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Protective Jacket Enabling Decision Support for Workers in Cold Climate

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Abstract—**The cold and harsh climate in the High North represents a threat to safety and work performance. The aim of this study was to show that sensors integrated in clothing can provide information that can improve decision support for workers in cold climate without disturbing the user. Here, a wireless demonstrator consisting of a working jacket with integrated temperature, humidity and activity sensors has been developed. Preliminary results indicate that the demonstrator can provide easy accessible information about the thermal conditions at the site of the worker and local cooling effects of extremities. The demonstrator has the ability to distinguish between activity and rest, and enables implementation of more sophisticated sensor fusion algorithms to assess work load and pre-defined activities. This information can be used in an enhanced safety perspective as an improved tool to advice outdoor work control for workers in cold climate.**

I. Introduction

Petroleum activities moving further north implies that workers will be exposed to extreme rough weather conditions (cold, snow and ice) that can lead to fatigue, impaired physical and cognitive performance [1][2][3]. The interaction between the thermal environment and performance of the workers in cold environments is largely dependent on how the body can compensate physiologically for thermal strain [4]. The most obvious effects of work in the cold are distraction and reduced manual dexterity associated with local cooling of finger and hands [5]. Finger and hand temperatures of 15°C and below are closely related to reduced manual performance [6][7]. There are several methods for assessment of cold stress. The most widely used index for workers in the cold is the wind chill index (WCI) to assess the risk of freezing of the unprotected human skin [3]. ISO 11079 provides recommendation on required clothing insulation and exposure times in the cold [6]. However, no standard exists today that provide easy accessible information about the thermal conditions at the site of the worker or local cooling of finger and hands. Knowledge of the physiological responses of the workers can provide more exact information about the critical temperature limits for safe performance in cold environments. Safety of the workers is significantly affected when temperature decreases [8] and at the same time there is high cost associated with temporary shutting down e.g. a plant due to rough climate. Therefore, the need for using the right criteria to abort work is essential. We hypothesized that sensors can be integrated in clothing to provide information about ambient conditions and physiological parameters and be used as a tool to set physiological threshold limits for safe performance in the cold without disturbing the user. Previously a simple demonstrator jacket has been developed for concept evaluation [9]. The demonstrator provided easy accessible information about the thermal conditions at the site of the worker and local cooling effects of extremities, but had no activity sensors. Also, a more integrated and robust electronic system was necessary to enable more excessive testing including field testing. This paper presents the development of an improved demonstrator jacket with added functionality and gives the results from a test run in the work physiology lab at SINTEF. The aim of this study was to show that the new demonstrator jacket can provide information that may improve decision support for workers in cold climate.

II. Design and Test of Sensor System

A. Electronic sensor system and integration in jacket

When the human body cools, blood vessels in the extremities are constricted to reduce blood flow and heat loss. Local cooling of the extremities has a detrimental effect on manual performance [5], but minimizes the total heat loss and maintains temperature in core areas. A study performed on petroleum workers in cold conditions showed that finger temperature was an important indicator of hand and finger dexterity and that finger skin temperatures below 15°C resulted in impaired manual performance [7]. Real-time information about skin temperatures on hands and fingers could function as an early warning to prevent the risk of reduced manual performance and hence ensure safe and proper accomplishment of tasks. A sensor system should ideally be positioned in a glove close to the fingertip, but this is however challenged by the fact that the workers often take off their gloves when performing assignments requiring fine motoric precision. A demonstrator consisting of a working jacket from Wenaas (http://www.kwintet.com) with integrated physiological sensors and wireless communication to a handheld device was developed (Fig. 1). The sensor system has been integrated into the lower right sleeve. This position was chosen because it is close to the hand, but still

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avoiding extensive wear and tear and conflicts when carrying or lifting objects. A miniaturized, flexible and robust sensor module, IsenseU, suitable for integrating in clothing has been developed [10]. The sensor module includes activity sensors, an infra-red (IR) skin temperature sensor and the possibility of adding two external sensors such as combined humidity and temperature sensors. The sensor module uses wireless Bluetooth Smart communication and has been designed for low power usage. The activity sensor provides acceleration and rotational motion, heading information and free fall detection.

