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Title: Evaluating the ventilation unit for personal cooling system (PCS)

Article Type: Research Paper

Abstract: Background: Workers are vulnerable to heat stress when they perform tasks in hot environments. Personal cooling system (PCS) is designed to reduce heat strain under conditions without air-conditioning. A cooling vest with ventilation fans is one type of PCS that can blow air around the body to facilitate convective and evaporative cooling.
Objective: This study is aimed at evaluating the performance of the ventilation unit for a tailor-made cooling vest designed to protect construction workers from heat stress. The performance of this newly designed ventilation unit (Unit B) was compared with that of the ventilation unit used in a commercially available cooling vest (Unit A).
Method: The designed ventilation unit consists of a pair of ventilation fans and a portable battery pack. A hot wire anemometer was used to measure the air velocity of the fan. The air volumes and work duration of different ventilation units were compared. A sweating manikin test was also conducted to further compare the cooling powers of the ventilation units.
Result: The ventilation Unit B powered by a 7.4 V lithium-polymer battery performed better in terms of airflow rate and work duration (at over 15 L/s for as long as 7 h) than the commercially available ventilation Unit A. The cooling power of Unit B on sweating manikin was approximately 68 W, which was higher than that of Unit A (51 W).
Practical applications: Results show that high airflow rate of the ventilation unit increased the cooling power in the manikin test. The ventilation unit designed in this study will be incorporated in a tailor-made PCS for protecting workers in the heat.

Highlight

A portable ventilation unit was designed for a tailor-made personal cooling system (PCS) for protecting workers in the heat.

We tested and compared the airflow rate and cooling powers of a commercially ventilation unit and the newly designed unit.

High airflow rate of the ventilation fan increased the cooling power in the manikin test.

Evaluating the ventilation unit for personal cooling system (PCS)

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Keywords: Personal cooling system (PCS); Ventilation unit; Manikin test.

1. Introduction

Heat generation within the body and heat transfer into the body should be balanced by heat dissipation from the body to the environment (i.e., heat balance between the human body and the ambient environment) to maintain a constant body core temperature (approximately 37 °C) (Parsons, 2014). The heat dissipation process is dependent on conduction, convection, radiation and evaporation of sweat. When the ambient temperature approaches or exceeds the skin temperature, heat loss diminishes and is even replaced by heat gain (Miller and Bates, 2010). A heat gain higher than heat loss contributed a positive heat storage and rise in body temperature. If no effective external cooling measures are taken, a person will be at high risk of heat stress. Under conditions where total air-conditioning is not feasible, individual cooling can be a practical solution to alleviate heat strain (Epstein et al., 1986). Personal cooling systems (PCSs) are designed to reduce the heat hazards resulting from rising body core temperature and improve the associated work performance. Generally, three types of PCS are widely used in the civilian and military sectors, i.e., liquid cooling garments (LCGs), air cooling garments (ACGs), and phase change garments (PCGs) (Mokhtari Yazdi and Sheikhzadeh, 2014). LCGs and ACGs are connected to external cooling devices and circulate cooled liquid or air around the human body. PCGs use precooled phase change materials (PCMs), e.g., ice, inorganic salt, and paraffin wax, to reduce body temperature. Previous studies reported that the cooling capacities of ACGs are lower than those of water- or ice-cooled garments because of the low heat capacity of air (Epstein et al., 1986; Harrison and Belyavin, 1978; Nunneley, 1970; Shapiro et al., 1982; Shvartz, 1975). However, air vests have physiological benefits similar to water or ice vests (Epstein et al., 1986; Kissen et al., 1971; Shapiro et al., 1982). Through direct contact between the skin and the dry-cooled air, ACGs enable the employment of the natural heat-dissipating mechanism (i.e., evaporation of sweat) besides the convective heat transfer of the cool air (Epstein et al., 1986). Moreover, in humid environments, the use of ACGs can keep the clothing and body dry as opposed to wetting it by the condensation of the liquid in LCGs or melting of ice in the PCGs used.

