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Personal Cooling System based on Vapor Compression Cycle for Stock Car Racing Drivers

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ABSTRACT

This work is related to the design, fabrication and test of a personal cooling system prototype for Stock Car racing pilots, who are exposed to very high temperatures inside the cockpit. The solution is based on a compact vapor compression system, which cools a secondary fluid that flows through the pilot vest. An experimental apparatus was especially developed for the prototype evaluation, simulating real environmental conditions. Subject tests were also performed and indicated the potential of such solution.

1. INTRODUCTION

Personal Cooling is a vast topic for discussions. Safety and health problems related to heat stress, such as skin eruptions, heat fatigue, cramps, exhaustion, stroke, are well known. Causes and ways to avoid them have been studied for a large group of experts and solutions are not straightforward due to the many variables involved. Human response to environmental extreme conditions (temperature, humidity, air speed, radiation) is very dependent on individual parameters such as, metabolic rate and clothing. The body must balance the heat produced within the body with the environment in order to maintain heat balance, as mentioned by Havenith (1999). If the environment is too cold, extra metabolic rate is produced. If the environment is warm the body must dissipate this heat. Clothing can direct affect heat balance, since it can increase work load and reduce convective, evaporative and radiant heat losses.

The result of heat balance is comfort, which is a very subjective sensation, and so, difficult to be measured. Age, sex, body build, ethnic differences, food, alcohol, national-geographic location are some of the special factors that can influence comfort. For an individual, the result is the integration of sensations of different body segments. Cold and warm areas can compensate each other, while wet parts cannot be compensated by dry parts.

Personal cooling systems (PCS) come into play helping a subject reach this heat balance and a state of thermal comfort. They can be classified in three categories: (i) liquid cooling, (ii) air cooling and (iii) ice / PCM (phase change material) vests. The first is based on the principle of letting a liquid cold flow inside small tubes in contact with the skin, absorbing heat from the skin and thus of the body. In the second category, an air flow over the skin is used so that the sweat produced can evaporate and thus cool the body. In the PCM vests a solid material with an appropriate phase change (melting) temperature is used and so, when placed over the skin it starts the melting process which removes the heat from skin (temperature is kept steady during this process).

McCullough and Eckels (2009) have evaluated the performance of systems in these three categories, which were developed by manufacturers in the private sector. Tests were done with a sweating manikin and human subjects (soldiers) under hot desert conditions.
Elbel et al. (2011) presented a different approach for miniature cooling system using vapor-compression technology. To reduce the complexity and mass of the system a direct expansion vapor compression cooling system was implemented. The miniaturized cooling system was then tested experimentally in order to evaluate its steady-state performance. Barbosa et al. (2012) mentioned that compact high efficiency vapor compression systems are potentially suitable for electronics and personal cooling due to high capacity by size ratio and lightweight. A wide review of such technologies was described, and both thermodynamic and thermal aspects of the cooling cycle and its components were discussed.

Several other PCS applications, besides cooling of infantry and motorized soldiers, can be listed. Firefighters, aircrew pilots, racing drivers, deep miners, emergency services personnel (police, ambulance crew), hypothermic and mobile therapy patients, can also benefit from such systems. However, their choices for a cooling concept tend to be very particular since the solution must be well integrated with their working environment. Outside climate, clothing requirements, protection from (chemical, biological, radiological, nuclear), work duration and intensity, possibility to use work-rest cycles, availability of power, are some of the variables taken into account.

The present work explores the specific environment of the Stock Car racing cockpit, where personal cooling requirements are very challenging. A solution based on liquid cooling by a vapor compression cycle was proposed. A prototype was built and tested in an experimental setup that simulated the application real conditions. Subject tests completed the prototype approval evaluation. Results are also presented and discussed here.

### 2. SUBJECT COOLING SENSATION

It is well known that air temperature inside Stock Car cockpits can easily reach 45°C at summer days. Therefore, experiments to estimate cooling sensation as a function of thermal load were performed with different subjects located inside an environmental chamber with temperature controlled at 45°C. They were wearing a pilot race suit and underneath that a vest cooled by a water flow from a thermal bath, as illustrated in Figure 1. The vest inlet and outlet water temperatures were measured with inserted thermocouples in the water flow. The water mass flow rate was obtained with a mass flow transducer and the thermal load was calculated via the energy balance at the water side. The water specific heat capacity was assumed temperature independent and equal to 4180 J.kg⁻¹.K⁻¹ at all calculations.

