Project no. COOP-CT-2004-508191

Safe&Cool

Development of a cost-effective moisture and thermal barrier layer for protective clothes based on an innovative combination of warp-knitted textiles and Hydrogel polymer coatings, introducing new standards which will prevent low quality imports and increase competition of 20000 European SMEs

Co-operative research Project

Publishable Final Report

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first revision

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1 Introduction

Publishable results of the Project are based on the preliminary presentation at ETPIS Seminar in Milan, December 2005, and on the paper published at ECPC Conference in Gdynia on May 2006, which imposed the Project outcome as a focus interest, due to the pragmatic approach and the tangible results. Also material from ESA website, and the final outcome employed to the accomplishment of the final batch of deliverables has been useful to draw the definitive publishable results of Safe&Cool Project.

This report, in the form of a research paper, has been prepared by D'Appolonia in cooperation with all the Project partners, mainly with those involved in the production of the different parts of the protective garment and of the final commercialization.

2 Publishable Results

2.1 Introduction

Wearing state of the art protective clothing for indoor work in non-ventilated areas, in hot temperatures or under radiating sources, while performing physically demanding work, is expected to hinder a worker ability to remain cool. Workers inability to shed excess heat results each year in many heat strokes in Europe. Less serious consequences of heat stress are more common, affecting several ten thousands workers per year all over Europe.

The 3D textile structure of the Safe&Cool textile layer is intended at replacing the interliner and moisture barrier in the classical three-layered protective clothing. The materials employed for its development are hydrophobic thermal comfort fibres (in contact with the body to avoid wet feeling) with hydrophilic fibres (creating suction channels to transport the moisture away from the skin) in appropriate combination. A cooling system consisting of liquid circulation through tubing inserted in the cavities available within the 3D structure will reproduce blood vessels for heat removal. The 3D spacer fabric will also facilitate convective effects due to its singular structure comprising vertical and diagonal spacer yarns, thus enhancing the cooling effect to the whole body surface. Water binding polymer will be added as a coating, or in the form of a powder dispersed inside the fabric thickness, with the purpose of absorbing and binding the excess of moisture migrating through the semi-permeable membrane if the temperature is maintained below the threshold controlled through the cooling system.

Safe&Cool is a Cooperative Research Project co-funded by the European Commission under the 6th Framework Programme. The Project started in 2004, and the research phase is currently completed. The participants are currently evaluating the perspectives and technical solutions for the exploitation of the results into marketable products.

2.2 Design Procedure and Fabric Prototypes

Design of the innovative interliner fabric layer is devoted to the achievement of superior insulation and protection to the wearer – industrial worker or firefighter – to help a safer working shield against heat. Design of the layer has to be performed according to the specific needs of insulation and of protection, keeping also in mind the ergonomics and the conditions of use. The wearer has not to be hindered in his/her tasks by the protective garment.

Specifications for the interliner characteristics can be derived from the thermal load, coming from the outside – exposition to radiant heat, flames or other sources – or from the inside: metabolic heat production. The optimum design is performed with a trade-off between the insulating properties, lightness and flexibility. Main parameters are the fabric layer characteristics, the liquid coolant circulating system and the water binding polymer embedded within the fabric. In the following paragraphs the approach to solve these aspects into a viable protective product is analyzed. A design software tool shall be developed, according to the parameters of use identified during the course of the Project. This is expected to help the selection of the most adequate protecting workwear, balancing the apparel protective performance, ergonomics, maintainability, and, of course, cost.

In Figure 1 the overall Safe&Cool concept is depicted: the moisture uptake channels are highlighted, as well as the water binding polymer layer and the cooling circuit.

