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Assessment of an active liquid cooling garment intended for use in a hot environment

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ABSTRACT

This paper discusses the construction of a designed active liquid cooling garment (LCG) that has been developed in order to reduce thermal discomfort of persons working in hot environments. It consists of clothing with a tube system distributing a cooling liquid, a sensor measuring the microclimate under the clothing, and a portable cooling unit with a module controlling the temperature of the cooling liquid depending on the microclimate temperature under the clothing. The LCG was validated through tests on volunteers in a climatic chamber at 30 °C, a relative humidity of 40%, and an air movement rate of 0.4 m/s. The obtained test results confirmed the beneficial effects of the cooling system used on mean weighted skin temperature, the physical parameters of the microclimate under the clothing, and the participants' subjective assessments, as well as confirmed that the functioning of the control system regulating liquid temperature in the LCG was correct.

1. Introduction

In Poland about 18 thousands people work in hot environments (at air temperatures ranging from 25 °C to 60 °C and a relative humidity of 10%–80%), for instance in metallurgy, the glass industry, mining, and also in a number of outdoor jobs during heat waves in the summertime (Central Statistical Office, 2015). Additionally, workers in hot environments are often exposed to hazards such as molten metal splashes or contact with other hot objects. In order to remove the hazards resulting from long-term worker exposure to hot environments, it is necessary to eliminate or reduce heat accumulation in the body. In extreme environmental conditions, active cooling may be the only viable option for reducing the heat strain (Selkirk et al., 2004). Unfortunately, in some workplaces it is impossible to install air-conditioning systems due to the technological processes used or large spaces. In the absence of any other possibilities to cool workers, it may be a good solution to apply individual cooling systems. Therefore, efforts are being made to design efficient individual cooling systems that would make it possible to dissipate the excess heat generated by one's body during work (Furtado et al., 2007).

The choice of a personal body cooling system to be used under protective clothing in a hot environment should be based on the choice of an appropriate **cooling medium**: ice (Smolander et al., 2004), water and air (Vallerand et al., 1991) or phase change materials (Bartkowiak et al., 2013). Such a system should be adjusted to the working conditions at a given workplace, taking into account the weight, mobility restrictions, cooling power, etc., of the system. All the above-mentioned media can be used as an effective solution for dissipating excess heat from the human body provided that the potential application of the system is taken into account in the design process. Ice cooling systems surpasses the others in terms of the effectiveness of dissipating excess heat by conduction and radiation. In turn, air cooling systems are the most effective in removing heat by convection and evaporation (Caldwell, 2008); however, their performance depends to a great extent on the physical parameters of the air and the properties of the protective clothing used. Liquid cooling systems are characterized by a higher level of heat reduction than air cooling systems because water has higher thermal conductivity than air, and thus are recommended for cooling workers who work in hot environments in impermeable protective clothing preventing sweat evaporation (Sakar and Kothari, 2014). In contrast to cooling systems with solid coolants (such as ice packs, phase change materials, gel packs, etc.), liquid cooling systems can be given a desirable shape that does not restrict the wearer's movements and does not limit the fit of the garment to the body. Moreover, they do not result in frequent donning and doffing of protective clothing to exchange coolant

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packs, which is a very important advantage over cooling systems containing solid coolants, as taking off protective clothing at the workplace is usually forbidden (Flouris and Cheung, 2006), (Nam et al., 2005).

In designing LCGs to be worn under protective clothing, of particular importance are the ergonomics and functionality of the system as a whole. In the market there are commercially available solutions, which are usually in the form of a vest with pipes distributing a cooling liquid. They often do not have a possibility to control coolant temperature as they are supplied with water cooled by the ice disposable cartridge (VESKIMO, 2016). At the same time, it has been proved that too low temperature of coolant (below 15 °C) can lead to a local overcooling what can be harmful for the user (Caldwell, 2008), (Lopez et al., 2008). Performed research has also shown that the amount of the heat received from the body to a great extent can be influenced by adjusting the temperature of the coolant and increasing the contact area with the body of the distribution system (Yang et al., 2008; Pu, 2005). Thus, considerable research effort is still being made to modify cooling systems with a view to adjusting their efficiency to the predicted applications (Nyberg et al., 2001).

Moreover, another aspect that has been highlighted relates to a construction of liquid cooling garment. In many liquid cooling garments the tubing is sewn to one layer of fabric so that they are in the direct contact with the skin. However, for better wearer comfort a three layer structure where the tubings are sandwiched between the inner and outer fabric layer is preferred (Cao et al., 2006).

