EFFECTS OF MULTILAYER CLOTHING SYSTEM ON TEMPERATURE AND RELATIVE HUMIDITY OF INTER-LAYER AIR GAP CONDITIONS IN SENTRY COLD WEATHER CLOTHING ENSEMBLE

Andrii Kurhanskyi[1], Sergij Bereznenko[1], Dmitriy Novak[1], Myroslava Kurganska[1], Vasyl Sakovets[2], Natalia Bereznenko[1] and Olga Haranina[1]

[1]Kyiv National University of Technologies and Design, N.-Danchenko 2, 01011 Kyiv, Ukraine
[2]Ministry of Defence of Ukraine, Melnykova 81, 04050 Kyiv, Ukraine
novak.knutd@gmail.com, kurganskij.av@knutd.edu.ua

Abstract: *The cold effects on sentry and the inter-layer air gaps microclimate conditions in cold weather multi-layer clothing ensembles used by the Armed Forces of Ukraine was analyzed. Comparative testing of two outer item variations for sentry cold weather clothing ensembles was conducted by human trials (n=10) and wireless body area network IBK3.4 in real time at a temperature of -18±1°C, a relative humidity of 15±10% and a wind speed of 5-10 m/s. The basic parameters of the upper inter-layer air gap microclimate of multilayer clothing system were obtained under real usage conditions. In order to improve outer item design and material the optimization of temperature and relative humidity sensor measurement points suggested. The results are significant for predicting of the maximum sentry comfort time and for optimization of a quantitative and qualitative composition of the wireless body area network sensors.*

Keywords: *multi-layer, clothing ensembles, sentry, cold, temperature, relative humidity, membrane, wireless body area network, microclimate.*

1 INTRODUCTION

A significant effect on reducing sanitary losses of dismounted soldiers from cold injuries (e.g., frostbite and hypothermia) are given by the use of multi-layer cold weather clothing ensembles as part of united personal combat ensembles (UPCE) which includes various item types of clothing, footwear and combat body armor etc.

The cold weather clothing ensembles ensures fulfillment of two tasks: increase of the effectiveness of soldier actions on the battlefield and lifesaving measures for the soldier. The concept of separation of combat and auxiliary equipment is the soldier must have with him all necessary equipment for a successful battle. The application of the concept of combat and auxiliary equipment separation has allowed reducing the equipment weight and increasing the soldier mobility. In addition, be able to combine different types of ammunition depending on the task type.

The modern UPCE for the Armed Forces of Ukraine (AFU) is modular and composed of standardized units to achieve maximum single soldier adaptability to various mission needs and environmental conditions [1]. The modern cold weather clothing ensemble (CWCE) is the part of UPCE used be AFU. Furthermore, improving the structure and requirements for CWCE had not scientifically justified, the most outdated USSR GOSTs and material manufacturer experience used [2]. The developers of existing military cold clothing systems was not reliably assessed the consumer attitudes about fabrics and clothing with appropriate psychometric techniques or conjoint analysis [3].

Additionally, the participation of people as subjects in the human trials requires their appropriate selection and requirements consideration for the repeated cycle of studies. The characterization of human traumas associated with cold processes is rather complicated; reactions to cold have a higher individual variability than reactions associated with heat transfer [4]. The clothing parameters are static and do not sufficient to describe the processes of heat and mass transfer from the skin through clothing to the environment. In addition, changing environmental conditions, human physical activity, moisture absorption, condensation, and vice-versa processes in clothing take affect the transfer processes [5, 6]. Also, modified textile materials exhibit improved functional properties as for example in [7]. In view of this, the further interest to implement such type textile materials in the manufacture of modern clothing systems.

Therefore, the integration of monitoring elements into clothing allows correcting the prediction and monitoring of the temperature state of the human body and its estimation in real time, which in turn can be a complement to the open body area network of physiological status monitoring (PSM) [8] and Warfighter Physiological and Environmental Monitoring [9, 10]. The CWCE items should be assembled as a complete ensemble designed for the specific conditions to be encountered such as environmental conditions and level of the physical activity [11, 12] spatially on the battle-field for frontline troops. The development of modular multi-layer ensemble for maximum protection requires the availability of heat and moisture transfer, biophysical and mechanical layer data variation for each ensemble entirely and for clothing items separately. An effective clothing ensemble is one that body could lose sufficient heat as the clothing design and the type of fabric does not restrict heat loss in some way [13].

2 EXPERIMENTAL PART

2.1 Setting the task

Certain types of duties of sentry and officers are required to stationed to keep guard with significant adverse effects of cold and wind on guard. The cold exposure effects on dismounted soldier performance are not entirely known [14]. For this purpose, a personal cold weather clothing system should offer greater protection against the elements whilst on guard. Currently, the fur coat, also well known as tulup, was developed for sentry protection. Fur coat is not a product of mass production, due to the curtailment of production at the base enterprises in the period 2014-2017. Therefore, the question of finding alternative clothing for protection of low-activity sentry from the cold has arisen.