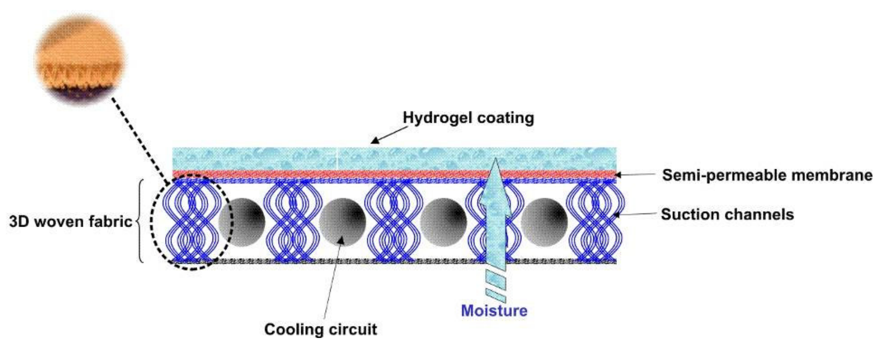

Figure 1 Safe&Cool textile layer concept

2.3 Textile Structure

The main issue for the fabric constituting the interliner in protective clothing is thermal insulation. However, it has to grant the wearer comfort as well as being lightweight, soft and mechanically resistant. The hydrophobic comfort fibers are to be placed in contact with skin, to ensure good wearability while avoiding wet feeling. The outer layer of the textile material has to be composed of the hydrophilic material, to collect the humidity creating a gradient of water concentration.

The rib warp-knit fabric for this purpose has been selected as the most suitable textile structure. This ensures to stabilize fabric thickness, opposing reactive force also to the compression flattening, and therefore enabling enhanced protective capabilities during use. The warp-knit structure furthermore allows designing the 3D structure of the different technical fibers according to the specific requirements of the fabric layer. Ribs are created, ensuring a trade-off between stability of the rib structure, reduction of bending rigidity and sufficient amount of channels for the tubes. The fabric prototype has been produced according to the above mentioned concept, with a total thickness of 5 mm, and a rib structure with two alternated upper and lower yarns enabling easy accommodation of the cooling pipes. A picture of the fabric layer is provided in Figure 2: it is possible to distinguish the hydrophilic white material from the black hydrophobic filament.

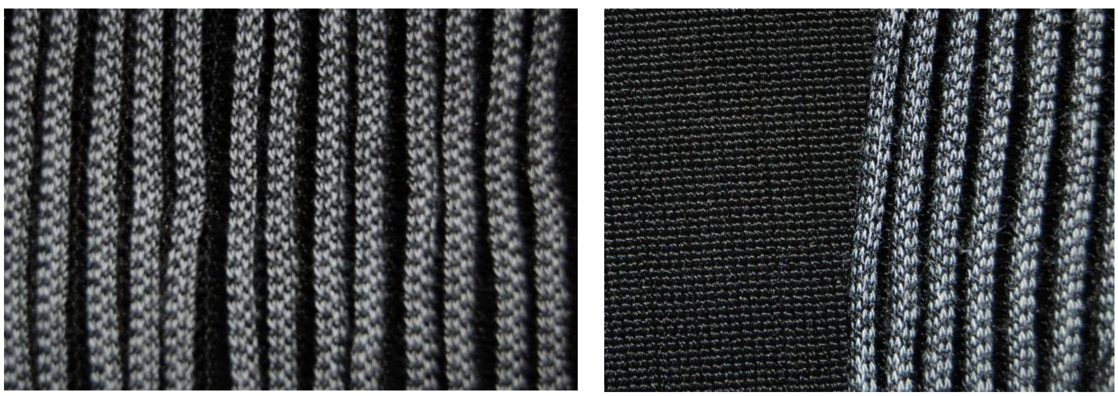

Figure 2: Safe&Cool prototype fabric layer, upper view (left image) and skin-upper layer fabric comparison

Enhanced prototype of fabric, with inferior thermal insulation and moisture management capabilities, designed on the same concept of composite hydrophobic - hydrophilic yarns in layered structure, reducing the overall weight of the fabric, is produced making it easier the integration within protective garments, where flexibility and wearability are the main issues to be respected. Pictures of this advanced layer are collected in Figure 3, jointly applied to membranes, and standing alone. It is possible to identify the hydrophobic, white yarn coupled with the hydrophilic gray yarn.

