Evaluating the Efficacy of a Thermal Exposure Chamber Designed for Assessing Workers’ Thermal Hazard

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Department of Environmental and Occupational Health, Medical College, National Cheng Kung University, Taiwan—This study was conducted on a thermal exposure chamber designed for assessing workers’ thermal hazard. In order to assess the efficacy of the studied chamber, three environmental conditions were selected to simulate high, middle and low thermal impact situations, with air temperatures (T_a) of 43.12, 36.23 and 25.77°C, globe temperatures (T_g) of 44.41, 41.07 and 29.24°C, relative humidity (RH) of 77, 59 and 39 %, and air flow velocities (V_a) of 1.70, 0.91 and 0.25 m/s, respectively. For the three specified thermal impact conditions, results show that the coefficients of variation (CVs) for T_a, T_g, RH and V_a measured in the chamber studied were consistently less than 10%, except for V_a under the low thermal impact condition (=50%). For each specified thermal impact condition, we generated 1,000 environmental combinations by using the Monte Carlo simulation approach according to the variations obtained from the four environmental factors. We directly adopted the ISO 7933 approach to estimate the allowable exposure time (AET) for each simulated environmental condition. This study yielded a range in the 95% confidence interval (95% CI) of the estimated AETs for the three specified thermal impact conditions which were consistently less than 5 min. We further conducted the sensitivity analysis to examine the effect of the four environmental factors on estimating AETs. We found V_a was the least important factor in estimating AETs for any specified thermal impact condition. In conclusion, although V_a was found with great variation for the chamber specified in the

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The four environmental factors, air temperature (T), air velocity (V), relative humidity (RH) and globe temperature (T_g), together with workers’ workload and clothing, were known to be the main factors affecting the extent of the thermal hazard for workers in thermal environments. Based on this concept, the ISO 7933 Standard entitled Analytical Determination and Interpretation of Thermal Stress Using Calculation of Required Sweat Rate proposed a physiologically-based approach in 1989 for estimating the allowable exposure times (AETs) for workers in various thermal environments. In principle, the use of the above approach for determining workers’ AETs requires no direct measurement of workers’ physiological responses (such as the worker’s sweat rate, metabolic rate and skin temperature etc.) in the field. Instead, it allows us to estimate workers’ physiological responses by incorporating the on-site measured environmental factors into the empirical equations proposed in ISO 7933. Indeed, the above approach has been criticized by many researchers. Nevertheless, recently the American Conference of Governmental Industrial Hygienists (ACGIH) has incorporated it into its work/rest-time regimen determination process. But because the physiological responses could not be directly measured in the field, it can be expected that the above approach might have some inherent uncertainties, which warrants the need for establishing a thermal exposure chamber that can accurately simulate various thermal environments.
In the past, many thermal exposure chambers (or so-called climate chambers) had been established for different research purposes. Table 1 summarizes the dimensions, establishing purposes, and applicable ranges of the environmental factors of six currently established exposure chambers. It can be seen that the first four chambers were only suitable for assessing workers’ thermal comfort. This is because (1) these chambers did not take the effect of radiation into account, and (2) these chambers were only applicable to the environments with $V_a < 1$ m/s and workers at the rest or with only light workload. Although the last two chambers were originally designed for assessing workers’ thermal hazard, data did not allow us to know the variation in each controlled environmental factor under various environmental conditions. Therefore, it is expected that the use of the above two exposure chambers for determining workers’ AETs might involve some uncertainties.

To the best of our knowledge, no thermal exposure chamber adequate for assessing workers’ thermal hazard in various hot environments has been established. This is mainly because a way to evaluate the efficacy of an exposure chamber has not yet been developed. For this purpose, the objective of this work was to devise an approach that can be used to assess the efficacy of a thermal exposure chamber for determining workers’ AETs in various hot environments. The whole study was conducted on a thermal exposure chamber designed by our research group for assessing workers’ thermal hazards. The feasibility of using the chamber studied for assessing workers’ thermal hazard in various specified thermal environments was then evaluated and reported on in this work.