Studies show that ACGs are effective in hot environments or under insulated protective suit to alleviate heat strain (Barwood et al., 2009; Chinevere et al., 2008; Hadid et al., 2008).

Heat stress is a serious condition in Hong Kong during the summer season, posing a health threat to industrial workers. Heat stress hazards have drawn the attention of the government, various statutory bodies, and concerned industries, promoting investigations on occupational and health problems in hot weather (Yi and Chan, 2014). During the summer of 2013, the Hong Kong Labor Department launched the "Cooling Vest Promotion Pilot Scheme", in which approximately 1,500 sets of the preferred hybrid cooling vest (a vest incorporated with a pair of ventilation fans and several ice packs) were distributed to industries including construction, outdoor cleaning and horticulture, kitchen work and work involving manual handling at the airport (Occupational Safety and Health Council, 2013). The study by Chan et al. (2015b) further assessed the applicability of this cooling vest, in which shortcomings of the current cooling vest was identified, including easily staining color, short cooling time, heavy weight, inflexibility (i.e., poses hazard around moving equipment), and lack of industry-specific design (i.e., lack of reflective strips).

Our project is aimed at developing a tailor-made PCS for construction workers by drawing from the findings of previous field studies. A portable ventilation unit is incorporated in the PCS to enhance convective and evaporative cooling. The ventilation unit, which consists of a battery pack and a pair of ventilation fans, is an integral part of the overall PCS design. The ventilation fans, which are powered by a lightweight mobile power pack, are expected to generate a constant flow rate of air the duration of one work shift (e.g., 6 hours) (Barwood et al., 2009; Chinevere et al., 2008; D'Angelo et al., 2014). The present study was conducted to evaluate the performance of the ventilation unit designed for PCS. A comparison was made between the new ventilation unit and the commercially available ventilation unit. Specifically, air volumes and the work durations of different ventilation units were compared. The cooling power of the ventilation units were further measured on a sweating manikin.

2. Methods and materials

The study for evaluating a ventilation unit for PCS was conducted following the steps illustrated in Figure 1. The ventilation unit was an essential part of the overall cooling vest design. The air volume of the commercially available ventilation unit (Unit A) was measured with a hot wire anemometer, and its work duration was also recorded. To achieve higher performance, a unit with newly customized fan and battery was proposed, i.e., Unit B. The air volume of Unit B was measured and compared with that of Unit A. The ventilation units were then inserted into the cooling vest, and a sweating manikin test was performed to compare their cooling powers.