3 MATERIALS AND METHODS

The fur coat alternative was chosen a waterproof and windproof long winter jacket X9.2 with a direct silhouette, hood, membrane laminated basic fabric, thermal insulation and sentry coat X9.1 with a direct silhouette, artificial fur insulation. Table 1 shows the characteristics of the entire AFU cold weather ensembles E1 and E2, its items and segmental division.

Total 10 cold weather ensemble items were selected in the established order. The upper layer items X9.1 and X9.2 are variable. Fabric characteristics of outer CWCE item are shown in Table 2.

The human trials were used to simulate the outdoor exercises for the sentry in the climate chamber. The research conducted in two steps according to the protocol (Figure 1) during the time 80 min, of which: 20 min - seats at a temperature of 20±0.5°C and a relative humidity of 58±4%; 60 min - walking up to 2 km/h at a temperature of -18±1°C, a relative humidity of 15±10% and a wind speed of 5-10 m/s.

Table 1 Characteristics of AFU cold weather ensembles and segmental division

Item code	Type of ensemble item	Structure of the ensembles		Segment number [15]
		E1	E2	
X4	Winter hat	+	+	S1
X10	Winter waterproof and windproof trousers	+	+	S6-S10-S11-S12
X13	Winter gloves	+	+	S9
X15	Winter scarf-pipe	+	+	S2-S3
X18, X19	Linen for cold weather (winter shirt and winter pants)	+	+	S4-S5-S6-S7-S8-S10-S11-S12
X21	Winter socks (trekking)	+	+	S13
X28	Winter combat boots	+	+	S12-S13
X7	Insulation suit jacket (fleece jacket)	+	+	S3-S4-S5-S6-S7-S8
X27	Ballistic helmet	+	+	S1
X9.1	Sentry coat	+	-	S3-S4-S5-S6-S7-S8
X9.2	Long winter jacket	-	+	S1-S3-S4-S5-S6-S7-S8

Table 2 Fabric characteristics of outer layer items of AFU cold weather clothing ensembles

Code of the ensemble	Type and code of the item	Type of fabric	Fibrous composition [%]	Normative values		
				Surface density [g / m^2]	Air permeability [dm^3/m^2.s]	Hygroscopicity [%]
E1	Sentry coat X9.1	Basic	65 CO, 35 PES	260	> 20	> 10.0
		Lining: Hair material Basis material	Artificial fur: 20 PE, 80 PAN 100 PES	320	-	> 1.5
E2	Long winter jacket X9.2	Basic	100% PA 6.6 +membrane 100% PTFE+PU	220	> 20	> 6.0
		Thermal insulation	100 PES	135	> 50	> 6.0
		Lining	100 PES	110	-	-

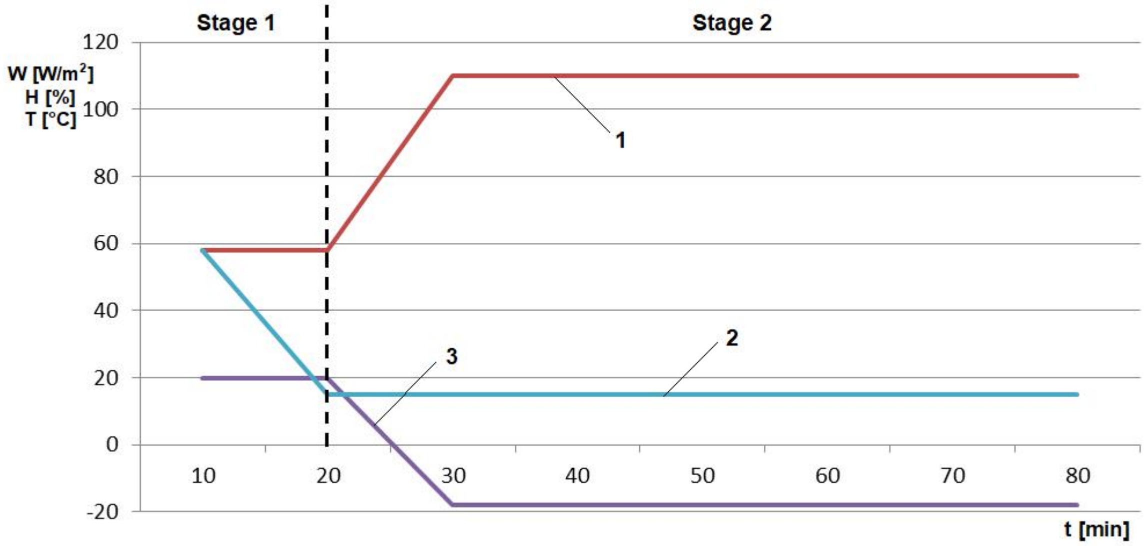


Figure 1 The protocol of comparative testing:
1 - energy costs of the subject *W*; 2 - relative humidity of the environment *H*; 3 - ambient temperature *T*

