A critical comparison of specific cooling power and the wet kata thermometer in hot mining environments

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SYNOPSIS

A new formula for the wet kata thermometer has been established in place of the currently used one which is believed to be fundamentally wrong and the new formula is compared with the recently proposed specific cooling power concept. Apart from a constant multiplier, it is concluded that the difference between the two concepts lies solely in the value of '*n*' in the function V^n and that this value for the cooling power of air on the sweating human body remains to be established reliably. The kata thermometer might yet be found to be a reliable predictor of heat stress in hot environments.

SINOPSIS

'n Nuwe formule vir die nat kata termometer is daargestel in plek van die huidige een wat blykbaar fundamenteel foutief is en die nuwe formule word vergelyk met die onlangs voorgestelde spesifieke koelvermoë konsep. Afgesien van 'n konstante vermenigvuldiger, word afgelei dat die verskil tussen die twee konsepte bloot geleë is in die waarde van '*n*' in die funksie V^n en dat hierdie waarde vir die koelvermoë van lug op die swetende menslike liggaam nognie oortuigend daargestel is nie. Daar kan moontlik nog gevind word dat die kata termometer 'n betroubare voorspeller is van hittespanning in warm omgewings.

INTRODUCTION

During most of the past half-century the wet kata thermometer has been used in South African gold mining for expressing a relative index of cooling power of the air. Sometimes this index was obtained by direct timing with a stopwatch but more often, during the past two decades, it was calculated from velocity and air wet bulb temperature according to a formula derived experimentally by Kitto[1].

Recently Mitchell and Whillier[2] proposed that the kata thermometer should be scrapped and replaced by their Specific Cooling Power (S.C.P.) concept, based on velocity and air wet bulb temperature.

The present study attempts to show that with various reappraisals and/or modifications, the wet kata thermometer might continue to serve as a useful and sensitive instrument for the routine determination of heat stress in hot mining environments. Six findings from the present study can be stated in summary from:

(i) Kitto's kata formula is fundamentally wrong although empirically and fortuitously it is not far off the mark for the present design of the thermometer.

(ii) Mitchell and Whillier's S.C.P. equation is identical in form to the forty-year old wet kata equation of Weeks[3].

(iii) The constants for Weeks' kata equation have been determined experimentally in the present study.

(iv) There is a constant numerical relationship between the S.C.P. and the new kata equation except for the exponent in the velocity function, V^n.

(v) The justification for extending Mitchell and Whillier's[2] S.C.P. concept to velocities as low as 0,1 $m\cdot s^{-1}$ is not proven.

(vi) The exponent '*n*' in the velocity function in both the S.C.P. and the kata equation is in question as far as the sweating human body is concerned. With some "give and take" on either side there might yet emerge a workable reconciliation between the two concepts.

KITTO'S KATA EQUATION

After carefully conducted experiments, Kitto[1], following the earlier general equations of Hill and Rees, arrived at the relationship:

$$H=0{,}4\ \theta+0{,}04\ \theta\ V^{0{,}5} \quad (1)$$

where H=cooling power of the air, millical$\cdot$cm$^{-2}\cdot$sec^{-1}

θ =97,5 − unventilated wet bulb temperature, °F.

V=air velocity, ft$\cdot$min^{-1}.

The first term in equation (1) above is velocity-independent and was, quite rightly, aimed at giving expression to the fact that at low air velocities, in directional sense, buoyancy or natural ventilation plays a distinct role and the cooling power of the air is, therefor, not zero at zero velocity. Kitto himself showed that the exponent '*n*' in the velocity function V^n should not be 1/2 but nearer 1/3 but for some unexplained reason he did not pursue the latter finding.

It is clear, however, that where both convective and

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evaporative heat exchange are taking place, the equation cannot be temperature-dependent only, but should have a term which includes the sum of temperature difference and vapour pressure difference. This means that fundamentally the expression for kata cooling power in relation to wet bulb temperature cannot be linear as indicated in equation (1).