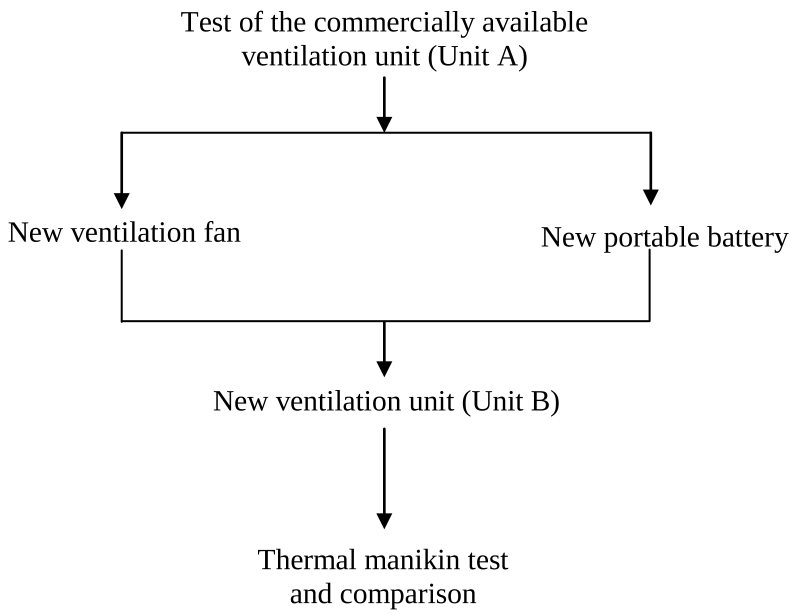


Figure 1 Overall framework of evaluating the ventilation unit for PCS

2.1. Ventilation unit

The ventilation unit consists of a pair of ventilation fans and a battery pack. The rated power of each fan is 2.5W, and diameter of the fan blade is 10 cm. In Unit A, the fans are powered by AA battery. In Unit B, the fans are powered by 7.4V lithium–polymer (Li-Po) battery. The fans are connected to the battery by a Y-type cable. Two kinds of AA batteries were available, i.e., 1.5 V alkaline AA battery with 2122 mAh capacity (Gold Peak Industries (Holdings) Limited) and 1.2 V nickel–metal hydride (NiMH) rechargeable AA battery with 1300 mAh capacity [Gold Peak Industries (Holdings) Limited] (Table 1). The 7.4V Li-Po battery had three capacities, i.e., 3000, 3800, and 4400 mAh (BAK Battery Co., Ltd) (Table 1). All the batteries were fully recharged just before each test.

Table 1 Parameters of battery

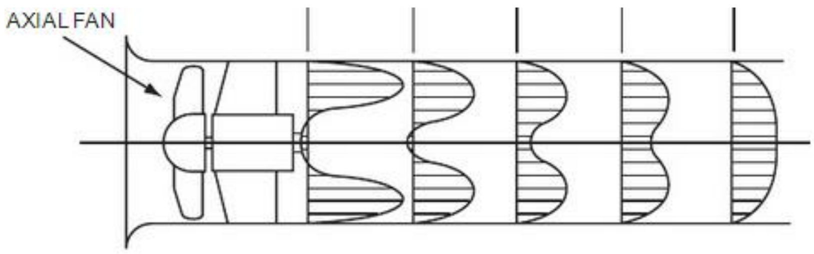
	Capacity (mAh)	Weight (g)	Voltage (V)
Unit A/4 pieces of alkaline AA battery	2122	95.33	6
Unit A/4 pieces of NiMH rechargeable AA battery	1300	87.63	4.8
Unit B/ Li-Po battery	3000	103.07	7.4
Unit B/ Li-Po battery	3800	138.64	7.4
Unit B/ Li-Po battery	4400	153.86	7.4

2.2. Air volume test

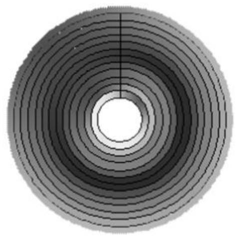
The performance of the ventilation unit was tested and compared under full-load operation, i.e., 7.4, 6, and 4.8 V. A controllable switch was used to compare fan performance powered by the same battery but under different output powers. With the use of the controllable switch, the unit can be adjusted to work at 60% output power. A hot wire anemometer was used (RS327-0640, Taiwan) to measure the air volume of the fan. The fan was connected tightly to a duct to make the air flow parallel through the duct. The hot wire probe was then inserted into the duct (10 cm in front of the axial fan) to measure the air flow rate. Figure 2a shows the changes in velocity profiles at various distances from the axial-flow fan outlets (AMCA, 2007). The airflow velocity is inconsistently distributed along the circular cross section. In Figure 2b, the darker the shade, the higher the airflow velocity (IEC, 1986; Zhao et al., 2012). The hot wire measured the airflow every 1 cm from the edge to the center of the circle, which was divided into five circle rings. The volumetric flow rate can be calculated by the following formula:

$$Q = \sum v_i \cdot A_i$$

where v_i is the airflow velocity in each circle ring, and A_i is area of the circle ring corresponding to v_i. Air velocity was measured every 30 min until the battery was exhausted. The overall work duration was recorded.