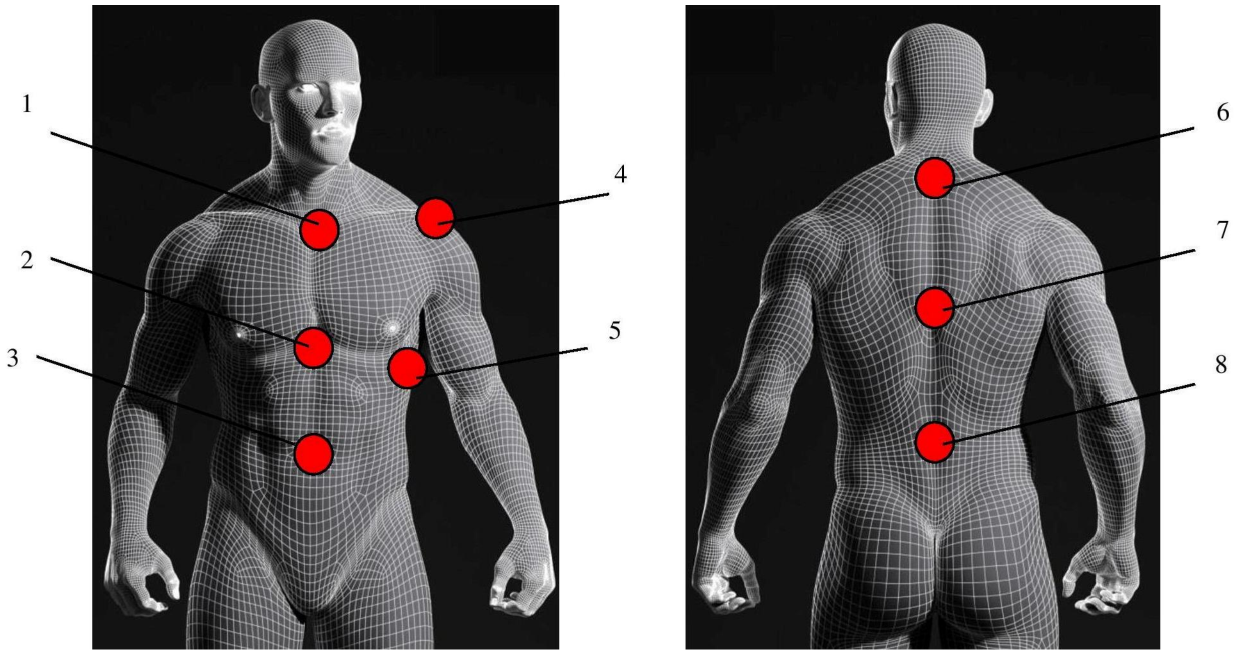


Figure 2 Schematic of the eight-point DT sensors location for IBK3.4 modules

The human trials were conducted with 10 volunteers (n=10). The volunteers are characterized by: age 45.5±1.5 years (16650.5±560.5 days), height 179.5±3.5 cm, weight 95.5±5.5 kg, breast circumference 110±1 cm, waist circumference 109.5±4.5 cm. The research and methodology have been selected in such a way that it is possible to use personal wireless systems in a reliable space to evaluate the biophysical properties of new CWCE samples [16]. According to the protocol, the volunteers were dressed in the ensemble for 20 minutes to stabilize the upper inter-layer air gap microclimate conditions.

The wireless measurement system (WBAN) IBK3.4 and software WBIM Soft 6.0 and WBIMSoft Core Analytics was chosen to conduct the research [16]. The system is easy to use and rugged enough to sustain the harshest environments.

The structure of the wireless body area network (WBAN) consisted of 4 remote modules with 4 dual-type sensors (DT sensors) in each [17]. The use of the system allows obtaining parameters of the inter-layer air gaps such as temperature and relative humidity in real time. The 8-point model of the location of DT sensors was selected for the studies (Figure 2) [18]. Additionally, further expansion of areas for measuring of the inter-layer air gaps microclimate parameters is possible due to the wider use of conductive polymers in the structure of fabric layer [19].

A multi-layer clothing system is developed and integrated with the human model based on [20, 21] with a coupled heat and moisture model of clothing materials for body element S4 (Figure 3).

