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ABSTRACT

Miniature cooling systems have lately gained increased attention due to ever increasing needs to locally cool hot spots. Miniaturized cooling is needed in a variety of different applications, for example to cool powerful yet highly compact electronics or to increase the thermal comfort of individuals through man-mounted systems. This paper focuses on the development of components suitable to be used in miniaturized vapor compression systems. Of particular interest is the achievable cooling output to system mass ratio. Miniaturized aluminum microchannel heat exchangers, positive displacement compressors, and passive expansion devices have been designed, developed, and investigated both experimentally and numerically. Relevant performance data are presented and improvement potentials are revealed and assessed. A measured cooling capacity of 57 W at 35 ^{o}C and a system mass of 2.2 kg (including power source) yields, with 26 W kg^{-1} one of the highest cooling output to system mass ratios ever reported in the open literature available for miniature cooling technology. It is clear that vapor compression technology can outperform many other approaches, including cooling systems based on phase change materials with respect to cooling output per unit mass. Human subject system evaluations confirm the laboratory measurements. The tested system impressively demonstrates much slower increases of core body temperature and heart rate over time in humans experiencing high levels of physical activity in hot ambient conditions in comparison to the same test person exercising at identical activity levels, but without having a man-mounted cooling system.

1. INTRODUCTION

The ever increasing heat dissipation rates of highly compact power electronics justify research on miniature cooling technology. The same type of technology can readily be used to implement man-mounted systems that are aimed at increasing the thermal comfort of individuals that are required to wear protective clothing. A number of different approaches exist and have been used successfully in the past to provide decentralized cooling. The most commonly found approaches include evaporative cooling, phase change materials, expansion of compressed gases (relying on either Ranque-Hilsch or Joule-Thomson effect), thermoelectric cooling, or vapor compression technology. Among the technologies listed, vapor compression systems are often seen as the most promising approach due to prolonged operating hours, high performance output, and relatively low system mass. This paper focuses on the development of components suitable to be used in miniaturized vapor compression systems. The results of a detailed literature review on the topic are summarized and discussed. Miniaturized aluminum microchannel heat exchangers, positive displacement compressors, and passive expansion devices have been designed, developed, and investigated both experimentally and numerically. Relevant performance data are presented and improvement potentials are revealed and assessed. Other relevant design parameters such as refrigerant (R134a) leakage characteristics and operating noise levels are addressed as well.

2. ADVANCEMENT OF STATE-OF-THE-ART TECHNOLOGY

The technological approaches on which currently available miniature cooling systems are based on vary widely. Based on Teal (2006), some of the most commonly found approaches are summarized in Figure 1. The figure allows for a comparison between the different cooling approaches by involving practical hours of operation and system mass for a given cooling capacity. The most commonly encountered systems are the evaporative-type, mainly due to simplicity and low cost.