Therefore, the aim of this paper is to present a new design of an active liquid cooling garment, which takes into account two aspects which are important from the user's safety and comfort point of view. The first one concerns adjustment of liquid cooling temperature to the comfortable level of temperature in the undergarment microclimate based on individual preferences. The second aspect relates to a special design of a garment in which a tube system distributing a cooling liquid was introduced between two layers of the modular knitted fabric directly worn on the human body for enhanced heat dissipation. Moreover, the inner layer of the LCG was made of conductive-diffusive material, while the outer layer was made of sorptive one. Such a construction promotes the transport of the sweat generated by the human body from the skin to the outer garment layer (Bartkowiak et al., 2015).

2. Characteristics of the active liquid cooling garment

2.1. Garment with a tube system distributing a cooling liquid

The garment with a tube system distributing a cooling liquid consists of a long sleeve underwear made of a specially developed two-layer knitted fabric composed of a module with joined layers, a spacer module whose layers form vertical channels for tubes distributing a cooling liquid, and a module with separate layers. A view of a profile of the spacer module is given in Fig. 1.

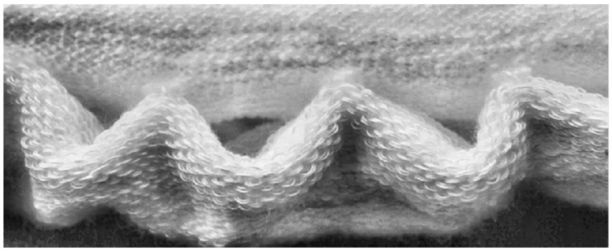

Fig. 1. A view of a profile of the spacer module showing channels for the tubes distributing a cooling liquid.

The inner layer of the knitted fabric is made of polyester and elastomer yarns and the outer layer is made of cotton and elastomer yarns. The inner polyester layer constitutes a conductive-diffusive layer, while the outer cotton layer is a sorption layer. Thanks to this construction, moisture is transported from the surface of the skin to the external layer of the garment. Results of basic physical and comfort-related properties for knitted fabric modules are presented in Table 1. Laboratory tests were conducted according to relevant standards.

The defining feature of the presented LCG is that the tube system distributing a cooling liquid is placed within vertical channels between the elastic layers of the spacer module of the knitted fabric. Given the fact that the garment is close-fitting, this means that the coolant distributing system fits the body very closely, thus increasing heat conduction and the efficiency of the cooling system. At the same time, the introduction of tubing between fabric layers has made it possible to eliminate the effect of local overcooling as the system is not worn directly on the body. Additionally, on the inner side of the long sleeve underwear, at the level of the shoulders, we placed a negative temperature coefficient (NTC) sensor to measure the temperature of the microclimate under the clothing with an accuracy of 0.1 °C. The sensor is an element of the system controlling the temperature of the cooling liquid, regulated by the cooling unit. A view of the long sleeve underwear with a tube system distributing a cooling liquid is given in Fig. 2.

2.2. Cooling unit

The cooling unit developed to be used with the liquid cooling garment is mobile and easy to carry around by means of a wheel system. Its weight do not exceed 10 kg. It is powered by replaceable and rechargeable batteries that can supply electricity to the unit for at least 1 h. The cooling unit is characterized by a cooling capacity of 300 W with a circulation speed of 3.8 l/min, as determined by analysis of work conditions in hot environments. The developed cooling unit operates at an air temperature of 30–45 °C and a relative humidity of 20–80%. To adjust cooling intensity to the needs of the user, the unit is equipped with both manual and automatic controls regulating the temperature of cooling water. The temperature control system reacts to the temperature of the microclimate under the clothing that is monitored by means of an NTC sensor placed in the garment. The garment with a tube system distributing a cooling liquid can be easily connected to and disconnected from the cooling unit by means of lightweight quick-connect plastic fittings with a two-sided safety lock preventing coolant leakage.

3. Test methodology

The main aim of the laboratory tests was to evaluate the adjustability of the cooling liquid temperature in the designed LCG to the temperature of the microclimate under the clothing. A proper operating of this function is particularly important in terms of ensuring user's comfort and safety. Therefore, a research methodology aimed at validation of LCG performance with varied physical load was applied. In such situation varied level of heat should be dissipated from the human body and therefore LCG should adjust its cooling performance to the current conditions. The analysis was based on tests of LCG on volunteers walking on a treadmill in a climatic chamber in specific environmental conditions.