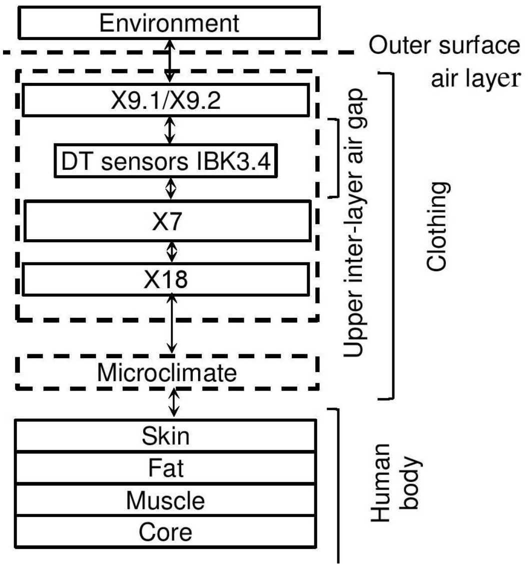


Figure 3 Human body-clothing-environment system for covered body segment S4 by cold weather clothing ensemble and for point 2 of DT sensors location

4 RESULTS AND DISCUSSION

Accordingly to [22] the classification of effects air gap characteristics for each point of DT sensors IBK3.4 were evaluated in Table 3.

The DT sensors (temperature and relative humidity) of the selected system were located over a thermal or sweat-wicking layer on insulation suit jacket X7 [18].

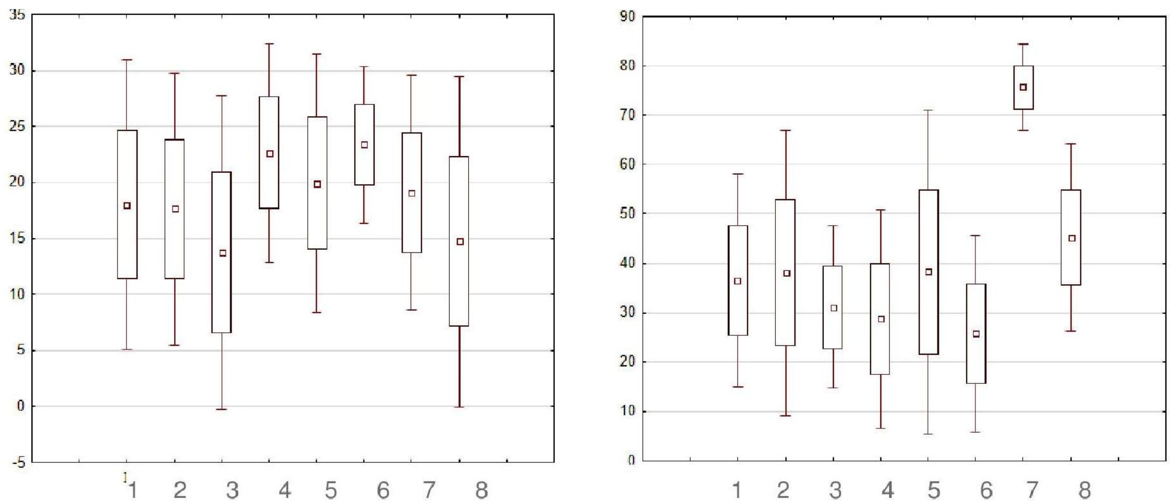
The second half part (30 min.) of step 2 in the research is determining according to the established procedure. The averages and standard deviation diagrams of temperature and relative humidity in the eight sensor points of the ensemble upper inter-layer air gap were plotted in the Figures 4 and 5.

As is shown in Figures 4 and 5, the average temperature values in eight points of the upper inter-layer air gap varied in the range 14-24°C for the E1 ensemble and 21-25°C for the E2 ensemble. The average relative humidity values varied in the range of 25-75% and 15-73% accordingly. The magnitude of the root-mean-square deviation of temperature and relative humidity for the E2 ensemble is significantly smaller than for E1 ensemble. The long winter jacket, unlike the sentry coat, creates conditions that are more comfortable and minimizes the temperature and relative humidity drops at different points of the upper inter-layer air gap.

The step 2 analysis shows that the presence of waist drawstrings in the long winter jacket allowed increasing the temperature for 47.94% at points 1, 2, 3 and 7 that completely leveled in the jacket design. Also, the temperature was 25% higher for the jacket due to the rack collar in the point 8 of the long winter jacket. The considerable elongation of the sentry coat and the absence of constructive restriction of air movement led to temperature decrease at the lower measurement points, which was not compensated by the heat production of the subject's movements. As is shown in Table 4, the moisture accumulation was decreased by 11% due to the use of the basic fabric laminated by the membrane for the jacket.

