Possibility of Modern Humidity Sensor Application in the Studies of Moisture Transport through the Sports and Outdoor Garments

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Abstract: Sensor nodes containing pairs of temperature and humidity sensors were assessed as a mean of garment performance and comfort studies. Modern sensors are small, low weight and produce minimal disturbance when placed under the garments and in the footwear. Four sensor nodes were used to provide dynamic information about heat and humidity transfer properties of garments during the tests in realistic conditions. Pilot studies were carried out for the few models of cross country skiing garments and waders. Main studies were carried out in the wind tunnel at Mid Sweden University having pivoted treadmill, temperature control and rain capacity. Additional experiments with the waders were carried out in a large water tank. Studies of the temperature and humidity dynamics under the garments containing microporous membranes illustrate the importance of recognizing main features of such materials. In particular, such membranes can only transport moisture from the side where humidity is higher. It means that garments and footwear containing such membranes will potentially behave differently when ambient air humidity changes. In particular, modern garments with incorporated microporous membranes being superior at low ambient air humidity can be dramatically less effective for moisture transfer from the body in the rain.

1 INTRODUCTION

Modern garments and footwear often incorporate innovative fabrics and can have quite complex, multilayer structure. This strongly complicates possibilities of adequate prediction of the overall garment or footwear performance and their assessment in targeted environment, even if the fabrics were tested in the laboratory using standard procedures, and the garment or footwear is individually fit. When the garment or footwear is designed to work in extreme conditions (cold, hot, humid environment) and should provide high degree of comfort of the person at different physical load levels, corresponding performance assessment may be quite challenging. Though modern garment and footwear research and development strongly depends on traditional ways of subjective assessment, there is a strong drive towards objective methods providing more reliable and reproducible data (Arezes et al., 2013). Present research is aiming at the assessment of compact temperature and humidity sensor system applications for the studies relative humidity and thermal comfort of garments in the controlled laboratory environment mimicking realistic conditions. Particular research questions were if such sensor systems can visualize the action of modern semi-permeable membranes incorporated into the garments, and if they can be used for the moisture transport studies.

Human thermoregulation system has a significant potential to maintain core body temperature in a comfort zone even with increasing heat production during work or exercise (e.g. Reilly et al., 2006, Lim et al., 2008). But this mechanism involves perspiration and thermal comfort is strongly influenced by the humidity at the skin surface (Jing et al., 2013). Thus it is quite important for the garments to support proper heat and humidity control (Gonzalez, 1988, Sullivan et al., 1992, Rugh et al., 2004, Senthilkumar et al., 2012, Troynikov et al., 2013, Nayak et al., 2014). Additional challenge for the heat and humidity control under the garments and footwear may be presented by cold (Watson et al., 2013) and wet (Abreu et al., 2012) environment. Significant progress in modern garment design is related to the development of “smart textile” and “smart garment” concepts (Parkova et al., 2011). Modern “active” materials can provide needed proactive heat and humidity control features (Van Roy, 1992, Chaudhari et al., 2005, Brzeziński et al., 2005). For example semi-permeable membranes

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facilitating gas and water vapour transfer but preventing liquid (water) getting through (Metz, 2003, Brzeziński et al., 2005, Frydrych et al., 2009). Though standards for measuring humidity transfer through the multi-layer fabric structures containing such materials do exist (Standard ISO 15496:2004). Studies on the impact of pro-active materials being part of the multi-layered structure of the smart garments in realistic conditions today are carried out using unique "sweating manikins" (Fukazawa et al., 2004, Farrington et al., 2005, Bogerd et al., 2012, Gao et al., 2016), or done with subjects wearing garments exercising on a treadmill (Roberts et al., 2007), outdoors or in the climate controlled indoor environment (Bäckström et al., 2016).

