

Design improvement and performance of the inflatable anti-immersion suit

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ABSTRACT – REZUMAT

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The human body's exposure to cold water can lead to rapid heat loss, even frostbite, cold stress and drowning. To protect the lives of individuals working in cold water environments, an anti-immersion suit is worn as protective equipment. But active anti-immersion suit faces problems such as single function, lack of warmth, poor floatability, poor thermal, wet comfort, poor body suitability and so on. In this paper, the performance of the anti-immersion suit was tested and evaluated by changing the inflatable thermal fabric as part of the inner layer and optimising the structure of key parts of the suit. It was found that the use of inflatable thermal inner layer materials and the improved design of the garment structure caused significant improvement of floating and thermal properties of the suit, inhibited the average skin temperature drop of the human body in a cold water environment, and improved the subjective comfort of the human body in a human subject experiment. Therefore, the results of this study may form the basis for research into a new anti-immersion suit.

Keywords: anti-immersion suit, inflatable thermal fabric, buoyancy, thermal manikin, average skin temperature

Îmbunătățirea designului și performanței costumului gonflabil anti-imersiune

Expunerea corpului uman la apă rece poate duce la pierderea rapidă a căldurii, chiar la degerături, stres din cauza frigului și înec. Pentru a proteja viața persoanelor care lucrează în medii cu apă rece, se utilizează costume anti-imersiune ca echipament de protecție. Dar costumele anti-imersiune active se confruntă cu probleme precum funcționalitatea redusă, lipsa căldurii, flotabilitate slabă, confort termic redus, confort redus în condiții de umiditate, adaptabilitate slabă la corp și așa mai departe. În această lucrare, performanța costumului anti-imersiune a fost testată și evaluată prin schimbarea materialului textil termic gonflabil care face parte din stratul interior și optimizarea structurii părților cheie ale costumului. S-a constatat că utilizarea materialelor termice gonflabile pentru stratul interior și îmbunătățirea designului structurii costumului au dus la o îmbunătățire semnificativă a proprietăților de flotabilitate și a celor termice ale costumului, au inhibat scăderea temperaturii medii a pielii corpului uman în medii cu apă rece și au îmbunătățit confortul subiectiv al corpului uman în cadrul experimentului pe subiecți umani. Prin urmare, rezultatele acestui studiu pot constitui baza pentru cercetarea unui nou costum anti-imersiune.

Cuvinte-cheie: costum anti-imersiune, material termic gonflabil, flotabilitate, manechin termic, temperatura medie a pielii

INTRODUCTION

In the process of sea rescue, due to the low sea temperature, a series of problems such as cold shock, hypothermia, respiratory failure and other problems will be caused if the operation time is too long or the rescue is not enough, which seriously threatens the health of the rescue workers [1, 2]. Studies have pointed out that the main cause of sea rescue and shipwreck deaths has been cold water immersion caused by hypothermia, and leading to a series of cases, the mortality rate was about 60% to 80% [3, 4]. Anti-immersion suits were indispensable personal protective equipment and used to prevent loss of temperature and drowning [5], thus prolonging the survival time and increasing the chances of rescue, and maximising the safety of search and rescue personnel [6]. By comparing the three types of

anti-immersion suits in the market at present, including SANTI Poland, HENSON Norway and SURVITEC England, and found that to meet the use requirements, the style of anti-immersion suit was basically a joint-type design and consisted of two layers. The outer layer was made of waterproof material as an anti-immersion layer, and the inner layer was made of warm material as an anti-cold layer. The anti-immersion suit also needs to be easy to wear and take off, thin and fit well, comfortable for sports, and to ensure the protective safety of the wearers to the maximum extent [7, 8].

Anti-immersion layer was mainly used to block water infiltration into clothing, to avoid direct contact between the human body and water, which could cause increased heat loss. Anti-immersion layer fabric should have good waterproof performance, in

addition to preventing sweat condensation and frostbite human body. Anti-immersion layer fabric should also have a certain degree of hygroscopicity and breathability. At present, anti-immersion fabrics mainly include coated fabrics, laminated composite fabrics, high-density fabrics with water repellent finishing, intelligent fabrics with anti-impregnation properties, and so on [9–12]. Positive thermal insulation materials, also known as energy collection and management materials, not only isolate or reduce the loss of human body heat like passive insulation materials, but also absorb and store external heat and transfer it to the human body through additional heating effects. They mainly include electric heating materials, moisture-absorbing heating materials, energy storage materials, and chemical thermal materials [13–15].

