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The model has been applied since 1971 with minor revisions as needed.

The AT model is elaborated from the work of Höschele (4). It integrates physiological factors in the body’s interior and skin tissues, the physics of the clothing and internal air layers covering part of the body, and the meteorological factors in the environment. The last three factors, ZP, ZS, and GQ, have a combined effect that is added to the dry-bulb temperature ZT and expressed as AT (‘‘in sunlight’’). The level of AT, i.e., the number of the three secondary parameters used in determining AT, is the numeral after AT.

The scale is established by setting GQ = 0, ZS at a level due only to the person’s movement (1.4 m/s) and zero external wind speed, and ZP at a neutral level nZP (12), given by

\[ nZP = sZP \text{ when } ZT < -2 \]
\[ nZP = 600 + 40 \text{ ZT when } -2 < ZT < 26.5 \]
\[ nZW = 12 \text{ g/m}^3, \text{ or } nZP = aZT/0.1814, \text{ when } ZT > 26.5 \]

as in most of the present paper. This corresponds to the same vapor concentration as at ZJ = 0.65, ZT = 20, the conditions specified for temperate-zone textile-testing laboratories.

In an evaluation of AT, steady-state conditions are used, with the body losing heat at the same rate as it is produced metabolically. This steady state does not imply thermal comfort, except when IT = 37°C. Contrary to a view that appears occasionally in the literature, AT, unlike effective temperature, with the latter’s base of ZJ = 0.5, is based on absolute, not relative, humidity. Tables show ZJ as a concession to convention and to simplify application.

In an application, if the clothing requirement for 30°C, for example, is obtained at these neutral or base levels, any other set of conditions calling for the same insulation has an AT of 30°C. Another paper (14) quantifies four reflex and seven conscious ways in which the person regulates heat loss. Moreover, breathing, a mechanism for regulating heat loss for some other mammals, is a part of convective and evaporative heat exchange and is proportional to MQ in humans. The lungs function as a recuperative heat and moisture exchanger having 94% efficiency, giving

\[ VQ = MQ \left[ (IT - ZT)/870 + (IP - ZP)/55,000 \right] \text{ W/m}^2 \]  

Of the four ambient variables, breathing heat loss depends only on ZT and ZP, and the evaporative component is the larger when ZT > -40°C. Total heat loss by breathing, VQ, accounts for as little as 3% of heat loss in hot or humid, and as much as 12% in cold, conditions at all activity levels.

In an unbiased scale, such as AT, effects of humidity, wind, and extra radiation can be positive, zero, or negative, although warming effects of wind are rare and slight. AT is obtained in two ways: by fitting values of FU (a measure of the amount of clothing needed) and of IT (a measure of physiological response) to the “neutral” ZT values. The AT values are quintic curve
fits, having SDs in both calibration and validation 
<0.09 K. If the two values, which always differ by <1 K, are denoted by AT' and AT'', then AT = PC × AT' + 
PB × AT''. Conventional AT has an approximately 
one-to-one correspondence with IT, IP, TR, FR, FU, TZ, 
FZ, PC, and PB. Curve fitting is the smallest of eight 
Sources of error inherent in the measurement and 
evaluation of the three levels of AT and the components. 
Along with two others that are derived from the effects 
of rounding off measured relative humidity and cloud 
cover in Australian official data, nine sources of error 
are quantified and summed in a table available free of 
charge from the author. Under less favorable condi-
tions, for example, a value of AT3 is expressed ±1.1 K, 
AT1 is ±0.7 K, and the effect of wind is ±0.6 K, 
provided that ZT is measured to ±0.1 and wet-bulb to 
±0.2 K.

Of the four independent variables, ZT is the most 
important, although there are conditions where it over-
or underestimates the effect of weather, even climatic 
averages, on a person by >10 K. Although AT3 takes 
account of all four, some users find it useful to have 
simpler measures. If only ZT and ZP are evaluated, as 
in the US heat index, the effect of humidity, for which a 
universal 95% confidence interval is approximately ±4 
to ±5 K, is obtained by subtracting the dry-bulb 
temperature ZT from the “indoor” AT1. Introducing 
wind speed at the person gives a second (“outdoor”) 
level, AT2, hence the effect of wind, AT2 – AT1, in an 
analogous range –8 to 0 K. This difference, the wind-
chill, is more moderate than values presented by the 
media when ZS10 < 19 m/s or ZS < 10 m/s. The popular 
scale, however, dangerously underestimates windchill 
at higher wind speeds, and efforts are being made to 
replace it (e.g., Ref. 9).

Complexities of estimating extra radiation GQ are 
explained elsewhere (12). When applied to solar radia-
tion, it has four components, taken as acting evenly on 
the person: direct (typically 0–100 W/m² of total body 
surface); diffuse (0–40); terrestrial (0–30); and long-
wave outgoing (–30 to 0). In total, values are 
about ±30 = GQ ≤ 120 for the walking human and –40 ≤ GQ ≤ 200 
for quadrupeds or a prone, sunbathing person. When 
GQ is introduced, AT3 is obtained, giving an effect of 
extra radiation, AT3 – AT2, usually in the range –2 K 
on a calm clear night to +6 K on the walking person 
exposed to sunshine at altitude angles near 50°. A 95% 
universal population-weighted interval for the com-
bined effect, i.e., the amount by which AT3 as sensed by 
an active person exceeds ZT, is –10 to +9 K.

In contrast to some older systems, which either 
assume or ignore values for YR, ZJ, YZ, IT, IP, ST, and 
their derivatives, all the key physiological parameters 
are evaluated as part of the process of deriving AT. 
Other indexes, if clothing is considered at all, usually 
assume PC = EE = GE = 1. In the popular windchill 
scale, VQ = EQ = PC = 0. The AT printout can be set up 
to provide as many as 20 physiological parameters and 
6 clothing variables. As AT changes, the corresponding 
change in IT is only 5 (cool) -10% (warm conditions) as 
great and is ignored by most workers in human bio-
meteorology. IT is both worthy of inclusion and indi-
rectly important because it is the key stimulus to the 
other 10 regulatory mechanisms that come into play.

