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DETERMINATION OF THE EFFECT OF WALKING ON THE FORCED CONVECTIVE HEAT TRANSFER COEFFICIENT USING AN ARTICULATED MANNLIKIN

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ABSTRACT

This study addresses the effect of the walking motion on local convective heat transfer coefficient at various body sites, employing an articulated mannikin. The forced convective heat transfer coefficient ($h_c$) is determined by the naphthalene sublimation technique. Circular naphthalene disks were affixed to various body segments of the articulated mannikin. The mannikin then simulated walking at five different gaits between 0 and 2.0 mph (0 to 0.9 m/s, 0 being stationary) under constant temperature (30°C) and wind speed (0.4~0.7 m/s depending on the body segment) in an environmental chamber. The amount of naphthalene weight loss through sublimation was translated to $h_c$ using the Chilton-Colburn analogy between heat and mass transfer. The results showed that arm movement during walking, unexpectedly, diminished the effective local convective transfer coefficient. Increased gait (from 0 to 2.0 mph) actually resulted in a decrease in $h_c$, as measured on the arms and legs. On the nonmoving body trunk, no significant difference in $h_c$ was observed with increased gait. When the mannikin was held stationary and the chamber wind speed increased, a corresponding increase in $h_c$ was observed. Thus, during walking, motion of the swinging limbs, the "pendulum" effect, tends to decrease the forced convective heat transfer coefficient as observed locally on the limbs. For the walking gaits applied in this study, a 5%~7% decrease in $h_c$ was observed.

INTRODUCTION

The effect of the swinging appendages during walking and running has been characterized as the "pendulum" effect [Clark et al. 1974] or, in connection with clothing insulation study, the "pumping" effect [Vogt et al. 1983; Olesen et al. 1982]. Clark et al. [1974] studied evaporative and dry heat loss of an athlete running outdoors, and reported that the local convective heat transfer coefficient could be increased by at least a factor of two, as a result of the extra velocity of the limb relative to the trunk. Although they mentioned that the effective evaporative coefficient would also be increased by the "pendulum" effect, they did not quantify the increase nor attempt to separate the convective and evaporative components of this effect. Vogt et al. [1983] studied the "pumping" effect on clothing insulation using human subjects. Olesen et al. [1982] performed similar studies using a movable thermal mannikin. Complicated by the extra layer of clothing and the microclimates the layer created, the results varied. Vogt concluded that "pumping" effect may increase or decrease the resultant clothing insulation depending on the air temperature. Olesen’s [1982]
data showed negligible change in thermal insulation value between sitting and bicycling; whereas, Olesen and Madsen [1983] and Olesen and Nielsen [1984] reported a 30%-50% reduction in insulation due to walking and wind effect.

This study focuses on how walking motion affects the convective heat transfer coefficient of forced flow. The effect of arm and leg swing on $h_c$ was investigated using an articulated mannikin. A mannikin offers the advantage of exact and repeatable motion, and also avoids the problem of perspiration and eliminates any evaporative contribution usually involved in exercising human subjects. Convective coefficient, $h_c$, is determined using a modification of the naphthalene sublimation technique [Nishi and Gagge 1970] based on heat and mass transfer analogy, independent of any energy and metabolism measurement.

**METHOD AND THEORY**

Heat-mass transfer analogy of a sublimating substance has been traditionally used to accurately predict the forced convective heat transfer coefficient [Sogin 1958; Neal 1974]. Naphthalene very conveniently sublimates at room temperature and thus has been used by a number of investigators to experimentally determine $h_c$. Sparrow and Tien [1977, 1979] studied forced convection to a square plate at different yaw angles. Sogin [1958] applied jet stream normally to naphthalene disks. Nishi and Gagge [1970] attached naphthalene balls to different body segments on human subjects. The convective transfer of the ball was then related to the corresponding body segment by approximating the body segment as a cylinder and using the known convective relationship between ball and cylinder.

In our study, circular naphthalene disks were attached to the surface of various body segments on a lifesize (18.08 ft$^2$, or 1.68 m$^2$), articulated mannikin. The naphthalene disks were appropriately curved to conform to the corresponding body segment curvature. Airflow was directed normally at the disk surface. Since the naphthalene disk conforms to the body segment curvature and sits directly over the specific body site, the local $h_c$ over the specific site is measured, rather than an average $h_c$ for the entire body segment. Scaling of results to translate from cylinder to ball, and extrapolation of body diameter and shape from cylinder study thereby become unnecessary.