IsenseU was attached to a tightly fitted sleeve, integrated in the protective jacket, by Velcro. The IR sensor (IsenseU IR) was included in the sensor module for non-contact temperature of the upper hand/wrist and was thus facing the skin, but without physical contact. Two external Sensiron SHT21 sensors were used to measure temperature and humidity. One sensor was placed on the outside of the jacket (IsenseU Out) whilst the second sensor was placed inside the jacket (IsenseU In). In the previous demonstrator [9] the outside temperature measurements were influenced by heat from the person wearing the jacket. Here, this effect was reduced by adding a layer of a heat reflecting foil (Tyvek Reflective material from DuPont™) in the jacket lining on the inside of IsenseU Out. A layer of rubber material (1 mm HYPALON®) was in addition placed around the outer sensor in order to reduce the heat flux through the jacket in this area. IsenseU Out and In have been packed on textile by vacuum molding using biocompatible silicone [11][12]. Conductive yarn was used as wiring between the external humidity/temperature sensors and the main sensor module. After vacuum molding, the conductive yarn was coated with silicon (Fig. 1). IsenseU has been verified in the lab for wireless communication, battery capacity and splash protection. The flexible conductors have been tested in salt water and in cold environment. The whole sensor system has been verified in a climatic chamber (Angelantoni Sunrise 250 C) for the range -20°C to 25°C with relative humidity from 0% to 50%.

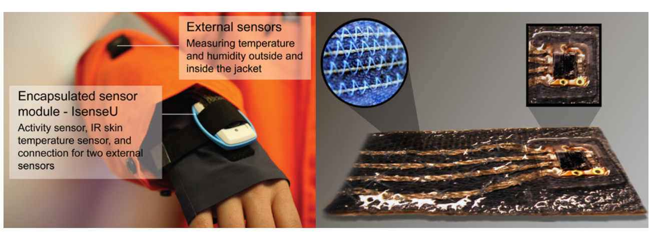

Figure 1 Jacket with IsenseU (left) and vacuum molded humidity and temperature sensors connected to flexible wires (right).

Table 1 Protocol (minutes after start) used in test of the demonstrator in the work physiology laboratory, subjective evaluation was performed at the end of each work period.

	Time (minutes after start)	
Description	**Start**	**Stop**
Rest in office environment	-30	0
Rest in cold chamber	0	15
Activity in cold chamber	15	30
Rest in cold chamber	30	45
Activity in warm chamber	45	60
Rest in cold chamber	60	75
Jacket off and left in cold chamber	75	90

Table 2 Reference sensors used in test of the demonstrator.

Reference sensors	Name	Position
Skin temperature: YSI 700, Yellow Spring Instrument, USA	YSI	Rectal, forehead, chest, upper arm, lower arm, right and left hand (Fig. 2), finger, abdomen, back, front thigh, back thigh and calf.
Humidity and temperature: HIH 360, Honeywell, USA	HIH	Right arm outside jacket (Fig. 2), right arm inside jacket, right arm inside underwear, outside underwear: chest, back and abdomen
Ambient humidity and temperature: Testo435, Testo, Germany	AHT	In the cold and warm chamber next to the treadmill, manual measurements

Figure 2 Location of YSI sensors on the hands (left picture) and location of HIH sensors compared to IsenseU Out (right picture).

