results to underground conditions would thus lead to an optimistic assessment (underestimate) of the heat stress.

The effect of body motion on the heat transfer experienced by clothed men performing actual industrial tasks in simulated industrial environments has not been investigated. An accurate assessment of the problem would require appropriate experimentation. However, practically useful results can be achieved by a relatively coarse classification of body motion. Other researchers have established the effect of body movement for the laboratory tasks of cycling and walking on a treadmill[3, 11–13]. These laboratory tasks were translated into practical terms by being put into three categories of body movement: low, moderate, and vigorous. The air speeds to be added to account for body motion in each of these tasks are presented in Table III.

The data presented in Table I provide a useful interim guide for the assessment of the effect of body motion in industrial heat stress: for low body movement the wind velocity should be incremented by 0,30 m/s, for moderate body movement by 0,55 m/s, and for vigorous body movement by 0,80 m/s.

Conclusion

The results show that, in the calculation of h_c, the wind velocity should be increased by 0,36 and 0,77 m/s for a nude man stepping respectively at 12 steps/min (h=0,110 m) and 24 steps/min (h=0,195 m). These results are in conflict with those of Mitchell and Hatze[4], who found that the rate of stepping does not affect the effective wind speed. The unexpected nature of Mitchell and Hatze's results, and consequently the discrepancy between their findings and those of the present study, are attributed to shortcomings in the technique of naphthalene sublimation when applied to moving subjects.

A comparison of data from various sources suggests that, in situations of industrial heat stress, the effects of body motion can be accounted for if an equivalent air velocity is added to the air velocity of the environment.

List of Symbols

a	Constant, defined by equation (2)
A_c	Area of skin surface active in convective heat transfer, m²
b	Constant, defined by equation (2)
h	Stepping height, m
h_c	Convective heat-transfer coefficient, W/m².°C
J_c	Convective heat transfer, W
n	Stepping rate, step/min
RSD	Relative standard deviation
r	Regression coefficient
t_a	Dry-bulb temperature of the air, °C
$\bar{t}_{sk}$	Mean skin temperature, °C
V	Wind speed, m/s
V_{eff}	Effective wind speed, m/s
δ	Constant, defined by equation (3), m/s

References

1. ASHRAE. *Handbook of fundamentals.* New York, ASHRAE, 1972.
2. McADAM, W. H. *Heat transmission.* New York, McGraw-Hill, 3rd Edition, 1954.
3. NISHI, Y., and GAGGE, A. P. Direct evaluation of convective heat transfer coefficient by naphthalene sublimation. *J. Appl. Physiol.*, vol. 29, no. 6, 1970. pp. 830-838.
4. MITCHELL, D., and HATZE, H. Effective air speed during block stepping. Johannesburg, Chamber of Mines, *Research Report* no. 119/72. 1972.
5. CARROLL, D. P., and VISSER, J. Direct measurement of convective heat loss from human subject. *Rev. Sci. Instr.*, vol. 37. 1966. pp. 1174-1180.
6. STEWART, J. M., VAN RENSBURG, A. J., and VOSS, W. W. Experimental investigation of convective heat transfer from nude man. Johannesburg, Chamber of Mines, *Research Report* no. 14/77. 1977.
7. MITCHELL, D., and WYNDHAM, C. H. Comparison of weighting formulas for calculating mean skin temperature. *J. Appl. Physiol.*, vol. 26. 1969. pp. 616-622.
8. HALLIDAY, E. C., and HUGO, T. J. The photodermoplanimeter. *J. Appl. Physiol.*, vol. 18. 1963. pp. 1285-1289.
9. GALIMIDI, U. C., VAN RENSBURG, A. J., and STEWART, J. M. A theoretical analysis of the skin wettedness factor for acclimatized men in typical underground environments. Johannesburg, Chamber of Mines, *Research Report* no. 48/77. 1977.
10. MITCHELL, D., WYNDHAM, C. H., VERMEULEN, A. J., HODGSON, T., ATKINS, A. R., and HOFMEYR, H. S. Radiant and convective heat transfer from nude man in dry air. *J. Appl. Physiol.*, vol. 26. 1969. pp. 111-118.
11. MITCHELL, D. Human surface temperature: its measurement and its significance in thermoregulation. Ph. D. Thesis, University of the Witwatersrand, 1972.
12. NELSON, N., EICHNA, L. W., HORVATH, S.A., SHELLEY, W. B., and HATCH, T. F. Thermal exchanges of man at high temperature. *Am. J. Physiol.*, vol. 151. 1948. pp. 626-652.
13. WINSLOW, C. E. A., and GAGGE, A. P. Influence of physiological work on physiological reaction to the thermal environment. *Am. J. Physiol.*, vol. 134, no. 3. 1941. pp. 664-681.