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Air/CO₂ cooling garment: Description and benefits of use for subjects exposed to a hot and humid climate during physical activities

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ABSTRACT

The severity of the hot and humid conditions to which miners are exposed increases as the depth of the work site increases. This can cause heat stress that can greatly affect the health and safety of workers. To resolve this, a cooling garment has been developed that uses an atmospheric discharge of liquid CO₂ to create a cool microclimate with an average temperature of 12.5 (±0.4) °C beneath the garment. To evaluate the garment's cooling efficiency, 19 male subjects participated in an experimental procedure. The two modes, cooling on and off, were compared. Significant physiological differences were found between the two modes after minute 27 ($p < 0.05$) until the end of the recovery phase for the heart rate (maximum difference of 10 beats per minute) and the internal body temperature (maximum difference of 0.33 °C). It was found that the modes also affected the subjects' perceptions. The ON-mode was associated with better well-being and thermal comfort, and reduced humidity sensation. Perceptions of exertion were lower in the ON-mode condition from minute 2. The findings provide strong evidence of the ability of this cooling garment to reduce heat stress in hot and humid conditions similar to those encountered in deep mines.

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1. Introduction

The severity of the heat stress experienced by miners increases as the work site depth increases and it can greatly affect the health and safety of workers. At great depths, the conditions are both hot and humid, leading to an increase in work-related accidents and a decrease in productivity [1]. As the air temperature of the environment exceeds mean skin temperature, the body gains heat from its surroundings by convection. The body increases the production of sweat in an attempt to cool down via evaporation. Unfortunately, in deep mines, ambient temperatures can easily reach 35 °C and the relative humidity (RH) levels of the surrounding air are saturated, that is, they frequently exceed 80%, thus preventing and/or limiting any relief through the evaporation of sweat [2].

To reduce the severity of heat stress and the level of danger it presents within this type of workplace, mines use several industrial cooling technologies, such as central air conditioning and ice and water cooling technologies [3–5]. Unfortunately, these systems are large, costly, energy intensive, and require modifications to adapt them to the various depths. Therefore, it is necessary to

develop alternative cooling methods, such as the use of personal cooling garments. Currently available commercialised cooling garments have not proven to be fully effective for the conditions in deep mines, due to the high level of relative humidity in these environments and the fact that these garments are unsuited to the mining environment [6].

Researchers are continuously optimizing and testing new cooling garments to achieve better effectiveness in reducing occupational heat stress. In 2016, Shirish et al. tested the effectiveness of a liquid-cooled garment on 24 workers performing their duties in an iron foundry [7]. There were no significant differences in mean oral temperature or heart rate when workers were asked to wear the garment. Researchers recorded significant differences in torso skin temperature, but not at any of the other skin points tested (head, arms, hands, thighs, and feet). Workers did not exhibit any signs of overcooling when they wore the garment and reported that wearing it did not interfere with their ability to perform their work, stating that the garment gave them thermal comfort while working in a hot environment (35.89 ± 1.25 °C and 35% RH). Similar results were found in 2017 by Bartkowiak et al. [8]. This study examined whether a liquid cooling garment that consisted of a jacket connected to a mobile cooling unit (weighing about 10 kg) on wheels could reduce the thermal discomfort of

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workers in a hot environment (30 °C and 40% RH). In 2017, Butts et al. evaluated the physiological and perceptual responses of 20 subjects wearing a phase-changing garment (PCG) exposed to heat simulating a work situation (34.2 ± 0.05 °C and $54.7 \pm 0.3\%$ RH) [9]. They found that the PCG effectively decreased skin temperature, increased heat loss, and reduced heat stress, improving perceptions of heat stress and decreasing body fluid loss in the subjects. Researchers today are comparing different cooling methods to evaluate the possibility of using them in the workplace, such as the use of cooling garments, executing arm immersion in cold water, inhaling heliox, and ingesting ice [10]. To the best of our knowledge, no personal cooling method has been developed for or is fully adapted to the mining industry. Most studies focus on developing and optimizing air cooling systems in underground environments through general ventilation in centralized systems. Thus, a prototype of a personal cooling garment suitable for miners has been developed. The objective of this garment is to assist the body in evacuating excess heat, which will lead to better working conditions and improved worker health and safety. The present study aims to test the effects of this prototype on physiological (heart rate and internal body temperature) and perceptual (exertion, thermal comfort, etc.) responses of subjects inside a climate chamber. The subjects performed physical activities in a simulated environment that reproduced the temperature and humidity conditions found in deep and ultra-deep mines.

