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TECHNICAL NOTE

SELECTED PROBLEMS OF DETERMINING PILOT SURVIVAL TIME IN COLD WATER AFTER THE AIRCRAFT CRASH

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Abstract: Survival of a pilot in an emergency catapult situation over bodies of water is an essential element for organizing a rescue operation. Also important is the ability to determine the survivability of a crash survivor in extreme conditions with prolonged immersion in cold water. This time depends on a number of factors, such as time in the water, sea condidions, water temperature, age, gender, fatigue and also biophysical parameters and predispositions of the pilot survivor. At present, the emergency services do not have the ability to determine the survival time of a pilot survivor taking into account a number of the factors mentioned.

This paper presents a mathematical and simulation model of the physical phenomena of heat transfer between a pilot survivor and an extreme water environment. The physical phenomena of heat transfer were described by nonlinear and non-stationary differential equations containing important elements from the point of view of determining the survival time of a pilot survivor. The model shown is a single-segment, multi-layered and flat model of a human body. The model takes into account a number of body layers that will be cooled in the heat transfer process due to the disturbed heat balance that existed before the immersion of a pilot survivor. By assigning input parameters to the model in the form of the pilot's position, body weight, body height, water temperature, protective clothing insulation and others, information can be obtained about the dynamic processes of heat loss and body temperature drop during cooling. An impor-

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tant piece of information obtained from the simulation model is the visualization of the process of hypothermia of the pilot's body and the attainment of life-threatening states. Parameters obtained from the model include time to unconsciousness and pilot's survival time. These times can be the basis for the correct organization of rescue operations. The article presents sample plots of the pilot's body temperature drop for various model input parameters.

Keywords: hypothermia, rescue of a pilot survivor, mathematical model, simulation model

INTRODUCTION

There are a number of studies on the problem in question. The most comprehensive analysis and review of the literature items is presented in [13]. The purpose of this article is to present more accurate mathematical and simulation models compared to those described in the available literature [1,4,6,7,10], etc., reflecting more physical phenomena and determining more parameters determining the cooling states of the body of a pilot immersed in a cold water environment after a crash.

There are virtually no references in the Polish literature to studies of human survival time in cold water. In 1998, such research work was carried out at the Military Institute of Aviation Medicine, with the aim of evaluating the pilot's marine attire to ensure the survivability until the arrival of outside help [11]. However, they have no reference to the issue of modeling heat transfer in aqueous environments.

An accurate mathematical description of the physical phenomena occurring during the cooling of the body of a pilot immersed in cold water after an emergency evacuation from the aircraft cabin has implications for the correct estimation of the pilot's survival time. Two approaches are most commonly used for description. The first one considers complex heat transfer in a steady-state thermal state.

While, the second takes into account dynamic heat transfer processes. The latter approach is more appropriate to the problem at hand and will be discussed further. There are numerous mathematical models considering the issues of human-environment heat exchange [1,4,6,10]. The most commonly considered environment is the air environment. Mathematical models for the cooling of a pilot's body in an extreme water environment after a crash are far fewer. In addition, these models do not comprehensively analyze physical phenomena, the capabilities of the human body, and due to their complexity, are greatly simplified by the authors [1,4,10], etc. This article deals with the single-segment, multilayered and flat model of a pilot survivor's body. The model takes into account and details a number of factors that affect the accuracy of determining the boundary parameters of a pilot survivor's body.

MATHEMATICAL MODEL OF THE PHYSICAL PHENOMENA OF HEAT TRANSFER OF A PILOT SURVIVOR IN AN AQUATIC ENVIRONMENT

As previously mentioned, a single-segment, multilayer and flat model of the pilot survivor's body. The general scheme of heat transfer in such a human body model is shown in Figure 1. Parameter figures for each body layer were obtained from [9].

The starting point for developing a mathematical model is the general differential equation of thermal equilibrium in dynamic states, which can be written as follows:

$$\rho \cdot c_p \cdot V_{pilot} \cdot \frac{dT_{core}}{dt} = q_{cond} + q_{end} + q_{conv} \tag{1}$$

where:

ρ - core density of the human body (pilot), [kg/m^3],

c_p - specific heat of the core, [J/kgxK],

V_{pilot} - body volume (pilot) [m^3],

$q_{cond} = -U_C \cdot A_{pilot} \cdot (T_{core} - T_{water})$ - from Fourier's law,

$q_{conv} = -\alpha_C \cdot A_{pilot} \cdot (T_{core} - T_{water})$ from Newton's law of cooling.

