New Approaches to Thermal Protection Wetsuits Development for Long-distance Swimmers Competing in Open Water

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Abstract: The article provides analysis of modern views on the development of thermal protection wetsuits for swimmers competing in open water. Requirements to generation of the predictive model of wetsuits are assessed in order to determine thermal characteristics of materials to be used to manufacture these wetsuits. Requirements to the simulating model are provided according to modern methods of assessment of thermal properties of material and physiology of athletes competing in open water. It is determined that due to many structural designs, features, thermogenesis dynamics and other devices' indices, the most promising method of experimental assessment of wetsuit materials' thermal characteristics is a use of thermal manikins. The article provides classification of modern thermal manikins and their parameters for manufacture of wetsuits.

1 INTRODUCTION

Development of promising, more ergonomic prototypes of wetsuits for marathon swimmers and their practical significance at the current stage of sport development consist in objective necessity for arranging of more comfortable conditions for their training and competitive activity. Objective necessity for improvement of existing wetsuits for swimmers who compete in open water is also related to the necessity for development of corresponding materials in order to improve competitive result and thermal characteristics. Currently, within the wetsuit quality indicator system, hygienic indicators are the most significant, they determine swimmer body thermal status, depend on heat and gas exchange between the body "envelope" and environment that is the entity of thermal regulation during training and competitions. Artificial microclimate should be created between athlete's body and wetsuit envelope; it provides comfortable conditions for vital activity of a swimmer, with minimum stress of thermal regulation function.

The recent studies show that application of modern wetsuit thermal characteristic assessment methods ensures the most accurate selection of materials for wetsuit manufacture (Abramov and Rodicheva, 2009, Abramov and Rodicheva, 2012, Bohuslavska et al., 2017). With that, application of thermal manikins enables to avoid involvement of volunteer testers for physiological and hygienic assessment of the sportwear sets to be created, thus significantly reducing financial expenses and excluding subjective factors.

2 ORGANIZATION AND METHODS

The main study method is predictive simulation modelling carried out according to modern methods of assessment of material thermal properties and physiology of athletes competing in open water. Analysis includes current methods of material thermal characteristics assessment for manufacture of sportwear.

Current approaches to selection of materials for wetsuits enable to predict thermal exchange process in the "swimmer – wear – water medium" system, using mathematical models (Abramov and Rodicheva, 2012, Bakayev and Bolotin, 2017, Bolotin and Bakayev, 2017a, Bolotin and Bakayev, 2017b). The purpose of mathematical prediction of "swimmer – wear – water medium" system

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condition is development of the thermal regime mathematical model for this system taking into account all existing factors of water medium, competitive activity specific features of athletes competing in open water, their physiology and heat-regulating structures principles (Bolotin and Bakayev, 2020, Gayvoronskiy et al., 2014, Zakharova and Mekhdieva, 2016). We have developed generalized algorithm that is used when building these mathematical models:

1st stage: preparation of the predictive model design geometry.

2nd stage: description of thermal exchange processes of swimmers within the fragment and on its boundaries. Calculations can be carried out using thermodynamic relations or in differential form.

3rd stage: setting of physical, initial and boundary conditions of the model that consider process features conditioned by interaction between materials and athlete's body and water medium.

4th stage: numerical solution of equations taking into account physical, initial and boundary conditions.

5th stage: visualization the results of basic solution complex for the predictive model.

3 RESULTS

Calculation results are represented as specific temperature distributions in materials or as temperature or heat flow field distribution. When carrying out further calculations or assessment of swimmer thermal state, average values can be used. Field distribution shows dynamics of the processes under consideration and, to a better degree, enables to determine influence of the considered material set option on thermal exchange processes within the "swimmer – wear – water medium" system. Generalizing modelling features at each of specified stages, the whole range of thermal exchange mathematical models is subdivided into the following models:

1. Predictive models for calculating thermal exchange within the "swimmer – wear – water medium" system under conditions of steady-state thermal exchange. In order to describe thermal exchange in materials and their boundaries these models apply thermodynamic relations.

2. Mathematical simulation models to calculate thermal exchange within the "swimmer – wear – water medium" system under conditions of dynamic thermal exchange. In order to describe a thermal exchange in multi material stacks and at their boundaries these models apply differential equations. This enables to consider thermal properties of materials for wetsuits and water medium parameters when carrying out calculations.

Predictive models that apply thermodynamic relations are mainly applicable to calculation of thermal exchange in stacks of traditionally used materials. As design geometry in these models, vertical section of material package is used that was initially proposed by Kolesnikov P. A. (1971) for rectangular and cylindrical geometry (Figure 1).

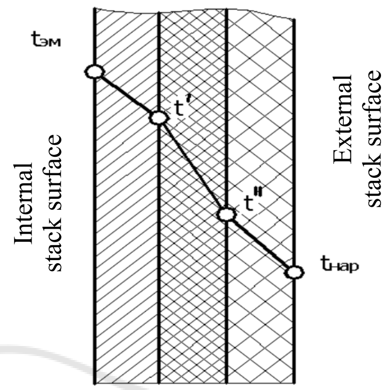

Figure 1: Design geometry of the classical predictive model of thermal exchange in the material stacks.