To take into account the coolant temperature, values of thermal load are shown as a function of water inlet temperature of the vest in Figure 1. Considering the subjectivity of the thermal comfort, the subjects were asked to point their cooling sensation according to their sensation of cold/hot. In order to guide them with the choice, the Table 1 was adopted:

<table>
<thead>
<tr>
<th>Point</th>
<th>Cooling sensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – Very Cold</td>
<td>Very uncomfortable / unbearably cold</td>
</tr>
<tr>
<td>2 – Cold</td>
<td>Slightly uncomfortable / mild cool</td>
</tr>
<tr>
<td>3 – Comfortable</td>
<td>Neutral</td>
</tr>
<tr>
<td>4 – Hot</td>
<td>Slightly uncomfortable / mild warm</td>
</tr>
<tr>
<td>5 – Very hot</td>
<td>Very uncomfortable / unbearably hot</td>
</tr>
</tbody>
</table>

These tests results indicate that for a mild cold sensation, a minimum of 120W must be removed from a static subject at 45°C ambient.

### 3. PERSONAL COOLING SYSTEM FOR STOCK CAR RACING DRIVERS

Based on inputs from experts and players, availability of key components and timeframe, we have decided for prioritizing the development of a secondary fluid (liquid cooling) concept solution for cooling the racing driver, as illustrated in Figure 2. Cold water flows through the vest in direct contact with the driver’s body, removing heat...
from the subject. This heat is transferred to the refrigerant, which flows inside a heat exchanger of a vapor compression system (water-refrigerant intermediated heat exchanger). The water cooled is then pumped through the vest, closing the loop.

A question that might remain is why not to flow the cold refrigerant from the vapor compression system direct through the vest, eliminating the intermediary water-refrigerant heat exchanger (direct cooling concept). Advantages of the chosen concept (as shown in Figure 2), compared with direct cooling can be listed as following: avoid pressurized fluid in contact with body (safety); tubing inside the vest remains flexible with fluid at atmosphere pressure; quick connectors can better hold fluids at atmospheric pressure; “standard” sealed refrigeration unit that might fit to more than one application (independent of the vest). In addition, it is always possible to downsize this secondary fluid concept solution by changing it to direct cooling if high-pressure (leakage proof) flexible tubing is available.

Figure 1. Subject cooling sensation at 45°C ambient, where the vest inlet water temperature was controlled with a thermal bath. Subject was wearing the vest and a pilot racing suit.
As already mentioned, Stock Car environment is very severe. For a typical summer day in Brazil, when ambient temperature is around 35°C, temperatures at the pilot cockpit can reach over 45°C. At the rear chassis, where the gearbox is located, is one of the places where high temperatures have been verified, more precisely the gearbox surface with 90°C and the gearbox cooling oil with 120°C.

Weight and size are also very important constrains. The lighter solution currently applied in Stock Car is based on an insulated bag containing a two liters mixture of water and ethylene-glycol, weights around 2.7 kg and has a total volume of 0.003 m$^3$. So, any alternative solution should not be much larger or heavier than that. The location available inside the car for fixing the cooling system is the rear chassis, above the gearbox. As exemplified above, temperatures are very high in this region and current solutions are not able to keep the fluid circulating cold through the vest during the entire race.

A cooling system based on a vapor compression cycle is the proposition. The PCS prototype was designed and fabricated, applying the Embraco microcompressor with dimensions and expected performance curves shown in Figure 3, 4 and 5.

The microcompressor is oil-free, so it can be installed in any position. This characteristic also allows the compressor proper operation when submitted to high lateral accelerations, common to racing cars. In the present application, the system works with R134a, but the compressor can operate with other refrigerants too. An inverter is used as the starting system, with possibility of varying the input voltage from 9 to 36 Vdc. The maximum motor input power is 100 W, and the shell temperature must be limited to 90°C. The microcompressor weights 1.17 kg.