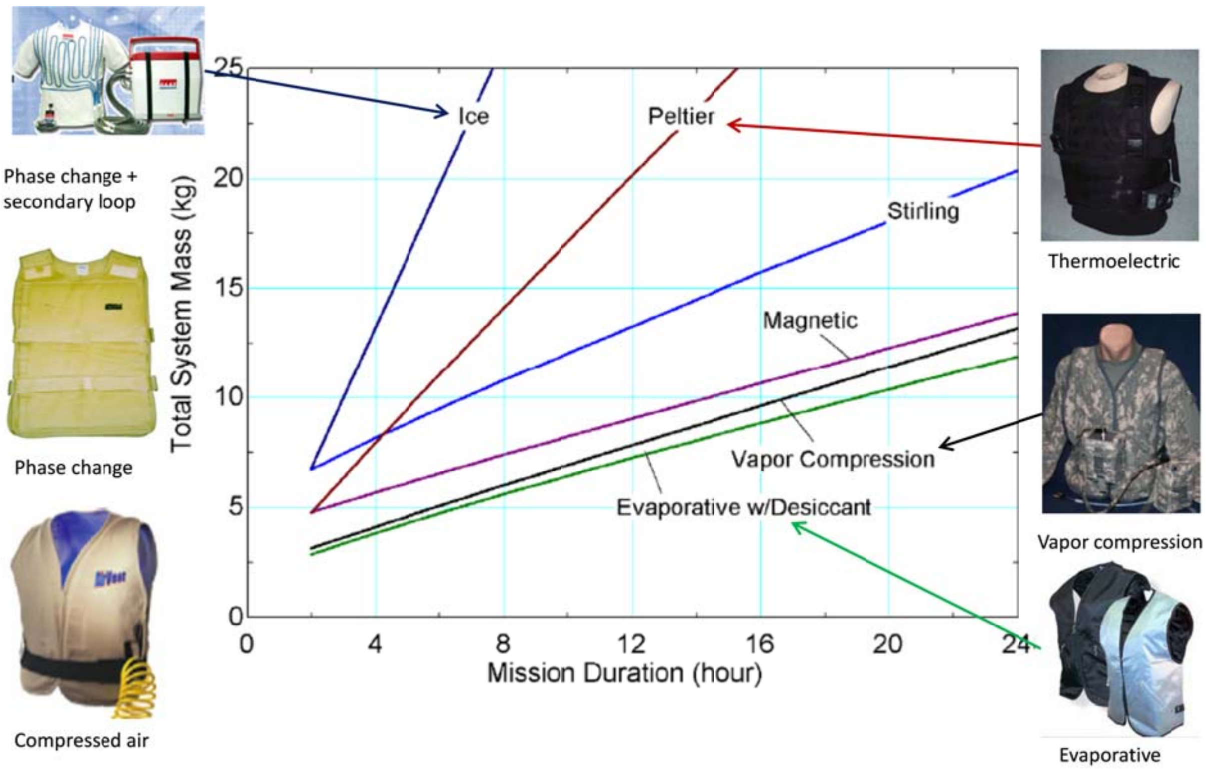


Figure 1: Comparison of system mass and mission duration for different cooling technologies at a given cooling capacity of 300 W at 35 °C, 75% RH (Teal, 2006)

The vest absorbs moisture and relies on evaporation to produce the desired cooling effect. Therefore, outer clothing needs to be removed for this approach to work properly. Consequently, this cooling method is ineffective when worn underneath protective clothing. Also, capacity is very limited in ambient conditions with very high humidity levels. Another approach utilizes passive phase change materials (PCM). Typical production vests can hold four to six frozen gel strips which are stored in specially designed pockets. PCM vests have been used by the U.S. Navy since 1991. Limited and decreasing capacities over time, as well as relatively high system mass are associated with this approach. Systems based on the phase change of ice typically provide more cooling capacity on a per weight basis than paraffin based systems. A pump operated by exchangeable batteries circulates chilled water between an ice bag and the garment. Depending on the capacity, some of the available systems are man mounted while smaller ones are hand carried. Other cooling systems for individuals are based on the expansion of compressed air. Cooling is driven by the Joule-Thomson effect. Many media, such as air, have negative Joule-Thomson coefficients. In that case, the medium experiences a temperature drop as the pressure is reduced. Other compressed air based systems utilize the Ranque-Hilsch effect. Vortex tubes make use of this effect. Efficiencies of compressed air-based systems are known to be relatively low. On the other hand, these systems can be built to be very robust due to the small number of moving parts. While air-based cooling systems are currently in production, these systems are not really considered to be autonomous. All of them require air compressors and storage vessels which strongly limit their suitability for cooling of individuals. The thermoelectric effect found in Peltier elements can also be harnessed to provide cooling to individuals. Two dissimilar metals form the Peltier element. By applying an external DC voltage a temperature difference is created. The biggest advantage is seen in reliability, because very few moving parts, if any, are needed to build a Peltier effect based cooling system. The control of cooling capacity is relatively simple because it can be realized electronically. However, it is often overlooked that the Peltier element requires good heat rejection on the hot side in order to reduce the temperature of the cold side to useful levels. In addition, cooling achieved with Peltier elements comes at relatively high cost, because of the inherently low efficiencies of the cooling elements.

When compared with the different cooling approaches described above, it becomes apparent that vapor compression technology offers significant advantages for miniaturized cooling applications where high levels of compactness and high energy efficiencies are among the most important design criteria (Ernst, 2005; Trutassanawin et al., 2006). The characteristics of vapor compression systems include long operating hours at relatively high cooling capacities achieved with low system masses. Among the miniature cooling systems that have been described in the open literature, the vast majority use a secondary cooling loop approach, in which a pumped chilled single phase fluids absorbs heat before it rejects it to the evaporator of the refrigeration cycle. In comparison to direct expansion (DX) systems, energy efficiencies are reduced because of additional temperature differences required in the single phase to refrigerant heat exchanger. Higher system mass represents an additional drawback, especially in mobile systems, due to the added water and pump mass. It is difficult to obtain exact data from the literature, but realistic estimates and measurements reveal that the mass of the secondary loop coolant can easily exceed the mass of the packaged refrigeration system. Also, for the mobile systems used to cool individuals, it is often not clear whether the mass of the power source is included in the reported system mass. By comparing the available numbers and actual results obtained in this research, it seems that many autonomous miniature cooling systems approach a cooling capacity to system mass ratio of approximately 20 W kg^{-1}. Although this number strongly depends on specific test and ambient conditions, it can serve as a rule-of-thumb for design purposes.