To enhance the protection effect of immersion suits, Lenfeldová et al. [16] suggested that inflating clothing could effectively enhance the thermal resistance of immersion-resistant suits and improve thermal insulation. Meanwhile, the outer layer fabric should utilise warp-knitted spacer fabrics with superior structural stability, which could effectively prevent the reduction in thickness and decline in thermal insulation performance caused by increased immersion depth. Jim et al. [17] improved the passive reflective system of immersion suits by increasing the area of reflective material and designing the position of reflective material. Jonathan et al. [18] conducted human wearing tests by using a hydraulic wave generator to create wave simulations of real sea conditions. They found that wind and waves increase the possibility of heat loss and immersion suit leakage, with actual performance lower than estimated laboratory performance. Based on the above experimental results, Jonathan et al. [19] calculated the minimum thermal insulation required to maintain heat balance in the human body, so that the laboratory test performance is closer to the actual use performance. To the best of our knowledge, at present, to improve the anti-immersion function, the main methods are the application of new materials, material function modification and theoretical optimisation. This paper analysed the thermal insulation principles of various materials, applied inflatable fabrics to an anti-immersion suit, and designed the clothing structure of an anti-immersion suit based on ergonomics principles. The comprehensive protective performance and comfort of the anti-immersion suit were tested and evaluated from aspects such as safety protection, convenient wearing and removal, physiological comfort, accessory functions, and visual aesthetics, making the anti-immersion suit have both thermal insulation and buoyancy properties.

EXPERIMENTAL SECTION

Clothes design

Insulating layer design

The anti-drenching clothing's inner layer insulation was made by combining an airbag material composed of Saty Gard nylon 6 filament produced by Allied Signal Company (surface density: 46 g/m²) and a Thermoplastic Polyurethane (TPU) waterproof film developed by our research group (surface density: 45 g/m²). As shown in figure 1, the U-shaped floating life-saving device structure was combined with the clothing structure to form the anti-drenching clothing's inner layer insulation. The raised collar at the back and the front of the garment forms a U-shape, providing support for the back of the neck.

Anti-immersion layer design

The design process of the Anti-immersion layer is flow in figure 2. The design of reflective material should meet the requirements of International Organisation for Standardisation (ISO) 15027-1 Immersion suits – Part 1, which states that the total area of retro reflective material shall be no less than 400 cm², with at least 100 cm² on the hat and 50 cm² on the back, while the rest is distributed throughout the body. To meet the requirements of good waterproof performance, certain tensile strength and tear

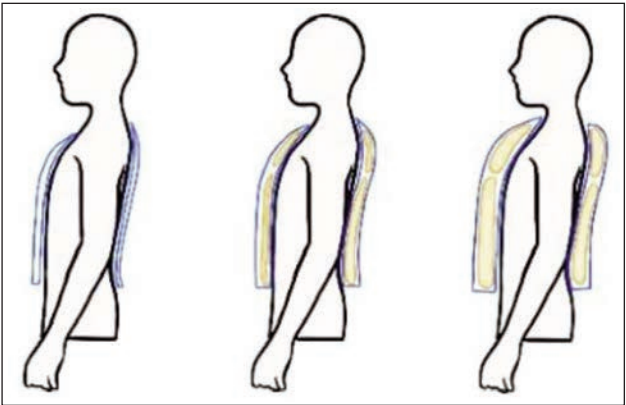


Fig. 1. Structure diagram of the insulating layer of the inflatable anti-immersion suit