2 MATERIALS AND METHODS

2.1 Sensors and Data Acquisition

A custom made system with four sensor nodes was designed and constructed. Each sensor node consisted of a small printed board with two temperature (T) and relative humidity (RH) sensors SHT21 by Sensirion AG, Switzerland (Sensirion web site, 2016) mounted on opposite sides of the boards (Figure 1). For better humidity resistance boards are coated with protection lacquer. The sensors have a precision of ±3% in RH in the full range (0 to 100%) and ±0.3 ºC in T in the range of interest (0 to 60 ºC). Digital interfaces of the sensors are connected via home-made multiplexer to the digital serial interface module NI USB-485 (by National Instruments).

Data acquisition is carried out using the LabVIEW platform by National Instruments. Sampling from all nodes simultaneously can be set to 5 or 10 seconds per sample.

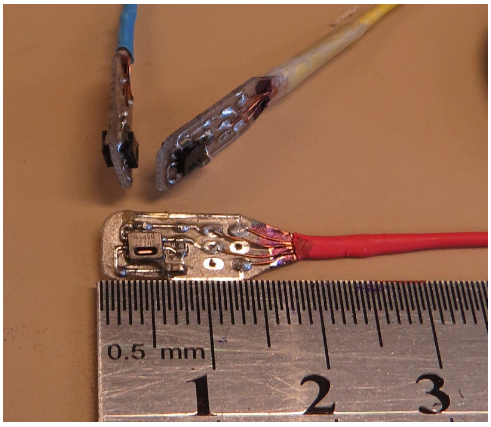

Figure 1: Experimental T and RH measuring nodes.

2.2 Sports Garment Tests

Garments of two different designs from the same manufacturer were tested. Both garments were the prototypes designed for the cross-country skiing and biathlon. Garment 1 is made using: fabric 106402 Vulcano Dry-Storm by Sport wear Argentona (70% Polyester, 20% Elastan, 10% Polyurethane) in 3 layers with microporous membrane inside, wind protection GG40; fabric W53798 by Schoeller (60% Polyacryl, 28% PES-Expand, 12% Lycra) in 2 layers, wind- and water-tight; mesh S-005 by Janmar Sport (94/ PES, 6% Elastan), single-layer. Garment 2 is made using: fabric 106406 Kanjut Dry-Storm by Sport wear Argentona (84% PES, 6% Elsatan, 10% Polyurethane), in 3 layers with microporous membrane inside, wind- and water- resistant; fabric S-013/300/DR by Janmar Sport (84% PES, 16% Elastan); mesh S-005 by Janmar Sport, single layer.

Tests were performed in the wind tunnel (for the wind tunnel description see Bäckström et al., 2016) with the subjects roller-skiing on the treadmill (Figure 2). The air temperature was 3-4 ºC and relative humidity was 75-80%.

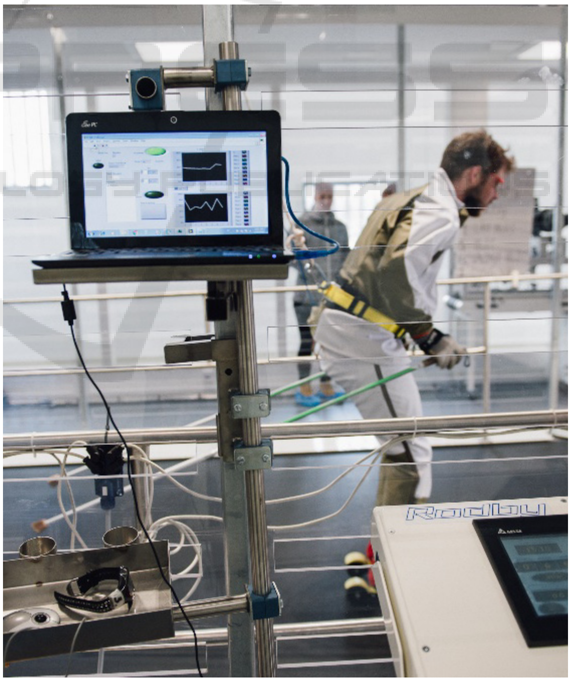

Figure 2: Test subject roller skiing in the wind tunnel.

Sensor nodes were placed over the underwear (Figure 3 visualizes the sensor node placement-positions and procedure). Two male cross country skiers with the experience on national level participated in this part of the study.

Figure 3: Sensor node placement- positions and procedure.