2. Method

2.1. Subjects

This study recruited 20 healthy male subjects. Subjects were informed about the experimental protocol, potential risks that might occur during the tests, and the purpose of the study prior to signing a letter of consent. The required tests were completed by 19 subjects, having an average age of $26.7 (\pm 4.3)$ years, average weight of $77.6 (\pm 10.5)$ kg, average height of $1.80 (\pm 0.07)$ m, and average body mass index of $24.1 (\pm 3.5)$ kg/m². The study's protocol was reviewed and approved by the Superior School of Technology Ethics Committee (ethical reference code: H20170802).

2.2. Prototype of a personal cooling garment

The prototype is composed of three major parts: the layers forming the garment, the air treatment system, and the distribution channels (Fig. 1). The outside layer of the garment is made of polyester to create a barrier between the surrounding air and the microclimate within the garment. The middle layer is composed of a moisture-wicking fabric, the main purpose of which is to increase the wearer's comfort by absorbing excess, non-evaporated sweat. The inside layer, which is in direct contact with the wearer's underclothing, is made of mesh polyester that allows mass and heat transfer between the skin and the microclimate. It is important to mention that the prototype should undergo some modifications to reach his highest technology readiness level

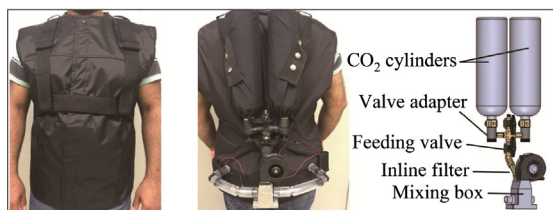


Fig. 1. Front view, back view, and the air treatment system of the cooling garment.

before it can be used as its final form in real mining activities. For instance, because the types of accidents that could occur in mines are mostly related to the mining activity (gold mining, coal mining or other), some modifications on the prototype's layers should be considerate when used in highly dangerous environments. In coal mines, major occurring accidents are methane explosions, gas and coal outburst and fire [11–13]. In this working environment, a fire retardant and ballistic fabric such as Kevlar and ballistic nylon should replace the outside polyester layer of the prototype.

The air treatment system uses an atmospheric discharge of highly pressurized liquid CO₂ (5.8 MPa) to cool and dehumidify the constant stream of air taken from the surroundings. For this purpose, two identical cylinders, each containing 0.68 kg of saturated two-phase CO₂ (liquid/gas) were mounted upside down on the back of the garment. When the feeding valve and valve adapters are open, the liquid CO₂ passes through the brass connexions through an inline filter and expands to atmospheric pressure as it passes through the orifice. Several orifice diameters were tested prior and the 0.089 mm diameter was chosen for its capacity to deliver a mass flow of 0.43 g/s of mixed gaseous CO₂ and dry ice when an all-liquid expansion occurred. The orifice is connected directly to a mixing chamber located inside a mixing box that contains a heat sink. The mixing chamber is also connected to a DC blower, operating on 13.2 V, which delivers 3.5 L/s of hot and humid air taken from the surroundings. The mixing box also contains a humidity chamber to collect the condensation (water) when the air is cooled under its dew point. Fig. 2 shows the temperature profiles of the air injected beneath the cooling garment (microclimate temperature) and the air inside the climate chamber when a 0.089 mm orifice diameter was used for atmospheric expansion of CO₂.