According to Gosney (1982), the curves in Figure 4 indicate that high evaporation and low condensation temperatures are desired in order to extract the maximum cooling capacity and COP (coefficient of performance) of the compressor. Due to the shell temperature limit, the cooling system was designed to work under condensations of 65°C. Regarding the evaporation limit, a key factor to be considered is the subject cooling sensation.
Figure 3. Microcompressor superior view.

Figure 4. Microcompressor lateral view.

Figure 5. Microcompressor performance curves, for a sub-cooling and super-heating of 35°C.
For a comfortable intimate contact of a coolant with the subject skin, the coolant temperature lower limit should be 18°C (Havenith, 1999). As in the application presented here, the water (coolant) flows inside hoses attached to a fabric, a thermal resistance exists between coolant and skin. Therefore, lower water temperatures are required to achieve the same comfortable cooling sensation as if intimate contact were possible. This agrees with results from Figure 1, where subjects did not complain with inlet water temperatures around 10°C (Note that the overall cooling sensation is also dependent on coolant mass flow rate and not only on coolant temperature). Based on this analysis, a minimum evaporating temperature of 5°C was taken for the water-refrigerant intermediated heat exchanger (evaporator) design.

Considering the physical limits (size and weight) inside the car, the prototype was developed using an air-refrigerant microchannel condenser with louvered fins as air-side heat transfer technique (Webb, 2005). This heat transfer technologies allowed a condenser weight less than 160 g and heat transfer rate higher than 200 W. To enhance the system performance, outside air was used to exchange heat with the condenser. This solution was possible by applying an air duct used to cool down the gearbox radiator. In this manner, when the stock car is moving, outside air is blown into the condenser in the same way as air-conditioner for automobiles. But since the PCS should operate continuously, a fan was also installed inside the prototype in order to provide necessary air flow when the car is on the box and/or running slow.

The expansion device was a capillary tube which passed through an intermediate suction line heat exchanger to enhance the refrigeration cycle performance. The evaporator was also based on microchannel tubes with louvered fins, mounted inside an aluminum housing which creates a water flow path through the heat exchanger surface. Due to the pressure losses inside the housing and along the hoses, a water pump of 14 W was used to pump water at 0.048 m$^3$/h.

In our water circuit we used a quick connector in the hoses connecting the vest with the cooling system. Quick connectors with leakage free feature are available in the market for a wide range of applications (medical, food distribution, etc) including car racing. This devices are very useful not just because its easy plug-and-play operation, but also because it can be easily detachable in case of fire or crash.

The final prototype is shown in Figure 6, containing also the electronic control board and the water pump. The insulated hoses presented in the Figure 6 must be connected to the driver vest. According to the rules, regarding the safety in Stock Car in Brazil, the PCS must be placed at the stock car rear chassis, as presented in Figure 7. The weight and volume of this PCS prototype version are 3.5 kg and 0.0078 m$^3$, respectively.

Figure 6. PCS prototype based on secondary fluid concept.
4. EXPERIMENTAL SETUP

Tests with the PCS prototype performance was evaluated in an experimental apparatus schematically illustrated in Figure 8. An environmental chamber with temperature controlled at 45°C represented the driver cockpit. A thermally insulated box was build to control the air temperature at 60°C around the prototype (representing the rear chassis environment) by an electrical heater and a PID controller. In order to simulate the car external air flow condition, electrical heaters were installed between the environment chamber and the outer environment. An air duct was attached from the heaters to the condenser inlet keeping the air flow at 35°C. The condenser outlet duct connects the PSC inside the thermally insulated box to the environmental chamber kept at 45°C.

For the driver thermal load emulation, an aluminum cold plate was placed over a plate electrical heater. For the cold plate insulation, two layers of ceramic fiber were used with a thickness of 25 mm each. The electrical heater was powered by a variable power supply and its power input was measured by a digital power meter.

Silicon rubber hoses were used to connect the prototype coolant ports to the cold plate. Each hose was insulated with 20 mm thickness polyurethane foam. Type T thermocouples were positioned at the PCS inlet and outlet hoses in three different interface positions indicated in Figure 6 by the points TC1, TC2 and TC3. A water flow meter was installed in the inlet hose between the insulated box and the cold plate.