The aim of the described research is to advance the current state-of-the-art in miniature cooling technology. The system to be designed represents a miniature personal cooling system (MPCS) to be used by military personnel wearing protective clothing. The following design requirements were considered in this research:

- Total system mass (including 1.5 kg battery power source): 2.25 kg
- Operation with one battery charge: 4 - 6 hr
- Maximum ambient temperature: 51.7 ^{o}C
- Cooling capacity and system efficiency (COP): maximized
- Non-flammable, non-toxic refrigerant; classification A1 according to ASHRAE 34 (2004)
- Full performance in any system orientation

For reasons described above it was decided to implement a DX vapor compression approach to further reduce complexity and mass. Besides aiming for high ratios of cooling output to system mass, a major challenge is seen in the fact that no current MPCS can offer satisfactory performance at the required low system mass. Many of the systems available have high cooling output, but at the same time high system mass. Therefore, another goal of this research is to demonstrate scalability of miniature cooling technology and build one of the smallest and lightest systems ever built.

3. DEVELOPMENT OF COMPONENTS AND SYSTEM INTEGRATION

3.1 Component development

R134a was selected as the refrigerant that meets all working fluid requirements specified above. However, none of the system components are commercially available at this point. Most of the components have been designed and built in-house according to the following design considerations.

Condenser

The miniature condenser is required to provide high levels of performance. At the same time, it has to have low mass. These requirements are best fulfilled with a brazed aluminum microchannel heat exchanger. Several different condenser designs were studied in detail and manufactured in-house. Fin options included folded serpentine louver fins, but also open-cell aluminum foam designs of various porosities. Two different condenser designs can be seen in Figure 2. Also shown is a comparison between experimental and numerical results obtained with a simulation model developed in-house to accurately predict miniature condenser performance. It can be seen that good agreement between model and experimental results have been achieved. Therefore, the results can be used to select an appropriate condenser fan. Air flow rates and therefore face velocities are chosen such that additional air flow increases would only yield small performance increases, i.e. the fan is selected such that the resulting face velocity is in the region where the performance curves flatten and become more horizontal as shown in Figure 2c. At the design condition, the air side pressure drop has been measured to be on the order of 7 Pa. Typical refrigerant side pressure drops were measured to be on the order of 5 kPa. Depending on the operating conditions, the condenser's overall heat transfer coefficient, based on the air-side, ranged from 100 W m^{-2} K^{-1} to 130 W m^{-2} K^{-1}, about four times higher than what is typically achieved with round-tube-plate-fin heat exchangers.