**Heat - Mass Transfer Relationship**

Mass transfer of naphthalene sublimation $h_m$ can be expressed as [Nishi and Gagge 1970]

$$h_m = R \cdot T_a \cdot \frac{\dot{m}}{P_s - P_a} \tag{1}$$

- $h_m =$ naphthalene mass transfer coefficient (m/s)
- $\dot{m}$ = measured naphthalene sublimation loss per surface area (kg m$^{-2}$ s$^{-1}$)
- $T_a =$ ambient temperature (K)
- $P_s =$ naphthalene surface vapor pressure (mmHg)
- $P_a =$ naphthalene vapor pressure in air (assumed = 0)
- $R =$ naphthalene gas constant (0.487 mmHg m$^2$ kg$^{-1}$ s$^{-1}$ K$^{-1}$)

Assuming that the heat of sublimation is negligible, $P_s$ may be considered as equal to the saturated vapor pressure at $T_a$ [Sherwood and Trass 1980],

$$\log_{10} P_s = 11.55 - 3765/T_a \tag{2}$$

or,

$$P_s = 10^{(11.55-3765/T_a)} \quad P_s \text{ in mmHg, } T_a \text{ in K}$$

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The Chilton-Colburn analogy j-factor [ASHRAE Fundamentals 1985] can be described:

For heat transfer
\[
j_h = \frac{h_c}{\rho c_p u} (Pr)^{2/3}, \quad \text{with} \quad Pr = \frac{c_p \mu}{\kappa} \tag{3}
\]

For mass transfer
\[
j_m = \frac{h_m}{u} (Sc)^{2/3}, \quad \text{with} \quad Sc = \frac{\mu}{\rho D_v} \tag{4}
\]

\[h_c = \text{heat transfer coefficient (W m}^{-2} \text{K}^{-1})\]
\[h_m = \text{mass transfer coefficient (m s}^{-1})\]
\[\kappa = \text{thermal conductivity (W m}^{-1} \text{K}^{-1})\]
\[c_p = \text{specific heat (J kg}^{-1} \text{K}^{-1})\]
\[\mu = \text{viscosity (kg m}^{-1} \text{s}^{-1})\]
\[Pr = \text{Prandtl's number (ND)}\]
\[Sc = \text{Schmidt's number (ND)}\]
\[D_v = \text{mass diffusivity (m}^2 \text{s}^{-1})\]
\[\rho = \text{density (kg m}^{-3})\]
\[u = \text{air velocity (m)}\]

Equating heat and mass transfer j-factor,
\[
\frac{h_c}{\rho c_p u} (Pr)^{2/3} = \frac{h_m}{u} (Sc)^{2/3}
\]

\[h_c = \rho c_p \left(\frac{Sc}{Pr}\right)^{2/3} h_m \tag{5}\]

\[h_c \text{ in W/(m}^2 \text{K)}\]

\[h_c = \rho c_p (Le)^{2/3} h_m \]

\[\text{Lewis number } = Le = Sc/Pr\]

Experiment

The articulated mannikin at the biophysics branch is capable of simulated walking up to 80 steps/min. Length of the leg stride and arm swing are individually adjustable. For this experiment, five walking gaits of 0 (stationary), 0.5, 1.0, 1.5, and 2.0 mph (0-0.9 m/s) were applied. The environmental chamber was set at \( T_a = 30^\circ \text{C} \), with dew point at 5°C (relative humidity ~20%). The regional air velocity ranged between 0.4 and 0.7 m/s at different body segments of the mannikin. The duration of each experiment was 55 minutes. The regional temperature and air velocity were measured at five sites: upper arm, lower arm, thigh, calf, and chest. Figure 1 gives a schematic representation of the locations of naphthalene disks on the mannikin. Omnidirectional thermal anemometers and thermistor temperature probes were placed approximately 2 cm above and 2 cm away from the naphthalene disk, in such a way as not to disturb the impinging airflow to the disk. The omnidirectional anemometers have a response time of two seconds. Airflow in the chamber is directed normally at the disks.