Sensor nodes were placed over the underwear (Figure 3 visualizes the sensor node placement-positions and procedure). Two male cross country skiers with the experience on national level participated in this part of the study.

Each of the skiers performed tests with both types of garments using roller skis on the treadmill for 15 minutes at a relative intensity of ~75% of their maximal heart rate. One of the skiers was using classical style double poling (15 km/h, 0° treadmill inclination) and the other was using free style gear 4 (20 km/h, 0° inclination). The wind tunnel created head wind corresponded to the speed of the treadmill. Heart rate was recorded along with the sensor data (T and RH) and the subjects were interviewed before and after the tests to assess the perceived comfort. Subjects were wearing small control box (on the belt) connected with a flexible cable to the data acquisition PC (Figure 2).

2.3 Waders Tests

In this part of the study three types of commercial waders were tested, ranging from the least expensive galon waders (Fladen, PVC-impregnated fabric type, http://www.jula.se) to the most expensive ones, using modern semi-permeable membrane materials (Kaitum and Alta, http://www.guideline.no/). Kaitum waders use 3-layer fabric sandwiches: outer layer is nylon, membrane layer is of the polyurethane (PU) coating type, qualified for 20000 mm Hg water pressure, fabric density 7000 g/m^2. From the waist up, Alta waders use 3-layer fabric sandwiches: outer layer is nylon/spandex, membrane layer is of the PU coating type, qualified for 15000 mm Hg water pressure, fabric density 3000 g/m^2. From the waist down, Alta waders use 4-layer fabric sandwiches: outer layer is nylon, membrane layer 1 is of the polyurethane coating type, membrane 2 is PU, qualified for 30000 mm Hg water pressure, fabric density 5000 g/m^2.

In each series of tests three subjects were participating wearing same sample waders. The first series of tests was performed in the wind tunnel with the subjects walking on the treadmill (18 ºC and 33% RH). Each of the tests consisted of steady walking for 10 minutes at 4 km/h followed by another 10 minutes at 6 km/h. Heart rate of the test subjects was kept at approximately 60% of maximum. Head wind was kept at the same speed as the treadmill one, and treadmill was horizontal throughout the test.

The second test series was conducted with the subjects staying waste deep in the water tank (air temperature 20 ºC, water temperature 14.8 ºC) for 15 minutes. Sensor node placement was same as for the ski garments tests. Subjects were interviewed before and after the tests to assess the perceived comfort. Figure 4 illustrates typical setup of the waders test in the water tank. In this case control box was placed at the back of the test subject close to the neck.

Figure 4: Waders test in the water tank.

3 RESULTS AND DISCUSSION

The main target of the study was preliminary assessment of the method and sensor system capacity to analyze the temperature and humidity under the garments, and the possibility to indicate the humidity flow direction. Thus small number of test subjects and relatively simple test protocols were used. So present results can be used as good indicators only, and more thorough research will be carried out in the near future.

3.1 Microporous Membranes

Modern gas and humidity permeable membranes used in fabric composites are represented by thin microporous polymer layers (e.g. Gore-Tex, a microporous PTFE-based material (Gore Tex web site, 2016). Figure 5 presents a scanning electron microscopy images of the untreated Gore-Tex membrane used in standard water vapour permeability tests (Standard ISO 15496:2004).

Transport rate of water vapour through such membranes strongly depends on the RH difference on the sides of membrane, temperature and air pressure (Metz, 2003). Thus adequately predicting performance of the full garment containing such membranes (placed only in certain places in sections, and also as parts of the composite fabric sandwiches) in real exercises is quite difficult.

Standard humidity transfer tests done on relatively small fabric samples (Standard ISO 15496:2004), are essentially static. Expected dynamic behaviour of the composite fabrics with such membranes can be explained as follows.

