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Hot Steam Transfer Through Heat Protective Clothing Layers

René Rossi
Eric Indelicato
Walter Bolli

EMPA (Swiss Federal Laboratories for Materials Testing and Research), St.Gallen, Switzerland

The aim of this study was to analyse the transfer of steam through different types of textile layers as a function of sample parameters such as thickness and permeability. In order to simulate the human body, a cylinder releasing defined amounts of moisture was also used. The influence of sweating on heat and mass transfer was assessed.

The results show that in general impermeable materials offer better protection against hot steam than semi-permeable ones. The transfer of steam depended on the water vapour permeability of the samples, but also on their thermal insulation and their thickness. Increasing the thickness of the samples with a spacer gave a larger increase in protection with the impermeable samples compared to semi-permeable materials. Measurements with pre-wetted samples showed a reduction in steam protection in any case. On the other hand, the measurements with a sweating cylinder showed a beneficial effect of sweating.

hot steam protection   heat protective clothing

1. INTRODUCTION

During firefighting situations, firefighters are surrounded by a hot but also moist environment. Sweat production under these circumstances can exceed 1 L in 20 min and most of it will be absorbed by textile layers. Furthermore, the extinguishing water may cause high water vapour pressure in the environment. Steam flowing from the outside towards the body or evaporating from the layers of textiles can lead to steam burns. These may be more severe than dry burns as hot moisture can be partly absorbed by the skin and transferred to deeper skin layers.

The influence of humidity on heat protection of heat protective clothing assemblies has already been analyzed several times [1, 2, 3, 4, 5, 6] with sometimes contradictory results as the presence of moisture alters several parameters of the fabrics like thermal conductivity, heat capacity, etc. Depending on the intensity of heat flux, moisture in the layers may have a positive or a negative influence. In none of these studies was the presence of hot steam in the layers discussed. Very few studies analyzed the impact of hot steam on multilayer assemblies [7].

The aim of this study was to analyse the transfer of steam through different types of textile layers and to compare it with the parameters of the samples like their thickness and permeability. The measurements were made either on flat or cylindrical samples. In order to simulate the human body, a cylinder releasing defined amounts of moisture was used.

Correspondence and requests for offprints should be sent to René Rossi, EMPA, Lerchenfeldstrasse 5, CH-9014 St. Gallen, Switzerland. E-mail: <rene.rossi@empa.ch>.

2. MEASUREMENTS

We attempted to simulate the transfer of hot steam in different steps. The first tests were made with flat samples exposed to freely flowing steam. The steam was produced by a recipient filled with water that we heated with a Bunsen burner. The recipient was closed with a synthetic cork, containing a tube. The samples of the material were placed directly above the tube to be exposed to the steam flowing freely from the tube. A calorimeter (a copper plate with an attached thermocouple) was used to measure the heat flux generated by the steam. With our system and the distance between the tube and calorimeter chosen, the heat flux reached 30 ± 2 kW/m^2. The flat samples were placed onto a frame and the calorimeter behind the samples of the material. The sample holder as well as the calorimeter corresponded to the European Standard EN 367:1992 [8]. Instead of measuring heat transfer indexes (HTI) as foreseen in EN 367:1992, we defined a steam transfer index (STI). STI12 was defined as the time to reach a temperature increase of 12 °C in the calorimeter and STI24 for an increase of 24 °C. The tests were performed three times for each sample and the mean value was calculated.

While working in hot environments, the human body produces a high amount of sweat and part of this sweat will be absorbed by the textile layers. We simulated this situation by definitely wetting the layers before exposure to steam. These tests did not however simulate reality adequately as the production of sweat is a continuous process. We wanted to take account of this continuous sweat production by using a cylinder approximately of the size of a human forearm. This metallic cylinder was heated to 35 °C (mean skin temperature) and equipped with sweating nozzles on three different levels (top, middle and bottom) to additionally simulate the effects of sweat on heat and mass transfer. The layers of the material were placed around the cylinder and the system was placed horizontally. The steam flow was adjusted in such a way that it hit the cylinder perpendicularly in the middle of the surface. The heating power to keep the cylinder to 35 °C was recorded. The cylinder was then heated with this constant heating power during steam exposure and the mean temperature increase of the whole cylinder was assessed.

3. MATERIALS

As heat and water vapour transfer induced by hot steam is dependent on the permeability and the thickness of the samples, materials with very different insulation and permeability were chosen for this study (Table 1). Two samples were totally impermeable, 6 had semi-permeable membranes and 2 were permeable. Two samples were hygroscopic with high moisture absorption.