Scintillation grade naphthalene with a melting point of approximately 80°C was poured into casting disk cassettes, which were modified from aluminum camera lens covers. The castings quickly hardened at room temperature, after which a nonadhering cover plate is removed to reveal a smooth naphthalene surface. The cassettes were appropriately curved to conform to surface curvatures of the upper arm, lower arm, thigh, calf, and chest of the mannikin. Casting cassettes used for the chest were not curved. The curved cassettes expose an elliptic rather than circular surface. The elliptic surface area of each cassette disk was measured and properly quantified during evaluation of the \( \Phi \) term in Equation 1. The disks were mounted into vinyl retainers which were in turn fastened to the mannikin with hook and pile straps. The square vinyl sheets have a circular hole cut in the middle. Circumference of the hole is slightly smaller than the disk cassette, so that each cassette snapped tightly into the retainer. Immediately after casting, the disks were stored individually in airtight containers. All naphthalene disks were allowed to equilibrate in the chamber at 30°C for 24 hours before using. The disks were weighed immediately before and after an experiment on a balance sensitive to ±0.01 mg.
RESULTS

Table 1 shows the regional air velocity with the manikin assuming a stationary position. This level of regional wind speed was maintained throughout the experiment. Also shown is the local $h_c$ at the specific sites, measured and computed using Equation 1 through Equation 5. For each study run, $h_c$ was averaged over the 55 minute experiment period. The results in Table 1 are the average of 15 runs.

Figure 2 gives the local $h_c$ at the five naphthalene disk sites: upper arm, lower arm, calf, chest, and thigh. The five walking speeds were 0 (standstill), 20, 40, 60, and 80 steps/min, which translate to gaits from 0 to 2.0 mph ($0.9$ m/s). In Figure 2, the five rows of bar graph represent $h_c$ measurement at the five naphthalene disk sites. The columns represent the manikin walking speed. For example, the bar graphs in the first row give the upper arm $h_c$ of 23.47, 23.05, 22.77, 22.51, and 22.42 W/(m²°C), at the five walking speeds of 0, 20, 40, 60 and 80 steps/min, respectively. Student's T-tests were evaluated between the stationary position $h_c$ and $h_c$ at each of the four gaits, to determine if the difference was significant. The t-values from the T-test are also included in Figure 2, and are shown at the bottom of each bar graph. A t-value $> 2.101$ indicates that the decrement is significant, with $p < 0.05$.

A more comprehensive set of the information presented in Figure 2 is tabulated in Table 2. Table 2a shows $h_c$ with the corresponding dispersion range (standard deviation value). In Table 2b, additional t-values are included. The 0-20, 0-40, 0-60, and 0-80 columns give the computed t-values between walking speeds of 0 and 20, 0 and 40, 0 and 60, 0 and 80 steps/min, respectively. The data in these first four columns represent the t-values included in Figure 2. Additionally, t-values between adjacent walking speeds are also evaluated. As an example, the 20-40 column indicates t-value between the 20 and 40 steps/min gaits.

The four walking gaits were 0.5, 1.0, 1.5 and 2.0 mph ($0.22$, $0.45$, $0.67$, and $0.89$ m/s). However, the arm swing and leg stride of the articulated manikin were set at different lengths to represent a natural human walking motion. The upper arm disk and lower arm disk necessarily experience different motion because they attach onto different portions of the arm swing arc. A similar condition exists for disks attached to the leg. Therefore, the equivalent forward velocity experienced by the disks was different from the walking gaits. The resultant linear velocities as experienced by the naphthalene disks at the four walking gaits are summarized in Table 3. The manikin walked at 20, 40, 60, and 80 steps/min. Linear velocities were calculated using the full swing length of 13 cm, 31 cm, 16 cm, and 51 cm for the disk mounted on the upper arm, lower arm, thigh, and calf, respectively. Table 3 represents only the singular effect of walking. The chamber air velocity, shown in Table 1, is an additional factor that interacts with the linear velocity of the disk during walking.

To further ascertain that the decrement in $h_c$ as shown in Figure 2 was indeed due to the walking motion and not artifact, another set of experiments were performed without the complication of limb movement. Figure 3 gives the data obtained when the manikin was held stationary, but with the chamber wind speed set at levels comparable to the walking gaits.