(a)



(b)

Figure 2 (a) Velocity profile in a straight length of outlet duct (adapted from AMCA 201-02, R2007, pp.5); (b) Airflow distribution on the circular cross section (adapted from Zhao et al. (2012), pp.291)

2.3. Sweating manikin test

Units A and B were each inserted into a cooling vest to measure the cooling powers of ventilation units for further cooling power comparison. The cooling vest was worn over the construction uniform (including a poly shirt and long pants) we developed in our previous studies (Chan et al., 2015a) (Figure 3). This uniform exhibited better performance in improving the physiological and perceptual responses of the wearers during exercise and recovery staged than the Construction Industry Council (CIC) uniform, which was commonly worn by construction workers in Hong Kong (Chan et al., 2015a).

Front view Rear view

Figure 3 Thermal manikin test of the cooling vest over construction uniform

A heated sweating thermal manikin, Newton, was used to measure the cooling power of PCS (F2371-10, 2010). The manikin consists of 34 individually controlled zones. Its segmental surface temperature could be individually controlled. During the test, the manikin surface temperature was controlled at 34 ℃. The sweating rate was set to 1200 ml/hr m^2 to simulate the human body in heavy sweating. The climate chamber’s ambient temperature was controlled at 34 ℃, similar to that of the manikin surface temperature. The air velocity was 0.4 m/s. The relative humidity was 60%, which was an average value measured in the construction field during the summer in Hong Kong from July 2011 to August 2011 (Wong et al., 2014). Segmental heat losses under each scenario were recorded at 1 min intervals. Each test scenario was repeated three times on the manikin and average values were used for calculations.

The cooling vest covered the manikin torso region. The torso heat loss, Q, in W/m^2, was area weighted by the six covered zones, i.e., upper chest, shoulders, stomach, mid back, waist, and lower back. The baseline test was performed with the ventilation fan turned off. The cooling power of the cooling vest under the fan-on condition was calculated by deducting the mean steady-state heat loss under the fan-off condition (i.e., the baseline) from the total observed heat loss under the fan-on condition.

3. Results

3.1. Air volume of the ventilation unit

Unit A, which was powered by 6V 2122 mAh alkaline AA battery and 4.8 V 1300 mAh NiMH rechargeable AA battery, worked for 6.22 and 3.75 h, respectively. The air flow rate was measured every 30 min, and only before second and third hours did the fan operate at a flow rate of over 5 L/s (Figure 4). The airflow of the fan powered by the AA battery subsequently decreased gradually to zero.

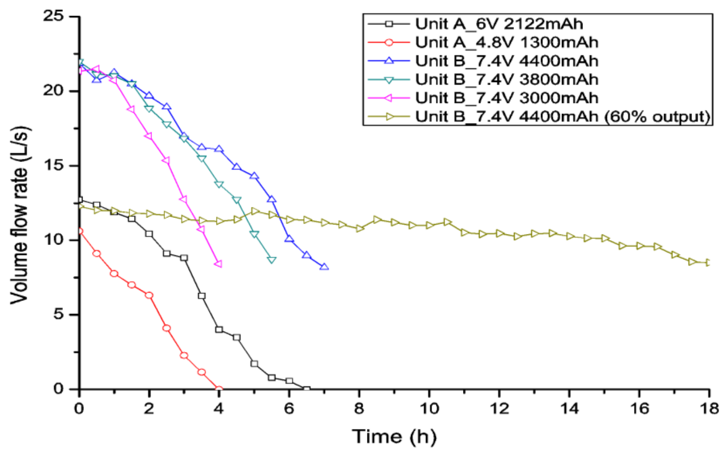
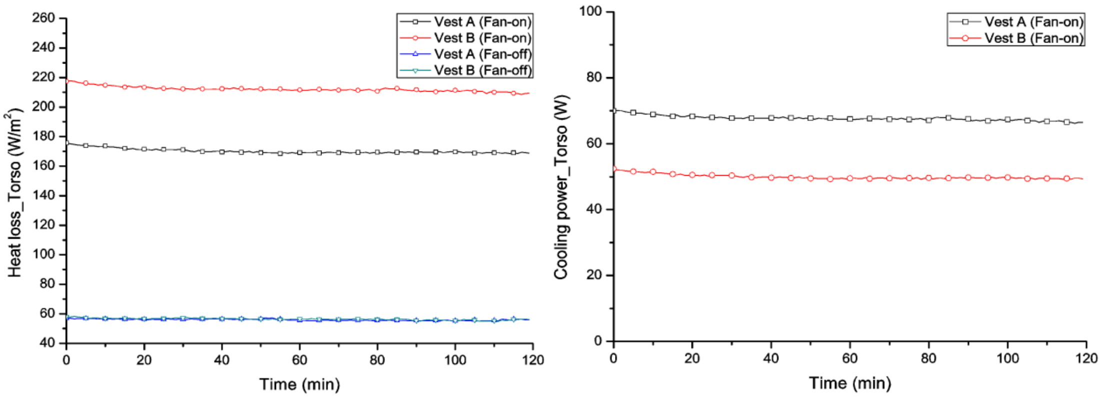


