Standard Test Method for Measuring the Heat Removal Rate of Personal Cooling Systems Using a Sweating Heated Manikin[1]

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INTRODUCTION

Personal Cooling Systems (PCS) are used when wearers could be exposed to conditions that render the body's thermoregulatory system inadequate to maintain body core temperature within a safe range. The use of PCS can reduce the possibility of heat stress related physiological disorders and can also provide increased comfort, which in turn could also result in higher productivity. Cooling needs vary greatly depending on the level of activity, the external temperature and humidity, as well as the personal protective equipment worn. The PCS should be selected that is best suited for the specific application. Sweating heated manikins provide a convenient tool to assess the effectiveness of PCS as they can provide objective and repeatable results. These instruments can be used to quantify, in a reproducible manner, the cooling rate and cooling duration provided by the PCS while eliminating the variables associated with human physiology. Sweating heated manikins can be used for direct comparisons of PCS.

1. Scope

1.1 This test method uses a sweating manikin in an environmental chamber to measure the heat removal rate and cooling duration provided by a personal cooling garment worn with a base ensemble.[2]

1.1.1 The use of a sweating heated manikin is essential because of the potentially large amount of heat dissipation from the body associated with evaporative cooling.

1.2 The experimental values obtained for the cooling rates and cooling duration apply only to the particular PCS and additional garments worn during the test and for the environmental conditions used.

1.2.1 It is feasible that this test method will yield unrealistically high cooling rates for ambient air circulation systems since the manikin's surface stays continuously saturated during the test and the relative humidity in the chamber is relatively low; consequently the convective and evaporative heat loss rates from the body to the environment are probably higher from the manikin than they would be from a human, particularly in environments with higher levels of humidity.

1.3 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

F1291 Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin

F1494 Terminology Relating to Protective Clothing

F2370 Test Method for Measuring the Evaporative Resistance of Clothing Using a Sweating Manikin

3. Terminology

3.1 For definitions of terms related to protective clothing used in this test method, refer to Terminology F1494.

3.2 *Definitions:*

[1] This test method is under the jurisdiction of ASTM Committee F23 on Personal Protective Clothing and Equipment and is the direct responsibility of Subcommittee F23.60 on Human Factors.

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[2] The present standard does not attempt to determine the thermal insulation and evaporative resistance of garments worn with the PCS, or these same properties for the PCS's themselves. Test Methods F1291 and F2370 are available for these measurements.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

3.2.1 *personal cooling systems (PCS)*—garment technologies that are designed to be worn with protective clothing in warm/hot environments to remove heat from the body and prevent heat stress; types include ambient air systems which circulate air between the body surface and clothing, phase change materials which are worn close to the body and absorb heat, and refrigeration systems and ice bath systems that circulate chilled water in tubes in a vest worn next to the body (that is, a liquid cooling garment).

4. Significance and Use

4.1 This test method can be used to quantify and compare the cooling provided by different personal cooling systems (PCS) worn with a common base ensemble. Any base ensemble can be selected based on the intended end use of the PCS.

4.1.1 The test method is intended to allow garments based on various cooling technologies to be evaluated fairly and objectively, by taking into account both dry and evaporative heat transfer.

4.2 The measurements of heat removal rates and duration of cooling provided by the PCS depend on the apparatus, the base ensemble, and the techniques used.

4.2.1 Departures from the instructions in this test method will potentially lead to significantly different test results.

4.2.2 Technical knowledge concerning the theory of heat transfer, temperature, air motion measurement, humidity, evaporative cooling, and testing practices is needed to evaluate which departures from the instructions given in this test method are significant. Report any departures with the results.

5. Apparatus

5.1 *Manikin*—A standing sweating manikin shall be used that is formed in the shape and size of an adult male or female and heated to a constant, average surface temperature.