### Method and Materials

1. **The Thermal Exposure Chamber Studied**

   Fig. 1 shows the layout of the thermal exposure chamber studied. This chamber ($L \times W \times H=500$ cm $\times 260$ cm $\times 230$ cm) consisted of 4 heaters, 3 ultra-sound moisturizers, 4 infra-red radiators, one driving unit (including 3 and 6 fans installed in the front and rear part of the chamber, respectively), a tunnel for the return air, and an air dispersing system (by means of a perforated baffle). The heaters, ultra-sound moisturizers, infrared radiators and the driving unit were controlled by an automatic feedback system in order to simulate various specified environmental conditions. The chamber tested was able to cover thermal environmental conditions with ranges for $T_a = 25–45^\circ C$, $T_g = 30–45^\circ C$, RH=40–80% and...
V_a = 0.25–1.70 m/s, respectively. In principle, the ranges of the above environmental factors were comparable with those described by Mairiaux and Malchaire to simulate all possible thermal environments occurring in the field and were applicable to the ISO 7933 approach. A testing zone designated for conducting this experiment was located in the middle section of the exposure chamber (L × W × H = 120 cm × 180 cm × 230 cm).

2. Test protocols

It is true that the index of the wet bulb globe temperature (WBGT) has been widely used as a reference for determining the work/rest-time regimen for workers in thermal environments, but one recent study has shown that the WBGT index was inadequate for characterizing the heat stress imposed on workers in various thermal environments. Because of this, the WBGT index was not adopted in this study as a reference for specifying the test thermal environments for the chamber studied. Instead, in order to cover the whole applicable range of the chamber studied for assessing workers’ thermal hazard, three thermal impact conditions were specified based on the upper, median and lower values in the applicable range of the four environmental factors. These included: (A) the low thermal impact condition (T_a = 25.77°C, T_g = 29.24°C, RH = 39% and V_a = 0.25 m/s), (B) the middle thermal impact condition (T_a = 36.23°C, T_g = 41.07°C, RH = 59% and V_a = 0.91 m/s), and (C) the high thermal impact condition (T_a = 43.12°C, T_g = 44.41°C, RH = 77% and V_a = 1.70 m/s), respectively.

For each specified thermal impact condition, measurements of the four environmental factors were conducted on three testing planes vertically located at the front, middle, and end of the testing zone. Each testing plane was further divided into 9 testing areas, and all measurements were conducted at the center of each testing area (i.e., a total of 27 measuring sites were selected for each specified thermal impact condition). The approaches adopted for the measurements of the four physical environmental factors were consistent with the method specified in ISO 7726. Here, T_a, T_g, and V_a were measured by means of thermocouple (measurable range = 0–1,100°C; precision = ± 0.02°C) (Yu-Tai, k-type, Taipei, Taiwan), a standard globe ball (diameter = 15.24 cm), centered with the same type thermocouple as used for measuring T_a, and a rotating-vane anemometer (measurable range = 0.0–45.0 m/s; precision = ± 3%) (TES, AVM-07, Taipei, Taiwan), respectively. RH was determined by means of a psychrometric chart according to the measured wet ball temperature (T_w) (by means of a psychrometer with a measurable range of −20–60°C and precision of ± 3%) (TES, TES-1361, Taipei, Taiwan) and the measured T_a. All measurements were conducted on the testing zone of the chamber studied. Data for each environmental factor were collected every 30 s continuously for 1 h after the chamber studied reached an equilibrium condition (i.e., waiting time = 10 min for T_a, T_w, and V_a, and 20 min for T_g). All data collected were used to determine the mean, standard deviation (SD) and coefficient of variation (CV=SD/mean) in order to describe the uniformities of the four environmental factors in the chamber studied.
3. Approach used to evaluate the suitability of the exposure chamber studied

In this study, we assumed that all workers were thermally acclimated and were wearing clothing with insulating value (I_v)= 0.6 clo. Three workloads of the (1) light workload (M=130 W/m²), (2) middle workload (M=200 W/m²), and (3) heavy workload (260 W/m²) were assigned to suit workers’ work conditions. Assuming the four environmental factors of Ta, Tg, RH, and Va were normally distributed in the testing zones of the chamber studied for all specified thermal impact conditions. This allowed us to establish 1,000 environmental combinations for each specified thermal impact condition by using the Monte Carlo simulation approach according to the measured variations obtained for the four measured environmental factors. The above simulation approach has been widely used for assessing health outcomes for workers’ exposure to various agents with different uncertainties16–18. The resultant 1,000 environmental combinations were then used to determine workers’ AETs (including the mean and 95% confidence interval) for each specified thermal impact condition by using the ISO 7933 approach. For pragmatic purpose, if the range in the 95% CI of the resultant AETs was found to be less than 5 min for all specified thermal impact conditions, the chamber studied was then regarded as suitable for assessing workers’ thermal hazard.