Quantitative Aspects

Most of the relationships that describe a person’s 
thermal reactions and relationships derive from an 
eclectic scavenging of the literature and are updated as 
new data become available.

In many publications, even contemporary ones, EQ is 
calculated (with perfect evaporative efficiency as-
sumed) to express the discrepancy between two other 
heat flows and sometimes comes up negative, and then 
is taken as zero, as if the person were impermeable to 
“active” sweat. If it exceeds “Emax,” a fresh set of 
assumptions is engaged. The AT system does not intro-
duce such immeasurable terms as wetted area of skin 
or wetness factor of clothing, although SJ and UJ can 
be evaluated. Because accuracy of the AT scale cannot 
be guaranteed if SJ > 0.90, it is commonly checked. 
Only 80% of the surface is exposed to full convection 
and 72% to full radiation, because heat transfer of 
much of the surface, especially of the limbs, is limited 
by other parts.

Estimation of physiological parameters is based partly 
on the work of Fanger (3). Clothing parameters are 
based on physical properties of average fabric en-
sembles. To provide a seamless analysis, i.e., with no 
gap or overlap between winter and summer scales, 
these ensembles are qualitatively the same for hot and 
cold conditions, varying in thickness and coverage, but 
the effects of temperature (including the effect of extra 
radiation on clothing temperature) and wind penetration 
on conductivity are allowed for (Eqs. 12 and 12a, below).

Figure 1 illustrates moisture flow from the body’s 
core to the environment. The potential is vapor 
pressure, and the three variable resistances are in series or 
additive. The flow follows Ohm’s law, even though the 
flow is in liquid form through TZ and vapor through FZ 
and YZ. More important than the flow is the evapora-
tion at the skin surface; for each gram that evaporates, 
a latent heat of 2,400 J is abstracted from both sides of 
the skin. This enthalpy change refers to the latent heat 
of evaporation at ST and the change of sensible heat as 
moisture temperature changes from IT to ST. It amounts 
to 2,400 ± 12 kJ/kg in all the conditions considered. 
Because the system is thermodynamically closed, isother-
mal heat lost in vapor expansion can be ignored (6).

This reasoning is now applied to heat transfer in Fig.
2. Sweat evaporates at the skin, and extra radiation is
absorbed at the surface, which has 0.7 absorptivity and 0.97 emissivity. Ohm’s law still applies but is combined with Kirchhoff’s law at the junctions. TQ and EQ are always in the direction shown, but the other arrows in Fig. 2 may reverse, especially in the hot conditions that are the focus of this paper. To obtain steady state and to clarify TQ

\[ MQ = TQ + VQ \]  

The following equations are expressions of Kirchhoff’s law and apply to the whole body, or to each of the body elements into which it is divided: at the skin

\[ TQ = FQ + EQ \]  

at the outer clothing surface

\[ FQ = YQ - GQ \]  

at bare parts

\[ FR = 0 \]

and

\[ TQ = YQ + EQ - GQ \]

Combining Eqs. 3 and 4 shows Eq. 5 to be valid also for clothed parts.

The three temperature differences can be expressed as

\[ IT - ST = TR \cdot TQ, \quad UT - ZT = YR \cdot YQ \]

and, where applicable

\[ ST - UT = FR \cdot FQ \]

It follows by addition that the evaporative efficiency

\[ EE = (FR + YR)/\Sigma R \]

and the efficiency with which absorbed extra radiation, positive or negative, adds to the person’s heat load (to engineers, the “inward-flowing fraction”) is

\[ GE = YR/\Sigma R \]  

When a weighted average over the whole body surface in steady state is obtained, representative values are \( 0.7 \leq EE \leq 0.85 \) and \( 0.3 \leq GE \leq 0.7 \), averaged over the walking person. Both efficiencies, especially GE, tend to diminish as wind speed increases, causing a reduction in YR. Re (the ratio of inertial to viscous forces) \( > 10,000 \) almost always, in sharp contrast to the free-convection scenario (see the GLOSSARY).

Many results are conveniently portrayed on psychrometric charts, such as Fig. 3, which shows isotherms of AT1. In two dimensions, only two independent variables can be displayed. The use of three-dimensional graphs has been tried, but with such a loss of clarity and ease of measurement by the reader that contour charts of the type used here, for which there is no satisfactory available software, continue to be drawn by hand, for the same reason as isobars on weather maps are drawn by hand. Figure 3 is more commonly presented as a table, often in Fahrenheit temperatures, as the heat index. Wet-bulb globe thermometer (WBGT) readings provide one of the few other four-factor measures of heat stress. Although WGBT is insensitive to wind, oversensitive to humidity, inappropriate in freezing temperatures, and gives results some 20% below the perceived temperature, it correlates well with AT (SD about linear regression line \( = 2.0 \) K in the range defined in SCOPE AND CONSTRAINTS, with the further restraint \( ZT > 0 \) ) but has to be adjusted upward to give a realistic impression of temperature. The conversion \( AT = 1.25 \) WBGT is a useful one in above-freezing conditions.

The human model has a mass of 72 kg, a volume of 73 liters, and a surface area of 1.9 m². These values are not critical in the relative assessment of the four independent variables ZT, ZP, ZS, and GQ. Applying standard
engineering reasoning gives a mean effective diameter (mSD) for the sides of a long cylinder, of $4 \times 0.073/1.9 = 0.17$ m. The separate variable diameters for the bare and clothed parts are obtained, with the significant diameter for the clothed parts being $OD = SD + 2FU$. The component bare and clothed diameters are not detailed here, because a more refined analysis of body dimensions was used in the free-convective scenarios. The AT scale is not applicable to infants, who have lower significant diameter $SD$ and, especially if premature, lower $TZ$.