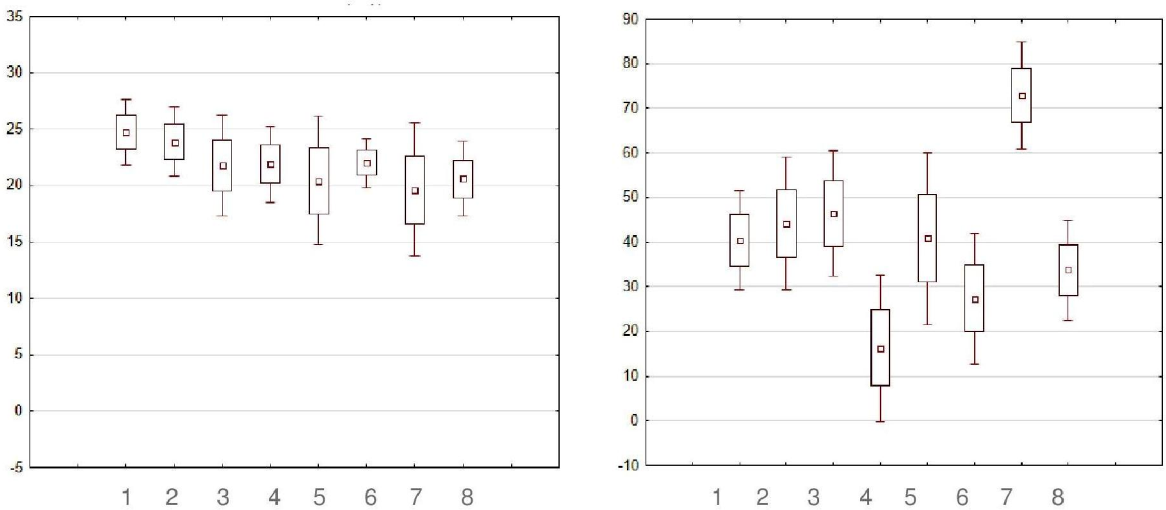
Table 3 The classification of air gap characteristics for each point of DT sensors IBK3.4

Code of point	Traits			Orientation	Dynamics
	Thickness	Location	Heterogeneity		
1	Variable	In clothing layers	Non-uniform thickness	Horizontal	Induced by human body motion
2	Constant		Non-uniform thickness		Induced by human body motion
3	Variable		Contact area		Induced by human body motion
4	Variable		Contact area	Vertical / Inclined	Induced by fabrics
5	Variable		Contact area	Horizontal	Induced by human body motion
6	Constant		Non-uniform thickness		Induced by fabrics
7	Constant		Contact area		Induced by fabrics
8	Variable		Non-uniform thickness		Induced by human body motion



a) b)

Figure 4 Comparison of mean values and root-mean-square deviation of temperature T (a) and relative humidity H (b) in eight sensor points of the upper inter-layer air gap in the E1 ensemble



a) b)

Figure 5 Comparison of mean values and root-mean-square deviation of temperature T (a) and relative humidity H (b) in eight sensor points of the upper inter-layer air gap in the E2 ensemble

Table 4 Comparison of E1 and E2 ensemble

Code of the ensemble	The number of the sampled signals obtained from sensors	The average value		The minimum value	
		T [°C]	H [%]	T [°C]	H [%]
E1	19688	14.4	34.1	7.52	11
E2	12000	17.7	32.5	10.3	12

4.1 Optimization of the quantitative composition of the microclimate dynamics indicators

The Pearson correlation matrix was constructed to establish the relationship between temperature and relative humidity. The matrix analysis showed that some parameters were correlated at a significance level of 0.95. Therefore, it is advisable to minimize the number of sensor measurement points to reduce the required time to perform measurements and calculations. Conditionally we divide the upper inter-layer air gap into three groups: front (1, 2 and 3 points), side (4 and 5 points) and back (6, 7 and 8 points).

The DT sensors located in the front of the jacket and sentry coat correlate with each other in temperature and relative humidity. Therefore, points 1 and 3 cannot be used and we focus on the point 2, which is located in the middle of the front upper inter-layer air gap.

The side-sensors have a temperature correlation for the jacket and sentry coat but do not correlate with the relative humidity for the sentry coat, so it is necessary to use points 4 and 5 of sensor data. The sensor point 6 for temperature and relative humidity correlate with point 8 for the back of the jacket and sentry coat. The points 7 and 8 do not have correlation dependence with the relative humidity index for the jacket; therefore, it is advisable to use the points 7 and 8. Therefore, for further research on the eight points that were used in the previous step, we can use the points 2, 4, 5, 7 and 8. The regression equations were determined for sensors 1, 3 and 6, which have been eliminated (Figures 6 and 7).