A microclimate with an average temperature of $12.5 (\pm 0.4)$ °C was created between the cooling garment and the wearer for the duration of 40 min, which is almost the length of time required to accomplish the experimental protocol of visit 2 and visit 3. When no more liquid was present within the cylinders, the remaining CO₂ was in a gaseous state and expanded through the orifice, decreasing the cooling capacity of the CO₂. This affected the temperature of the microclimate beneath the garment. This change can be seen in Fig. 2 with an increase in temperature after minute 41.

The distribution channels used to create the microclimate are made of PVC tubes with different diameters. Because the sweat rate for the posterior torso during physical activity is approximately double that of the chest area, the PVC tubes are perforated in such a way as to deliver two thirds of the treated airflow to the wearer's back (approximately 2.3 L/s) and to maintain a constant flow through these perforations [14]. The diameters of perforations varied between 4.5 and 8 mm and a total of 20 perforations were equally distributed between the back and the front. This distribution system is imbedded between the wicking fabric and mesh polyester. The air treating system is attached to the back of the garment through pockets, straps and Velcro™ fastening ribbons. Three

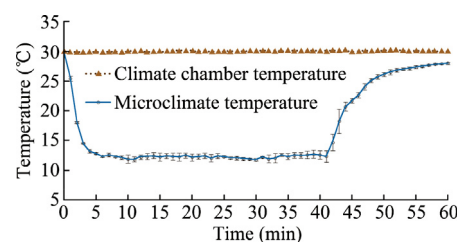


Fig. 2. Temperature profiles of the microclimate and climate chamber.

pockets are also used to hold the battery boxes for powering the fan and the overall weight of the prototype is 5.1 kg. Because that any extra load carried by workers would affect negatively their performances, reducing the overall weight of the prototype is necessary [15]. A 1 kg decrease in weight can be achieved by switching the aluminum cylinders with more expensive ones, made from carbon fibre.

2.3. Climate chamber

The study was conducted inside a 54 m³ climate chamber that was connected to 2 type J thermocouples and 2 humidity detectors, using the LabVIEW platform [16]. Due to the ethical committee's restrictions on the maximum heat stress allowed during tests with human subjects, the surrounding environment inside the chamber was maintained at a dry-bulb temperature of 30 ± 1 °C and relative humidity (RH) of 60% ± 2%. Since the cooling garment injects CO₂ into a closed environment, a ventilation rate of 5.5 air change per hour was maintained inside the climate chamber so that the concentration of CO₂ would not exceed 0.5% (the occupational limit of CO₂ for 8-h exposure) [17,18]. A CO₂ detector, mounted in the breathing zone 1 m from the subject, registered CO₂ levels for the entire duration of all the tests.

2.4. Physiological measurements and subjective perceptions

The subjects' weight was measured using a digital body scale (accuracy ± 5 g). Heart rate was recorded using a H10 Polar™ heart rate sensor placed around the chest and connected to a V800 Polar™ watch [19]. Internal body temperature was measured using a Braun™ ThermoScan® 7 Age Precision® (IRT6520) ear thermometer with a maximum error of ±0.2 °C. When the cooling garment was worn (ON-mode and OFF-mode), and during the exercise phase, subjects indicated their rating of perceived exertion (RPE) using a 10-point scale for thermal comfort (from -6 = extremely cold to 4 = hot), humidity sensation (from -6 = soaking wet to 4 = dry) and overall well-being (from -6 = extremely unpleasant to 4 = pleasant) at 5 min intervals [20].

2.5. Experimental protocol

Each subject was asked to perform different tests over a period of 3 visits, separated by 1-week intervals. During the first visit, the height and weight of each subject was recorded. Subjects were then asked to wear an H10 Polar heart rate sensor connected to a V800 Polar watch, and to enter the climate chamber, which was set at a dry-bulb temperature of 22 °C ± 1 °C dry and 40% ± 2% RH. Subjects mounted a stationary bicycle and began to pedal at a cycling power of 50 W (low cycling power: LP). Cycling power was increased in increments of 25 W every 2 min until the subjects reached 70% of their theoretical maximum heart rate (220-age) [21]. The final cycling power reached (MP) was recorded for each subject and was considered as the subject's personal 100% MP during the other two visits.