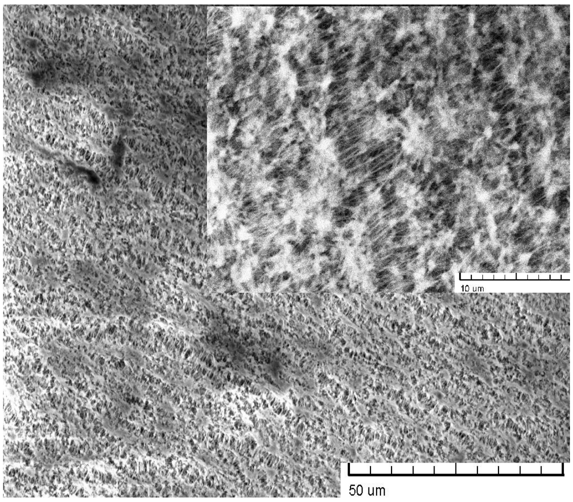

Figure 5: SEM images of the Gore-Tex microporous membrane. Magnification: x 2200 (x 8800 for insert).

When ambient humidity is lower than the one under the membrane (towards human body) certain water vapour transport towards the outer side of the garment should take place. When humidity under the garment is becoming higher than the one outside it water vapour transport towards the body takes place.

During intense exercising humidity under the garment starts to increase, increasing the water vapour transport through the garment. Water vapour transfer rate increases with increasing RH difference, and the growth of humidity under the garment will be governed by a competition of the humidity "production" and humidity transfer. If the membrane has high transfer capacity humidity under the garment should be kept almost stable (or at least should grow very slowly). At some point the capacity limit of the membrane will be reached (saturation), and humidity under the garment should start to grow fast, possibly reaching 100%. Intense exercising is accomplished by the changes of the temperature under the garment. And both temperature and humidity levels matter for the proper thermoregulation and comfort. So measuring dynamics of both parameters is important.

Processes of moisture transfer by such membranes can be better understood using analogies with the microporous membranes used in osmosis (Zhao et al., 2012, Nicoll, 2013). In this case membrane attempts to level the osmotic pressures on both of its sides. In simplest cases with water salt solutions these membranes attempt to level the salt concentrations on two sides of the membrane. From this analogy point of view one can treat humidity as moisture concentration in the air, and microporous membrane working to level such concentrations on both sides of it. This analogy is also useful to stress the presence of strong temperature and air pressure dependence of moisture transport through microporous membranes. Indeed, relative humidity is not a simple concentration of the water vapour in the air: "the relative humidity of an air-water mixture is defined as the ratio of the partial pressure of water vapour in the mixture to the equilibrium vapour pressure of water over a flat surface of pure water at a given temperature" (Relative humidity definition, Wikipedia). Simply speaking it is the ratio of the water amount that is now in the air, to the maximum amount of water the air at this temperature and pressure can hold without forming condensation droplets (fog). And this maximum amount is significantly temperature and pressure dependent. And even though absolute amount of water in the air can be constant, RH is changing when air temperature and pressure changes.

3.2 Ski Garment Tests

Figure 6 presents typical data from the posterior thigh sensor node (ski garment tests, skating style) when testing two different garments by the same test subject.

Analysis of the dynamic temperature curves (Figure 6, top graph) indicates that garment 1 is warmer than garment 2: temperatures of the sensors on the surface of the underwear (1i, “inner” T sensor) and towards the garment inner surface (2i) have rather small difference of the values. For the garment 2 the sensor facing towards the inner garment surface (2o, “outer” sensor) shows much lower temperatures as compared to the values from “inner” one. Also temperatures of both sensors in the node during all 20 minutes of test are lower for the garment 2 indicating higher hear loss. This also can be explained by potentially looser fit of garment 2 for the same test subject. Looser fit can lead to the intake of cooler ambient air into the gap between the underwear and the garment. It is interesting to note that steady state temperature is reached in about 1 minute from the beginning of the test for the “inner” sensor, and in about 3 minutes for the “outer” sensor. Heart rate dynamics of the test subject shows that steady state value is reached during the first three minutes of the test, corresponding to the “warming up” period.