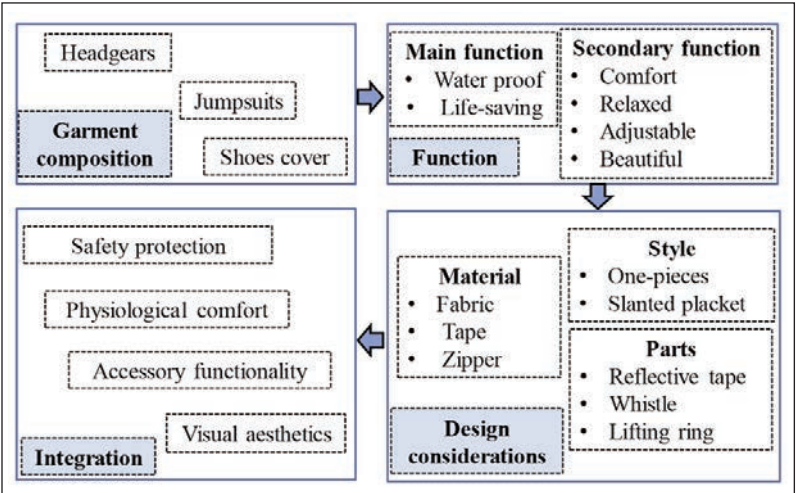


Fig. 2. Outer design flow of inflatable anti-immersion suit

Table 1

MATERIAL AND PERFORMANCE ANALYSIS OF SHELL FABRICS AND ACCESSORIES			
Type	Material	Property	Application site
Shell fabric	Three-layer waterproof fabric (Nylon + Polytetrafluoroethylene film + mesh fabric)	Thickness: 0.82 mm; Thermal Resistance: 1.5 clo; Compressive strength: 15.2 Mpa; Hydrostatic pressure: 10000 mmH ₂ O; Warp tensile strength: 1600 N; Weft tensile strength: 1300 N	Whole costume except for headgear and cuffs
Accessory	Chloroprene Rubber light skin neoprene; IZIP airtight zipper; Nylon mesh fabric pocket; Safety of Life at Sea maritime reflective tape; YETOM company waterproof sticker	Skin-friendly, high elasticity, tightly sealed and waterproof; High strength, wear-resistant; No water retention; High reflectivity, excellent visibility at sea; Hydrostatic pressure at the cross seams: 3000 mmH ₂ O; Peel strength: 35.6 N/cm	Headgear; cuff placket; head of all front outer layer pockets; body of the garment; all interior seams

resistance, and good thermal insulation properties for an anti-immersion suit, the selection and performance characteristics of the materials used are shown in table 1. The anti-drenching clothing parts were bonded and assembled using adhesive technology to form an inflatable anti-immersion suit.

Performance test and evaluation

Floating ability

According to ISO 12402-1: 2005 Personal flotation devices – Part 1: Lifejackets for seagoing ships – Safety requirements and Archimedes’ principle, the buoyancy of the sample was measured and calculated in air and water, respectively. The testing method was shown in figure 3.

Buoyancy calculation formula of an anti-immersion suit:

$$F_i = M \cdot g = (M_1 - M_2) \times 9.8 \tag{1}$$

$$F_s = M \cdot g = (M_1 - M_3) \times 9.8 \tag{2}$$

$$P_b = \frac{F_i - F_s}{F_i} \times 100\% \tag{3}$$

where F_i is the initial flotation of the inflatable anti-immersion suit; M_1 is the total mass of the metal cage and weight suspended in water; M_2 and M_3 are the total mass of the metal cage, weight and anti-immersion suit before and after soak for 24 hours, respectively; P_b is the loss of anti-immersion suit soaked in water for 24 hours.

Thermal resistance

Thermal resistance is a parameter indicative of the thermal insulation performance of clothing. Its value is inversely proportional to the thermal conductivity of the clothing. According to ISO 15831-2004 Clothing-Physiological effects-Measurement of thermal insulation by means of a thermal manikin, the thermal resistance performance of an anti-immersion suit was tested using a walk-in environmental chamber (ESPEC Corporation, Osaka, Japan) and a 34-segment sweating thermal manikin “Newton” (Measurement Technology Northwest, Seattle, USA). The immersion suit produced by Helly Henson Company from Norway (H-suit) was selected as the control group, and its performance was compared with that of the inflatable immersion suit (S-suit) designed in this paper. Before testing, the immersion suit was placed in an environmental chamber at a temperature of 20±5°C and a relative humidity of 50±5% for 12 hours. The skin temperature of the thermal manikin was set to 34°C, and the immersion suit was worn on the surface of the thermal manikin. The thermal manikin consisted of 34 independent segments with different temperatures, heat fluxes, and sweating rates (figure 4), and data were recorded through sensors in each segment, lasting for 20 minutes, and tested three times to obtain the average value.