It should be pointed out that Kitto's main experiments were conducted at only one wet bulb temperature of 75 °F (about 24 °C), except in still air. For purposes of later comparison, equation (1) is given here in metric units:

$$H=30{,}1\ \theta+42{,}2\ \theta\ V^{0{,}5} \quad . . . . \quad (2)$$

where H = cooling power in $W \cdot m^{-2}$
θ = 36,4 − unventilated wet bulb temperature, °C
V = air velocity, $m \cdot s^{-1}$

MITCHELL'S AND WHILLIER'S SPECIFIC COOLING POWER

Mitchell's and Whillier's[2] complete and somewhat complicated equations for cooling power will not be repeated here because they can be written into a single and much simpler equation, following the method of Weeks[3] and as already indicated previously by Lambrechts[4]. This simplification is made possible by the fact that the cooling power of an air/water vapour mixture on wet surfaces is independent of dry bulb temperature, as Mitchell and Whillier[2] themselves concluded. Their modified equation is, leaving out the small radiant heat term for the time being:

$$H=8{,}32\left[\left(35{,}0-T_w\right)+1{,}83\left(e_{35}-e_{T_w}\right)\right]V^{0{,}6} \quad . \quad (3)$$

where H = cooling power, $W \cdot m^{-2}$
35 = assumed human skin temperature, °C
T_w = air wet bulb temperature, °C
e = saturated water vapour pressure, mbar
V = air velocity, $m \cdot s^{-1}$

(Note: The atmospheric pressure was chosen at 1 013 mbar to cancel out an awkward term. This is close enough to the value of 1 000 chosen by Mitchell and Whillier).

The above equation (3), with the small radiant cooling term added as per Fig. 1, will produce the same specific cooling power chart as recommended by Mitchell and Whillier[2] in their Fig. 4, p. 96, for practical use in hot mining environments. It should be pointed out that Mitchell's and Whillier's S.C.P. concept allegedly applies to human beings but in fact is only valid, strictly speaking, for a heated, wetted life size dummy, with no physiological variant at all.

Argument on the validity of the constants in equation (3), particularly the exponent 0,6 in the velocity function will follow later.

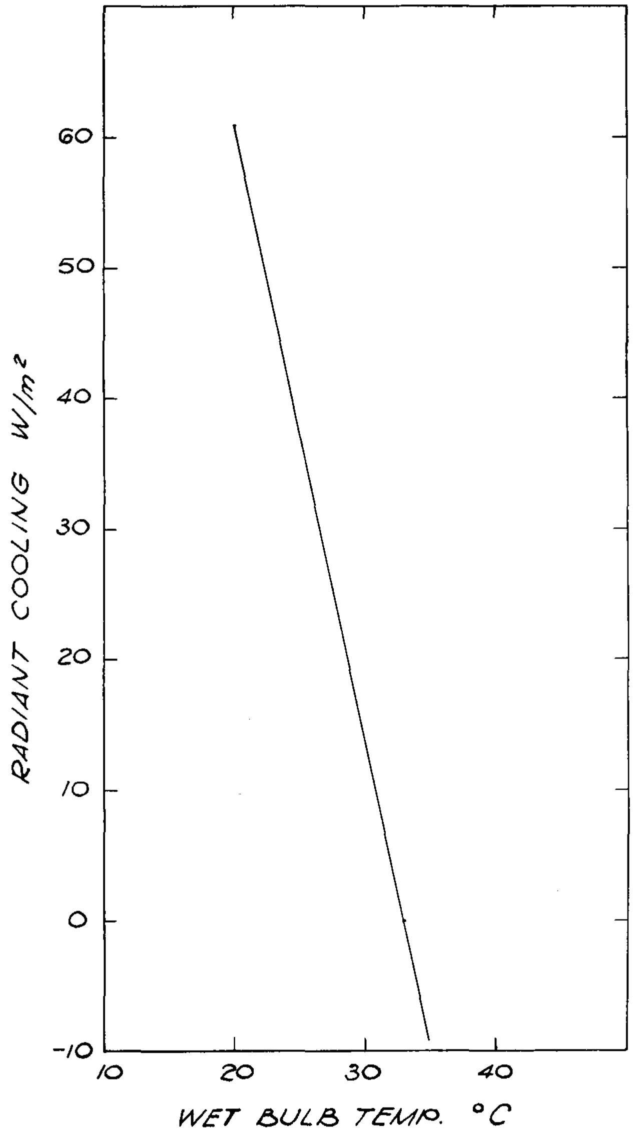

Fig. 1 Radiant cooling (After Mitchell and Whillier,[2] Equation 2)