Figure 3: Safe&Cool prototype fabric layer, more lightweight construction

2.4 Cooling Circuit

The dimensions and placement on the different body surface areas of the cooling circuit are developed according to the cooling needs, taking advantage of the large space destined to the passage of small tubes by the rib structure. Silicone tubes with maximum diameter 2.5 mm have been selected as the optimum material for cooling, having good resistance to thermal load, thin wall and low bending rigidity, ensuring easy placement in the selected position. It is foreseen that this system is used for the firefighter garment only, where the possibility to rescue human lives justifies the use of this specific application.

In Figure 4 a conceptual sketch for the cooling circuit is presented, enabling to concentrate the cooling effect where the heat generation is more intense and the discomfort due to wet feeling is more relevant.

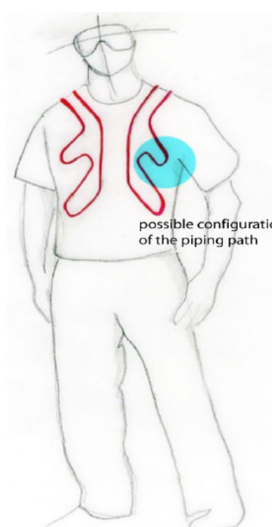

Figure 4: configuration of the piping path on the torso

First fabric prototypes have been produced to validate the concept of the piping insertion, and performing tests at lab-scale. The cooling unit is designed in order to be as light and compact as possible, while granting sufficient autonomy (power or phase change material) for the firefighter to complete the mission.

2.5 Water Binding Polymer

Different methods have been investigated for the deposition of the water binding polymer on the fabric layer; the most promising techniques are currently under investigation for the purpose of extending the lab-scale trials at industrial scale. In Figure 5 the results for the different methods are presented: Racla deposition method and polymer powder embedded with quilted membrane.

Figure 5: Safe&Cool water binding polymer on fabric layer: Racla coating (left image) and quilted membrane retaining water binding polymer (right image)

The Racla coating has proven to be simpler and easily adaptable to industrial processing, adopting the correct formulation for the binding agent. It provides a tough layer, suitable for a reduced water binding rate for application where the lightness and flexibility of the material is a major need. Quilted structure increases the polymer capability of water retention, and the quickness of humidity absorption. Furthermore, the free spaces of the textile layer are sufficient for accommodating the polymeric material also in its swollen state (volume increases up to 900%). The required amount of binding agent has been selected, enabling to retain the polymeric water binding material, and to leave unchanged the activity and the kinetics of absorption.

2.6 FEM Simulation

The behaviour of the fabric layer in different environmental conditions and garment configurations has been simulated via FEM analysis. The fabric layer has been considered alone, or coupled with a standard layer of protective Nomex fabric. The water binding membrane has been considered in its fully dry and wet state. The thermal load has been simulated both in convective conditions, and in highly demanding conductive heat transfer. Radiant heat transmission has not been simulated, due to the scattering of the radiant exposure under use conditions; however, the resistance to radiant heat is experimentally verified, in order to understand the enhancement in the protective capabilities under such conditions.

The results of the simulations have provided interesting results on the Safe&Cool performances, in terms of resistance to the most demanding conditions. In Table 1 a resume of the basic resistance parameters under the different conditions is collected: testing method EN 367 under convective conditions has been taken as reference, evaluating the time required for 24°C temperature rise at contact with skin (marked as $t_{24°C}$ in Table 1) starting from the initial level of 20°C. The reference temperature of 120°C has been taken as limit for the integrity of the textile layer – even if the layer still retains some protective capabilities (marked as t_{integr} in Table 1).