The first experiment was to predict the heat loss of the electrical heater attached to the cold plate to the surroundings during its operation. For this purpose, the evaluation of the insulation thermal conductance was performed as follows: environment chamber was kept at a constant temperature and the cold plate was maintained without water flow. Under these conditions, the electric heater power input and the cold plate temperature were measured. The insulation thermal conductance was calculated as a ratio of the power input by the temperature difference between the chamber and cold plate surface.

Furthermore, other experimental tests were carried out to obtain the thermal conductance of the silicon hoses. Using a thermal bath, the water flow was set at three different inlet temperature conditions.

For each condition the water inlet and outlet temperatures were measured, together with the water flow, to calculate the heat exchange along the hoses, resulting in the prediction of the silicon hose thermal conductance as function of the water inlet temperature.

In order to evaluate the transient performance of the PCS, the thermally insulated box initiates at 45°C (same temperature of the environmental chamber) and then is controlled to operate at 60°C (temperature of the stock car
rear chassis). The whole experimental apparatus takes around 4 hours to reach steady condition. Water flow temperatures with variation smaller than +/- 0.1°C within 10 minutes were considered as steady state criteria.

Figure 8. Experimental apparatus for PCS evaluation with three zones temperature control to simulate Stock Car environment.

5. RESULTS

To evaluate the influence of the rear chassis temperature, the PCS prototype was set to operate in four different environment temperatures and using different insulation layouts.

The environment chamber was kept at 45°C, and the insulated hoses outside the thermal insulated box (rear chassis) did not have an increase in the heat transfer, as shown in Figure 9. The temperature variation of the insulated hoses inside the box shows a strong relation with the rear chassis temperature, reaching up to 50 W of heat gain (cooling decrease) at 100°C.

The importance of the insulation was also observed in the prototype performance, as presented in Figure 10. The increase of the rear chassis temperature induces a decrease in the cooling capacity at any condition. The prototype performance without any insulation presented a cooling capacity of 83 W when the rear chassis temperature was kept at 80°C.

Noting its limited performance under higher temperatures, insulation for its shell was investigated. The prototype had its shell covered and its performance increased up to 88 W at 80°C in the insulated box. Additionally, it also performs 80 W at 100°C.

Furthermore, after observing the increase in the prototype performance, an additional insulation for the air duct was investigated in the experimental facility. In this last configuration the prototype showed an increase in the cooling capacity performance of 21% up at 80°C. The prototype could deliver up to 94 W at 100°C rear chassis temperature. Note that the duct insulation installed at the PCS prototype had a greater increase in the performance than shell insulation, when the rear chassis were at temperatures higher than 60°C.
The performance result with insulation in the air duct and in the shell at 60°C insulating box temperature was chosen as a reference to be overlaid in the cooling sensation plot. In Figure 11, the prototype performance based on the cold plate results reaches a cooling sensation scale of 3 (comfortable), comparing it with the nearby results. Finally the prototype was set to operate with a subject test and the cooling sensation scale obtained was 3, with cooling capacity of 134W at 17.3°C inlet vest temperature.
Subject cooling sensation tests indicated that for a mild cold sensation, a minimum of 100 W must be removed from a static subject using inlet water below 15°C at 45°C ambient, wearing a cooling vest and a driver racing suit over it. An experimental apparatus was built to test prototypes under three different environment temperatures simulating the stock car cockpit, rear chassis and outdoor. The influence of the rear chassis temperature in the hoses of the cooling system was evaluated, indicating cooling capacity losses up to 50 W at 100°C. The insulation of the prototype shell and the air duct are significant, showing that at 80°C the insulation can increase the cooling capacity up to 21%, reaching 101 W of cooling capacity.

The measured PCS prototype cooling capacity was 134W, with inlet water vest temperature at 17.3°C, when the subject, the environment where prototype was located and the air flow through prototype were at 45°C, 60°C and 35°C, respectively. In these conditions, at steady-state, the subject cooling sensation was between comfortable and cold, indicating that such solution for cooling racing drivers, still with room for future optimization, has already a great technologic potential.

REFERENCES


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