The left side of equation (1) corresponds to the heat stored in the human body as a result of heat capacity, that is: $q_{cap} = \rho \cdot c_p \cdot V_{pilot} \cdot \frac{dT_{core}}{dt}$. Considering these correlations, the following differential equation is obtained:

$$\rho \cdot c_p \cdot V_{pilot} \cdot \frac{dT_{core}}{dt} = -U_C \cdot A_{pilot} \cdot (T_{core} - T_{water}) + \\ + q_{end} - \alpha_C \cdot A_{pilot} \cdot (T_{core} - T_{water}) \tag{2}$$

Due to the nature of the parameters, it is a non-linear differential and non-stationary equation,

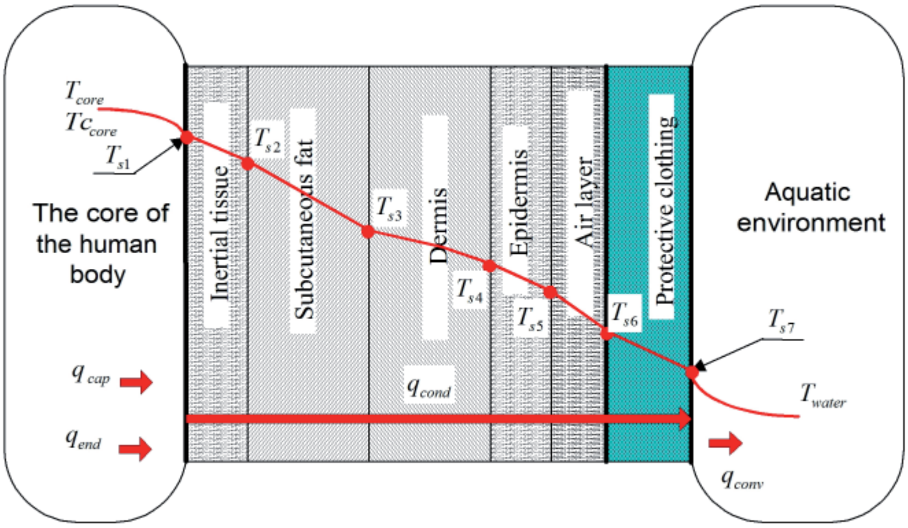

Fig. 1. Heat exchange between the human body and the environment for a pilot survivor wearing protective clothing [own elaboration].

T_{core} - human body core temperature [*K*], Tc_{core} - human body core temperature [°*C*], $T_{s1} \div T_{s7}$ - contact point temperature [*K*], T_{water} - temperature of the aquatic environment [*K*], q_{cap} - heat flux density in the core of the human body (from heat capacity) [*W*], q_{end} - endogenous heat flux density generated by the human body [*W*], q_{cond} - conduction heat flux density in the layers of the human body [*W*], q_{conv} - convection heat flux density between the human body (or protective clothing) and the water body [*W*].

where:

$A_{pilot}=0.203 \cdot m_{pilot}^{0.425} \cdot H_{pilot}^{0.725}$ - body surface area [m^2] according to DuBois [5],

m_{pilot} - body weight [kg],

H_{pilot} - body height [m].

The resultant heat transfer coefficient $\left[\frac{W}{m^2 \cdot K}\right]$ is given by the relation:

$$U_C = \frac{1}{\frac{\delta_1}{\lambda_1}+\frac{\delta_2}{\lambda_2}+\frac{\delta_3}{\lambda_3}+\frac{\delta_4}{\lambda_4}+\frac{\delta_5}{\lambda_5}+\frac{\delta_6}{\lambda_6}} \quad (3)$$

δ_k - thickness of individual body layers [m],

λ_k - heat transfer coefficients of individual body layers $\left[\frac{W}{m \cdot K}\right]$,

α_C - convection heat transfer coefficient $\left[\frac{W}{m^2 \cdot K}\right]$.