Results

1. Uniformities of the four environmental factors in the exposure chamber studied under the three specified thermal impact conditions

Table 2 shows the uniformities of the four controlled environmental factors in the exposure chamber studied. For T_a, this study yielded CVs=5.39%, 2.99%, and 1.95%, and the chambers studied were specified as at the low, middle and high thermal impact conditions, respectively. Similar results can also be found for RH (CVs= 6.38%, 2.42% and 1.94%, respectively) and T_g (CVs= 5.51%, 4.29% and 2.43%, respectively). But for V_a, the results obtained in this study were somewhat different from those for T_a, T_g, and RH. Whereas V_a was for the high and middle thermal impact conditions, we found the corresponding CVs were 6.59% and 9.41%, respectively. But whereas V_a was specified for the low thermal impact condition, the corresponding CV was found to be as high as 50.0%. The above results clearly indicate that the four environmental factors were quite uniformly distributed in the testing zone of the exposure chamber studied at the three thermal impact conditions, with the exception of V_a which was at the low thermal impact condition.

2. The variations in the estimated AETs for the three specified thermal impact conditions

In this study, 1,000 environmental combinations were created by using the Monte Carlo simulation approach for each specified thermal impact condition. Table 3 shows the means, 95% confidence intervals (95% CIs), and the ranges of the 95% CI of the estimated AETs for each of the three specified thermal impact conditions. Results show that the mean AETs were decreased as both the thermal impact and workers’ workload increased. For the high thermal impact condition, we found that the ranges of 95% CIs of the estimated AETs for workers with the heavy, middle and light workload conditions were 0.04 min, 0.10 min and 0.14 min, respectively. The above range values were consistently less than those for the middle thermal impact condition (±0.18 min, 2.34 min and 2.82 min, respectively). But for the low thermal

<table>
<thead>
<tr>
<th>Measured environmental factor</th>
<th>Thermal impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ta (°C)</td>
<td>High</td>
</tr>
<tr>
<td>43.12</td>
<td>36.23</td>
</tr>
<tr>
<td>1.95%</td>
<td>2.99%</td>
</tr>
<tr>
<td>Tg (°C)</td>
<td>44.41</td>
</tr>
<tr>
<td>2.43%</td>
<td>4.29%</td>
</tr>
<tr>
<td>RH</td>
<td>77</td>
</tr>
<tr>
<td>1.94%</td>
<td>2.42%</td>
</tr>
<tr>
<td>Va (m/s)</td>
<td>1.70</td>
</tr>
<tr>
<td>6.59%</td>
<td>9.41%</td>
</tr>
</tbody>
</table>
Table 3. The mean, 95% confidence interval (95% CI), and the range, 95% CI of the estimated allowable exposure time (AET) for the three specified thermal impact environments, and the three selected workload conditions

<table>
<thead>
<tr>
<th>Specified thermal environments</th>
<th>Estimated AET (min)</th>
<th>Workload</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heavy</td>
<td>Middle</td>
</tr>
<tr>
<td>High thermal impact</td>
<td>Mean</td>
<td>25.85</td>
</tr>
<tr>
<td></td>
<td>95% CI</td>
<td>25.83–25.87</td>
</tr>
<tr>
<td></td>
<td>Range</td>
<td>0.04</td>
</tr>
<tr>
<td>Middle thermal impact</td>
<td>Mean</td>
<td>48.11</td>
</tr>
<tr>
<td></td>
<td>95% CI</td>
<td>48.02–48.20</td>
</tr>
<tr>
<td></td>
<td>Range</td>
<td>0.18</td>
</tr>
<tr>
<td>Low thermal impact</td>
<td>Mean</td>
<td>314.22</td>
</tr>
<tr>
<td></td>
<td>95% CI</td>
<td>313.71–314.73</td>
</tr>
<tr>
<td></td>
<td>Range</td>
<td>1.02</td>
</tr>
</tbody>
</table>

*: No 95% CI and its corresponding range could be estimated since the mean AET=480 min

impact condition, because we found the estimated AETs for both the light and middle workload conditions were greater than 480 min (i.e., workers were allowed to perform their job continuously for 8 h), no 95% CIs were calculated. Nevertheless, we found the range of 95% CI (=1.02 min) for the heavy workload condition was wider than those for the other two thermal impact environments with the heavy workload. Here it should be noted that all resultant ranges of 95% CI were still much less than 5 min. These narrow ranges of 95% CI suggest that the use of the chamber studied for assessing workers’ thermal hazard would provide estimated AETs with small variations.