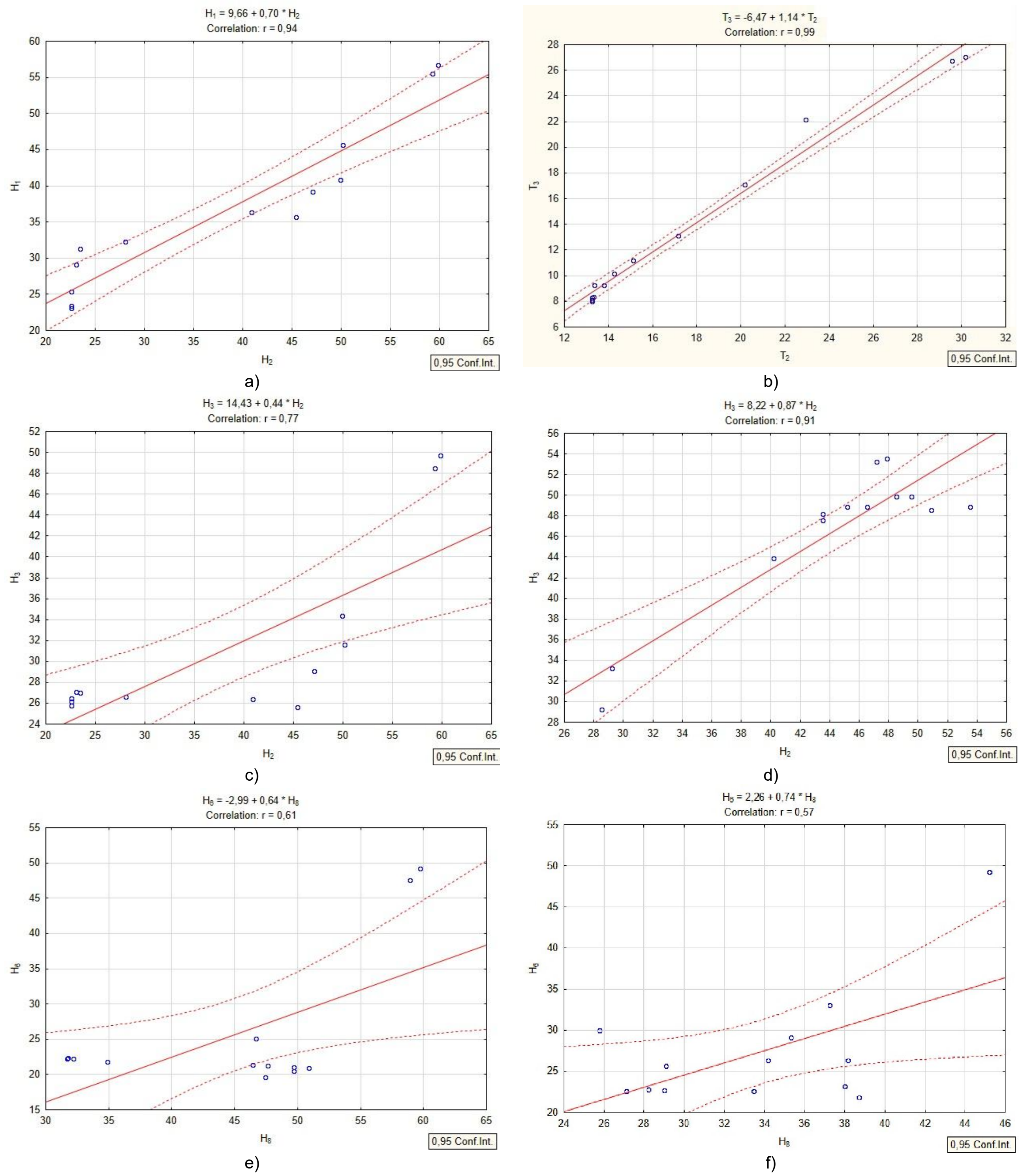


Figure 6 The regressive models of the relative humidity at given measurement points: a, c, e - E1 ensemble; b, d, f - E2 ensemble