For these two other visits, subjects wore the cooling garment prototype and during one visit, it was activated (ON-mode) and during the other it was deactivated (OFF-mode). To eliminate any interfering effects between the last two visits, half of the subjects completed their second visit with a garment that was in ON-mode, and the other half's garment was in OFF-mode. The climate chamber was set at a dry-bulb temperature of 30 °C ± 1 °C and 60% ± 2% RH. The test protocol was identical for both visits.

Upon arriving at the facility, subjects had their internal body temperature measured at the tympanic level (baseline measurement). Subjects then layered the H10 heart rate sensor, T-shirt, and cooling garment before entering the climate chamber and

mounting the stationary bicycle. The H10 heart rate sensor was activated, and the subject remained still for 2 min (acclimation phase). After two minutes, the internal temperature was measured (T0 interval) and subjects were asked to pedal for 5 min at 50% of their personal MP (warm-up phase). After the warm-up, peddling of the stationary bicycle was set to 100% of the subject's MP and subjects were asked to pedal for 30 min (exercise phase from T5 to T30). During the exercise phase, body internal temperatures were measured every 5 min, and the subjects reported their various perceptions (exertion, thermal comfort, well-being, and humidity) using the scales provided.

After the exercise phase was completed, subjects continued to pedal at a 50-Watt cycling power (LP) for two minutes (active recovery phase) and finally, the subjects rested on the stationary bicycle for three minutes (passive recovery phase). Internal body temperature and perception were taken one last time before the subjects exited the climate chamber (R5 interval). The cooling garment and H10 Polar heart rate sensor were removed, and subjects were offered water and snacks before leaving the facility once they felt relaxed. Fig. 3 shows the cycling protocol during the second and third visits.

2.6. Statistical analysis

Standard statistical methods were used to calculate the mean and standard deviations. The Gaussian distribution of the data was verified by the Shapiro–Wilk test and homoscedasticity by a modified Levene's test. Compound symmetry, or sphericity, was verified using Mauchly's sphericity test. When the assumption of sphericity was not met, the significance of F-ratios was adjusted according to the Greenhouse–Geisser procedure for cases where the epsilon correction factor was <0.75, and the Huynh–Feldt procedure for cases where the epsilon correction factor was >0.75. For each physiological and perceptual measure, a two-way analysis of variance with repeated measures (ANOVA: condition [ON/OFF] × Time) was performed. Multiple comparisons were made with the Fisher's Least Significant Difference (LSD) post-hoc test. The significance level was set at $p < 0.05$ for all analyses.

3. Results and discussion

The maximum CO₂ concentration measured inside the climate chamber during ON-mode tests was 0.42%. A maximum value of 0.11% was recorded for the OFF-mode tests. Results for internal body temperature were averaged and are presented in Fig. 4. It is clear that the average internal temperature was lower when the garment was functional (ON-mode). Higher internal temperatures for both conditions (ON-mode and OFF-mode) were present at the end of the exercise phase (T30), with an average value of 37.85 (±0.5) °C for OFF-mode and 37.52 (±0.4) °C for or ON-mode (0.33 °C difference). The ANOVA test revealed a significant main effect of time ($p < 0.05$) and a significant interaction (Condi-

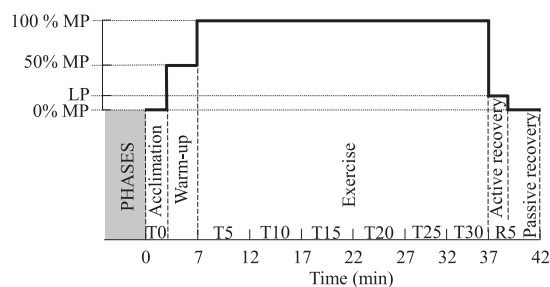


Fig. 3. Cycling protocol during visits 2 and 3.