The computational form of the differential equation (2), prepared for numerical calculations is of the following form:

$$\frac{dT_{core}}{dt} = -\frac{U_C \cdot A_{pilot} \cdot (T_{core}-T_{water})}{\rho \cdot c_p \cdot V_{pilot}} + \frac{q_{end}}{\rho \cdot c_p \cdot V_{pilot}} - \frac{\alpha_C \cdot A_{pilot} \cdot (T_{core}-T_{water})}{\rho \cdot c_p \cdot V_{pilot}} \quad (4)$$

The analytical solution of this differential equation is of the following form:

$$T_{core}(t) = \left[T_0 - T_{water} - \frac{q_{end}}{A_{pilot} \cdot (U_C + \alpha_C)}\right] \cdot \exp\left[-\frac{A_{pilot} \cdot (U_C+\alpha_C)}{\rho \cdot c_p \cdot V_{pilot}} \cdot t\right] + T_{water} + \frac{q_{end}}{A_{pilot} \cdot (U_C+\alpha_C)} \quad (5)$$

where: T_0 - the initial temperature of the human body [K], *t* - time [s].

In doing so, it is necessary to determine a number of unknown parameters and relate them to parameters of the human body and the water environment.

SIMULATION MODEL OF HEAT TRANSFER BETWEEN THE PILOT SURVIVOR AND THE WATER ENVIRONMENT FOR A SINGLE-SEGMENT, MULTILAYER AND PLANAR MODEL OF THE BODY

The simulation model was created in the Matlab-Simulink environment (The MathWorks, Inc., Natick, USA) and is presented in Figure 2.

The following input quantities can be changed in the set parameters module:

1. Position of the pilot survivor (0 – lying down, 1 – standing),
2. Initial temperature of the pilot survivor (body core): T_0 [K],
3. Water temperature: T_water [K],
4. The characteristic velocity of the fluid, as the averaged velocity of the entire water flow: u_water [m/s],
5. Loss of consciousness temperature: Tc_cons [^{0}C],
6. Step of integration of differential equations: step [s],
7. Cold water survival limit temperature: Tc_survival [^{0}C],
8. The height of the pilot survivor: H_pilot [m],
9. Shiver factor: K_shivers [-],
10. The mass of the pilot survivor: m_pilot [kg].

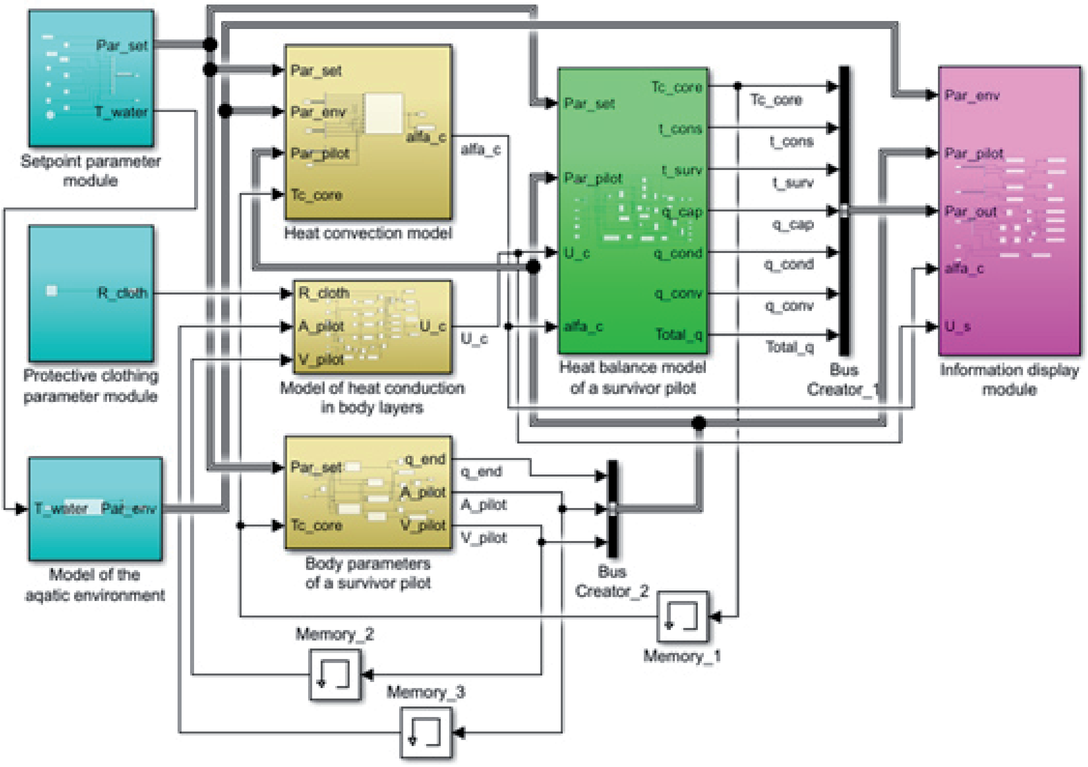

Fig. 2. Simulation model of heat exchange between the pilot survivor and the water environment [own elaboration].