DISCUSSION

Rapp [1972] defined the free and mixed convection region as that ambient air velocity is $< 0.2$ m/s. Hence, from Table 1, the experimental condition in our study was well into the forced convection region. The measured $h_c$ should, therefore, be predominately $h_c$ from forced airflow. Nishi and Gagge [1970] reported for subjects undergoing free walking at 4 mph ($1.8$ m/s), that the regional $h_c$ at the arms and legs were 16-17 W/(m²°C). They operated at a normal ambient air movement of 0.15-0.2 m/s. Considering that chamber air velocity in this study was between 0.4-0.7 m/s, the range of $h_c$ shown in Table 1, 22-23 W/(m²°C), appears to be in a reasonable range when compared to their original work.

Figure 2 and Table 2 give the regional $h_c$ at the five naphthalene disk sites, upper arm, lower arm, calf, chest, and thigh, at the five walking speeds, 0, 20, 40, 60, and 80 steps/min. On the upper and lower arms, there is clearly a decreasing trend for $h_c$ as the manikin walking speed increased from 0 to 80 steps/min. Decrease in $h_c$ was between 5% and 7%. The t-value from Student's T-test showed each decrement to be statistically significant. In contrast, for the chest site, $h_c$ stayed quite constant, and t-value showed no
statistically significant difference between gaits. The motion of the arm apparently caused a
decrease in the forced convective heat transfer coefficient, evident, perhaps from localized
wind currents at these sites. Although the exact mechanism is not apparent, one possible
explanation could be that the naphthalene disks experienced nonuniform airflow during the arm
swing cycle. On the forward stroke of the arm swing, the naphthalene disks were moving in the
opposite direction to the chamber airflow. The airflow that the disks encountered was
enhanced (a vector sum). Conversely, on the backward stroke of the arm swing, the arm and
chamber airflow were in the same direction. Airflow experienced by the disk was therefore
diminished (a vector difference). Naphthalene sublimation rate, hence $h_c$, does not vary
linearly with changing air velocity [Nishi and Gagge 1970]. The effect of a vector sum
(forward stroke) and a vector difference (backward stroke), not surprisingly, do not cancel
each other. The measured $h_c$ thus is rationally a combination of the two effects, averaged
over the 55 minute study period. At present, we can only ascertain the average air velocity
from the data. Our omnidirectional anemometers (response time = 2 second) do not have fast
enough response time to distinctly measure the different air velocities that must exist on the
forward and backward strokes. An investigation with faster response anemometers to study the
air velocity variation during each arm swing is currently underway.

On the calf, a 7% decrease in $h_c$ was also evident. Here, however, we found that $h_c$ did
not further decrease after walking speed of 80 steps/min but, rather, showed an increase at 80
steps/min. From Tables 1 and 3, chamber air velocity on the calf (1.54 mph, Table 1) and
local linear velocity of the calf disk at 80 steps/min (1.52 mph, Table 3) became comparable.
It could be that at a point prior to the two speeds becoming comparable, the combined vector
sum and vector difference yielded a minimum average airflow over the disk, hence a minimum $h_c$.
This minimum should also exist for the upper arm and lower arm cases, but the articulated
mannikin’s walking speed could not be further increased to reach this point of minimum.
Faster response anemometers should also facilitate the determination of this minimum point.

The thigh data in Figure 2 showed no particular pattern. One peculiarity about the thigh
data is also evident in Nishi and Gagge’s [1970] results. Comparison of Nishi and Gagge’s
Tables 3 and 4 showed that on the bicycle ergometer, increase in $h_c$ paralleled the increase
in air movement on the thigh. However, with free walking, $h_c$ is 25% lower on the thigh than
other sites, e.g. upper arm and legs, with similar air movements. Nonetheless, relative
motion of the limbs could still be the determinant. Only this time, there were two relative
motions involved. It can be seen from the schematic representation of Figure 1, the
naphthalene disk on the thigh was at the same level as the hand. As the mannikin walked, the
hand swung in the opposite direction to the thigh. Movement of the hand could thus disturb
the impinging airflow over the thigh disk. On a bicycle ergometer, presumably the arms do not
swing in opposite directions to modify airflow over the thighs. In our study, relative motion
of the arm and leg could have generated a very complex airflow pattern over the thigh disk,
the result of which simply cannot be visualized from only the averaged anemometer data.