5.1.1 *Size and Shape*—The manikin shall be constructed to simulate the body of a human being; that is, it shall consist of a head, chest/back, abdomen, buttocks, arms, hands (preferably with fingers extended to allow gloves to be worn), legs, and feet. Total surface area shall be 1.8 ± 0.3 m^2, and height shall be 170 ± 10 cm. The manikin's dimensions shall correspond to those required for standard sizes of garments because deviations in fit will significantly affect the results.

5.1.2 *Sweat Generation*—The manikin must have the ability to evaporate water from its surface. The sweating system can be a water fed capillary body suit worn over a thermal manikin. Sweating can also be simulated by supplying water to and maintaining it at the inner surface of a waterproof, but moisture-permeable fabric skin.

5.1.2.1 *Sweating Surface Area*—The entire surface of the manikin shall be heated and sweating including the head, chest, back, abdomen, buttocks, arms, hands, legs, and feet.

5.1.3 *Surface Temperature*—The manikin shall be constructed so as to maintain a uniform temperature over the nude body surface, with no local hot or cold spots. The mean surface (skin) temperature of the manikin shall be 35°C. Local deviations from the mean surface temperature shall not exceed ±0.5°C. Temperature uniformity of the nude manikin shall be evaluated at least once annually using an infrared thermal imaging system or equivalent method. Repeat this procedure after repairs or alterations are completed that could affect temperature uniformity, for example, replacement of a heating element.

5.2 *Power-Measuring Instruments*—Record the time history of the power input to the manikin over the entire test period. Overall accuracy of the power monitoring equipment must be within ±2 % of the reading for the average power for the test period. Since there are a variety of devices and techniques used for power measurement, no specified calibration procedures shall be given. However, an appropriate power calibration procedure is to be developed and documented.

5.3 *Equipment for Measuring the Manikin's Surface (Skin) Temperature*—Measure the mean skin temperature with point sensors or distributed temperature sensors.

5.3.1 *Point Sensors*—The following are acceptable point sensors: thermocouples, resistance temperature devices (RTD's), thermistors, or equivalent sensors. They shall be no more than 2.0 mm thick and shall be well bonded, both mechanically and thermally, to the manikin's surface. Lead wires shall be bonded to the surface or pass through the interior of the manikin, or both. The sensors shall be distributed so that each one represents the same surface area or are area-weighted when calculating the mean skin temperature for the body. If point senors are used, a minimum of 15 point sensors are required. At least one sensor shall be placed on the head, chest, back, abdomen, buttocks, and both the right and left upper arm, lower arm, hand, thigh, calf, and foot. These sensors must be placed in the same position for each test and the placement of the sensors shall be given in the report.

5.3.2 *Distributed Sensors*—If distributed sensors are used (for example, resistance wire), then the sensors must be distributed over the surface so that all areas are equally weighted. If several such sensors are used to measure the temperature of different parts of the body, then their respective temperatures need to be area-weighted when calculating the mean surface (skin) temperature. Distributed sensors shall be less than 1 mm in diameter and firmly attached to the manikin surface at all points.

5.4 *Controlled Environmental Chamber*—The manikin shall be placed in a chamber at least 2 by 2 by 2 m in dimension that can provide uniform conditions, both spatially and temporally.

5.4.1 *Spatial Variations*—Spatial variations shall not exceed the following: air temperature ±1.0°C, relative humidity ±5 %, and air velocity ±50 % of the mean value. In addition, the mean radiant temperature shall not be more than 1.0°C different from the mean air temperature. The spatial uniformity shall be verified at least annually or after any significant modifications are made to the chamber. Spatial uniformity shall be verified by recording values for the conditions stated above at heights of 0.1, 0.6, 1.1, 1.4, and 1.7 m above the floor at the location occupied by the manikin. Sensing devices specified below shall be used when measuring the environmental conditions.

5.4.2 *Temporal Variations*—Temporal variations shall not exceed the following: air temperature ±0.5°C, mean radiant temperature ±0.5°C, relative humidity ±5 %, air velocity ±20 % of the mean value for data averaged over 5 minutes. (See 5.4.5).