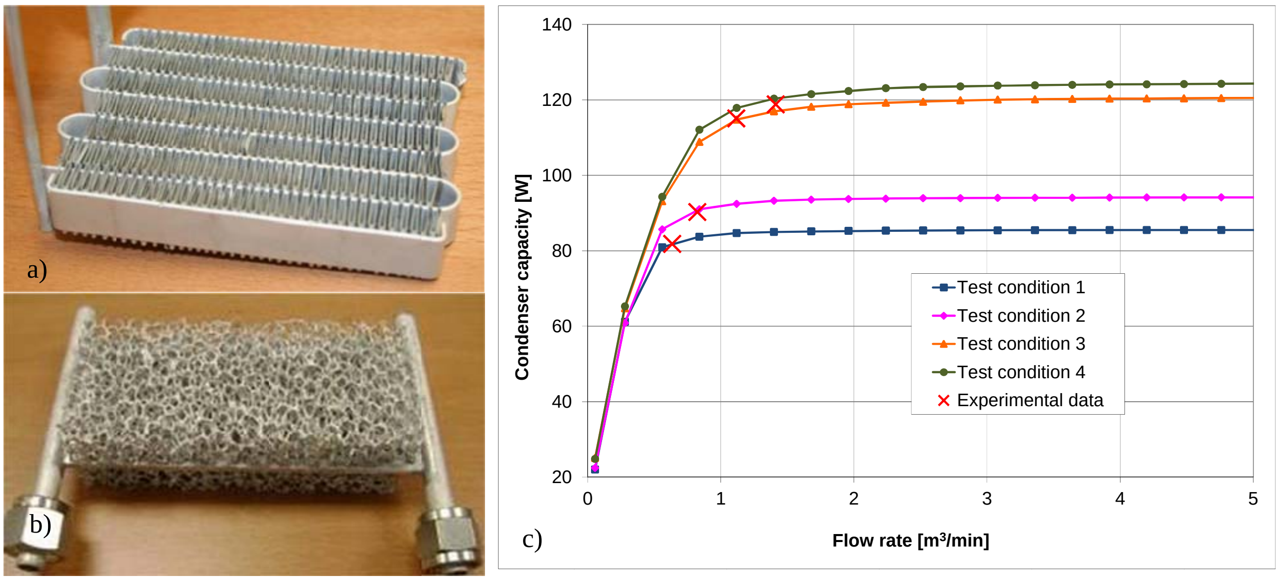


Figure 2: Development of miniature condenser designs; a) brazed aluminum microchannel folded serpentine louver fin; b) brazed aluminum microchannel open-cell foam fin; c) comparison of experimental and numerical results obtained with in-house simulation model

Evaporator

The chosen DX approach requires a completely different evaporator design in comparison to personal cooling systems that utilize vapor compression technology to chill a secondary fluid such as water or glycol. In those systems the chilled secondary fluid is circulated through coolant loops that are mounted inside the cooling vest. While single phase coolants facilitate uniform distribution in multi-pass circuitries, the added mass of the coolant and circulation pump are inherent disadvantages of the secondary loop approach. The DX evaporator used here can ultimately result in higher system efficiencies, because the eliminated secondary loop reduces the average temperature difference between the body and refrigerant. In the approach presented here, pressurized refrigerant circulates directly through the cooling loops inside the vest. It is therefore necessary to find suitable pressure resistant tubing materials that are compatible with refrigerant and that offer sufficient resistance to leakage. At the same time, the tubing material should be flexible enough so that the user's movements are not restricted. Single pass evaporator designs are not affected by refrigerant side mal-distribution. However, the combination of hydraulic diameter and tube length, as well as surface roughness of the tube material can lead to unacceptably high refrigerant-side pressure drop. In that case, multi-pass evaporator designs, such as those shown in Figure 3, provide reduced pressure drop characteristics, although at the expense of more complicated refrigerant distribution solutions.

Furthermore, multi-pass evaporators can create the basis for redundant system design. Key to the evaporator design is to ensure good contact between the body and the tubes. Figure 3 also shows the effect of fin material that is used to enhance heat transfer, but to also provide additional structural support to the tube layout. Different special polymer materials have been successfully tested in this research. Tube lengths of approximately 20 m yielded satisfactory cooling results. For single pass evaporators, typical tube side pressure gradients were measured to be less than 5 kPa m^{-1}.

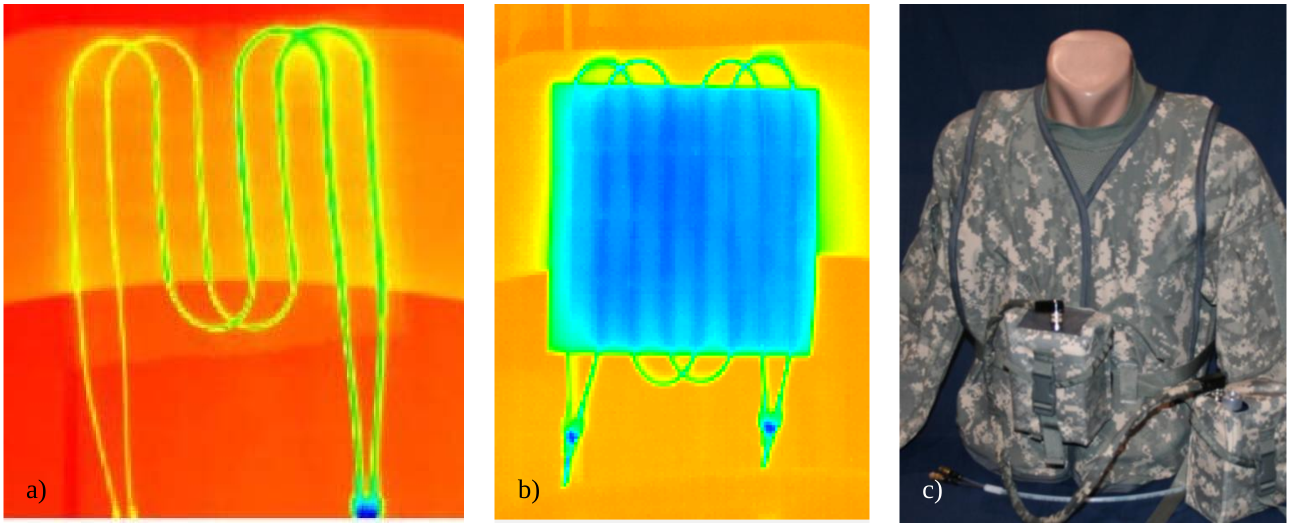


Figure 3: Development of evaporator designs; a) multi-pass design; b) multi-pass design with additional fins; c) cooling vest design with integrated evaporator and condensing unit attached