As the body’s core temperature changes, its vapor pressure changes appreciably. Saturation vapor pressure is given by $sP = 1,000 \exp(-0.4863 + 0.07121 T - 0.0002258 T^2)$.

In view of the limit that Eq. 8 imposes on skin humidity of both clothed and bare parts, any result in which $sJ > 0.90$ at the wettest part of the skin is suspect and is possibly associated with free liquid on, or even dripping off, wetter parts of the skin. Such results are denoted by dotted lines (figures) and suffixes in the author’s tables. A necessary but insufficient condition for this outcome at the metabolic levels considered here is $ZP > 2,400$ Pa. The internal temperature, which is used as a measure of AT, is related to the body’s mean thermal resistance by

$$\text{MQ} = \text{VQ} + \text{PB} \left[ \text{IT} - \text{ZT} + \beta YR \left( \text{IP} - \text{ZP} \right) \right]$$

$$+ \text{PC} \left[ \text{IT} - \text{ZT} + (\text{FR} + cYR)(\text{IP} - \text{ZP}) \right]$$

$$+ \left( \frac{1}{7 \text{ TR}} \right)$$

The surface resistance $YR$, referring to the parallel flows of convective and radiative heat from the surface to the environment, adjusted for clothing thickness but referred always to the skin surface area, is given by

$$YR = SD/(\text{CH} + \text{RH})/OD$$

The convective dry heat-transfer coefficient for 80% of full convection is derived by fitting linear relationships to $YK$ and $YV$ for air at 60% saturation as functions of $YT$, substituting, because air is a perfect gas, $1/aY$ for $\beta$, and applying $Nu = 0.22 Pr^{0.31} Re^{0.58}$ for the range of wind speeds encountered outdoors

$$\text{CH} = (3.84 - YT/516)(ZS \times OD)^{0.58}/OD$$

The radiative coefficient for 72% of full radiation is obtained by factorizing the equation describing radiant exchange between UT and ZT for skin and clothing emissivities of 0.97

$$\text{RH} = 4.00 \times 10^{-8} (aUT + aZT) (aUT^2 + aZT^2)$$

If the radiant temperature of the surroundings differs from that of the ambient air, the difference is expressed as extra radiation. Another publication (13) shows how extra radiation is related to operant temperature and mean radiant temperature. Equation 15 is solved iteratively by entering an initial value of TR to find a trial value of the right-hand side (RHS) and repeatedly adjusting TR by $(\text{RHS} - \text{MQ}) (\text{TR}/1.6)^{1.6}$ until the two sides of Eq. 15 differ by <0.02 W/m². To avoid a fluke solution before the parameters have
stabilized, this condition is prescribed for two successive iterations. More than 30 iterations are seldom needed. Corresponding values of FU and IT are substituted into curve fits to get AT.

Trials in which Reynolds’ analogy (10) was applied to the dimensionless numbers (see the glossary) verified that the psychrometric constant is close to 61 Pa/K over the range of conditions pertinent to the free-convective anomaly, although as low as 59 in saturated cool conditions. The analogous resistance to moisture transfer is

\[
YZ = \frac{SD}{(61 \, CH/OD)} \quad (18)
\]

In the outdoor conditions in which the heat index is determined, FR is commonly the highest dry resistance and TZ is the highest “moist” resistance. The effect is to keep the skin warm but dry. The rest of this paper will examine stagnant or still conditions where FR and especially YZ are on the same order of magnitude as the body and clothing resistances. In still conditions, YZ sometimes accounts for more than one-half of \( \Sigma Z \) and becomes the limiting factor in moisture transfer.

TOWARD AN AT SCALE FOR INDOOR CONDITIONS

There is much interest, especially from industrial engineers and medical specialists, in heat stress associated with indoor work. In the absence of much air movement, a person is more sensitive to extra radiation; when the person is resting or less active than a walking person, lower perspiration renders the person generally less sensitive to humidity than in the outdoor AT model. Partly, too, for forensic purposes and in sports medicine, an AT scale encompassing low air movement was needed. Work began in 1985 on this apparently routine task, with the intention of publishing scales at various levels of GI within a year. Unexpected and puzzling complications soon arose. They led to refinements, such as the division of the body into 100 equal areas having different “hydraulic” or effective diameters.

The analysis performed here refers to the most stagnant conditions that a person is likely to encounter, and the reader’s professional judgment is needed in interpolating between the outdoor AT scale and the “still” scale (see Evaluation). Potential applications of “phone-booth conditions,” in which purely free convection is approached, are to such scenarios as the following: 1) a person working at a furnace or oven, or in a confined space, e.g., an attic; 2) a heat-stressed collapsed athlete; 3) children and pets in parked cars; 4) animals closely confined, such as battery hens and live-animal cargoes; 5) a person sunbathing in the absence of wind; and 6) a person engaged in underground mining.

Because the anomaly occurs at AT levels at which the sustained use of human subjects would be forbidden, there is scant experimental evidence to support quantitatively the conclusions reached theoretically in this paper. In view of the heat fatalities that occur indoors, especially in heat waves and occupationally, the prompt publication of an unconfirmed and partly unconfirmable set of results is better than a large gap in our quantitative knowledge. Refinements to the theory should obviate the need for any human experiments in such distressing conditions. However, a few pieces of anecdotal evidence pointing to “superheating” in still conditions have come to the author’s attention and have been edited to remove some colorful adjectives and nonstandard units: 1) “I felt cool enough until I collapsed.” (Runner in “fun run” at AT = 35°C); 2) “It must be 60°C in that attic.” (Electrician. Measurement showed 41°C with ~40 W/m² of extra radiation (AT3 = 47°C). Later it will become clear that he was in the middle of the free-convective anomaly. An advertisement for attic fans claims an attic temperature of 70°C; 3) “It got hot each time I went down the straight,” i.e., when the tailwind had the same velocity as the athlete. (Walker in 10,000-m track event with ZT = 33°C, conventional AT = 38°C); and 4) “Once it goes above ~40°C, you don’t notice much difference.” (Expatriate manager working in Dubai; the author would argue that the claim is true only in the range 41 ≤ ZT ≤ 45°C).