III. Test of Demonstrator

The demonstrator jacket was tested in the work physiology laboratory at SINTEF using reference temperature sensors in warm (22°C / 50% relative humidity (RH)) and cold (-15°C) climatic chambers. One volunteer test subject (25 years, 182 cm, 60 kg) was fitted with thermistors, heart rate recorder (Polar Sports Tester (Polar Electro, Finland) and dressed with thin woolen underwear (Janus Pro Antiflame rib sweater and pants), the Wenaas demonstrator jacket and Wenaas plain trousers, beenie and wool mittens. The experimental protocol included periods of rest and moderate work chosen to simulate a petroleum worker's condition during parts of a day, varying between in-house and outdoor assignments. The work periods were performed by walking on a treadmill at 50-60% of maximal oxygen consumption, which is assumed to be realistic work intensity during hard outdoor work. This intensity will increase metabolic heat production and, especially in warm conditions, lead to profound sweating. An overview of the protocol is given in Table 1. The reference sensors used in the experiment (Table 2) included skin temperature sensors (YSI), wearable combined humidity and temperature sensors (HIH) as well as ambient temperature and humidity sensors (AHT). Subjective evaluation of thermal sensation and comfort was assessed using the scales described by Nielsen et al. [13] and measured seven times during the test. The evaluation on thermal sensation included the body, feet, hands, head and neck, questions on shivering/sweating and the overall thermal comfort of the test subject.

IV. Results and Discussion

A. Skin temperature measurements

Fig. 3 shows the skin and core temperature for the test subject measured by YSI sensors. During the first period of rest in cold environment the skin temperature dropped. For most sensors the decrease continued in the following cold activity period but for the finger there was a sudden increase in temperature towards the end of this period. The fluctuation in finger temperature can be explained by the physiological process of finger vasodilatation and constriction. This is the way the body controls the rate of heat exchange with the environment by regulation of the skin blood flow. The perceived thermal sensation correlated well with the measured temperatures of the body (not shown due to page limitation). Fig. 4 includes two of the graphs from Fig. 3 (YSI sensors right and left hand) and compares the hand skin temperature measured by IsenseU IR and the YSI sensors. It shows that there was a clear relationship that can be used as a tool to give early warnings of critical temperature limits for manual performance. This could represent an improvement compared to existing current international standards for work in cold environments.

There are however some small differences that must be taken care of in a decision support algorithm. In the start of the first period of rest in cold environment, the IsenseU IR sensor measured a slightly higher temperature than the YSI sensors. Additional testing (results not shown) indicates that this is partly due to different sensor location (Fig.2), and partly due to more insulation under the IsenseU sensor. The left hand temperature was higher than the right hand temperature and additional testing indicates that this was mainly due to different sensor placement (Fig. 2), but it might also be affected by different jacket sleeve design or physiological differences between the two hands. During activity in warm environment a decrease in temperature measured by IsenseU IR sensor was seen. A possible explanation can be that sweat might slightly affect the temperature measurement by IR sensors due to change in skin emissivity or if the sensor surface get contaminated by the fluid.

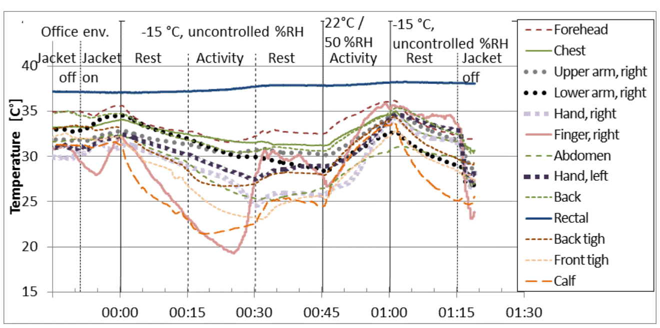

Figure 3 Skin temperature of the test subject measured by YSI sensors.