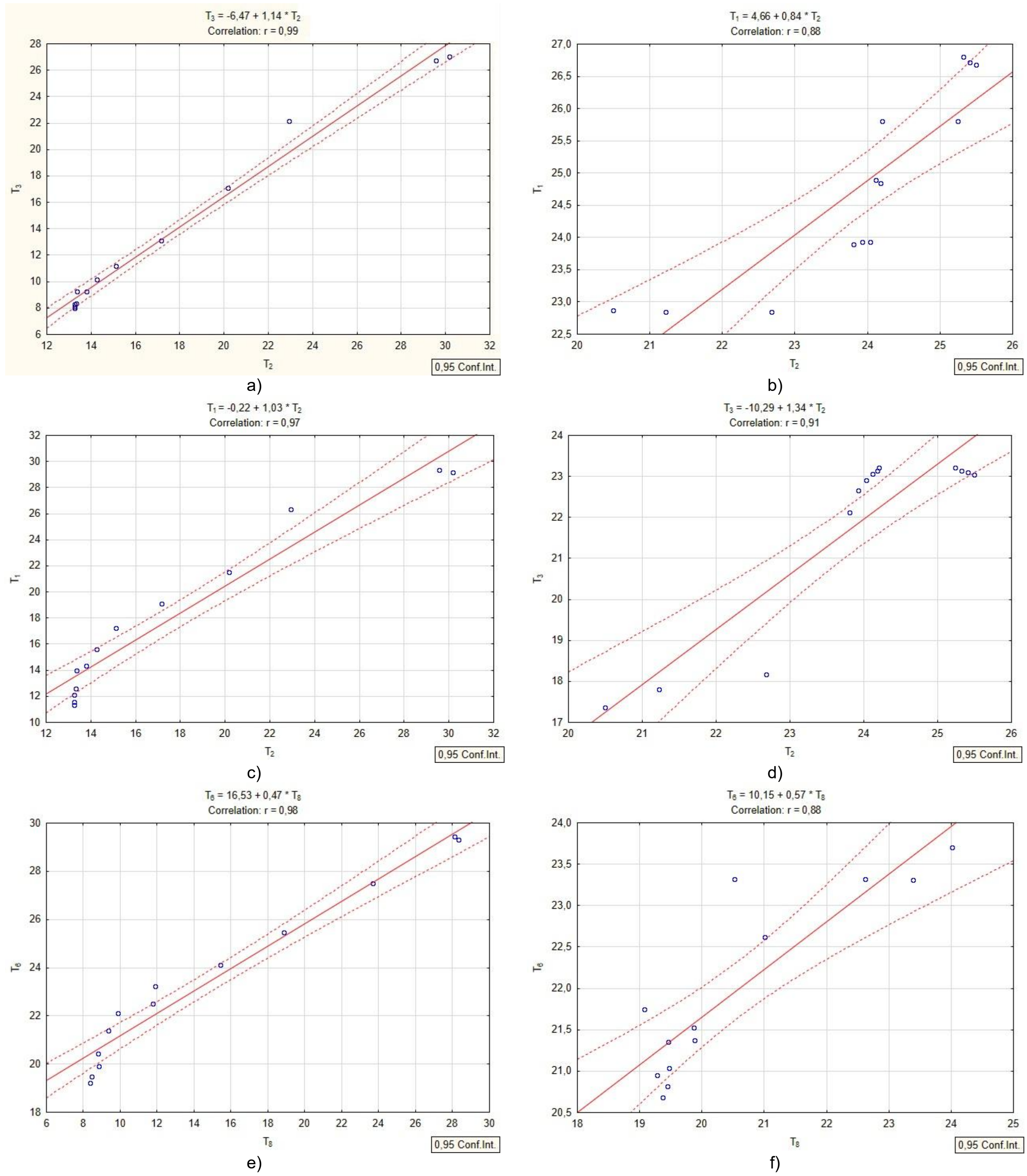


Figure 7 The regressive models of the temperature dependencies at given measurement points: a, c, e - E1 ensemble; b, d, f - E2 ensemble

5 CONCLUSIONS

To conclude, the tests of studies of various samples of the upper layer of the cold weather clothing ensemble on volunteers in a climate chamber showed a significant influence of the outer_layer item on the temperature dynamics and relative humidity of the inter-layer air gaps microclimate.

The E2 ensemble has an average temperature value of 18.6% and a relative humidity 4.9% lower in the upper inter-layer air gap compared to the sentry coat. The minimum value of the temperature for E1 ensemble is 27% lower and the relative humidity is 8.3% lower than for the E2 ensemble.

The finding reported can be used by developers of military clothing systems to better understand microclimate dynamics (e.g., temperature and relative humidity) of inter-layer air gaps. Thus, in future studies, it is advisable to pay considerable attention to the volume and mass optimization of the cold weather clothing ensemble and influence on inter-layer air gaps parameters.