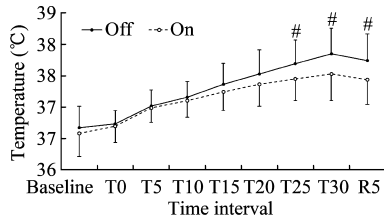


Fig. 4. Kinetics of internal temperature during exercise and recovery, # significant difference is between conditions ($p < 0.05$).

tion \times Time; $p < 0.05$). This interaction indicates that during the ON-mode tests, internal temperature did not increase as much as it did during OFF-mode tests. From minute 27 up to the end of the recovery period (T25, T30, and R5), there were significant differences between the two conditions.

The subjects' perceptual responses recorded during visits 2 and 3 are presented in Fig. 5.

A significant main effect of time on all perceptual measures ($p < 0.05$) was found. All the subjects reported an improvement in their feeling of exertion during the exercise phase when the garment was in ON-mode. Significant differences in the rating of perceived exertion were recorded at T20, T25, and T30 with 1, 1.1, and 1.4 level difference, respectively (RPE, $p < 0.05$).

These findings indicate that wearing the cooling garment generates a positive influence on the self-reported measure of work intensity. When the body felt cool, the feeling of work intensity decreased. In ON-mode, the garment improved the thermal comfort of all the subjects. Significant differences in thermal comfort were found at each time interval (from T5 to R5). Maximum variance was noted at the end of the recovery phase (R5) with a two-level difference value. According to the subject-reported mea-

sure of humidity, the cold microclimate generated beneath the garment greatly influenced sweat evaporation Fig. 5.

A probability value of less than 0.05 was found at every time interval (from T5 to R5) and a decrease in humidity sensation (or improvement) was recorded when the garment was in ON-mode. Maximum variance was found simultaneously at T20, T30, and R5, with an equal level difference of 1.77. Subjects felt better during the exercise and recovery phases when the garment was in ON-mode (compared to when the garment was in OFF-mode), which can be seen in the measurement of well-being in Fig. 5. Significant differences were found at every time intervals during the exercise and recovery phases, with a maximum of 1.95 levels (at T30).

Heart rate responses were recorded and then averaged for each time interval, from the baseline measurement to the end of the recovery phase. Results are presented in Fig. 6. A main effect of time ($p < 0.05$) and a significant interaction (Condition \times Time, $p < 0.05$) were found. This interaction revealed that during ON-mode tests, heart rate did not increase as much as it did in OFF-mode tests. Significant differences were found at T25, T30, and R5. The maximum average difference in heart rate was recorded after the recovery phase (R5) with a value of 10 beats per minute (bpm). At T25 and T30, the difference in heart rate was 8 bpm.

When looking at the physiological measurements, the cooling garment had a significant effect in reducing both the internal body temperature and heart rate of the subjects from T25 to R5. This finding indicates that the cooling garment reduced the heat stress produced in the subjects by both the physical activity and heat of the surrounding environment. The garment's cooling capabilities also greatly influenced the recovery speed, which is shown by the significant differences found at R5 for each physiological measurement.

As for the perceptual responses, the cooling garment in ON-mode was able to improve thermal comfort, humidity, and well-being at all the time intervals. Subjects felt that the cooling pro-