The protective clothing parameters module calculates the value of the coefficient of thermal resistance (thermal insulation) of the pilot's protective clothing depending on the selection of the variant of the MUP-1 Marine Pilot Clothing. These parameters were measured and determined with the participation of the Central Institute for Labor Protection in Warsaw [3].

The water environment model determines the parameters used in the heat balance of the pilot survivor and the heat convection model. The input parameter is the temperature of the water body in which the pilot resides. The model determines the following parameters: ρ_{water} - density of water, μ_{water} - dynamic viscosity of water, and λ_{water} - thermal conductivity of water.

In the heat convection model, the basic parameter is determined: α_C - convection heat transfer coefficient. This coefficient takes into account natural convection resulting from the change in density of water due to heating or cooling, and forced convection resulting from the flow of water around the pilot.

The algorithm for determining this coefficient [2], with some modifications, is as follows:

- Calculation of the Prandtl number: $\Pr = \frac{c_p \cdot \mu_{water}}{\lambda_{water}}$,
- Calculation of the Reynolds number: $\mathrm{Re} = \frac{\rho_{water} \cdot u_{water} \cdot l}{\mu_{water}}$, where: l - characteristic dimension,
- Calculation of the Nusselt number - $\mathrm{Nu}=0.023 \cdot \mathrm{Re}^{0.8} \cdot \mathrm{Pr}^{1/3}$,
- On this basis, the convection coefficient is calculated according to the relation:

$\alpha_C = \frac{Nu \cdot \lambda_{water}}{H_{pilot}}$ - for the vertical position of the pilot survivor,

$\alpha_C = \frac{Nu \cdot \lambda_{water}}{2 \cdot \sqrt{\frac{V_{pilot}}{\pi \cdot H_{pilot}}}}$ - for the horizontal position of the pilot survivor.

In the heat transfer model, the heat transfer coefficient U_C is determined depending on the parameters of the pilot survivor's body and the parameters of the protective clothing according to relation (3).

The model of the pilot survivor's body parameters determines the value of endogenous heat flux, which is variable in the process of cooling of the human body, as well as the body's surface area and volume. The model uses the set parameters and the core body temperature calculated in the heat balance model of the pilot survivor. The internal structure of this model is presented in Figure 3.

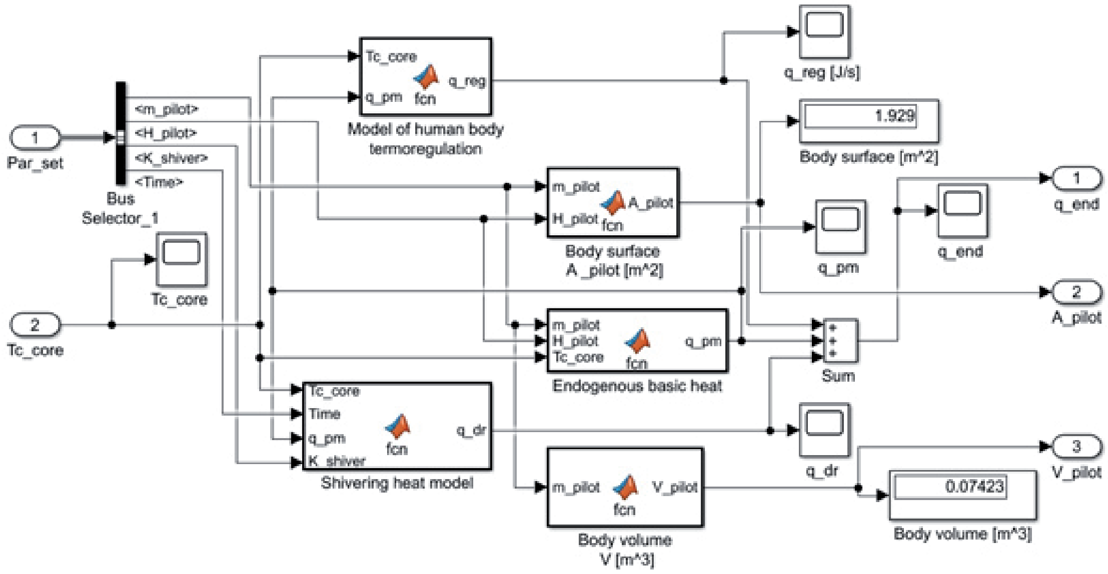

Fig. 3. Internal structure of the model of the pilot's body parameters after an aircraft crash [own elaboration].