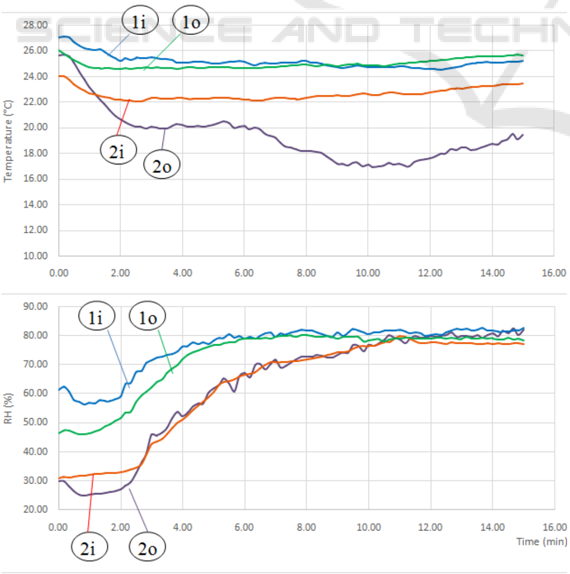

Figure 6: Dynamic data from the posterior thigh sensor node, ski garment test, skating style. (1o) and (1i) mark the data from the test on type 1 garment, (2o) and (2i)- on type 2 garment correspondingly. (1o) and 2(o)- outer, (1i) and (2i) -inner sensors of the node.

Analysis of the dynamic humidity curves (Figure 6, bottom graph) indicates that garment 2 provides much better humidity control than garment 1 almost through the whole duration of the test. Even at the beginning of the test humidity under the garment 1 is higher (it took some time to rig the measurement system and test subjects were already wearing the garments for about 5 minutes before the test started).

For 2 minutes there is no significant change in the humidity detected by both sensors in the node for both garments. After that humidity starts to increase, more rapidly for garment 1, reaching saturation at about 6th and 11th test minutes for garments 1 and 2 correspondingly. So it indicates that humidity control in garment 2 is more effective. It is also supported by the larger difference between the RH values detected by “inner” and “outer” node sensors.

3.3 Waders Tests

Figures 7 and 8 present typical data from the posterior thigh sensor node in waders tests. Same subject was testing three different waders in the wind tunnel walking (Figure 7) and water tank tests (Figure 8) correspondingly.

Sample waders 1 are made of traditional waterproof materials (galon, impregnated fabric), samples 2 and 3 are using the modern composite fabrics incorporating microporous membranes.

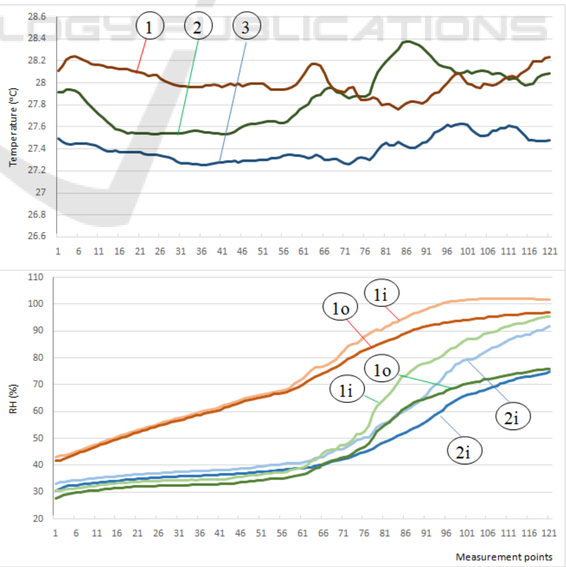

Figure 7: Dynamic data from the posterior thigh sensor node, wader walking test. (1), (2) and (3) - waders samples ##1-3; (i)- "inner" sensor placed towards underwear, (o)- "outer" sensor towards the waders. 10 seconds between data points.