Alternative Models

Although the human model described here and in the references was modified appropriately for still conditions, it was apparently intractable in the early stages of this work. Some alternatives were developed, e.g., having different metabolic levels, different formulas for clothing insulation (Eq. 18), and different body sizes. One version was nude, i.e., only the four reflex, but not the seven conscious, thermoregulatory mechanisms were allowed. The criterion for terminating iterations, a difference of 0.002 W/m² between the sides of the heat-balance equation, was narrowed successively, without improvement. In every instance, the problem of multiple solutions somewhere in an anomalous region became evident and persisted. Finally, the present model, describing as realistically as possible the person’s reaction to heat stress, whether due to temperature, humidity, extra radiation or stagnation, was refined and adopted.

Clothing Requirements

Because there is a one-to-one correspondence between AT and FU, the effects of increasing the resistances FR and TR are described. On those parts (cylinders) that are clothed, the rings are numbered from 99, corresponding to the hips, down to the least clothed, the remainder being bare (Fig. 4). At ZT = 40°C, 43 of the rings are bare and the other 57 progressively but lightly clothed. Although TR, by virtue of its derivation as a harmonic mean, is uniform for the purpose of analysis, the resistance offered by the mth annular clothing layer is

\[
FR_m = (16 \, TR)^3 + 0.02 - 0.7 \exp(-m/25) \quad (11a)
\]

Reflecting the absence of a bellows effect (5), the clothing conductivity is lower
FK = 0.038 + ZT/12,000 + 0.0027 ZS + GQ/150,000

(12a)

Corresponding to a clothing thickness FU = FR × FK, where FR is the logarithmic mean resistance in the annulus, the amount by which the clothing increases the radius is

\[
FD = FU^2/SD + \sqrt{\left(\frac{FU^2}{SD}\right) + FU^2}
\]

In general, OD = SD + 2FD.

Although FZ is usually a small part of ΣZ, the effects of increasing FR are the following: 1) generally to reduce the outward dry flow of heat when ZT ≤ 36; 2) to reduce inward dry flow when ZT ≥ 38; 3) to increase EE slightly, especially important in conditions when EQ > MQ; 4) to reduce GE, thereby reducing inward-flowing solar and other radiation if GQ > 0; 5) to increase PC, increasing EE further; 6) to increase surface area, hence slightly reducing YR and YZ, which are referred to skin area; 7) to impede moisture vapor flow only slightly; and 8) to bring UT closer to ZT, hence reducing CH and raising YZ, often the chief effect.

These sometimes conflicting effects help explain why increasing FR sometimes tends to increase heat loss, but only when UV ~ ZV and when YR and YZ are dominant resistances. These conditions were found to appear only when MQ < 100 and low CH < 2.2.

Peculiarities of Free Convection

Natural or free convection occurs whenever there is a density gradient in a fluid. In particular, the density of an air-water vapor mixture next to the body's surface generally differs from that of the surrounding air and/or water vapor. The potential controlling free convection from or to the body is not exactly temperature, but virtual temperature. Because the molecular weight of water vapor is 18, compared with 29 for dry air, the virtual temperature is given by

\[
V = aT [1 + 18 P/29(P_{tot} - P)] - 273.15°C
\]

where \( P_{tot} \) refers to total atmospheric pressure, 101,350 Pa at sea level, the only value considered in this work. The net effect of air pressure on AT of a person walking outdoors has been found to be slight (11). The author has not managed to find enough accurate data about the effect of density on the properties of air and water vapor, particularly \( K, \nu, \) and \( \alpha, \) to extend the indoor analysis to higher altitudes. Because UP is usually some kilopascals above ZP, the virtual-temperature excess, UV − ZV, is typically 3–4 degrees above UT − ZT. If this were not so, e.g., if water had a molecular weight similar to that of air, the onset of the anomaly would be at a ZT 3–4 degrees cooler, and the problem of superheating would be more common. That it is not can be ascribed to yet another remarkable property of water. The direct effect of diminished convection on dry heat transfer is not serious, because there is always ample radiation; indeed, low convection is helpful, in a direct sense, when ZT > UT. The problem is in the indirect effect of low convection on the removal of moisture vapor.

All values of Gr in this work are below \( 10^8 \) and correspond to laminar flow. Gr is physically the ratio of buoyancy to the square of viscous forces. At this level, convective heat transfer from cylinders having vertical axes with 80% of full exchange is described by \( \text{Nu} = \)
0.44 (Gr × Pr)\(^{0.25}\). From Reynolds’ analogy, St = 0.44 (Gr × Sc)\(^{0.25}\). Because Sc ≈ Pr, St for free convection is ~5% less than Nu in air. Nu, in physical terms, is the ratio of the significant length (OD, here) to the thickness of the equivalent boundary layer of still air.

To improve the precision of the analysis, especially at the very low values of Nu where the anomaly is most apparent, the conventional formulas for free convection were split into a conductive part (with Nu = 1) and a remaining convective part. The small conduction has as its potential UT = ZT and its equivalent coefficient is

\[
KH = (0.024 + YT/13,500)/OD
\]

Substituting the relevant physical properties for the free-convective part gives

\[
NH = (1.02 - YT/2,000) \times (UV - ZV)/OD^{0.25} \times OD/SD
\]

In practice this parameter is highly variable in an iterative solution if |UV - ZV| is near zero. In the program it is damped by a factor of nine to avoid instability, at the cost of generally slower convergence to the final value.