Thermal exchange processes in these options of the design geometry are described using original interpretations of classical Fourier, Stefan – Boltzmann, Newton – Richmann thermal exchange laws. The main disadvantages of predictive models for calculation of thermal exchange within the "swimmer – wear – water medium" system under conditions of steady-state thermal exchange are:

1. Computation is carried out with constant values of thermal properties of materials that does not enable to consider dynamics of improved properties of the modern materials.

2. The model considers water temperature and water current velocity. At the same time, objective data of the thermodynamic relations provided are not considered.

Thus, predictive models within the "swimmer – wear – water medium" under steady-state thermal exchange can be used to calculate thermal exchange between an athlete and water medium under moderate and severe cold conditions, when variation of conditions in the "swimmer – wear – water medium", can be conditionally considered as neglectable. Methods of simulation mathematical modeling, that use differential equations enable to carry out multiple computations under various initial conditions that provides the possibility of more detailed modeling of operational efficiency of wetsuit thermal properties at dynamic conditions of thermal exchange.

Application of these methods provides wide range of mathematical models of thermal exchange in material package. For example, computer model “Computational Bioengineering System for Thermal Functional Design of Textile Products” enables to carry out calculations taking into account wide range of factors (Lijing, 2008). Introduction of input parameters for each subsystem of the “swimmer – wear – water medium” integrated system provides qualitatively efficient interface form. The list of environment parameters is provided for the following factors: water temperature, current water velocity. The program enables to set wide range of physiological parameters of athlete’s organism that determine his/her level of thermogenesis. Physical properties of materials are set as functions and tables that enables to better consider dynamics of new material improved properties in case of variation of thermal exchange conditions within the “swimmer – wear – water medium” system. Predictive simulation models of thermal exchange in the material package are combined with mathematical models of thermal exchange of a swimmer that enable to present body morphology and influence of organism thermal regulation mechanisms in order to obtain more accurate results.

Currently, attempts to describe thermal exchange processes within the “swimmer – wear – water medium” system are made taking into account athlete's body morphological traits or its individual elements.

“Human thermal comfort model”, proposed by the specialists of National Renewable Energy Laboratory is one of the most elaborated mathematical models of human body thermal exchange taking into account thermal regulation mechanisms (Farrington et al., 2004). Its geometry is three-dimensional and assumes exact representation of morphology of each human body layer. Model representation of a leg in the area of human thigh is shown in Figure 2.

This model considers all body features accurately enough, that is achieved by using of about 40,000 nodes in the calculation. When carrying out calculations, material stack of the sportwear set under consideration can be represented fully enough.

It is reasonable to define materials thermal conductivity value using one of the methods of the below-stated classification of experimental studies of their thermal properties.

1. By the type of the thermal exchange condition to be modeled within the “swimmer – wear – water medium” system:

- Methods based on the steady-state condition principles.
- Methods based on the dynamic condition principle, that, in turns, are subdivided into unsteady-state and quasi steady state conditions.

2. By configuration of the sensing element:

- Methods that use a flat sensing element.
- Methods that use a cylindrical sensing element.
- Methods that use spherical sensing element.
- Methods that use a sensing element that is very similar to swimmer body morphology in terms of configuration.

The last group of methods includes application of thermal manikins that are characterized by wide variety of structural design, structural features, thermogenesis dynamics and other indicators.

Therefore, there was a proposition on the following generalized classification of modern thermal manikins:

1. By quality of temperature field representation on a surface, low-segment and multi-segment thermal manikins are distinguished.
2. By type of processes to be modeled general and “perspirable” thermal manikins are distinguished.
3. By parameters of dynamics static, “swimming” and “breathing” thermal manikins are distinguished.

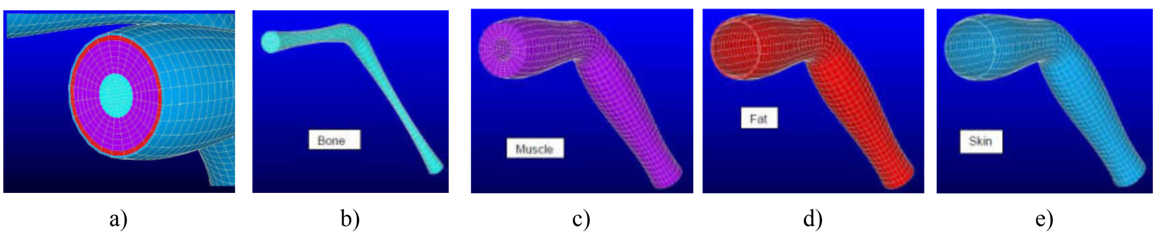

Figure 2: Model representation of a human body as a system of nested cylindrical envelopes in the human thermal exchange model of NREL (a – model representation of a leg in the area of a thigh; b – bone tissue model representation; c – muscle layer model representation; d – subcutaneous tissue layer model representation; e – skin model representation).