The formula for calculating the total thermal resistance, I_t , of the immersion suit was as follows:

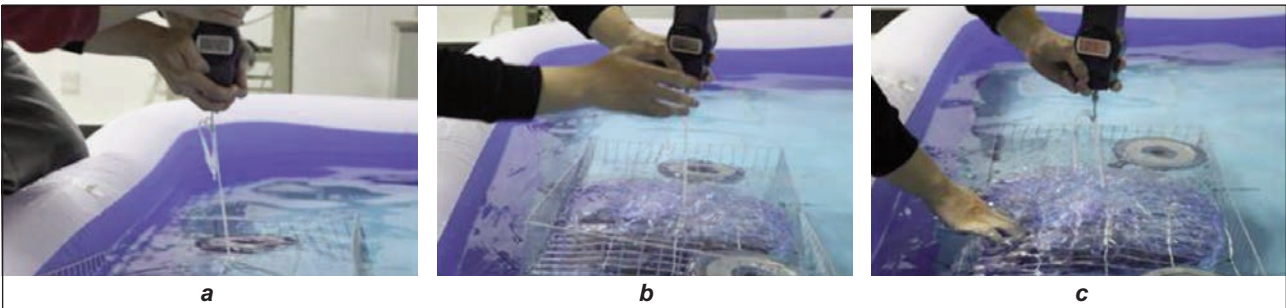


Fig. 3. Buoyancy test process: weigh the mass of: a – metal cage and weight; b – metal cage, weight and anti-immersion suit; c – metal cage, weight and anti-immersion suit after soaking 24 h in water

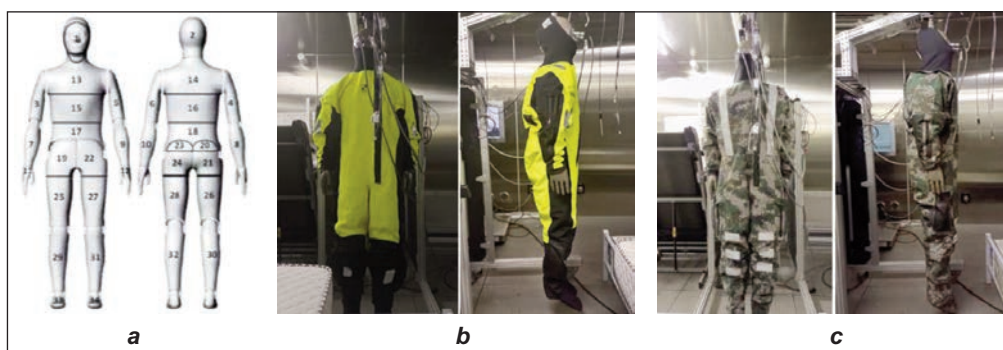


Fig. 4. Photos of: a – Newton 34-zone thermal manikin; b – test procedure of HENSON anti-immersion suit (H-suit); c – test procedure of inflatable anti-immersion suit (S-suit)

$$I_t = \sum_i \frac{S_i}{S} \times \frac{T_i - T_a}{H_i} \quad (4)$$

The local thermal resistance I_{tp} was calculated as follows:

$$I_{tp} = \frac{S_i}{S} \times \frac{T_i - T_a}{H_i} \quad (5)$$

where I_t is total thermal resistance of anti-immersion suit, col; I_{tp} is local thermal resistance in section i of anti-immersion suit, col; S is total body surface area of thermal manikin, m^2 ; S_i is local body surface area in section i of thermal manikin, m^2 ; T_i is shell temperature in section i of thermal manikin, $^{\circ}C$; H_i is heat flow rate in section i of thermal manikin, W/m^2 .