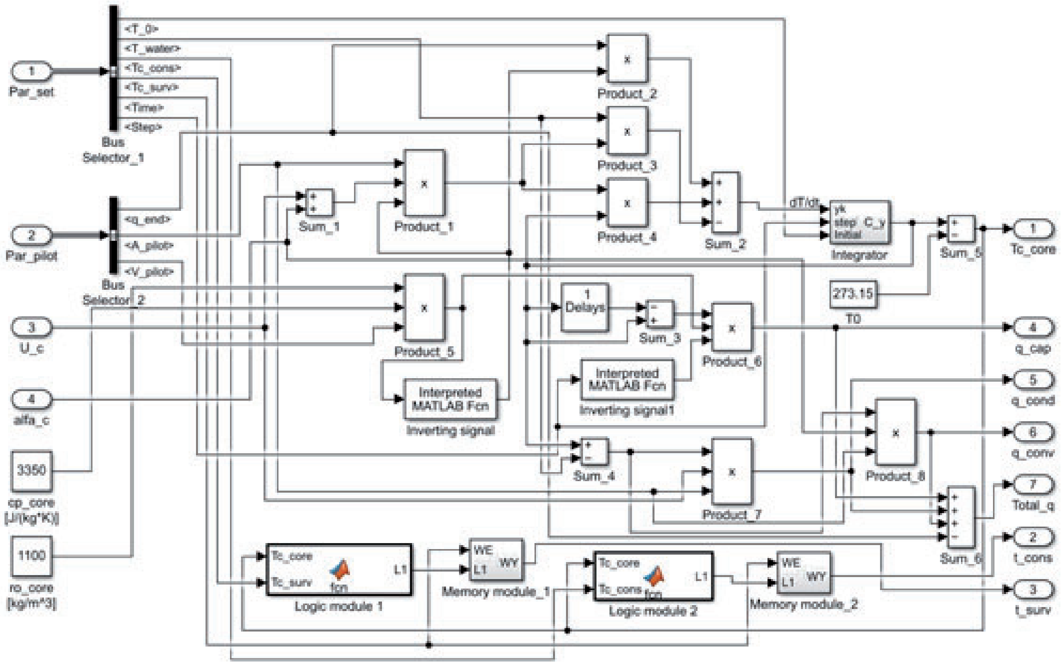

Fig. 4. Internal structure of the pilot survivor's heat balance model [own elaboration].

The model includes the human body's thermoregulation algorithms that occur when the body cools down and defends against heat loss. The basic endogenous heat produced by the human body depends on the weight and height of the pilot survivor. The human body's defense against heat loss takes into account the occurrence of shiver heat, which occurs when the core temperature drops to the interval between $32^{o}C$ and $35^{o}C$. The occurrence of shiver heat is also limited by time.

The main element in the simulation model of heat exchange between the pilot survivor and the water environment is a model of the pilot survivor's heat balance. The internal structure of this model is presented in Figure 4. The internal structure reflects the numerical solution (5) of the differential equation (4). The nonlinear and non-stationary parameters of the differential equation are input quantities determined in previous calculation modules.