Compressor and expansion device

Different miniature piston-type prototype compressors have been successfully used in this research. Designs are still proprietary at this point, which is why detailed compressor specifications are not provided by the manufacturer. Among the most important features is the fact that all compressors tested have been oil-free. An oil-free compressor design significantly contributes to ensuring that the cooling system can be operated in any orientation at full performance level. Unlike many other man-mounted miniature cooling systems, the system developed in this research cannot experience compressor problems and premature system failures caused by insufficient oil return. Furthermore, the implementation of variable speed technology allows the adjustment of the cooling performance to existing load levels and the implementation of control strategies that can prolong the battery life if needed.

In consideration of requirements for compactness and system mass it was decided to use a passive, instead of an active, expansion device. A special test stand was developed with which a capillary tube was properly sized for this application and its typical operating conditions. It should be noted that, due to the small diameters, clogging is one of the potential problems. Therefore, slightly larger capillary tube diameters, compensated by longer lengths, are used. Additional system performance is obtained by attaching the capillary tube to the tube carrying the vapor that exits the evaporator. This type of internal heat exchange is commonly found in household refrigerators.

3.2 System integration

All components were then integrated to form an autonomous man-mounted miniature cooling system. Some of the key elements are shown in Figure 4. Besides heat exchangers, expansion device and compressor a miniature axial condenser fan was selected. A condensing unit housing was designed and fabricated from lightweight polymer material. The compressor, fan, and the condenser, along with some control and safety features were integrated into the condensing unit that is also shown in Figure 4.

Two different battery types have been investigated as the system’s power source. Among them are rechargeable batteries of the lithium-ion type and disposable batteries of the lithium-manganese-dioxide type. Both battery types are commonly used by US Army and have high energy storage capacities. Similar to the condensing unit, the battery is housed inside a carrying pouch for easy mounting. Quick connect fittings between the evaporator and the condensing unit establish the refrigerant-side connections. A power cable connects the power source to the condensing unit. An image of how the condensing unit is mounted to the cooling vest is shown in Figure 3c. It should be noted that the fully assembled condensing unit weighs less than 560 g, while the power supply and connection cable have a combined weight of approximately 1600 g. The total system mass is therefore just below the maximum design target of 2.2 kg, making it probably one of the lightest miniature vapor compression cooling systems every reported in the open literature

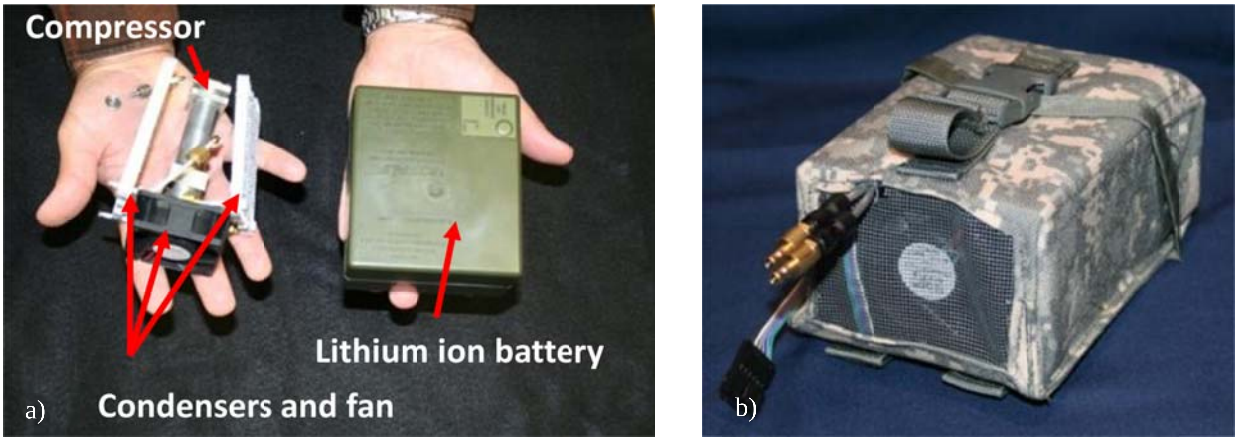


Figure 4: System integration; a) some of the key components;
b) condensing unit design inside carrying pouch