WEEKS' KATA FORMULA

The formula arrived at by Weeks[3], and using the same symbols as in the present paper, is:

$$H=h_c\left[\left(T_s-T_w\right)+\frac{1}{mP_a}\left(e_{T_s}-e_{T_w}\right)\right]+\text{a radiant term} \quad . . . . . \quad (4)$$

where h_c = convective heat transfer coefficient
T_s = temperature of the surface film
T_w = air wet bulb temperature
m = psychrometric constant = 0,000 66 (temp. in °C)
P_a = atmospheric pressure
e = saturated vapour pressure

substituting: h_c = a constant $C \times V^n$
T_s = 35 °C (i.e. a little lower than the mean kata temperature of 36,4 °C)
m = 0,000 66
P_a = 1 013 mbar

one obtains, again leaving out the small radiant term:

$$H=C\left[\left(35{,}0-T_w\right)+1{,}50\left(e_{35}-e_{T_w}\right)\right]V^n \quad . . . . \quad (5)$$

It will be seen that equation (5) is in the identical form of equation (3) with only the constants C and n still to be evaluated for the wet kata thermometer.

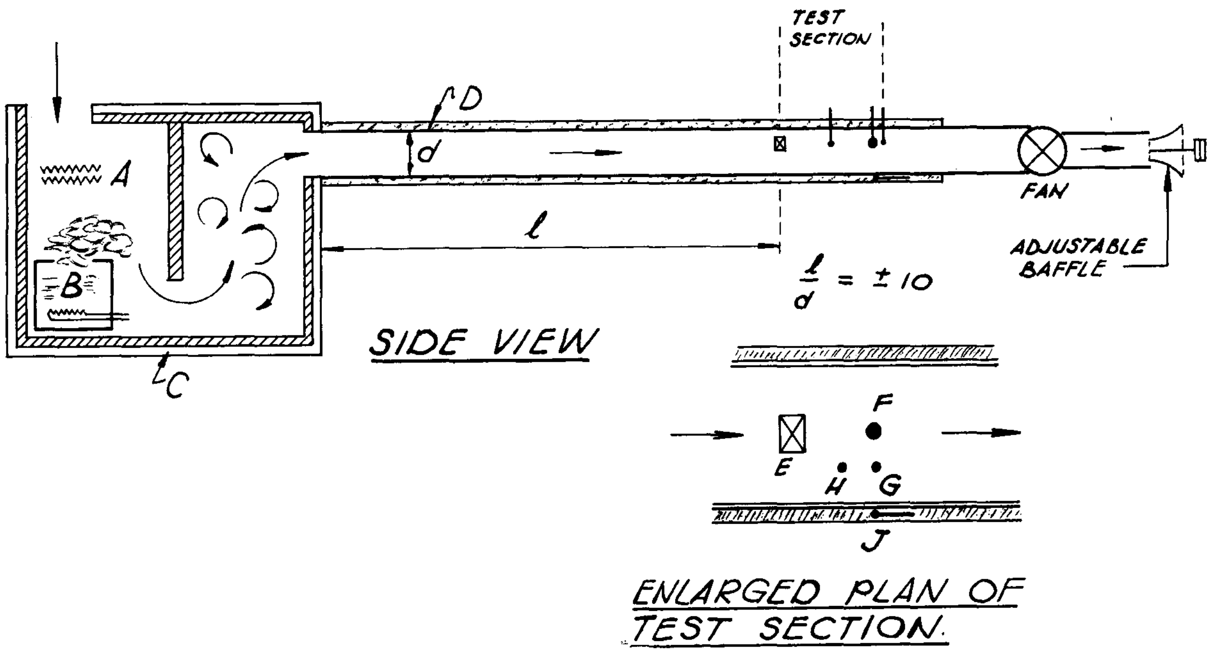

Fig. 2 Test set-up for kata experiments. Diagrammatic, not to scale

A = **electric heating elements (4 X 500 Watt) variac transformer**
B = **electric steam generator (2 X 2 800 Watt) variac transformer**
C = **wooden heating and mixing box, polystyrene lining inside**
D = **23 cm diameter iron pipe with felt insulation outside**
E = **7 cm diameter direct reading electric anemometer**
F = **standard wet kata thermometer**
G = **wet bulb thermometer with small irrigation bottle**
H = **dry bulb thermometer**
J = **thermometer, insulated outside, in contact with pipe.**

WET KATA CONSTANTS C AND n

Kata experiments were conducted in a somewhat crude but apparently effective set-up depicted in Fig. 2 which is self-explanatory. Heating and humidification were by means of electric heating elements and direct steam injection. Plenty of time was allowed between various temperature and velocity settings for stable conditions to develop. A constant watch was kept on the dewpoint temperature and the metal pipe temperature to avoid condensation in the test section. The dew point was kept a few degrees below the metal duct temperature and absence of condensation could also be visually observed through a small perspex window in the test section. Only one kata thermometer was used, with repeat readings at each setting but this thermometer was checked against several others and agreement was good.