4. RESULTS AND DISCUSSION

4.1. Measurements With Flat Samples

The transfer of hot steam was dependent on the water vapour resistance of the material as well as thermal resistance. As the measurements were not made under steady-state conditions, steam transfer also depended on the heat and moisture absorption capacities of the fabrics. In general, the higher the water vapour resistance, the higher the protection against hot steam. Protection of the impermeable samples A4 and A5 was not much higher than that of some breathable (semi-permeable) fabrics like A1 or A6. In the breathable fabrics, part of the steam went through the material and then transferred heat directly to the calorimeter. For impermeable fabrics, there was only dry heat transfer from the outside of the sample to the calorimeter. As the samples were not very thick, dry heat was quickly transferred to the calorimeter. A6 had the highest protection against

TABLE 1. Properties and Steam Transfer of the Samples

Sample	Description	Weight (g/m^2)	Thickness (mm)	Rct[1] (10^{-3} m^2 K/W)	Ret[1] (m^2Pa/W)	STI12 (s)
A1	Outer layer laminate (aramid + PES membrane)	300	0.34	5	8.5	27.4
A2	Outer layer laminate (aramid + PES membrane)	250	0.52	7	6.2	19.8
A3	Aramid outer layer	190	0.53	21	3.8	9.4
A4	PVC coated outer layer (coating outside)	570	0.60	5	>10,000	30.0
A5	PVC coated outer layer (coating inside)	590	0.63	11	>10,000	28.1
A6	Outer layer laminate (cotton + PES membrane)	490	1.05	18	33.2	36.6
F1	Lining (aramid with PU membrane)	380	3.66	120	32.3	33.7
F2	Lining (aramid with PU membrane)	360	4.51	159	13.2	14.9
F3	Lining (aramid with PU membrane)	420	3.34	118	30.3	30.8
F4	Wool lining	620	6.64	215	18.8	31.8

Notes. 1— measured according to ISO 11092:1993 (sweating guarded hotplate) [9]; PVC— polyvinyl chloride, PES— polyester, PU— polyurethane, Rct— thermal resistance.

steam, probably because of the hygroscopicity of cotton, which caused the absorption of part of the steam. The wool lining F4 had comparable steam transfer to F1 and F3 although these two samples had higher water vapour resistances. This result may be explained by the higher thermal resistance and thickness of this sample, but also it seems to confirm that hygroscopicity may have a positive influence on protection against hot steam. The same tendency of higher steam protection than would be expected from water vapour resistance was observed with the samples with a hydrophilic polyester (PES) membrane (A1 and A2). The PES membrane first has to absorb moisture and swell before the transfer of moisture sets in.

The tests were repeated with the samples A4 and A6, with the addition of a lining or a spacer material between the outer layer and the calorimeter. In this case, the impermeable sample A4 reached much higher values than the semi-permeable sample A6 (Table 2). The thicker the lining and spacer material, the bigger the difference between the two samples. The protection time STI12 with the impermeable sample A4 increased linearly with the thickness of the spacer (correlation coefficient $R = .99$). This result was expected as thermal conduction is directly proportional to the thickness of the material. On the other hand, the increase in protection time with

TABLE 2. Time to Reach a Temperature Increase of 12 °C (STI12) Depending on Different Spacer Thicknesses

Outer layer	Lining	Spacer (mm)	STI12 (s)
A4	F1	0	123
A4	F1	3	234
A4	F1	9	423
A6	F1	0	71.5
A6	F1	3	101
A6	F1	9	152

increasing thickness of the spacer was slower for the semi-permeable sample A6, showing that apart from dry heat transfer, some of the steam passed through the sample and contributed to heat transfer.

The influence of a wet layer on heat and mass transfer was also analysed by wetting the surface of the samples. The materials were first conditioned at 20 °C and 65% RH and then sprayed uniformly with water. Surplus water, not absorbed by the samples, was removed.

As shown in Table 3, the steam protection times STI were reduced for all wetted samples. The only exception was a slightly higher STI12 for the wetted F4 wool sample. The biggest reduction was measured with the sample A6, which also had the highest water uptake. On the other hand, the smallest reduction was reached by the sample F4 with the second highest water uptake. Therefore, the reduction in protection could not be correlated to the water content of the samples. The reduction was generally higher for STI24 compared to STI12. The presence of water did not seem to hinder the transfer of steam. As the thermal conductivity of the wet samples was higher, conductive heat transfer was increased, which probably explains the lower protection of the samples when wetted.