Pure natural convection from the living person is impossible even if there is complete protection from ambient air movement, including that due to heating, ventilating, and air conditioning systems. Involuntary movements such as breathing correspond to a minimum relative movement of ZS = 3 mm/s, averaged over the surface. At this speed, Re < 100, and forced convection, similarly over 80% of the area, is described by Nu = 0.32 Pr\(^{0.31}\) × Re\(^{0.5}\). This small component translates to

\[
LH = (3 - YT/1,850) \times \sqrt{ZS \times OD/SD}
\]

KQ and the much larger RQ are heat flows in parallel or antiparallel with CQ, but the composition of CQ is more complex. LQ, especially in the “fan” scenario, is essentially horizontal, whereas NQ is vertical, upward or downward, allowing the heat flows to be composed as vectors. Figure 5, averaged over all 100 cylinders, gives a clearer picture of the convective flows as ZT changes, positive values of Q corresponding to the outward flow of heat.

In the conventional literature, only the larger of NQ or LQ is considered, leading to substantial errors in some of the conditions considered here and rendering continuous slopes in the scales impossible. Because the coefficients are at right angles, CH, on which YZ depends, is always given by

\[
CH = \sqrt{(NH^2 + LH^2)}
\]

The determination of CQ is less simple. Only when NQ and LQ > 0, CQ = \(\sqrt{(NQ^2 + LQ^2)}\) (Fig. 5, zone A, left of ZT = 35.5, at which point LQ = 0 and CQ = NQ). If both components are negative, CQ = \(-\sqrt{(NQ^2 + LQ^2)}\) (zone B, right of ZT = 40.6, at which point NQ = 0 and CQ = LQ). The scenario LQ > 0, NQ < 0 is a null set in human biometeorology, but if LQ < 0, NQ > 0, then, if NQ > LQ, CQ = \(\sqrt{(NQ^2 - LQ^2)}\) (zone C); but if NQ < LQ, CQ = \(-\sqrt{(LQ^2 - NQ^2)}\) (zone D). At the boundary of these last regions, there is no net convection, CH is minimal and corresponds to the highest YZ = 1/(CH +

---

**Fig. 5.** Components of convection in neutral conditions. A-D, zones of convection. See text for details.
KH) for that cylinder (as high as 90 for 1 cylinder), with 
mYZ never \( > 52 \) in the anomalous region, but \( < 30 \) elsewhere.

Evaluation

The above may be summarized in the effects of curtailing CQ when \( UV = ZV \). The effect on dry heat flow is slight because CQ \( < RQ \) in all still conditions. However, because radiation has no analog in mass transfer, the correspondingly low moisture transfer from the surface becomes the chief source of heat stress in the anomalous region. Although the focus is on conditions where YZ is very high because of low air movement, convection (in its classic sense) to remove vapor is never absent even in phone-booth conditions because of 1) the involuntary body movements (TOWARD AN AT SCALE FOR INDOOR CONDITIONS); 2) the small conductive component (Peculiarities of Free Convection); and 3) variation in body diameter and surface temperature; even when one cylinder is surrounded by stagnation, other surface virtual temperatures, UV, are, in general, hotter and cooler than ZV; this is the chief source of relief from superheating due to stagnation.

This work uses a resting level of \( MQ = 60 \text{ W/m}^2 \) to provide a continuous scale, a near-minimal level for a standing person. MQ would be greater if the person were well enough to resist metabolically either extreme cold or extreme heat, and an active person who had just collapsed. Another modification is a slight one, in recognition of the notion that the lower activity level affects vasoconstriction more than it affects body temperature

\[
IT = 33.5 + 1/(7TR)
\]  

(9a)

In the original AT model, the person's surface is divided into only clothed and bare parts. In the present work, erratic results conducted refinement of the model, to have five different thicknesses of clothing on the work, erratic results conduced refinement of the model, divided into only clothed and bare parts. In the present scenario. The two initial values, developed by trial and error to ensure that they were always higher and lower, respectively, than the final values, are

\[
iuTR = 0.067 - 0.00055ZT - 0.000024ZP - 0.00008GQ + 0.008ZS
\]

and

\[
idTR = iuTR - 0.016
\]

This curve fit is achieved by omitting results in the anomalous region, which is not automatically or objectively defined. Depending secondarily on ZP and GQ, the anomaly peaks at \(-41 \degree \text{C}\) and is evident in the range \(36 \leq ZP \leq 45 \degree \text{C}\) when ZP and GP have neutral levels, i.e., levels used in preparing the curve of best fit. Accordingly, input values for preparing this fit were in the ranges \(20 \leq ZT \leq 34\) and \(46 \leq ZT \leq 57 \degree \text{C}\). The curve fit was extended beyond 55°C because an earlier fit ending at 55°C had a regression, long undetected, in the relationship between X (defined below) and AT; it was removed by a minor change to Eq. 17. This yielded the general equation

\[
AT = 36.39 - 15.646X + 2.64X^2 - 1.70X^3 - 1.58X^4
\]

(25)

where \( X = \ln(140 FD_{99}) \) and \( FD_{99} \) is the thickness of clothing on the thickest and most clothed ring; the multiplier 140 is chosen to minimize the coefficients in Eq. 25. SE of the curve fit is 0.09 K. This smooth curve is then applied to the whole range \(22 \leq AT \leq 55 \degree \text{C}\), although it gives results \( \approx 0.20 \) and 0.09 K high when
validated at 34 and 46°C, respectively, showing evidence of the anomaly even at the fringes.