5.4.3 *Relative Humidity Measuring Equipment*—Any humidity-sensing device with an accuracy of ±5 % relative humidity and a repeatability of ±3 % is acceptable (for example, wet bulb/dry bulb, dew point hygrometer). Only one location needs to be monitored during a test to ensure that the temporal uniformity requirements are met.

5.4.4 *Air Temperature Sensors*—Shielded air temperature sensors shall be used. Any sensor with an overall accuracy of ±0.15°C is acceptable (for example, RTD, thermocouple, thermistor). The sensor shall have a time constant not exceeding 1 minute. The sensor(s) shall be 0.5 m in front of the manikin. If a single sensor is used it shall be 1.0 m above the floor. If multiple sensors are used, they shall be spaced at equal height intervals and their readings averaged.

5.4.5 *Air Velocity Indicator*—An omni-directional anemometer with ±0.05 m/s accuracy shall be used. Measurements shall be averaged for at least 1 min at each location. If it is demonstrated that velocity does not vary temporally by more than ±0.05 m/s, then it is not necessary to monitor air velocity during a test. However, the value of the mean air velocity must be reported. If air velocity is monitored, then measurement location requirements are the same as for temperature.

5.5 *Calibration*—Calibrate the sweating heated manikin in accordance with Test Method F2370.

6. Sampling and Test Specimens

6.1 *Personal Cooling System*—It is sufficient to test only one sample of a personal cooling system, with replicate measurements made on that single sample.

6.1.1 *Size and Fit*—Select the size of the PCS garment that best fits the manikin. Base fit on the manufacturer's specifications for fitting the garment to an actual human body. It is expected that certain PCS ensembles will not fit properly due to the rigidity of sweating thermal manikins. State the size of each PCS used and any fit discrepancies in the report.

6.2 *Specimen Preparation*—Test the PCS in the as-received condition or after dry cleaning or laundering in accordance with the manufacturer's instructions.

7. Test Procedure

7.1 *Environmental Test Conditions*—The following isothermal conditions shall be considered standard.

7.1.1 *Air Temperature*—The air temperature shall be 35 ± 0.5°C during a test.

7.1.2 *Air Velocity*—The air velocity shall be 0.4 ± 0.1 m/s or less during a test (that is, still air conditions).

7.1.3 *Relative Humidity*—The relative humidity shall be 40 ± 5 % during a test.

7.2 *Mean Surface (Skin) Temperature of Manikin*—The manikin's surface temperature shall be maintained at 35 ± 0.5°C for all tests. The mean surface temperature shall not be allowed to drift more than ±0.2°C during a 2 hour test.

7.3 *Sweating*—The entire manikin surface must have water available for evaporation throughout the test period. The water on the surface needs to be supplied or added to the surface of the manikin in the same manner as was used to generate the evaporative resistance value during calibration (see 5.5).

7.4 Pre-wet (for example, spray) the manikin's surface until it is saturated. Then start delivering water to the manikin's surface so as to keep it saturated. This water must be heated to 35 ± 0.5°C before being delivered to the manikin.

NOTE 1—It is usually possible to detect saturation visually by a color change (that is, surfaces that are wet will be darker than those that are dry). An IR camera is also acceptable for use to ensure that the surface is completely saturated. It is possible that a gradual decrease in power over time will indicate that the manikin is drying out in places, and the manikin's surface is no longer saturated.

7.5 *PCS Baseline Test*—First, conduct a baseline test on the PCS ensemble without cooling. The PCS shall be placed on the manikin, but not activated, so that no cooling is provided. In the case where the PCS cannot be turned off (for example, an ice vest, or phase change material), carry out the baseline test with the PCS components in equilibrium with the atmosphere in the test chamber by previously conditioning them in the chamber for at least 12 hours.