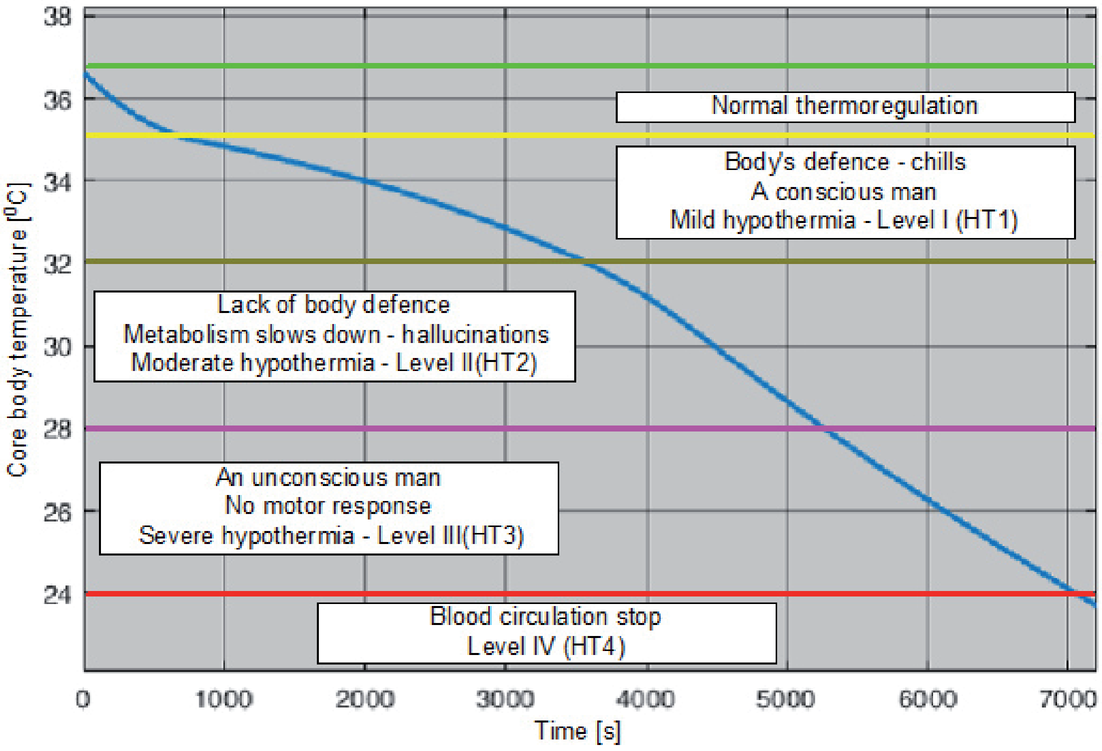

Fig. 5. An example of the course of a pilot survivor's body temperature drop when immersed in water with a temperature of [own elaboration].

The output quantities in this model are:

1. The core body temperature of the pilot survivor: Tc_core.
2. Time of consciousness of the pilot survivor: t_cons.
3. Survival time of the pilot survivor: t_surv.
4. Heat flux from the heat capacity of the pilot survivor's body in dynamic states: q_cap.
5. Conduction heat flux of the pilot survivor's body in dynamic states: q_cond.
6. Convection heat flux from the pilot survivor's body in dynamic states: q_conv.
7. Total heat flux of the heat balance in dynamic states: Total_q.

SELECTED RESULTS OF SIMULATION, DYNAMIC CHANGE OF PARAMETERS IN THE PROCESS OF SURVIVAL OF A PILOT SURVIVOR IN COLD WATER

Cooling of the body while in a cold water body occurs rapidly if the pilot survivor is not protected by special protective clothing to prevent hypothermia. An example of the simulation result of the temperature drop for this situation is shown in Figure 5.

Pilot survivor's weight m_{pilot}=65 kg, pilot survivor's height K_{pilot}=1.6 m, position in the water — standing. A pilot survivor without clothing to protect against hypothermia. The pilot survivor loses consciousness after 1.46 hours. Survival time of the pilot survivor — 1.95 hours.

Within the range of normal thermoregulation, the human body is homeothermic, that is, it regulates internal temperature through physiological and behavioral actions. These processes are directed at maintaining a constant body temperature in the presence of various thermal disturbances. When the body temperature drops below 35°*C*, the body's defense mechanisms are activated — shivering lasting 4–6 hours and an increase in endogenous heat produced by the human body. In the temperature range from 32°*C* to 35°*C*, the temperature gradient curve (Figure 5) has a smaller slope. With further cooling of the body, the body's defense mechanisms decline, metabolism slows down and hallucinations can occur. The limit of human consciousness is considered the core body temperature of 28°*C*, at which severe hypothermia occurs. Cardiac arrest occur at the body's core temperature of 24°*C* and this is considered the limit of survival. For this example, the simulation results obtained are in line with generally accepted studies of this problem and published in [8] and [12].

The survival time of a pilot survivor (without protective clothing) in cold water depending on its temperature is shown in Fig.6. The temperature of the water has a significant impact on the survival time of a pilot survivor. Prolonged exposure to cold water causes a state of hypothermia and a poses a threat to the pilot's life. The effect of temperature on the survivability of a pilot survivor in cold water is shown in Figure 7. The parameters of the pilot survivor are identical to those in the previous example. The example shows that an increase in water temperature from $2^{\circ}C$ to $6^{\circ}C$ results in an increase in time to loss of consciousness by T_{P2}-T_{P1}=0.38 h and an increase in survival time by T_{Z2}-T_{Z1}=0.5 h. Temperature range from $6^{\circ}C$ to $10^{\circ}C$ is much more beneficial. The same increase in temperature results in an increase in time to loss of consciousness by T_{P3}-T_{P2}=0.99 h and an increase in survival time by T_{Z3}-T_{Z2}=1.07 h.