Heat-moisture comfort

Clothing heat-moisture comfort refers to the performance of garments that enables the clothed human body to exchange heat and moisture with the environment under varying environmental conditions and levels of physical activity, ultimately reaching equilibrium and providing a comfortable sensation. This property is collectively determined by the thermal

conductivity and moisture transfer capabilities of the clothing. So, six healthy and proportionate adult males were selected for the real-life underwater test of immersion suits to test their heat-moisture comfort. Each subject participated in two experiments with a time interval of two days. The experimental procedure followed the flow chart shown in figure 5, a and b. After entering the water at a depth of 30 cm and a temperature of $15^{\circ}C$ lasted for 2.5 hours. During the experiment, the physiological indicators of the subjects were tested and recorded using a thermocouple sensor MSR®145-100 (MSR Electronics GmbH, Zurich, Switzerland), a heart rate monitor Polar® (Polar Electro Oy, Kempele, Finland), and a cardio-respiratory function tester COSMED® (Cosmed Srl, Rome, Italy).

1. Mean skin temperature (MST): The collection point of human body temperature was shown in figure 5, c, and the calculation formula of MST was as follows:

$$MST = 0.07 \cdot S_1 + 0.175 \cdot S_2 + 0.175 \cdot S_3 + 0.07 \cdot S_4 + 0.07 \cdot S_5 + 0.05 \cdot S_6 + 0.19 \cdot S_7 + 0.2 \cdot S_8$$

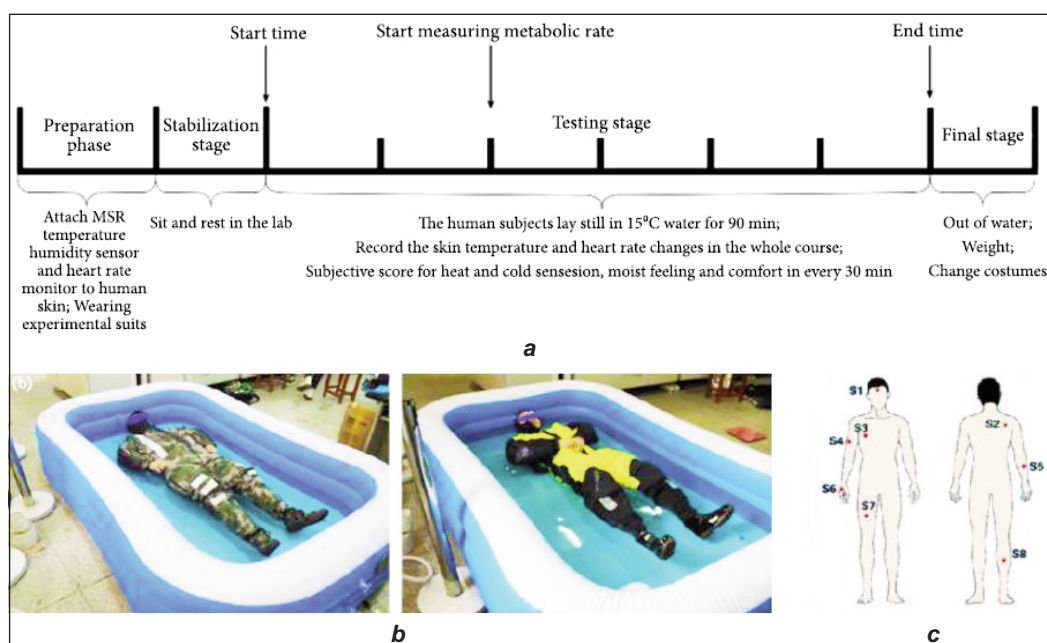


Fig. 5. Graphical representation of: a – the test process flow diagram; b – actual test pictures; c – location of heat flow sensors of human subject experiment

Table 2

SUBJECTIVE RATING SCALE					
Cold-heat sensation		Comfort level		Humidity sensation	
Very warm	3	Very Comfortable	3	Very Dry	3
Warm	2	Comfortable	2	Dry	2
Slightly Warm	1	Somewhat Comfortable	1	Slightly Dry	1
Neutral	0	Neutral	0	Neutral	0
Slightly Cold	-1	Somewhat Uncomfortable	-1	Slightly Humid	-1
Cold	-2	Uncomfortable	-2	Humid	-2
Very cold	-3	Very Uncomfortable	-3	Very Humid	-3

2. Heart rate (HR): Heart rate collection was recorded every 30 s.

3. Metabolic rate (MR): 30 minutes after the start of the experiment, the metabolic rate was continuously collected for 5 min under the stable state.