4. SYSTEM MEASUREMENTS AND EVALUATION

4.1 Steady-state cooling performance

Accurate evaluation of steady-state cooling performance can be more challenging for small systems, because relatively small losses in absolute terms represent large relative deviations. Two different test facilities were used for development and evaluation purposes; both are shown in Figure 5. A so-called breadboard test facility was designed and built. The components of the miniature cooling system were tested under idealized conditions to explore performance limits. Different components and operating conditions, such as variable speed compressors, different condensers and air flow rates, different evaporators and tube materials and lengths, as well as different expansion devices were tested in this arrangement at a variety of different ambient temperatures. The data was then used to validate the underlying simulation tools that have been developed during the course of the project. The condensers were installed in an ASHRAE 41.2 (1992) wind tunnel in which air flow rates could be changed to analyze the effects on capacity. The heat load to be removed from the body was simulated by an electrically heated and insulated drum. The polymer coils of the DX evaporator were wound around the drum to realistically reflect the conduction based heat transfer taking place inside the cooling vest. For the condenser, independent energy balances were calculated on the air and refrigerant sides. For the evaporator, two independent balances were obtained from refrigerant side and electric power measurements. COPs were calculated based on electric power input measurements to the compressor and the fan located inside the condensing unit. Some representative system test results are shown in Figure 6.

Additional steady state cooling performance tests were carried out in an external lab that specializes in sweating manikin tests according to ASTM F2371 (2010). The aim of the test is to determine the heat removal rate from the body in an environment set at 35 ^{o}C and 40% relative humidity. The manikin surface temperature is controlled to 35 ^{o}C during the test. In addition, the manikin surface is such that it can continuously evaporate water to simulate sweating. Total power input (latent and sensible) is first measured with the manikin wearing the cooling system while it is turned off. That way a baseline case is established. Once the cooling system is turned on, the power input to the manikin system increases to maintain steady temperature. The additional power required equals the heat removal rate of the cooling system. It should be noted that this type of testing can lead to unrealistically high sweating rates, because by the nature of the test the manikin surface is always kept at 100% relative humidity. Especially cooling systems that utilize air circulation instead of tube-to-body contact cooling can experience an advantage due to significantly higher latent loads. Furthermore, this test really determines the heat removal rate from the body, and not the cooling capacity of the cooling system, because losses to the ambient caused by insufficient cooling vest insulation increase the system capacity, but not the rate at which heat is removed from the body. The system investigated in this research achieved a body heat removal rate of 57 W. Although the test only requires 2 hours of steady-state testing, system measurements show that this cooling rate could have been sustained for approximately 6 hr on a single battery charge.