4.2. Measurements With the Sweating Cylinder

The same steam system was used for these measurements, but the flat sample with the calorimeter was replaced by a cylinder placed horizontally. The increase in the mean temperature of the cylinder was assessed and compared to the results with the flat samples for five combinations (F1, A4 + F1, A6 + F1, A4 + A6, A4 + F1 + 3-mm spacer).

Although the time to reach an increase of 12 °C was much higher in the cylinder than in the flat samples, due to the higher mass of the cylinder, the results of the five combinations analysed both on the flat plate and on the cylinder gave fairly good agreement (Figure 1, correlation coefficient $R = .93$). The geometrical factors (different convection effects) did not seem to have a large influence on the performance of the different samples.

The measurements with the sweating cylinder allowed an analysis of the effect of sweating during exposure to steam by continuously supplying sweat water to the system instead of only pre-wetting the samples as was done in the first part of this study with the flat samples.

The simulation of sweating slowed down the temperature rise of the cylinder in any case (Figure 2 shows 3 examples of the results).

TABLE 3. Steam Transfer of Dry and Wetted Samples

	Dry Samples			Wetted Samples	
Sample	STI12 (s)	STI24 (s)	Water Uptake (%)	STI12 (s)	STI24 (s)
A1	27.4	62.0	6.8	22.8	48.4
A6	36.6	87.3	43.0	25.0	51.0
F1	33.7	74.8	18.0	26.3	54.2
F3	30.8	68.5	18.4	23.3	52.5
F4	31.8	64.6	20.4	33.2	59.5

Notes. STI12—time to reach a temperature increase of 12 °C, STI24—time to reach a temperature increase of 24 °C.

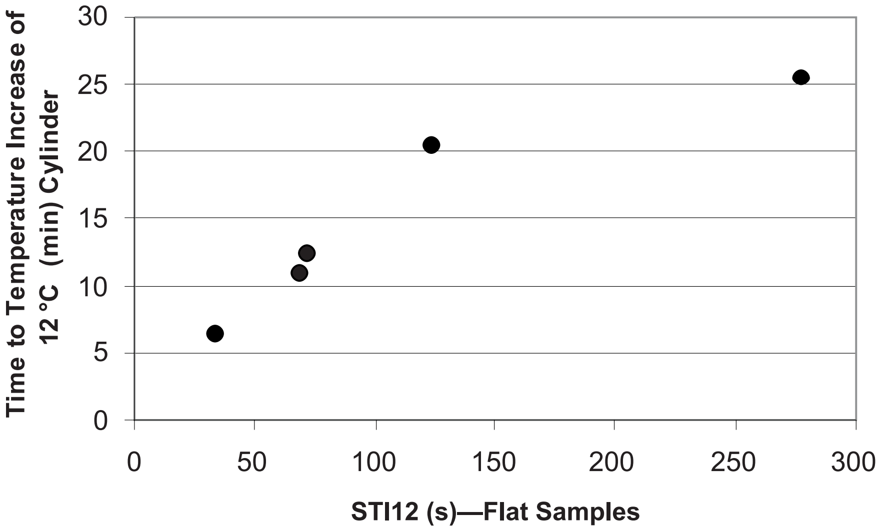

Figure 1. Comparison of steam protection between flat and cylindrical samples.