Figure 4 Air flow rate and work duration of the Unit A and Unit B

Unit B, which was powered by 4400, 3800, and 3000 mAh Li-Po batteries could work for 7.05, 5.87, and 4.03 h, respectively. The volume flow rate was measured every 30 min, as shown in Figure 6. The fan stopped working abruptly because the embedded protection circuit module in the Li-Po battery pack ensured overcharge/discharge, over-current, and short-circuit protection. When the battery discharged to approximately 4 V, the circuit was cut off to stop the fan. Before the end point, the fan could maintain a flow rate of 8–22 L/s. Under the same voltage, i.e., 7.4V, the axial fan operated longer when powered by a battery with a larger capacity. When the output power of the 7.4V 4400 mAh battery was reduced to 60%, i.e., the overall capacity remained the same while the output voltage was adjusted to 4.5 V by a controllable switch, the fan worked as long as 18 h at a lower air flow rate of 8–12 L/s (Figure 6).

3.2. Cooling power provided by the ventilation unit

The cooling vest with a running ventilation unit increased the heat loss in the manikin. The heat loss was approximately 56 W/m^2 when the ventilation unit was turned off (Figure 5a). The heat loss increased to 215 W/m^2 under the fan-on condition of Vest B (the vest inserted with Unit B) and 173 W/m^2 under the fan-on condition of Vest A (the vest inserted with Unit A) (Figure 5a). The ventilation unit provided persistent and steady cooling effect during the 120 min test. The cooling power of Vest B was approximately 68 W, which was higher than the cooling power of Vest A (51 W) (Figure 5b).



(a) (b)

Figure 5 (a) torso heat loss and (b) torso cooling power

4. Discussion

The ventilation unit in the cooling vest can enhance the air flow around the body to improve evaporative and convective cooling efficiencies in the heat. This study specifically evaluated a ventilation unit consisting of a pair of small axial fans (supplying high-volume, low-pressure air) and a portable battery. Its cooling performance was tested on a sweating manikin. Unit B provided an 8-22 L/s airflow for 7 h when powered by a 7.4V 4400 mAh rechargeable Li-Po battery. In occupations with long-duration exposure to heat, maintaining a constant airflow for a long period without battery replenishment is necessary. Unit A, powered by a 6V disposable alkaline battery pack and a 4.8 V rechargeable NiMH battery pack sustained a >5 L/s airflow for only 3 and 2 h, respectively. The difference in airflow rates might have resulted from the differences output voltages. The lower the output voltage, the slower the airflow. The work duration under the same output voltage was generally influenced by battery capacity. The 4400 mAh Li-Po battery with worked longer than the 3800 and 3000 mAh Li-Po batteries. When the batteries used different chemicals, the capacities of the batteries under the same weight depend on the energy densities of the chemicals. The rechargeable NiMH battery has a lower specific energy (360 J/kg) than the disposable alkaline AA battery (616 J/kg) and the rechargeable lithium battery (645 J/kg) (Wikipedia contributors, 2015). Ready-to-use, right-out-of-package, high-energy-density, and one-time-use alkaline batteries are still desirable for some consumer applications. Lithium batteries have comparably high energy densities. In addition, they can be charged and recharged more than 500 times (BAK Battery Co., Ltd.) without a reduction in performance. Thus, these are environmentally friendly.