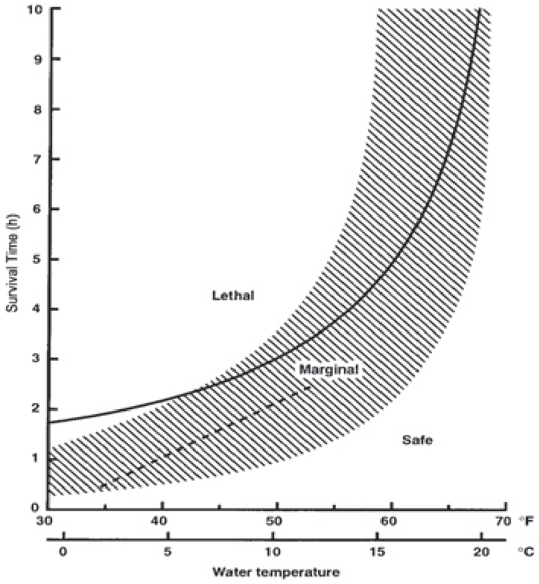

Fig. 6. Survival time of a pilot survivor in cold water [8,12].
Lethal — 99% mortality, Marginal — 50% mortality, Safe — 0% mortality

The situation is completely different when the pilot survivor is dressed in protective clothing preventing hypothermia. This situation is presented in Figure 8. The parameters of protective clothing and, in particular, its thermal insulation have a definite impact on the survivability of a pilot survivor in cold water. With a constant water temperature of $2^{\circ}C$ and the parameters of the pilot survivor as in the previous examples, the decrease in the core body temperature depending on the thermal insulation of the protective clothing was simulated. Protective clothing significantly extends the time to loss of consciousness and survival time of a pilot survivor. These charts can be used to select an

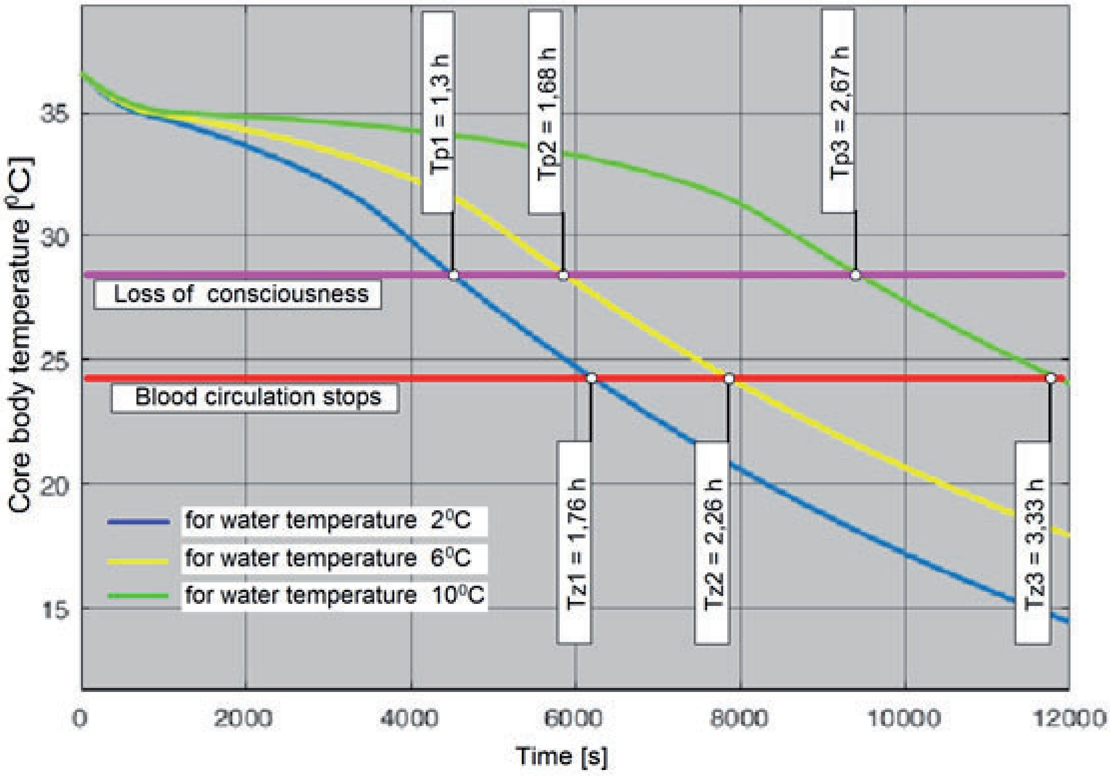

Fig. 7. Effect of water temperature on survivability of a pilot survivor in cold water [own elaboration].