Resistance in the Anomalous Range

To illustrate the complications of the still scenario, especially in the triple-solution range, a trial was done in which selected values of TR were evaluated for their effect on heat loss. “Their” includes a syndrome of concomitant parameters, namely, TR, FR, TZ, FZ, PB, and OD, and, less directly, IT, IP, YR, and YZ. The total heat loss in this trial, \( VQ + TQ \), was not set equal to MQ but treated as the dependent variable, with GQ = 0 and ZP held at the neutral levels corresponding to ZW = 12. The effects on heat loss Q are described in Fig. 6.

When \( ZT \leq 40 \) and \( ZT \geq 45°C \), the results are “normal”, i.e., increasing R causes diminishing Q. But the curves of intermediate temperatures show inflections and regions where increasing R also increases Q. These are places where UV < ZV, at least at many values of OD, and some of the usually minor effects in Alternative Models predominate. A further requirement for a triple solution is that the line MQ should intersect the curve in three places. That this can happen only at fairly low MQ explains why only stationary people are sensitive to the superheating. At least as important is the movement associated with higher levels of activity, which provides forced convection at a much higher rate than that due to breathing. The curves also show that appreciable displacement of resistance from the middle solution is likely to lead to a new steady state corresponding to the highest or lowest resistance, hence the use only of those two, uFD99 and dFD99, which are first averaged to determine AT from Eq. 25.

RESULTS

Advantages of the theoretical approach are that harsh and dangerous conditions can be safely explored; hundreds of subjects can be averaged without employing any; no time is wasted in bringing subjects to steady state, complete consistency is ensured in comparisons, and an almost unlimited number of conditions can be examined quickly, e.g., for preparing charts. Although the chief emphasis is on AT, the output file can include any other variables of interest, such as IT, bST, cST, UT, SP, SJ, UV, TR, FR, FU, CH, RH, YR, TZ, YZ, PC, or PB, VQ/MQ, OD/SD (the “clothing factor”), TQ, EQ, EE, and GE, usually averaged over the whole person. It is worth repeating that many publications shed little light on these subsidiary parameters; indeed, they are treated in one of two ways: assumed or ignored. As an example, the popular US windchill scale sets ST = UT = 33°C, then declares in places, “Exposed flesh freezes.” The logical process makes it easy to obtain by subtraction in the following order: 1) effect of humidity (by using conventional outdoor AT1 = ZT; solid lines in Fig. 3); 2) effect of stagnation and inactivity (Fig. 7); and 3) effect of extra radiation.

The following observations are made on the above three points. The still AT scale confounds the effects of humidity, stagnation, and inactivity. The first is already available, at least for the active person, relative to the base humidity ZW = 12. The other two are not readily separable, because any level of steady activity having MQ > 60 is likely to be accompanied by movement. The chief caution is that, owing to the lower rate of activity and especially perspiration, the resting person is less sensitive to humidity changes, especially
when $ZT < IT$. Hence, at the lower temperatures considered here, near $ZT = 28$, the person has a relative sensation of $AT$ as much as $3$ K warmer as $ZP = 4,000$.

When $ZT \approx 38$ and sweating becomes copious, the differences can be fairly interpreted as due mostly to stagnation.

Inner and Outer Solutions in Anomalous Region

Given the inflexions in the anomalous region, there are necessarily some discontinuities when $ZT$, $ZP$, $GQ$, or any combination changes. Reverting to the analysis where $TR$ and its derivatives are dependent variables and total heat loss $= MQ$, we examine the effect of gradually increasing $AT$ when $ZT > IT$ and refer to Fig. 7. At moderate levels, say 40°C, depending secondarily on $GQ$ and $ZP$ (which are held constant at their neutral levels for this exercise), the person reduces $TR$ (vasodilation), $TZ$ (sweating), $FR$, and $FZ$ (thinner clothing) to offset the higher $YR$ and especially $YZ$; $PC$ also falls.

Outside the anomalous region, and sometimes within it, this effects steady state, i.e., $TQ + VQ = MQ$. But these changes also reduce ($UT - ZT$), thus increasing $YZ$ to a point where a steady state cannot be reached further. An increase of $UT > ZT$ by enough to lower $YZ$ to a point where evaporation offsets the now substantial inward flow of heat, and another steady state is established at a lower value of $TR$ or a higher value of $IT$. The spectrum of conditions over the 100 rings limits the scope of triple solutions. The differences between the two outer values, $uAT - dAT$, are shown in Fig. 8 for all the scenarios where they exist.

The most extreme example of this discontinuity to be found when $GQ = 0$ was at $ZT = 43$, $ZP = 2,663$, when $uTR = 0.02538$, giving $uAT = 51.61$ and $umYZ = 39.9$. The slightest increase in $AT$, whether due to $ZT$, $ZP$, or $GQ$, upsets this unstable equilibrium. In this instance $ZP$ was changed incrementally to 2,664, with $umYZ$ now 42.8 and $uTR$ now 0.02430, corresponding to $uAT = 53.97$. There was little change in $dAT = 55.59$ at both vapor pressures, so that $AT$, on the basis of the mean of $uTR$ and $dTR$, showed a step change from 53.46 to 54.72. Such steps are all $< 1$ K when $AT < 50$, and have little effect on the contour charts, except that in the $AT$ model, there is no exact value of $ZP$ corresponding to the contour $AT = 55$ when $ZT = 44$.

Within the loosely defined anomalous region, the region where $(uAT - dAT) > 1$ K are relatively rare, but there is some uncertainty about the vortex of the anomaly, because of the three solutions, the high skin humidity, and $AT$ (Fig. 7, which includes the same conditions). The numbers shown in Fig. 8 refer to the differences between the two extreme solutions.

Figure 7 illustrates the regions where relief from stagnation causes $AT$ to fall despite an increase in $ZT$. There are a few places, with $ZT - 41$, where an increase in $ZP$ causes a slight reduction in $AT$, but no instances were found where increasing extra radiation lowered $AT$, although microscale reductions could conceivably occur in the anomalous region for a small change in $GQ$. Only steps of 20 W/m² were investigated.