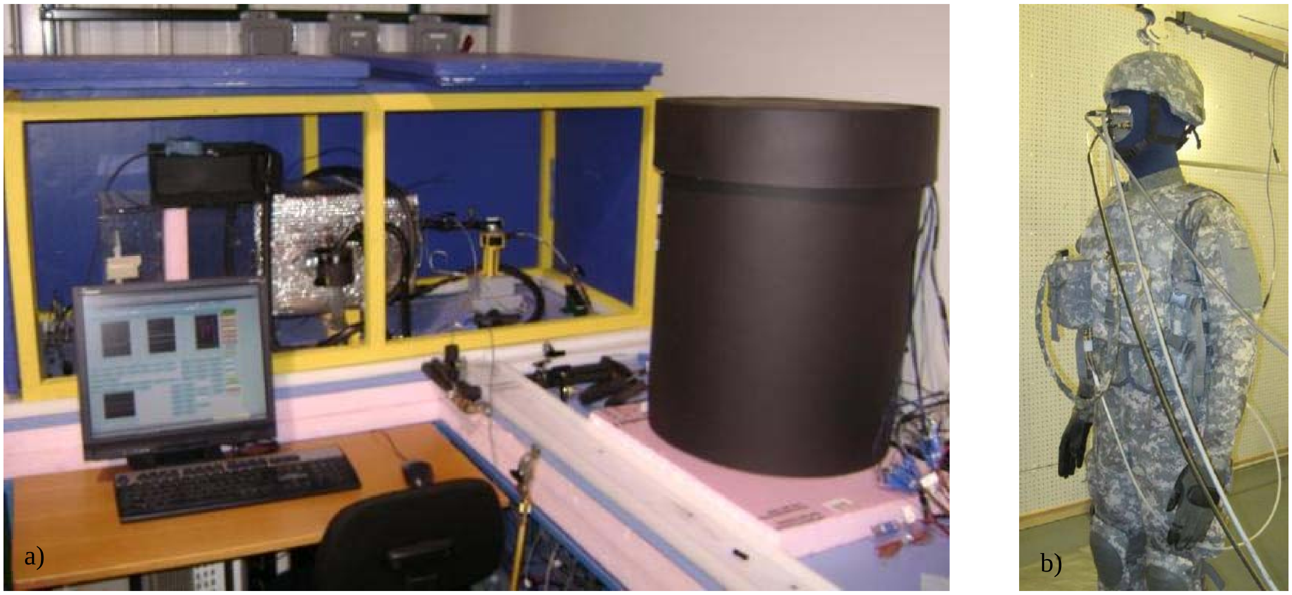


Figure 5: Test for evaluation of steady-state cooling performance; a) in-house breadboard test facility; b) external laboratory using sweating manikin facility

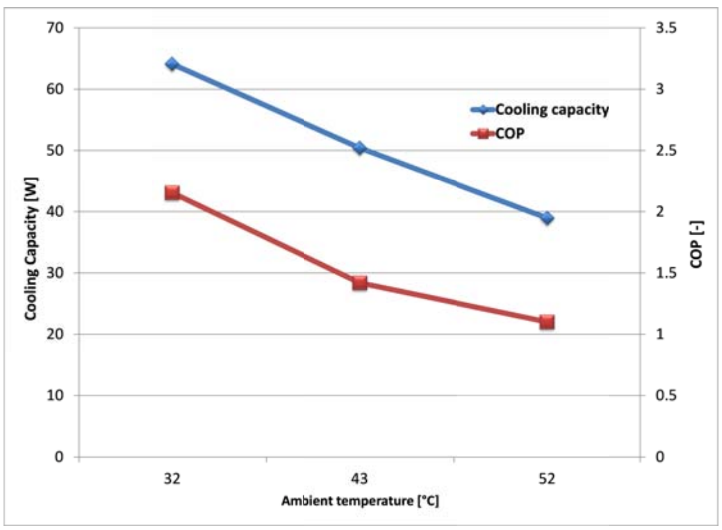


Figure 6: Experimental miniature cooling system results obtained in in-house breadboard test facility

A series of additional tests were carried out with the fully packaged MPCS worn by volunteer test persons. Even at the highest ambient temperature of 52 ^{o}C the investigated MPCS was fully functional and showed high levels of performance. A particularly interesting finding was that both cooling capacity and evaporation temperature have significant influence on how cooling is perceived by the test persons. It appears that lower evaporation temperatures can offset reduced cooling capacities to some extent.

More elaborate human subject tests with the described cooling system were carried out at an external laboratory under the careful supervision of qualified medical personnel. The fully clothed test persons had to exercise on a tread mill at an ambient temperature of 45 ^{o}C and a relative humidity of 40%. The tread mill velocity was adjusted in pre-tests for each individual to simulate comparable heat stress situations for the different test persons having different heights and body weights. That procedure ensured that each test person exercised at the same load level. Each test person had to undergo two 120 min exercise runs: one with cooling system and the other one without cooling system. The results shown in Figure 7 demonstrate much slower increases of core body temperature and heart rate over time for the test run with cooling system. In fact, one of the test persons had to stop the baseline test without cooling system early, because of a body core temperature increase that was deemed too high by the medical staff supervising the test. However, the same test person was able to successfully complete the 2 hour test run with cooling system, demonstrating the positive effect of man-mounted cooling on humans experiencing high levels of thermal stress.