There was the further slight concern about the possibility that the somewhat open-weave standard kata sleeve might dry out before the end of a reading or rather, that the liquid water film might break in the interstices between the cotton threads. This was checked in two ways:

(i) By microscopic examination of the water film under darkground illumination, with a piece of the standard wetted muslin on a glass slide. Movement of dust particles in the liquid water film could be observed for several minutes whereas kata cooling times are in practice invariably less than one minute.

(ii) A kata thermometer with standard sleeve (about one third visible open area) was compared with two other katas, one with a thin close-mesh silk sleeve and the other a thin close-mesh cotton sleeve. In neither of the latter two cases was there any obvious free space so that breaking of the water film was hardly likely. Yet all three katas compared very well even under adverse drying out conditions.

One concludes that for all the kata readings the surface of the bulb remained fully wet throughout. The experimental results are recorded in Table I, temperatures and kata readings having been converted, respectively, from °F to °C and $mcal \cdot cm^{-2} \cdot sec^{-1}$ to $W \cdot m^{-2}$.

TABLE I

WET KATA EXPERIMENTAL RESULTS
(Barometer = 877 mbar)

Velocity	Wet bulb temperature	Dry bulb temperature	Cooling power
$m \cdot s^{-1}$	°C	°C	$W \cdot m^{-2}$
3,29	28,2	31,0	920
3,29	22,7	28,4	1 390
2,15	33,5	38,1	253
2,15	29,0	31,9	713
2,15	25,2	30,3	1 040
1,17	33,4	37,4	239
1,17	29,1	34,7	575
1,17	23,4	28,7	968
0,72	32,6	41,3	253
0,72	29,1	35,8	478
0,72	23,5	30,9	788

A velocity substantially lower than 0,72 $m \cdot s^{-1}$ was not attempted because this would have taken one too close to the lower limit of reliability of the anemometer. Also, a third and substantially higher temperature at the highest velocity was not possible with the available heating capacity. It should be noted that the wet bulb temperatures recorded are the so-called "unventilated" readings. Even at the lowest velocity used, however, it is known that the unventilated does not differ significantly from the ventilated temperature, which would have been preferred.