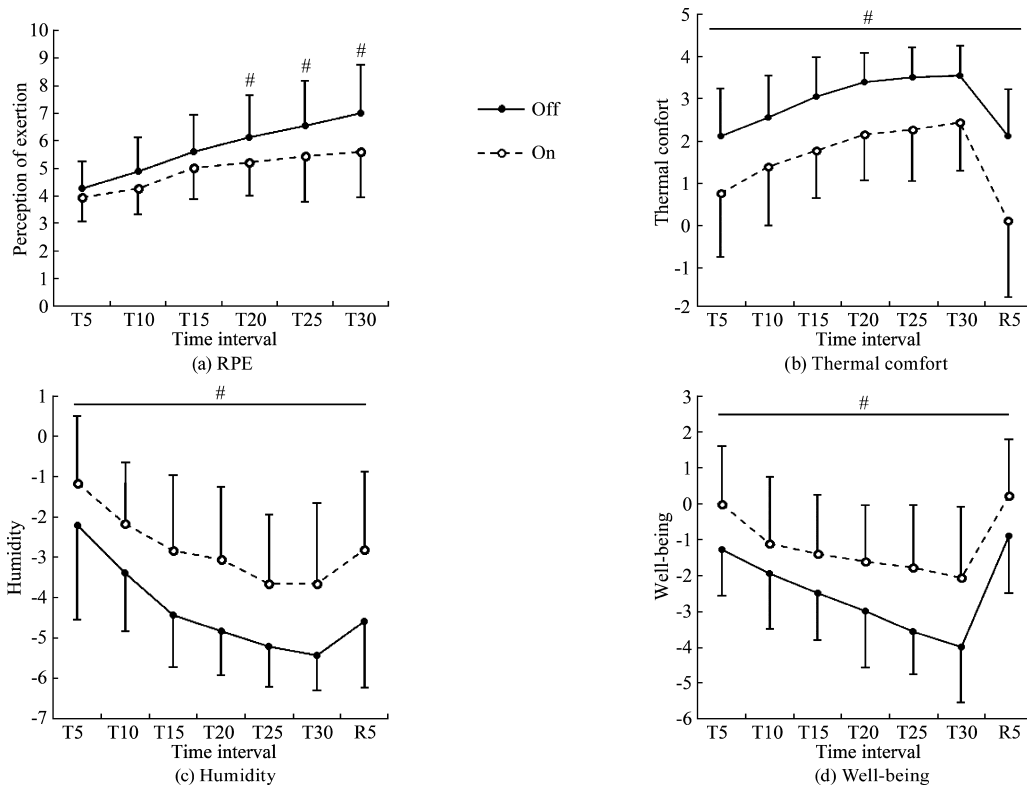


Fig. 5. Perceptual responses during exercise and recovery, and #significant difference between conditions ($p < 0.05$).

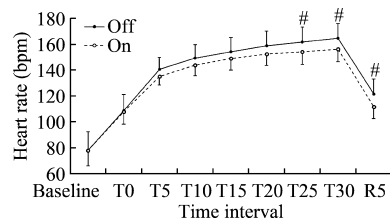


Fig. 6. Heart rate responses during exercise and recovery, # significant difference between conditions ($p < 0.05$).

vided by the garment lowered exertion levels and rendered the physical activity more tolerable, from T20 up to T30.

4. Conclusion

A personal cooling garment was developed for use in deep mining activities. The garment weighs 5.1 kg and uses the atmospheric discharge of highly pressurized CO₂ to create a cool microclimate between the body (torso) and its surrounding environment. The purpose of this study was to evaluate the effects of the cooling garment on the physiological markers and perceptual responses of subjects exposed to a hot and humid work environment. Findings show that the cooling garment lowered the subjects' internal body temperature and heart rate. The garment also improved the subjects' well-being, thermal comfort, exertion level, and reduced the humidity sensation. All these findings provide strong evidence of the cooling garment's ability to reduce heat stress in an environment simulating the work conditions of deep mines. When compared to an actual mining environment, our study has some limitations. The average age and body weight of miners' are higher than those of the subjects that participated in this study [2]. The workload and surrounding conditions (temperature and relative humidity) also vary from the conditions simulated in this study. It is important that future studies direct their efforts towards testing the garment's effects with miners in real mining conditions.

Conflicts of interest

The authors of this study declare no potential conflicts of interest.

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