Data in Figure 3 were obtained with the mannikin held stationary and the chamber air speed
set at levels comparable to the walking gaits. On a standstill mannikin, $h_c$ from all five
naphthalene disks increased accordingly with increasing chamber air velocity. The observation
that it is the walking motion that decreased the effective local $h_c$, is further reinforced.

Another implication of the above result is that when human subjects are used in a study,
the nonconvective heat loss could be a much more significant factor than Clark et al. [1974]
had suggested. The naphthalene sublimation method measures only the convective transfer.
Also, since a mannikin does not perspire, all evaporative processes, such as evaporation and
contamination of naphthalene by sweat, are eliminated. Assuming that the pendulum motion of
the limbs indeed doubles the heat loss as described by Clark, this doubling cannot be
attributed to an enhanced convection, because pure convective heat loss, as found in this
study, is decreased rather than increased by the "pendulum" effect. Hence, the major bulk of
the increase in heat loss by the "pendulum" effect during human walking and running must be
nonconvective, perhaps evaporative and radiant, in nature.
CONCLUSION

This study looked at the effect of walking on the convective heat transfer coefficient of forced airflow. It was found that walking, or the motion of the swinging limbs during walking, generally decreased the forced $h_c$ as measured on the arms and legs. For the walking gaits applied in this study, a 5%-7% decrease in $h_c$ was observed. This amount of decrease in $h_c$, displayed in Figure 2, must represent, quantitatively, the "pendulum" effect. A further study with faster response anemometers are needed to investigate in detail, the mechanism that caused the $h_c$ decrement.

REFERENCE


ACKNOWLEDGMENT

The authors wish to express their thanks to Robert A. Oster, M.S. for his assistance in the statistical analysis.
# TABLE I

Regional air velocity and local $h_C$ on a stationary articulated manikin

<table>
<thead>
<tr>
<th>naphthalene disk site</th>
<th>regional air velocity (mph (m/s))</th>
<th>local $h_C$ (W/(m²·°C))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Arm</td>
<td>$1.35 ± 0.04$</td>
<td>$23.47 ± 0.42$</td>
</tr>
<tr>
<td></td>
<td>$(0.61 ± 0.02)$</td>
<td></td>
</tr>
<tr>
<td>Lower Arm</td>
<td>$1.59 ± 0.02$</td>
<td>$22.64 ± 0.39$</td>
</tr>
<tr>
<td></td>
<td>$(0.71 ± 0.01)$</td>
<td></td>
</tr>
<tr>
<td>Thigh</td>
<td>$0.93 ± 0.03$</td>
<td>$18.84 ± 0.34$</td>
</tr>
<tr>
<td></td>
<td>$(0.42 ± 0.01)$</td>
<td></td>
</tr>
<tr>
<td>Calf</td>
<td>$1.54 ± 0.05$</td>
<td>$24.37 ± 0.52$</td>
</tr>
<tr>
<td></td>
<td>$(0.69 ± 0.02)$</td>
<td></td>
</tr>
<tr>
<td>Chest</td>
<td>$1.09 ± 0.03$</td>
<td>$16.62 ± 0.38$</td>
</tr>
<tr>
<td></td>
<td>$(0.49 ± 0.01)$</td>
<td></td>
</tr>
</tbody>
</table>
TABLE 2a

Local $h_c$ at walking speed of 0, 20, 40, 60, and 80 steps/min.