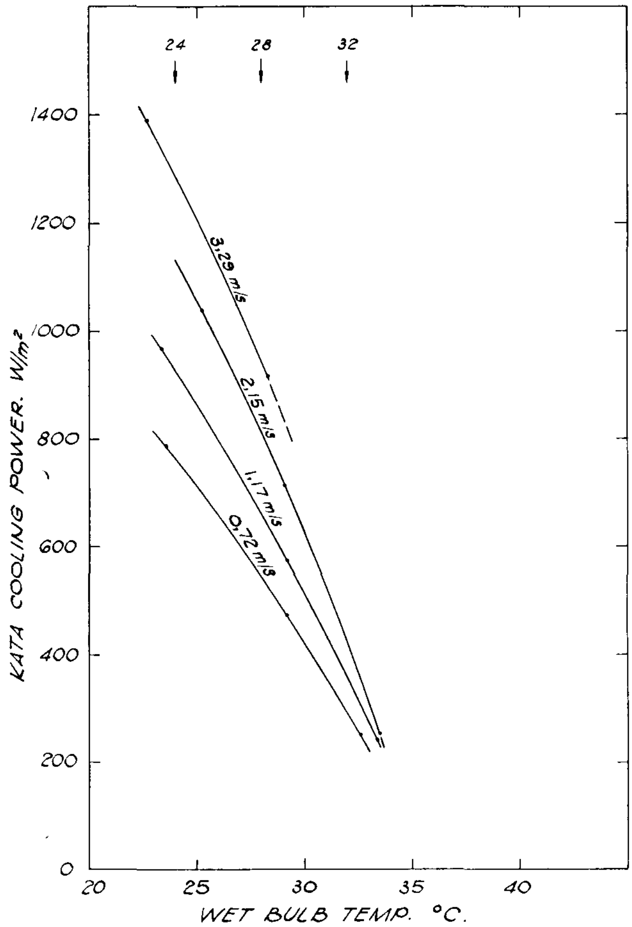

Fig. 3 Experimental kata results

The results in Table I are graphed in Fig. 3 and cooling powers were read off at three constant temperature intercepts namely 24, 28 and 32 °C. Pairing off between different velocities at these three temperatures, 15 values of the exponent n in equation (5) emerged, bearing in mind that for a given wet bulb temperature the whole of the expression inside the double bracket in equation (5) is constant.

Average n in equation (5)=0,346 (say 0,35)

Now using the above average exponent of the velocity function, the value of C in equation (5) can be found. Average of 11 values, C=16,1

So finally, substituting the above values for C and n in equation (5):

$$\text{Kata C.P.}=16{,}1\left[\left(35{,}0-T_w\right)+1{,}50\left(e_{35}-e_{T_w}\right)\right] V^{0,35} \quad \ldots\ldots\ldots \quad (6)$$

$$\text{Specific C.P.}=8{,}32\left[\left(35{,}0-T_w\right)+1{,}83\left(e_{35}-e_{T_w}\right)\right] V^{0,6} \quad \ldots\ldots\ldots \quad (3)$$

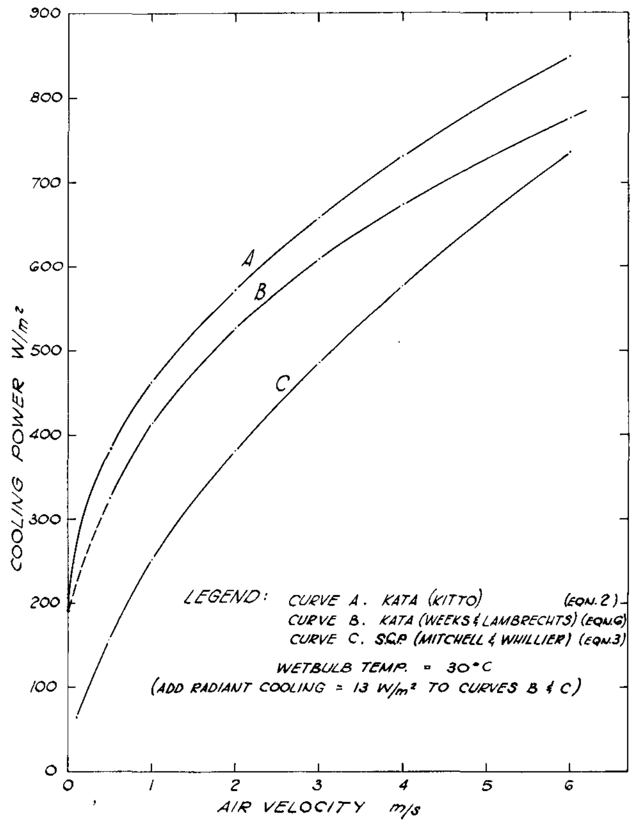

Fig. 4 Comparison of cooling power formulae

Temporarily rewriting equation (6) and (3) above, for a given wet bulb temperature as:

$$H\ (\text{kata})=C_1V^{0,35} \quad \ldots\ldots\ldots \quad 6\ (a)$$

$$H\ (\text{S.C.P.})=C_2V^{0,6} \quad \ldots\ldots\ldots \quad 3\ (a)$$

it can be shown by numerical substitution of various wet bulb temperatures and corresponding vapour pressures that

$$\frac{C_1}{C_2}=\text{constant}=1{,}65 \quad \ldots\ldots\ldots \quad (7)$$

Therefor,

$$\frac{\text{Kata cooling power}}{\text{Specific cooling power}}=1{,}65\frac{V^{0,35}}{V^{0,6}} \quad \ldots\ldots \quad (8)$$

(with V in $\text{m}\cdot\text{s}^{-1}$)

In other words, the difference between the two cooling powers lies solely in the exponent in the velocity function, apart from the constant multiplier.

A direct comparison is shown in Fig. 4 between cooling powers calculated for an arbitrarily chosen wet bulb temperature of 30 °C and pressure about 1 000 mbar, for (a) the currently used Kitto kata equation (b) the Weeks kata equation, with constants fixed in the present study and (c) Mitchell's and Whillier's specific cooling power equation. Kitto's equation, incidentally, is the only one which can be anywhere near correct for very low velocities, say below 0,3 $\text{m}\cdot\text{s}^{-1}$.

DISCUSSION OF THE VELOCITY FUNCTION, V^n

There can be little dispute about the value n=0,35 for the kata thermometer; this value checks very well with the earlier cube root value found by Kitto[1] in his Fig. 5.

Concerning the value $n=0,6$ for the human being working in a hot environment, one is not quite so happy. Physiologists have tended to accept a value of 0,5 in the past and now Mitchell and Whillier[2] have proposed a value of 0,6. This value is based on the earlier work of Mitchell et al[5, 6] published partly in Germany[5] and partly in America[6]. This work was conducted on human males and their coefficient of convective heat exchange was measured by varying the air temperature and wind velocity. The authors were in fact, doing experiments on direct human calorimetry with the subjects doing no work but responding physiologically to changes in temperature and air velocity. Air dry bulb temperatures varied between 12,8 and 49,1 °C, wet bulb temperatures between 6,7 and 23,2 °C and wind speeds between 0,67 and 4,94 $m \cdot s^{-1}$. Part of the time the subjects were not perspiring and were losing heat convectively; part of the time they were perspiring, losing heat evaporatively and gaining heat convectively. Experimental results scattered considerably.

These were certainly not the best of circumstances under which to fix the exponent n in the velocity function at 0,594 and rounding it off to 0,6. More-over, they fell back on the wellknown Lewis relationship which postulates the constancy between convective heat and mass transfer coefficients. But actual calculation by the present author from Figs. 5 *a* to *e* in Mitchell et al's[6] paper leads to a value of $n=0,35$ for evaporative cooling, at their highest temperature when *all* the heat loss was evaporatively. There can be much discussion on this controversial subject yet.

For example, Hanhoff in an excellent doctoral thesis[7], and a further paper, partly published[8], gave the n values in the V^n velocity function as suggested by various researchers. (See Table II). Hanhoff's own work in the German climatic chamber, at two air velocities of 0,5 and 2,0 $m \cdot s^{-1}$ led him to conclude that for evaporative cooling the exponent n in $V^n=0,68$. But it should be added that for "velocity" he used an "effective" wind speed which was the summation of velocity and the movement of the subjects themselves. Calculating only on the directly measured velocities of 0,5 and 2,0 $m \cdot s^{-1}$ the present author finds Hanhoff's n value to be 0,45.