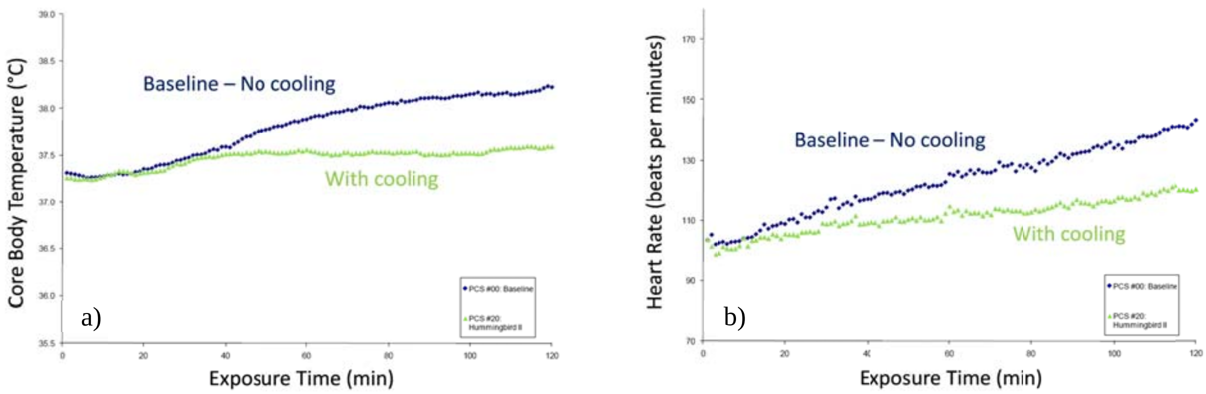
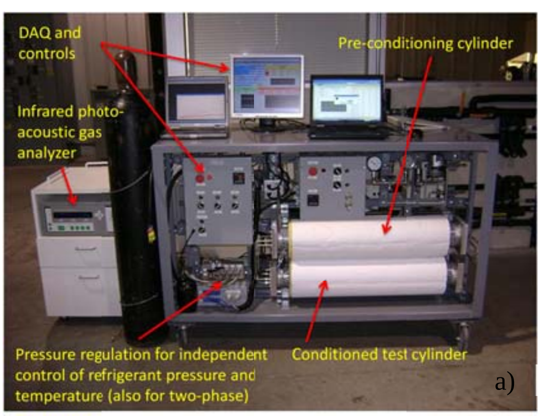


Figure 7: Comparison of core body temperature (a) and heart rate (b) of test person exercising in identical environments with and without cooling system

4.2 Quantification of refrigerant emission

The chosen DX system approach requires the selection of suitable evaporator tubes that possess acceptable leakage characteristics. Besides that, the tube material has to provide sufficient structural strength to withstand elevated refrigerant pressures. High tube flexibility is advantageous for integrating the DX evaporator tubes into the cooling vest. Suitable materials and leakage characteristics have been carefully identified by using a test stand specifically constructed to accurately quantify refrigerant emissions. The test method relies on an online, infrared photo-acoustic measurement principle that resolves refrigerant concentrations of parts per billion in a sealed environment. The resulting refrigerant emission rates that can be resolved are less than 0.1 g yr^{-1}. Figure 8 shows a picture of the test facility and some representative tube leakage rates. The same facility was used to investigate refrigerant emissions caused by other system components such as tube fittings and connectors.



Storage temperature	Polymer A	Polymer B
32 °C	4 g yr^{-1} m^{-1}	Not detectable
52 °C	27 g yr^{-1} m^{-1}	< 0.01 g yr^{-1} m^{-1}

b)

Figure 8: Quantification of refrigerant emissions; a) test facility; b) evaporator tube test results

4.3 Measurement of noise in operation

Besides low system mass and high compactness, low operating noise is among the most important requirements for man-mounted cooling systems. In this category, the compressor and the condenser fan of vapor compression systems can lead to disadvantages over other cooling techniques such as cooling systems based on phase change materials. Furthermore, increasing system mass typically results in lower noise levels, which, unfortunately, is opposite of what is desired for mobile cooling applications. However, proper system design including careful condenser fan selection and optimized compressor mounting can reduce operating noise to acceptable levels even for vapor compression technology. A sound intensity measurement system was used to determine operating noise levels at different conditions. This dual microphone approach can be used in realistic environments, because it does not require the use of an anechoic chamber. Sound power can then be calculated from the measured sound intensity readings. A significant difference in sound power was observed between operating the condensing unit when mounted on a person in comparison to sitting on a flat surface. In the first case the human body works as very effective noise suppression; an average sound power of 65 dB(A) was determined at maximum system capacity, which is comparable to the noise level of a restaurant conversation or background music.

5. CONCLUSIONS

This paper on miniature personal cooling technology presented system and component level research. The chosen DX vapor compression approach resulted in a system with a cooling output per unit mass ratio of 26 W kg^{-1} (including power source) at 35 ^{o}C ambient temperature. It is one of the most compact and lightweight systems ever reported in the open literature. Human subject tests carried out with the man-mounted cooling system confirm the positive effect on humans experiencing high levels of physical activity by much reduced increases in heart rate and core body temperature.

NOMENCLATURE

COP	Coefficient of performance	MPCS	Miniature personal cooling system
DX	Direct expansion	PCM	Phase change material

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