Discussion

This study yielded CVs for $T_a$ which were consistently less than 6% for the three specified thermal impact conditions (Table 2). The above results clearly indicated that the driving unit and air dispersing system installed in the chamber studied were able to disperse $T_a$ uniformly. For the same reason, it is not so surprising to see that RH in the testing zone of the exposure chamber was also quite uniformly distributed (< 7%, Table 2). Similar results were found for $T_j$ (< 6%, Table 2), which indicates that the aluminum foil that was used to cover the whole inner wall of the exposure chamber could provide uniformly distributed thermal radiation conditions. For $V_a$, this study also yielded CVs < 10% for both high and middle thermal impact conditions. But whereas the chamber was for low thermal impact condition, the corresponding CV was as high as 50.0%. A similar result was found in a wind tunnel study for assessing the aspiration efficiencies of aerosol samplers under various moving air conditions. At this stage, whether the above high CV value was due to the low control ability of the air dispersing system at the low wind speed or the yaw-effect arising from the alignment of the rotating vane anemometer requires further investigation.

This study shows that the estimated mean AETs decreased as both the thermal impact and workload increased (Table 3). Similar results have also been found in other field studies and laboratory studies. Obviously this is because as the increase in both the thermal impact and workload result in an increase in both the external and internal thermal stress imposed on the human body, there is an increase in heat storage, resulting in a decrease in the estimated AETs.

For any workload, we found the ranges of 95% CIs of the estimated AETs decreased as the specified thermal impact increased (Table 3). This is not so surprising because the CVs of the four controlled environmental factors decreased as the specified thermal impact increased (see Table 2). Nevertheless, regarding the ranges of 95% CI for all estimated AETs, that they were consistently less than 5 min (Table 3) might be worth discussing further. As shown in Table 2, it is known that the measured CVs of the four environmental factors for the three thermal impact conditions were consistently less than 10%, except for $V_a$ of the chamber studied for the low thermal impact condition (= 50%). The above results suggest that the variation in $V_a$ might have only a very limited effect on estimating AETs.

In order to justify the above inference, we further conducted a sensitivity analysis to examine the sensitivities of the four environmental factors in determining AETs. The sensitivity analysis technique used in this study was carried out by regression of the output values (i.e., AETs) against the input values (i.e., $T_a$, $T_j$, RH, and $V_a$), leading to a measurement of sensitivity by the input variable. The results were displayed as a “tornado” type chart, with the longer bars at the top representing the most significant input variables.
This method has been used in a risk assessment study to identify the rank of different variables that contribute to human health-risk\textsuperscript{21}). The sensitivity results are shown in Fig. 2. For both the low and middle thermal impact conditions, we found $T_g$ was the most sensitive factor in estimating AETs. On the other hand, RH became the second most sensitive factor in estimating AETs for the high thermal impact condition. Here it should be particularly noted that in no circumstance was $V_a$ the most sensitive factor in estimating workers’ AETs. Based on this, it is not so surprising to see that, although $V_a$ was found to vary greatly in the low thermal impact condition, its effect on estimating AETs was quite limited. Furthermore, considering that the CVs for both $T_g$ and RH were consistently less than 7\% for all specified thermal impact conditions (Table 2), it is not so surprising to see that all resultant 95\% CIs for the estimated AETs were found to have quite narrow ranges (Table 3).

**Conclusions**

In this study, we found the three environmental factors, $T_a$, $T_g$, and RH, were quite uniformly distributed in the exposure chamber studied for all specified thermal impact conditions. But for $V_a$, although uniformity can also be achieved for both the high and middle thermal impact conditions, great variation was found for the low thermal impact condition. Because $V_a$ was found to be the least sensitive factor on determining AETs for any given thermal impact condition, it is not so surprising to see that all resultant AETs were found to have quite small variations. Therefore, it is concluded that the exposure chamber studied, although with great variation in $V_a$ for the low thermal impact condition, can still be regarded as able to be used for assessing workers’ thermal hazards.

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