$h_c \pm$ standard deviation $W/(m^2 \cdot ^\circ C)$

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Arm</td>
<td>23.47 ± 0.42</td>
<td>23.05 ± 0.45</td>
<td>22.77 ± 0.19</td>
<td>22.51 ± 0.17</td>
<td>22.42 ± 0.20</td>
</tr>
<tr>
<td>Lower Arm</td>
<td>22.46 ± 0.39</td>
<td>22.34 ± 0.38</td>
<td>22.03 ± 0.29</td>
<td>21.48 ± 0.23</td>
<td>21.08 ± 0.28</td>
</tr>
<tr>
<td>Calf</td>
<td>24.37 ± 0.52</td>
<td>24.11 ± 0.44</td>
<td>23.44 ± 0.33</td>
<td>22.69 ± 0.19</td>
<td>24.05 ± 0.25</td>
</tr>
<tr>
<td>Chest</td>
<td>16.62 ± 0.38</td>
<td>16.85 ± 0.37</td>
<td>16.76 ± 0.25</td>
<td>16.75 ± 0.21</td>
<td>16.66 ± 0.27</td>
</tr>
<tr>
<td>Thigh</td>
<td>18.84 ± 0.34</td>
<td>19.63 ± 0.38</td>
<td>19.35 ± 0.31</td>
<td>19.40 ± 0.19</td>
<td>19.61 ± 0.27</td>
</tr>
</tbody>
</table>

TABLE 2b

t-value between different walking speeds

t-value between walking speeds

<table>
<thead>
<tr>
<th></th>
<th>0-20</th>
<th>0-40</th>
<th>0-60</th>
<th>0-80</th>
<th>20-40</th>
<th>40-60</th>
<th>60-80</th>
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<tbody>
<tr>
<td>Upper Arm</td>
<td>2.670</td>
<td>5.908</td>
<td>8.212</td>
<td>8.721</td>
<td>2.211</td>
<td>3.978</td>
<td>1.259</td>
</tr>
<tr>
<td>Lower Arm</td>
<td>2.170</td>
<td>4.839</td>
<td>10.000</td>
<td>12.625</td>
<td>2.435</td>
<td>5.812</td>
<td>4.283</td>
</tr>
<tr>
<td>Calf</td>
<td>1.473</td>
<td>5.828</td>
<td>11.720</td>
<td>2.168</td>
<td>4.742</td>
<td>7.517</td>
<td>-16.777</td>
</tr>
<tr>
<td>Chest</td>
<td>-1.708</td>
<td>-1.166</td>
<td>-1.183</td>
<td>-0.328</td>
<td>0.827</td>
<td>0.063</td>
<td>1.041</td>
</tr>
<tr>
<td>Thigh</td>
<td>-6.046</td>
<td>-4.361</td>
<td>-5.626</td>
<td>-6.946</td>
<td>2.206</td>
<td>-0.498</td>
<td>-2.517</td>
</tr>
</tbody>
</table>
TABLE 3
Local linear velocity as seen by the naphthalene disks as result of the walking motion

<table>
<thead>
<tr>
<th></th>
<th>full swing length</th>
<th>walking speed (steps/min)</th>
<th>local linear velocity mph (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Upper Arm</td>
<td>13 cm</td>
<td>0.10</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.04)</td>
<td>(0.09)</td>
</tr>
<tr>
<td>Lower Arm</td>
<td>31 cm</td>
<td>0.23</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.10)</td>
<td>(0.21)</td>
</tr>
<tr>
<td>Thigh</td>
<td>16 cm</td>
<td>0.12</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.05)</td>
<td>(0.11)</td>
</tr>
<tr>
<td>Calf</td>
<td>51 cm</td>
<td>0.38</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.17)</td>
<td>(0.34)</td>
</tr>
</tbody>
</table>
Figure 2: Comparative heat transfer coefficients

Figure 1: Schematic diagram showing locations of the Nathanson disk on the mannequin.
Figure 3 $h_c$ with stationary manikin at increasing chamber air velocity
**Discussion**

**E.G. PLETT, Carleton University, Ottawa, Ontario:** Wouldn’t you need to account for the flow all around the body and each limb, rather than just the front stagnation region, since the flow around the side of a cylinder yields a higher convective coefficient than in the stagnation region?

**S.KW. CHANG:** The gist of your question is correct. Our results represent only the local convective coefficient and not that of the entire circumference of a body segment. I suppose if we had used cylindrical naphthalene rings rather than disks, they might account for convection all around each body segment. A compromise had to be made, as in all experimental studies, between what is ideal and what can reasonably be accomplished. Ideally, we should encase each body segment entirely with naphthalene to study the total convection of each body segment---but that simply isn’t practical. We used disks because they can be made easily and quickly, and we had to make a large number of them for our study.