An interesting corollary observation was that, although most triple solutions are associated with slight absolute values of $GQ$, they occurred when $GQ = 60$, $ZT > 47$, but in reverse, i.e., apparently because of the...
protection that the body's resistances give to extra radiation, uAT > dAT in this very limited and oppressive range, where an experimental check of the result would be hazardous.

Fundamental Findings

Figure 7 showed the effect of stagnation for the inactive person. The anomaly is clearly greatest around ZT = 42 and increases with increasing ZP, when removal of perspiration becomes critical. The rapid approach to the limit AT = 55 limits our insight into this region. At high humidities when 38 ≤ ZT ≤ 45, possible skin wetness, and hysteresis between the two solutions, reduce certainty.

The physical conditions are examined more closely in a series of parameters graphs, which refer only to "neutral conditions," corresponding to GQ = 0 and the neutral vapor pressures shown by the zero line in Fig. 3, and described by ZW = 12. Figure 9 examines the changes in temperatures, averaged over the body when necessary, at the various nodes of Fig. 2. The anomaly, the vertical difference between the AT curve and the dashed line showing ZT, peaks at ZT = 41. There is a slight cooling effect as ZT increases further, until increasing inward heat flow adds to AT. With a range in ZT of 22 K, the sensitivities of the other temperatures to change in ambient temperature are 0.09 for ZT, 0.13 for mST, and 0.35 for mUT. The last becomes so great at high ZT that it exceeds ST, even though the two are identical on the predominant bare parts of the body, i.e., heat is transferred inward through clothes. mST < IT always, as most of the body's heat output must be conducted through the skin. [Observations of poikilothersms (cold-blooded animals) and, occasionally, of panting quadrupeds have shown measurements of ST > IT in extreme conditions.]

There is no crossing in the lines of Fig. 10, which shows corresponding vapor pressures. These curves illustrate the heat stress of the anomalous region, where intense perspiration occurs. As more of the surface is bared, the lines of UP and UT approach those of SP and ST, respectively. Perspiration to compensate for stagnation is such that, at least when ZP = nZP, UP reaches a maximum at ZT = 42. Figures 8 and 9 can be used to derive approximately the corresponding mean values of V and J (not illustrated).

Figure 10 illustrates thermal resistance cumulatively, the total resistance to heat flow being a major controlling factor. As ZT increases, so does RH, offsetting the reduction in CH as UV approaches ZV. After the anomalous region, both RH and CH increase, helping to make the consequent "fall" in most parameters steeper than the rise in the approximate range 35 ≤ ZT ≤ 41. These resistances are arithmetic, not harmonic, averages of the 100 rings, and in general differ from values obtained by dividing the mean heat flow (TQ, FQ, or YQ) into the mean temperature difference.

Figure 11 is the corresponding depiction of resistances to moisture transfer. Because of its superficial similarity to Fig. 12, its peculiarities are described. Although TZ is the controlling resistance in cool and moderate conditions, and FZ of normal clothing is always small, the rise of mYZ to > 40 when UV = ZV limits sweat dissipation. In the absence of radiation, ΣZ, unlike ΣR, reaches a maximum in the anomalous region.
To clarify the influence of mYZ at all vapor pressures, it is plotted in Fig. 13. When ZT ≈ 45 with GQ = 0, the rapid restoration of free convection as all parts of the surface develop a temperature difference from the surroundings becomes apparent. Because any extra radiation warms the surface, this transition occurs at slightly higher values of ZT. The lowest values of YZ occur when GQ ≈ −20. The next section examines effects of extra radiation more fully.

Effects of Extra Radiation

Extra radiation has much the same effect on AT as a rise in ZT. A first approximation is

\[ \Delta AT = GQ \times YR \]  

This equation takes no account of breathing, sweating, or efficiency of absorption, but, in practice, it is a useful guide to the effect of sunshine, for example,
especially at average temperature and humidity. The locus of this crude approximation can be made to traverse most charts, both in outdoor (e.g., Ref. 15) and still conditions, and is shown as a thin curved line in the three figures illustrating extra radiation (Figs. 14-16). Within (above) this curve the absolute effect on AT exceeds the value that Eq. 26 would indicate. Because of the equivalence between the effects of ZT and GQ, one might at first expect that a higher GQ might move the anomaly to the left. The surface-warming effect mentioned in the last part of Inner and Outer Solutions in Anomalous Region is the controlling factor, and the superheating that is superimposed on the radiant heating is deferred to higher values of ZT.

At a mild level (GQ = 60, Fig. 14), warming of a still person covers a wide range of effects, possibly reaching 14 K in the anomalous region. At this level, there are no triple solutions except in the marginal range ZT > 47.

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**Fig. 11.** Resistances to moisture flow. $ZW = 12, GQ = 0$.

**Fig. 12.** Resistances to heat flow. $ZW = 12, GQ = 0$. 
The synergism of both temperature and humidity with extra radiation is apparent in the narrowing gaps between the AT isotherms as ZT and ZP increase.

The strong extra radiation in Fig. 15 (GQ = 120) refers especially to full sunshine, a level likely to be exceeded only when the sun's altitude is between ~50 and 75°, and more likely near the perihelion. The epicenter of the anomaly has now moved off-scale, but AT > 55 at all levels to the right of ZT = 43.

Fig. 13. Surface resistances to moisture flow (YZ). ZW = 12.

Fig. 14. Effect of moderate extra radiation. Dashed lines, AT when GQ = 60. Change.
Even higher levels of GQ, near 200, are absorbed by a prone white person sunbathing when the sun's altitude is high, but the present model is not suited to the sunbathing scenario, where there is much contact with the ground, of vaguely specified temperature. Modifying rigid traditional formulas to recognize the variability in skin temperature, de Freitas (2) has examined heat transfer in sunbathing.