Thermal manikin is a thermal model of a human body where the following is represented accurately enough:

- human body organization morphological features;
- features of heat generation processes within the volume of a thermal manikin taking into account variable intensity of the work to be performed;
- features of the process of heat dissipation from a body surface.

There are two main components required to be distinguished in the thermal manikin structure: external envelope and automation system located inside (Figure 3). The thermal manikin envelope consists of individual segments each of which is an independent and finished node that differs from other segments by external shape. The segment of modern thermal manikins is equipped with a heater, temperature gauge and heat meter connected with the automated system. Heater operation mode is controlled by the automated system on the basis of difference between temperature gauge readings and the target temperature value set in the program. A heat meter enables to measure amount of heat consumed to maintain the set temperature. The segment of "perspirable" thermal manikins is equipped with the nozzles that supply fluid simulating body perspiration.

The thermal manikin automation system is equipped with software packages that regulate heating and nozzle operation modes for each segment depending on its location. Segments can have various sizes and configuration that enables to approximate temperature field on a thermal manikin surface to distribution that is specific to a human body.

Low-segment thermal manikins contain about 10–15 segments. Their shape conditionally conforms to human body morphology. Multi-segment thermal manikins contain about 30 segments. The most accurate representation of human body morphology is ensured in ADAM thermal manikin design due to application of 150 segments (Mandal et al., 2017).

Using the software package "Human thermal comfort model" developed by the socialists of the University of California, Berkeley (Farrington et al., 2004), sufficiently high degree of similarity of temperature distribution on a thermal manikin surface to distribution observed on a human body surface is ensured.

"Breathing" and "swimming" dynamic thermal manikins enable to study influence of swimmer dynamics during wetsuit operation on his/her thermal state. One of the most commonly used "breathing" thermal manikins is engineered by T. L. Madsen (1999). Likewise human body, a thermal manikin breathes colder ambient air in and breathes

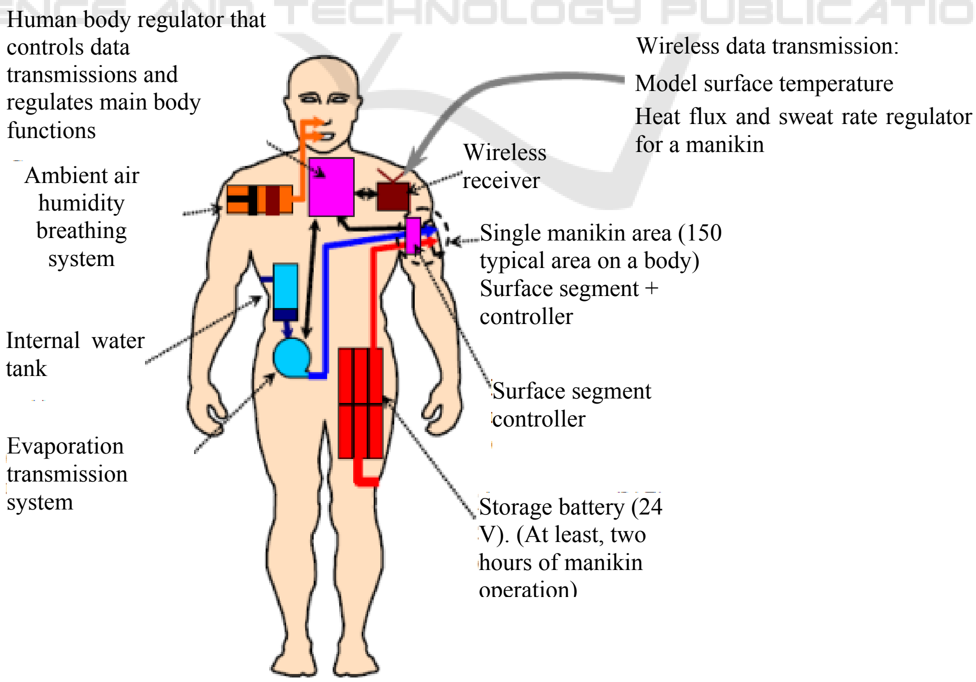

Figure 3: Thermal manikin diagram.

warmer air out. Respiration rate is regulated by means of the program.

Application of thermal manikins enables to study processes that occur in the material package of wetsuit thermal properties in more detail. Particularly, using them the following can be measured: temperature field distribution on a thermal manikin surface and in wetsuit structure, heat flux density on a thermal manikin surface.

4 CONCLUSIONS

Due to the necessity to improve sportwear, a question of quality of materials to be used can be solved using various assessment methods and the respective software that can process formulas of classical thermal exchange laws. Study methods using thermal manikins are very similar to experimental methods involving testers. When carrying out studies on development of new wetsuit prototypes it is necessary to involve specialists in the field of exercise physiology, human thermal exchange, programming, sports metrology.

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