	Convection 80°C No polymer No cooling	Convection 80°C No polymer With cooling	Convection 600°C Dry polymer With cooling	Convection 600°C Wet polymer With cooling	Conduction 200°C Dry polymer No cooling	Conduction 600°C Wet polymer With cooling
$t_{24°C}$ [s]	>80	>240	50	110	50	40
t_{integr}[s]	-	-	70	180	90	35

Table 1: meaningful results extracted from the textile layer simulation under different thermal load

Figure 6 presents the result of the FEM thermal simulation on the textile layer: it is possible to see the cooling tube and the rib structure in these sections.

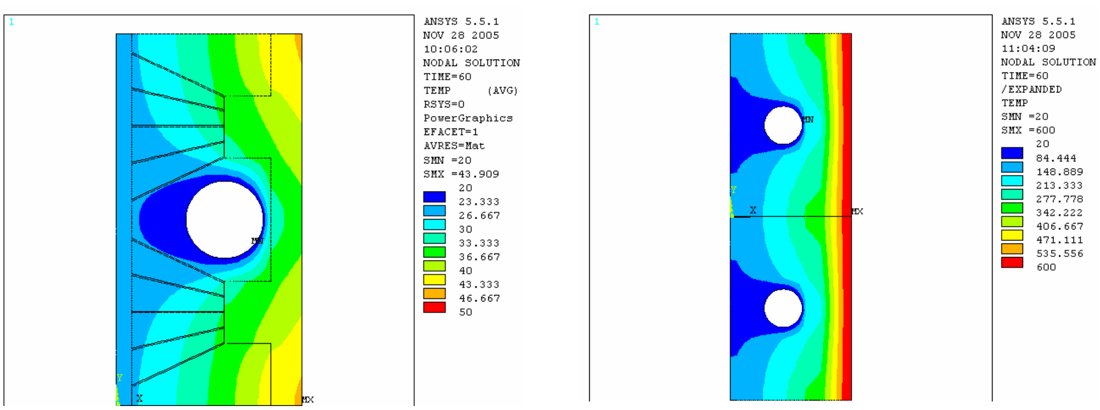

Figure 6: Safe&Cool FEM simulation of thermal profile under convection, 80°C with cooling (left image) and conduction, 600°C with cooling (right image) both after 60 seconds

Thermal flux has been estimated as well for the superposed thermal load. Results showed that, even if the wet water binding polymer layer has the effect of delaying the thermal uptake inside the fabric due also to the increased thermal capacity, the heat flux is greater for the wet state. This fact enabled to perform consideration on the need to avoid the presence of liquid water inside the structure of the protective clothing. Water binding polymer thus can be a simple yet reliable solution, to bind the excess humidity present in the layer.

2.7 Garment Prototypes and Testing

Result of garment design and prototyping is based on the result of the FEM analysis and on the assessment of risk evaluation, taking advantage also of the experience developed in Protective Garment design by the European producers. Particular attention was devoted to the definition of the optimal materials, coupling and assembly, to develop a viable product. The garment prototypes were produced to cover the main different fields of application foreseen: a cooled vest, workers complete turnout, wood firefighters coat and specialized firefighters jacket have been produced, to validate Safe&Cool concept within different fields of application. The complete turnouts produced were tested in comparison to standard garments by end users communities in order to establish the potentialities for application. The process of optimization, started from the fabric layer and the water binding polymer treatment, to be furthered according to the most suitable construction: insertion of membrane and materials coupling for ensuring the best characteristics to be achieved according to the final use of the garment.

Figure 7: images of the Safe&Cool garment prototypes

Results of the testing, performed on reduced scale samples enabling to evaluate the performances of the material under different operating conditions, in terms of moisture transmission, humidity uptake, heat shielding and resistance under conduction, radiation and convection, as well as the fundamental testing of comfort with the instrumented manikin and the fire resistance, enabled to assess and validate the construction developed. Materials and design proved to be appropriate to perform as requested, confirming the approach and furthermore validating the FEM studies performed on the material assemblies.