7.5.1 Dress the standing manikin in the PCS and the type of protective garments that would normally be worn with the PCS (for example, military ensembles containing body armor, chemical protective suits). If the PCS is not designed for any particular application, dress the manikin in light shorts or briefs and a t-shirt, the PCS, and a coverall. Follow the manufacturer's instructions as to the order of layering the garments and PCS on the body (for example, does the PCS go under or over the coverall?). Record a description of the ensemble components and the dressing procedures. Position the manikin so that it is hanging with its arms at its sides and its feet above the floor. Take a photograph of the ensemble on the manikin for the report (optional).

7.5.2 With the PCS not activated, bring the dressed, sweating manikin to 35 ± 0.5°C and allow the system to reach steady-state (that is, the mean surface temperature of the manikin and the power input remain constant ±3 %). Run a baseline test to determine the power input to the manikin.

7.6 *PCS Performance Test*—Enter the environmental chamber and turn on the PCS, or in the case of phase change materials, switch out the components as quickly as possible.

NOTE 2—If is it necessary to turn off the manikin and instrumentation so that some garments can be removed and components switched out or turned on, the manikin power must not be turned off for more than 5 minutes.

7.6.1 Start the timed manikin test immediately and record the manikin's surface temperature, the air temperature, the relative humidity, and the power to the manikin's body segments at least every 1 minute over the test period. At the time data recording starts, it is possible that the manikin's surface temperature will be below the target temperature (35°C ± 0.5°C). It is assumed that this drop in temperature is mainly due to the action of the PCS, as compared to other losses to the environment. Take measurements until the effective cooling rate (power input to the manikin, minus the baseline cooling rate obtained in 7.5.2) has decreased to 50 W, or up to a maximum of 2 hours.

7.7 *Replication of Tests*—Perform the baseline test followed by three independent replications of the PCS cooling test. Remove the PCS from the manikin at the end of each test, and don again at the beginning of the next replication. The manikin must come to steady-state with the PCS not activated or the components at ambient temperature before they can be turned on/switched out and another PCS test can begin.

8. Calculation

8.1 Calculate the cooling rate as the time average of the power input to the manikin from the time the PCS was activated and the test was started until the effective power (power input to the manikin minus the baseline value obtained in 7.5.2) has decreased to 50 W, or for a maximum of 2 hours. The time-average power is obtained from the numerical integration of the power input versus time until the effective cooling rate has decreased to 50 W, divided by the time it took to reach that value (from when the time data is recorded). Effective cooling rate is determined by subtracting the average power input value and the baseline power value.

8.2 Record the duration of cooling as the time required for the net cooling power to decrease to 50 W (use cooling power values corrected for the baseline power value). If such a decrease was not observed within the 2-hour maximum testing period, the duration is defined as "more than 2 hours."

9. Report

9.1 State that the PCS ensembles were tested as directed in Test Method F2371.

9.2 Report the following information:

9.2.1 Describe the PCS and garments worn.

NOTE 3—It is recommended to include a photograph of the manikin dressed in each PCS ensemble in the report.

9.2.2 Report the average cooling rate values for each PCS, in accordance with the calculation method outlined in Section 8.

9.2.3 Report the average duration of cooling for each PCS, as specified in Section 8. If the cooling is generated by a "non-depletable" power source, such as power from an electrical plug or a fixed chiller, report the type of power source and indicate that the cooling duration is not relevant.

9.2.4 Report the coverage area of the PCS in square meters (optional). This information can be provided by the manufacturer.

9.2.5 Specify the environmental test conditions listed in 7.1.

9.2.6 Explain any departures from the specified apparatus or procedure.

10. Precision and Bias

10.1 *Precision*—In comparing two independent observations of the effective cooling rate values, the variation must not exceed ±10 % of the average of the two measurements when the measurements are taken by the same well-trained operator using the same testing equipment. Otherwise, additional replications must be conducted until this criterion is met.

10.2 *Bias*—The procedure in this test method for determining the effective cooling rate of PCS's has no bias because the value can be defined only in terms of a test method.

11. Keywords

11.1 comfort; cooling rate; heat stress; personal cooling systems; personal protective equipment; sweating manikin; thermal manikin