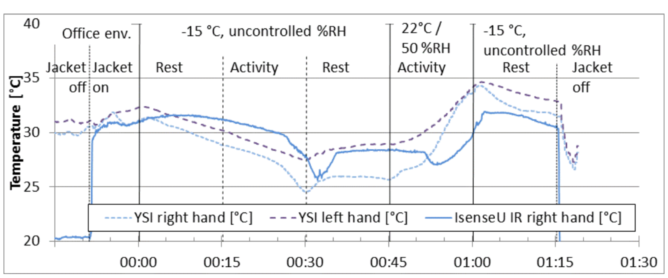

Figure 4 Skin temperature on the hands of the test subject measured by YSI and IsenseU IR. When the jacket was off the IsenseU IR sensor was measuring temperature in the jacket (emissivity ≠ 0.98).

B. Measurement of ambient conditions

In Fig. 5 the temperature and %RH measured by IsenseU Out are compared with HIH sensor data as well as the chamber settings. The temperature data follow each other closely. However, the response time of IsenseU Out was slower than the HIH sensors for both temperature and %RH. This was probably due to the different packing of the sensors: The HIH sensors laid "open" between two metal plates, and were thereby shielded from the jacket fabric with a small air gap. The IsenseU Out/In sensors were in contrast attached directly to the jacket fabric by vacuum molding and the opening of the humidity sensor were covered by a GORE-TEX® membrane [11]. The measured IsenseU Out temperature was approximately 4°C higher than the corresponding HIH sensor in the cold environment. It was thus clearly under influence of the temperature from the jacket/body, but the difference where considerable less than with the previous demonstrator. However, this difference must be compensated for in a decision support algorithm.

The %RH measurements by IsenseU Out and corresponding HIH sensor differed by approximately 15% in the cold environment. This might partly be an effect of the different temperature measurements. Also at lower temperatures the saturated vapour pressure is lower and small differences in amount of water in air will give relatively large changes in relative humidity. When entering the warm environment the HIH outside sensor saturated to 100% RH, probably due to condense. The IsenseU Out %RH sensor was more protected and did not saturate. However, the IsenseU Out sensor needed more time than the HIH outside sensor to decrease to correct level.

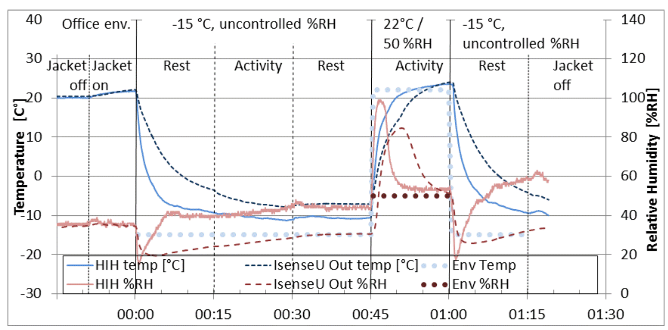

Figure 5 Measurements on the outside of the jacket of the test subject: Comparing IsenseU Out with corresponding HIH sensors and chamber settings.

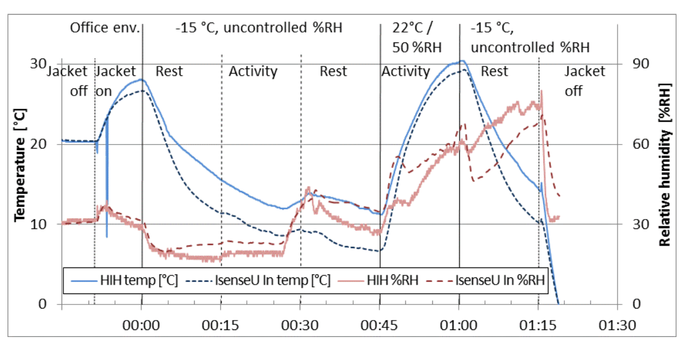

Figure 6 Measurements on the inside of the jacket of the test subject: Comparing IsenseU In sensors with corresponding HIH reference sensors.