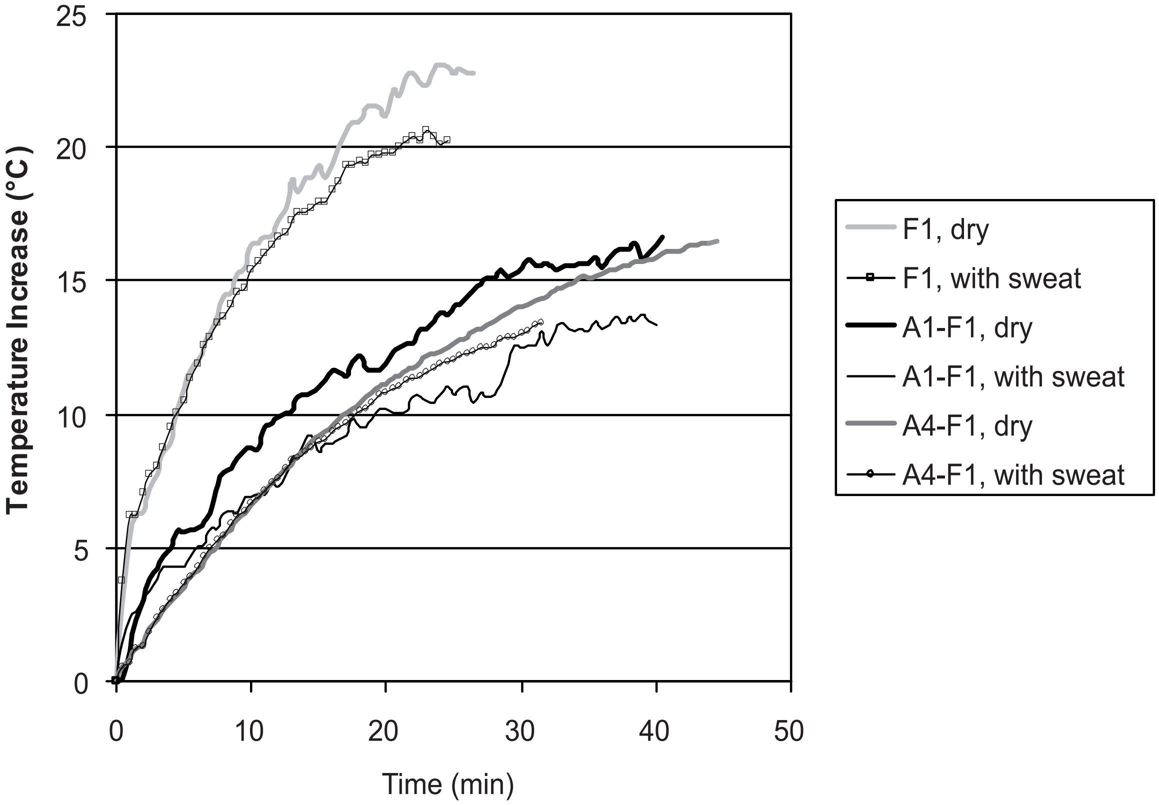

Figure 2. Temperature rise on the sweating cylinder during steam exposure with and without sweat.

Even for impermeable samples (A4-F1 in Figure 2), the effect of sweating was positive, although the difference between the tests with and without sweat was smaller than for the other samples. This result cannot be easily interpreted as the influence of humidity on protection should be negative due to the higher thermal conductivity of wet fabrics than for the flat sample measurements. This test was repeated for different sweating rates and always gave better results than without sweating. These results might be explained by the fact that the sweat water supplied to the cylinder was always more or less at 35 °C. If the temperature of the cylinder rose above this temperature, sweat water probably had a cooling effect even if it could not evaporate. It is however questionable if the cylinder simulates the human body realistically for this situation. Further measurements are needed to verify if the adaptation of the temperature of sweat water to the outside temperature of the cylinder would change this result.

The temperature rises with the semi-permeable samples (example A1-F1 in Figure 2) were much slower than with the F1 lining alone. In dry conditions, these materials offered less protection than the impermeable ones, but during the measurements with sweating, the temperature rose faster with the A4 impermeable material. Therefore, the evaporation of sweat in breathable combinations had a positive effect on the temperature increase. As the cylinder was metallic, the temperature was similar all over its surface. As only one side of the cylinder was exposed to steam, the other side could be cooled down by evaporation of sweat, which partly compensated the temperature increase due to steam. Here again, the apparatus used was probably not totally representative of a human body as the metallic cylinder had a much higher thermal conduction than the human skin and core. In the human skin, there would be only a limited positive effect on a steam burn in one specific part of the skin if sweat was evaporated elsewhere on the skin. Further measurements are therefore needed to analyse how the use of a metallic cylinder can be used to simulate the behaviour of human skin.

5. CONCLUSIONS

The results show that in general impermeable materials offer better protection against hot steam than semi-permeable ones. The transfer of steam depended on the water vapour permeability of the samples, but also on their thermal insulation and their thickness. Increasing the thickness of the samples with a spacer gave a larger increase in protection with the impermeable samples compared to semi-permeable materials. Materials with good water vapour (steam) absorbency also tended to offer higher protection against hot steam. Measurements with pre-wetted samples showed a reduction in steam protection in any case. On the other hand, measurements with the sweating cylinder showed a beneficial effect of sweating. The sweat water released by the cylinder had a constant temperature of 35°C and the high heat capacity of the water probably prevented a fast temperature rise of the cylinder. However, we will analyse in further measurements if the use of a metallic sweating cylinder can adequately replicate the human skin.

This study showed that the presence of moisture in fabrics may have either a positive or a negative effect on protection. The mechanisms of hot steam transfer through textile layers are very complex and further studies will be necessary to exactly quantify the steam protection of assemblies. The cooling effect of moisture in the sweating cylinder during exposure to steam has to be quantified and its effect on the lower temperature rise for breathable samples compared to impermeable materials has to be studied thoroughly.

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