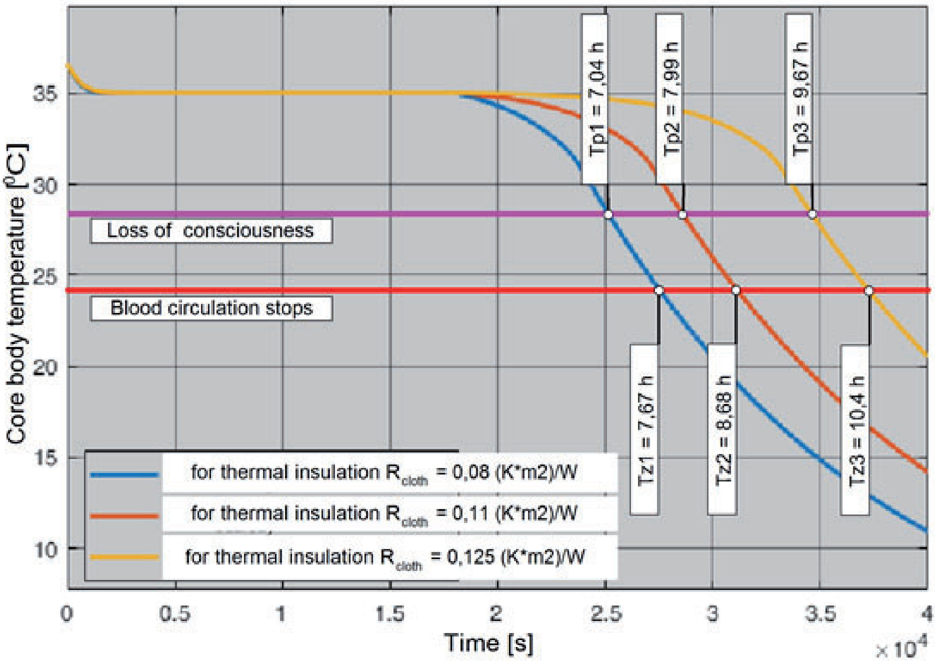

Fig. 8. Effect of thermal insulation of protective clothing on survivability of pilot survivors in cold water [own elaboration].

appropriate set of protective clothing for the crew of an aircraft performing tasks over bodies of water. Knowing the temperature of the body of water depending on the season or reported by the relevant services and the time capabilities of the emergency services can be used to select a set of protective clothing.

CONCLUSIONS

1. The simulation model presented here accurately reflects physical phenomena and allows the determination of parameters that determine the condition of a pilot survivor's body in a cold water environment. It allows a wide range of input parameters relevant to estimating the survival time of a pilot survivor in cold water to be adjusted. No such models exist in the available literature.
2. The simulation model takes into account nonlinearities and non-stationarities of thermal processes occurring during a pilot survivor's body temperature drop.
3. The model takes into account the human body's defense mechanisms during the cooling process through additional endogenous heat generation.
4. The simulation model will enable aircraft crews to select appropriate hypothermia protection clothing in emergency situations.
5. The simulation results can facilitate organizing rescue operations.
6. The model presented in the article was parameterized using data available in the literature. For its precise calibration, it is advisable to conduct sectional (under safe conditions) tests on people with a wide enough range of physical characteristics (e.g., height, weight, body fat percentage, etc.), under different external environment parameters.

AUTHORS' DECLARATION:

Study design: Przemysław Stężalski, Sławomir Michalak, Jerzy Borowski. **Data collection:** Przemysław Stężalski, Sławomir Michalak, Jerzy Borowski. **Statistical analysis:** Przemysław Stężalski, Sławomir Michalak, Jerzy Borowski. **Manuscript preparation:** Przemysław Stężalski, Sławomir Michalak, Jerzy Borowski. **Funds collection:** Przemysław Stężalski, Sławomir Michalak, Jerzy Borowski. The authors declare no conflict of interest.

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