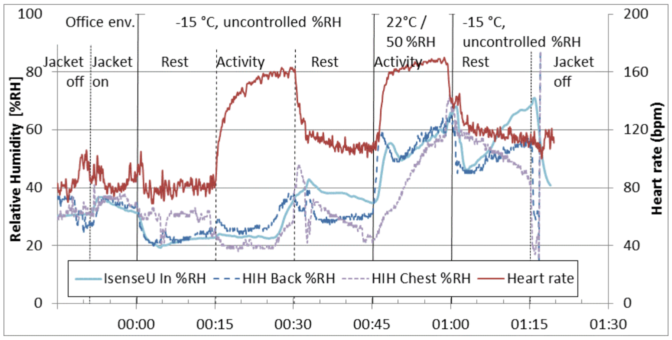

Figure 7 Heart rate and measured relative humidity for the test subject.

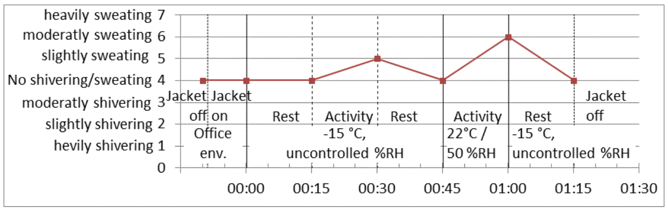

Figure 8 Subjective evaluation of perspiration from the test subject.

C. Measurement inside the jacket

Fig. 6 shows the humidity and temperature measurements inside the jacket; IsenseU In sensors are compared with corresponding HIH sensors. IsenseU In measured an overall lower temperature than the HIH sensor. IsenseU In was attached to the jacket lining and was therefore more affected by the lower jacket temperature than the HIH sensor which was isolated from the lining by a small air gap. This was supported by the results from the last test period: When the jacket was taken off and left in the cold chamber the two sensors measured the same temperature.

The relative humidity measured by IsenseU In, the HIH sensors at chest and back, as well as the heart rate, are plotted in Fig. 7. This figure together with a subjective evaluation of sweat (Fig. 8) indicates that the humidity sensor inside the jacket can be used as an indicator for perspiration. The start of perspiration during activity was easy to measure, the humidity increased fast. This was true in both chambers.

D. Activity and decision support

Fig. 9 shows the raw accelerometer data for the three individual axes (in g). The data correlates well with the activity according to the protocol in Table 1, hence it is possible to use this data as well as data from the gyroscope and the digital compass in sensor fusion algorithms to

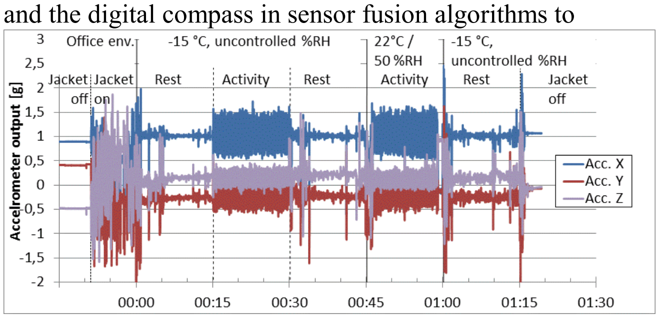

Figure 9 Accelerometer data (g) in all three directions from IsenseU integrated in the right arm of the jacket of the test subject.

distinguish between work, rest periods and risk related movements, as well as assessing work load. The activity sensors are monitoring the position of the right wrist of the test subject, this position must be kept in mind while developing algorithms for detecting risk related movements.

V. Conclusion

This study showed that the demonstrator provided easy accessible information about the thermal conditions at the site of the worker and local cooling effects of extremities. There was a clear relationship between the reference temperature at the hands and IsenseU IR measurements that can be used in the future as a tool to give early warnings of critical temperature limits for manual performance. The demonstrator has the ability to distinguish between activity and rest and more sophisticated sensor fusion algorithms might be implemented to assess work load and activity. All this information can be used in an enhanced safety perspective, as an improved tool to advice outdoor work control for workers in cold climate and thereby represent an improvement compared to existing current international standards.

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