The cooling power of the ventilation unit was measured on a sweating manikin. The test lasted for 2 h, and both units provided persistent and steady cooling effect during this period. Unit B showed a higher cooling performance than Unit A. Under the fan-on condition, increases of 200% and 280% heat losses were respectively observed in Vests A and B compared with the unit under the fan-off condition at 34 ℃ and a relative humidity (RH) of 60%. The findings are comparable with those obtained in previous manikin test studies. Lu et al. (2015) used a ventilation unit on a long-sleeved jacket, which allow for a 160% increase in heat loss in the upper body region under hot and humid conditions (34 °C, 75% RH). Zhao et al. (2013) proposed a short-sleeved air jacket that contributed to an increase of 205% heat loss in the torso region compared with that under the fan-off condition in the same environment (34 ℃, 75% RH). The flow rates of the ventilation fans used in the two aforementioned studies were approximately 12 L/s, which was lower than that of Unit B used in our study. The high flow rate of the designed ventilation unit could improve evaporative cooling because of the increased air velocity around the body (Candas et al., 1979; Zhao et al., 2013). Previous researchers also designed different ventilation units in ACG for human trials. Hadid et al. (2008) used the BREEZE model vest (Rabintex Industries, Israel), which consists of two small fans each supplying 3 L/s non-cooled airflow at ambient temperature (40 °C or 35 °C). The ventilation system can operate for approximately 12 h on eight AA batteries. The system effectively relieves heat strain during walking but not during resting recovery period. Ryan et al. (2014) used an ACG with a lower flow rate of 1.67 L/s under ambient temperature (35 °C) condition. However, the developed air ventilation system failed to significantly reduce thermal strain (as indicated by decreased ΔT_{re}). In both studies, strengthening the airflow was suggested to increase heat loss, thereby improving the total cooling effect.

In some indoor occupations, ACGs can be connected to a cooling device to cool down the inlet temperature of the circulating air. ACGs with cooled inlet air at a certain lower flow rate, e.g., 13 °C at 4.67 L/s (Vallerand et al., 1991), 20 °C -27 °C at 7.075 L/s (Pimental et al., 1987), 12 °C at 9.17 L/s (McLellan et al., 1999), have significantly reduced heat strain and enhanced the heat tolerance of the subjects. In the study of Shapiro et al. (1982), the airflow was set to 5.2 L/s for cooled air and 8.03 L/s for ambient air. Cooled air with a low flow rate was effective in both hot and mildly hot environment, whereas the ambient air-ventilated vest showed advantages only under mild heat conditions and could not be used under conditions with very high temperatures because of possible damages to the skin by high-velocity hot air (Muza et al., 1988). Acceptable air speed and air temperature combinations in certain environments have been investigated. McIntyre (1978) found that at 28 °C, the preferable air speed (provided by a ceiling fan) is 1.4 m/s for male subjects, and 1.0 m/s for females. In our test, a controllable switch was used to adjust the air velocity of the fan. The fan could blow 8–12 L/s air for 19 h when the output power was reduced to 1.5 W (i.e., 60% of the rated power 2.5 W) by the switch. The use of a switch can allow users to conveniently adjust the air speed to their thermal comfort level according to their occupations and environments. This will avoid body discomfort and excessive battery energy consumption caused by unnecessary excessive airflow.

5. Conclusion

In this study, ventilation units were tested and compared in terms of air volume and cooling power. The newly designed Unit B could produce an airflow rate of 8–22 L/s for 7 h, exhibiting a much better performance in terms of air volume rate and work duration than the commercially available Unit A. The sweating manikin tests further proved that Unit B had higher cooling power (68 W) than Unit A (51 W). This study specifically evaluated the cooling effects of different ventilation units in the cooling vest. PCM packs can be adopted in future studies to provide a hybrid cooling effect. Human trial is necessary to test this hybrid cooling vest and will be performed in our following studies.

Acknowledgements

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