***Acknowledgment**: The research was supported by the project through the financial support of the Ministry of Education and Science of Ukraine registration number 0117U007237. In addition, the views, opinions, and findings in this paper are those of the authors and should not be construed as an official Ministry of Defence of Ukraine position or decision unless so designated by other official documentation.*

6 REFERENCES

1. Giesbrecht G.: Cold weather clothing, Accessed: 2018-07-18, Available from: https://www.umanitoba.ca/faculties/kinrec/hlhpri/media/Cold_Weather_Clothing.pdf
2. Kurhanskyi A., Sakovets V.: Predicting thermophysiological comfort limits to simulate the personal protective equipment abilities, Proceedings of Naukovi rozrobky molodi na suchasnomu etapi, September 2017, KNUTD, Kyiv, pp. 97-98
3. Schutz H.G., Cardello A.V., Winterhalter C.: Perceptions of fiber and fabric uses and the factors contributing to military clothing comfort and satisfaction, Textile Research Journal 75(3), 2005, pp. 223-232, https://doi.org/10.1177/004051750507500307
4. Potter A. W. et al.: Comparison of cold weather clothing biophysical properties, US Army, Canadian Department of National Defence, and Norwegian Military, US Army Research Institute of Environmental Medicine Natick United States, 2018
5. Xu X., Werner J.A.: A dynamic model of the human/clothing/environment-system, Applied Human Science 16(2), 1997, pp. 61-75
6. Kurganska M., Bereznenko S., Pavlova M.; Vasylenko V.: Effects of physical properties of clothes on parameters of the microclimate layer, Bulletin of KNUTD 110(3), 2017, pp. 77-82
7. Garanina O.: The development of scientific foundations for the finishing of textile materials, taking into account the nanostate of dyes, Qualifying scientific work on the manuscript, The dissertation for the degree of doctor of technical sciences, specialty 05.18.19 - technology of textile, garment and knitwear, Kyiv National University of Technology and Design, Kyiv, 2017
8. Tharion W.J., Hoyt R.W.: Form Factor Evaluation of Open Body Area Network (OBAN) Physiological Status Monitoring (PSM) System Prototype Designs, US Army Research Institute of Environmental Medicine Natick United States Vol(18-06), 2018
9. Oviatt C.M.: Perception vs. Reality: Improving Mission Commander Decision Making Capabilities by use of Heart Rate Zone Feedback in Training Environments, Air Force Institute of Technology Wright-Patterson AFB United States, 2017
10. Kutilek P. et al.: Wearable systems and methods for monitoring psychological and physical condition of soldiers, Advances in Military Technology 12(2), 2017, pp. 259-280
11. Das A., Alagirusamy R., Kumar P.: Study of heat transfer through multilayer clothing assemblies, AUTEX Research Journal 11(2), 2011, pp. 54-60, http://www.autexrj.org/No2-2011/5_0013_11.pdf
12. Marszałek A., Bartkowiak G., Dąbrowska A.: Assessment of the effectiveness of modular clothing protecting against the cold based on physiological tests, International Journal of Occupational Safety and Ergonomics, 2018, pp. 1-12, DOI:10.1080/10803548.2017.1376927
13. Birnbaum R.R., Crockford G.W.: Measurement of the clothing ventilation index, Applied Ergonomics 9(4), 1978, pp. 194-200, https://doi.org/10.1016/0003-6870(78)90079-0
14. Tikuisis P., Keefe A.: Effects of cold strain on simulated sentry duty and marksmanship, Aviation, space, and environmental medicine 78(4), 2007, pp. 399-407
15. Lotens W.A., Havenith G.: Calculation of clothing insulation and vapour resistance, Ergonomics34(2), 1991, pp. 233-254, https://doi.org/10.1080/00140139108967309
16. Kurhanskyi A.V., Vasylenko V.M., Kurganska M.M., Sakovets V.V.: Remote monitoring system for microclimate and pressure in real time based on native touch networks, Bulletin of the Kyiv National University of Technologies and Design 108(2), 2017, pp. 114-119
17. Kurganska M.M., Vasylenko V.M., Kurhanskyi A.V., Sakovets V.V., Maliy A.O., Opanasenko K.V.: Prediction of dynamic characteristics of thermal insulation properties of winter clothing sets, Bulletin of the Kyiv National University of Technologies and Design 112, 2017, pp. 82-88
18. Bogdan A., Zwolińska M.: Future trends in the development of thermal manikins applied for the design of clothing thermal insulation, Fibres & Textiles in Eastern Europe 20(4), 2012, pp. 89-95
19. Novak D., Budash Y., Bereznenko N.: Graphic modeling of conductive filler spatial distribution in polymer matrix, Vlakna a Textil (Fibres and Textiles) 23(2), 2016, pp.37–42
20. Stolwijk J., Hardy J.: Control of body temperature, Comprehensive Physiology, 2010, pp.45-68, https://doi.org/10.1002/cphy.cp090104
21. Wan X., Fan J.: A transient thermal model of the human body–clothing–environment system, Journal of Thermal Biology 33(2), 2008, pp. 87-97, https://doi.org/10.1016/j.jtherbio.2007.11.002
22. Deng M., Wang Y., Li P. Effect of air gaps characteristics on thermal protective performance of firefighters' clothing: A review, International Journal of Clothing Science and Technology 30(2), 2018, pp. 246-267, https://doi.org/10.1108/IJCST-07-2017-0103