Exposure to a clear night sky corresponds to GQ $\approx -30$, depending on temperature and especially humidity. The extreme value $GQ = -40$ is evaluated in Fig. 16. Some of the greatest cooling effects are where the greatest warming effects of stagnation occurred at $GQ = 0$. The range of that chart limits the comparisons in Fig. 16. When $GQ = -40$, and when $GQ = 120$, there is only one solution of Eq. 15 through...
out the figures. In indoor industrial practice, GQ is seldom below \(-10\), because the insulation around refrigerated spaces brings the inner temperature of walls close to ZT.

**Figure 17** summarizes generally the effect of extra radiation when ZP is neutral. An approximate locus describing the displacement of the anomaly as GQ increases is sketched. Examination of the isolines,

**Table 1.** Free-convective apparent temperature as a function of relative humidity

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**Table 1 cont.** Free-convective apparent temperature as a function of relative humidity

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**ZJ, ZT, and sZP: ambient relative humidity, temperature, and vapor pressure, respectively; s, saturation; AT and IT, ambient and internal temperature, respectively; GQ, absorbed/emitted extra radiation heat flux density; SJ99, skin surface relative humidity at 99th ring. ΔATGQ=100, effect on AT when GQ = 100 at neutral ZP and ZT = 40 and 30°C, respectively. †AT > 39. †SJ99 > 0.9. ‡Approximate result, included only to facilitate interpolation.
especially in the anomalous region, shows that, in general, unlike outdoor AT, the effect of GQ is not exactly proportional to GQ.

The information developed so far enables compilation of Table 1, which describes the "stagnant" heat index as a function of ZT and relative humidity, as well as estimating the effects of 100 W/m² of extra radiation when ZT = 40 and 30, subject to the restrictions in SCOPE AND CONSTRAINTS.

Relieving Heat Stress by Air Movement

Modest air movement provides cooling (Fig. 18), even when ZT > UT, because most heat loss is by evaporation at such high temperatures. A person suffering in any way "from the heat" benefits from immersion in water at a temperature below IT, because CH is some 16 times higher than in air, despite the absence of radiation. Only exposure to air is considered here. A horizontal airspeed of only 0.4 is chosen, so that LH has the same order of magnitude as RH and the higher levels of NH, the first averaging near four at all temperatures. This is enough to reduce the highest mYZ to 13 and the highest SJ to 0.87.

In view of an opinion, apparently deriving from an extension of the earlier effective temperature
scale, that fans may aggravate heat stress, the key result in Fig. 18 is that air movement reduces AT in all conditions. There is much variation in the cooling effect, which is greatest where the anomaly occurred in still conditions. Even at this low wind speed, there are no triple solutions but a one-to-one relationship between resistance and AT. Higher speeds provide more cooling, although not in proportion to fan speed.

Alternative Measures of Heat Stress

Of the many ways of estimating heat stress, most can be classified as related in some way to a measure of one of the following: 1) temperature, as in the present work; 2) perspiration; and 3) skin “wetness” or humidity. Accordingly, the perspiration rate and average skin humidity were plotted as contours in Fig. 19. Perspiration through the skin (not the lungs) is appreciable at
all temperatures, and gross perspiration EQ exceeds MQ (60) when ZT ≥ 38. As ZT increases, perspiration intensifies; i.e., the solid isolines become closer. At low temperatures, when perspiration is more passive, it is greater at low humidities, i.e., when ΔP is high, but at higher temperatures the dependence on perspiration to relieve the stress of both temperature and humidity is so great that a reverse tendency becomes apparent. Clearly, the isolines of EQ have slopes so similar to those of ZT that perspiration rate is little more than a measure of ZT alone.

The isolines of skin humidity, although distorted by the anomaly, are essentially horizontal and provide merely a measure of absolute humidity, ZP. If one needs a measure of total heat stress, where the slope of the isolines is between those of the wet-bulb or adiabatic cooling lines and the dry-bulb lines, measures of perspiration and skin wetness are both unsatisfactory, a fact that is even more obvious in outdoor AT, where there is no free-convective anomaly.

Analysis of Heat Flows

For neutral conditions, Fig. 5 showed the contributions of natural and forced convection in the stagnant scenario. In contrast to outdoor conditions, \( |CQ| < |RQ| \), generally. All dry flows from the surface are compared in Fig. 20. Virtual temperature causes convection to become negative at a temperature some 4 K above the level for radiation and conduction. At high temperatures, this heat gain, as well as heat production MQ, must be offset by evaporation.

Evaporation is described in Fig. 21, which shows it to greatly exceed breathing loss due to both heat and moisture exchange. When evaporation occurs at the skin under still conditions, where ZR, hence also EE, is high, ~ 85% of the cooling is abstracted from the body, only ~ 15% from the surroundings. The slightly lower net EQ from the body is also shown, because only it can be directly compared with MQ and VQ. Only if CQ, RQ, and KQ are multiplied by \((FR + YR)/ΔR\), the various heat losses can be added to confirm that the sum equals MQ.

SUMMARY AND CONCLUSIONS

The one-to-one relationship between total resistance and AT that is the basis of the outdoor AT scale fails when applied to still conditions. When ZT just exceeds AT, especially when ZV = UV, there is little air movement due to free convection, hence limited means of removing perspiration vapor. Furthermore, the complexity of heat and moisture flows leads, in an anomalous zone, to three solutions of the human heat-balance equation, where an increase in the resistance ensemble sometimes leads to an increase in heat loss. An immediate and serious effect is for the AT in the range 38–44°C to be several degrees hotter than expected when there is no external air movement around a person. Extra radiation has a greater and more variable effect on the still person than the walking person and shows synergy with both temperature and humidity. Use of a fan, or any means of providing air movement, always provides a stationary person with relief from heat.

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