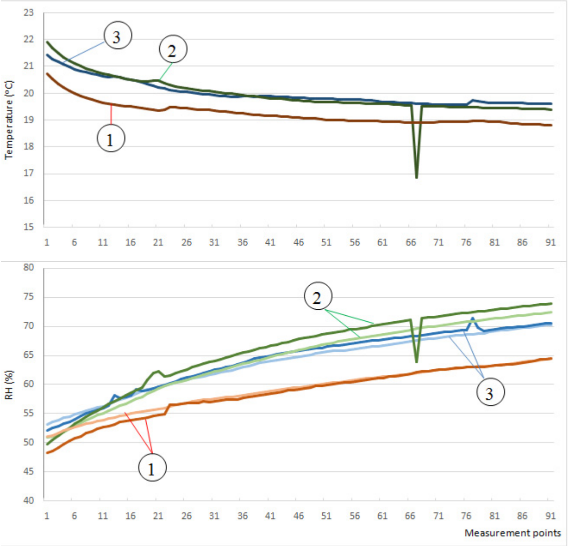

Figure 8: Dynamic data from the posterior thigh sensor node, wader "water tank" test. (1), (2) and (3) – waders, samples ##1-3. 10 seconds between data points.

In walking tests the heart rate of the subjects was stabilizing after about 3 minutes. Similarly, the temperature on the node sensors was also stabilizing in about 2-3 minutes (Figure 7, top graphs).

As expected, temperature under the old style waders (sample 1) was generally higher, as compared to the modern style ones (samples 2 and 3). It can be also expected that humidity under the old style waders should be generally higher as well (which is confirmed), but humidity dynamics is quite interesting (Figure 7, bottom graphs). Humidity under the old style waders is steadily growing straight from the beginning of the test increasing the rate after about 10 minutes from the start as the treadmill speed was increasing from 4 to 6 km/h. But new style waders with microporous membranes are capable of maintaining close to constant humidity within comfortable range up to 12 minutes of the walking test and some longer. And even towards the end of the test humidity transport in modern style waders is not reaching saturation.

During the water tank test temperature under the old style waders (sample 1) was generally lower, as compared to the modern style waders (samples 2 and 3), as illustrated in Figure 8 (top graphs). This can be explained by the fact that modern materials provide better heat insulation. But counter intuitively the humidity under the old style waders in the water tank test was also generally lower, as compared to the modern style ones (Figure 8, bottom graphs).

Both tendencies are opposite to the ones acquired in the walking tests. There are few spurious disturbances on the graphs corresponding to the "out of trend" T and RH values. So far we were not able to attribute these to any issue, but these are not changing any trends. Also, there are temperature instabilities in the second half of the test. Most probably it can be attributed to the relatively loose fit of the waders. At higher treadmill speed during the second half of the test ambient air was probably starting to get under the waders.

The counter intuitive humidity results can be explained through the basic property of microporous membranes. In these membranes direction and rate of humidity transport depends on the RH difference on the membrane sides: transport always goes from higher to lower humidity. In the walking test ambient humidity is lower than that under the garments, and membranes work to decrease the humidity inside. In the water tank test humidity outside the garments is 100% (water) and the membranes will always tend to increase the humidity under the garments, even though water droplets are not getting through the microporous membrane. This fact is worth taking into account when designing garments and footwear that will be working in different ambient humidity conditions and occasionally wet environments. Also, moisture transport properties of such membranes are generally temperature dependent, and thorough garment and footwear tests in realistic conditions are advisable in such cases.

4 CONCLUSIONS

Sensor nodes containing pairs of temperature and relative humidity sensors are well suited for the indoor and field applications. These sensors are small, low weight and produce minimal disturbance when placed under the garments or inside the footwear. Multiple sensor nodes can provide the information about heat and humidity transfer properties of garments and footwear during work or exercising in realistic conditions. There are clear indications that such sensor nodes can provide information about not only the rate of moisture transfer, but also its direction. Such systems can be effectively used for the assessment and comparison of the garment and footwear performance, especially the ones containing modern active and "smart" materials. Application of arrays of such sensors allows for the analysis of temperature and humidity dynamics under the garments and footwear during outdoor and indoor tests. Preliminary studies of the temperature and humidity dynamics under the garments containing microporous membranes carried out in realistic conditions illustrate the importance of recognising main features of such materials. In particular, such materials can only transport moisture from the side where humidity is higher. This means that garments and footwear containing such membranes will potentially behave quite differently when ambient air humidity dramatically changes. Additional work is now in progress to better adapt sensor nodes for the footwear comfort studies.

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