Hanhoff commented on the fact that evaporative cooling might not have been maximal in all his quoted examples. But the same comment applies to the findings of Mitchell et al[6, 7] as well as to the practical mining situation. Can one in fact, assume *maximum* evaporative cooling at all times in the practical mining situation? And can one so readily assume, as Mitchell and Whillier[2] did that the whole human body area is available for evaporative cooling, bearing in mind the wearing of hard hat, leggings, boots and some clothing?

The above Table II merely illustrates how widely opinions differ and it should be remembered that in deep-level gold mining in South Africa, where dry bulb air temperatures are close to human body temperatures, evaporative cooling dominates the picture. It is, therefor, vitally important to know the correct n value in the overall velocity function V^n and it is concluded that Mitchell's and Whillier's[2] value of 0,6 is unproven. It is suggested that the best value lies somewhere between 0,35 and 0,6. The implications of the difference between $n=0,35$ and 0,6 are of great importance physiologically, technologically and financially, in weighing up the relative importance of volume circulation of air versus air cooling or refrigeration.

TABLE II

HANHOFF'S[7] TABLE OF EVAPORATIVE COOLING n VALUES IN V^n

Authority	Maximum Evaporative Cooling $kcal \cdot m^{-2} \cdot hr^{-1}$	Publication Year	Remarks
Nelson et al	$10,2 \cdot V^{0,37} \cdot \Delta e$	1947	
Clifford et al	$12,6 \cdot V^{0,63} \cdot \Delta e$	1959	
Haines & Hatch	$10,2 \cdot V^{0,37} \cdot \Delta e$	1952	Based on Nelson (1947)
Belding & Hatch	$11,6 \cdot V^{0,40} \cdot \Delta e$	1955	Based on Nelson (1947)
Givoni	$17,4 \cdot V^{0,30} \cdot \Delta e$	1962	
Ionidis et al	$13,13 \cdot V^{0,60} \cdot \Delta e$	1945	
Present study	$5,84 \cdot V^{0,35} \cdot \Delta e$	—	Based on Mitchell et al[6] Fig. 5

(Note: Δe = vapour pressure difference, mm Hg.)

MINIMUM VALUE OF VELOCITY FOR VALID APPLICATION OF EQUATIONS

It is known that because of buoyancy or natural ventilation effects and also the bodily movements of workers, the measured transverse air velocity is less than the actual speed of air movement. Unless a velocity-independent term is included in any cooling equation, care has to be exercised not to extrapolate into the region of very low velocities. Mitchell and Whillier[2] quoted Vermeulen[9] as having demonstrated that buoyancy effects "are not apparent experimentally at wind speeds as low as 0,5 $m \cdot s^{-1}$" but they then proceeded to extrapolate down to 0,1 $m \cdot s^{-1}$. They were hardly justified in using an increase from 0,1 to 1,0 $m \cdot s^{-1}$ as an *example* in trying to prove the superiority of their S.C.P. concept over the currently used wet kata formula. The lower limit of validity for both the S.C.P. and the modified Weeks kata equation is almost certainly higher than 0,1 $m \cdot s^{-1}$.

SUGGESTED FURTHER RESEARCH

It is suggested that research to establish the effect of air velocity *per se* on the cooling of the human body under hot mining conditions should be further pursued.

At the same time, if a simple instrument such as the wet kata thermometer can be modified so that it does in fact simulate the human body cooling process relatively correctly, then it will remain a valuable instrument for this purpose. That the kata cooling power will always be substantially higher than human body cooling is a known fact because of the size scale effect. If, however, it can be made to measure too high by a fixed percentage, this will be of no consequence because the difference can simply be eliminated in the calibration factor.

The kata thermometer has a very streamlined shape and the thought occurs that if the round shape of the bulb were changed to square or hexagonal there might be more eddying around the bulb and maybe the exponent n will increase. It has already been shown that Specific Cooling Power, if this is the preferred criterion, can be predicted from the wet kata reading because:

$$\frac{\text{Kata C.P.}}{\text{S.C.P.}} = \text{a constant} \times \frac{V^{n_1}}{V^{n_2}}$$

where n_1 and n_2 are the exponents for the two techniques. Therefore, if the two n values are the same, the wet kata should be a direct predictor of cooling power on the human body.

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