Subjective psychological feelings were evaluated using a questionnaire, which included ratings of local (measured points), and overall cold-heat sensation, comfort level and humidity sensation (table 2). During the experiment, subjective evaluations were performed every 30 minutes, with a total of four evaluations.

RESULTS AND DISCUSSIONS

Floating ability

The buoyancy performance of the anti-immersion suit was tested and calculated according to formulas 1–3. The initial buoyancy of the anti-immersion suit was found to be 200.6 N, and after being immersed for 24 hours, the buoyancy measured was 197.6 N. The loss of buoyancy of the suit was 1.4%, which met the requirement of ISO 12402 that the buoyancy loss after 24 hours of immersion in fresh water should be less than 5% for a survival suit (table 3).

Table 3

FLOATING ABILITY OF ANTI-IMMERSION SUIT	
Samples	Values
Initial buoyancy of anti-immersion suit (N)	200.6
Buoyancy of anti-immersion suit after soaking in water for 24h (N)	197.6
Buoyancy loss of anti-immersion suit after soaking in water for 24h (%)	1.4

Thermal resistance

Thermal resistance of clothing refers to the resistance of clothing to heat flow in the process of heat exchange between the human body and the environment. It was a basic indicator for measuring the thermal insulation performance of clothing. In our previous work [20], the insulation performance of the inflation layer was optimal with the inflation thickness of 1.5 cm, and the thermal resistance was basically stable at 0.21 clo. The total thermal resistance of the H-suit, S-suit in the un-inflated state (S-suit+con) and

S-suit in the inflated state (S-suit+full) was 1.88 clo, 2 clo and 2.10 clo, respectively (figure 6, a). This indicated that the overall thermal resistance performance of the inflatable anti-immersion suit was better than that of the H-suit, and the thermal resistance performance was significantly improved after inflation, which was similar to the previous research findings [16, 20]. It could be seen in figure 6, b and c, the thermal resistance of H-suit, S-suit-con and S-suit-full in section upper body section was 3.21 clo, 3.20 clo and 3.60 clo, in the arm was 2.90 clo, 3.37 clo and 3.80 clo, in the lower part of the body was 2.58 clo, 3.16 clo and 3.16 clo, respectively. The results indicated that inflation had an impact on the local thermal resistance of the clothing, with an increase in thermal resistance and improved warmth. The local thermal resistance of the S-suit was significantly higher than that of the H-suit in the inflated state, indicating that the insulation of the inflated inner layer was superior to that of traditional cotton materials.

Heat-moisture comfort

The subjects wore two sets of anti-immersion suits during the test, with metabolic rates of 1.65 metabolic equivalents (METs) (S-suit) and 1.61 METs (H-suit), respectively. The linear fit of the subject's heart rate and average skin temperature is shown in figure 7, a and b, respectively. Throughout the experiment, the trend of heart rate change for both sets of anti-immersion suits was basically the same, gradually decreasing with time. The heart rate of subjects was higher in the S-suit than in the H-suit. As shown in figure 7, b, at the beginning of the experiment, the average skin temperature of the subjects wearing both sets of anti-immersion suits was roughly the same. With the progress of the experiment, the average skin temperature of the subjects wearing the S-suit gradually increased, reaching its highest value (about 32.2°C) at 20 minutes, and then decreased with the extension of underwater time, with a temperature difference of 0.55°C before and after. The average skin temperature of the subjects wearing the H-suit slowly decreased over time during the experiment, with a temperature difference of 1.05°C before and after.

The subjects conducted a subjective evaluation of the overall comfort of the two sets of anti-immersion

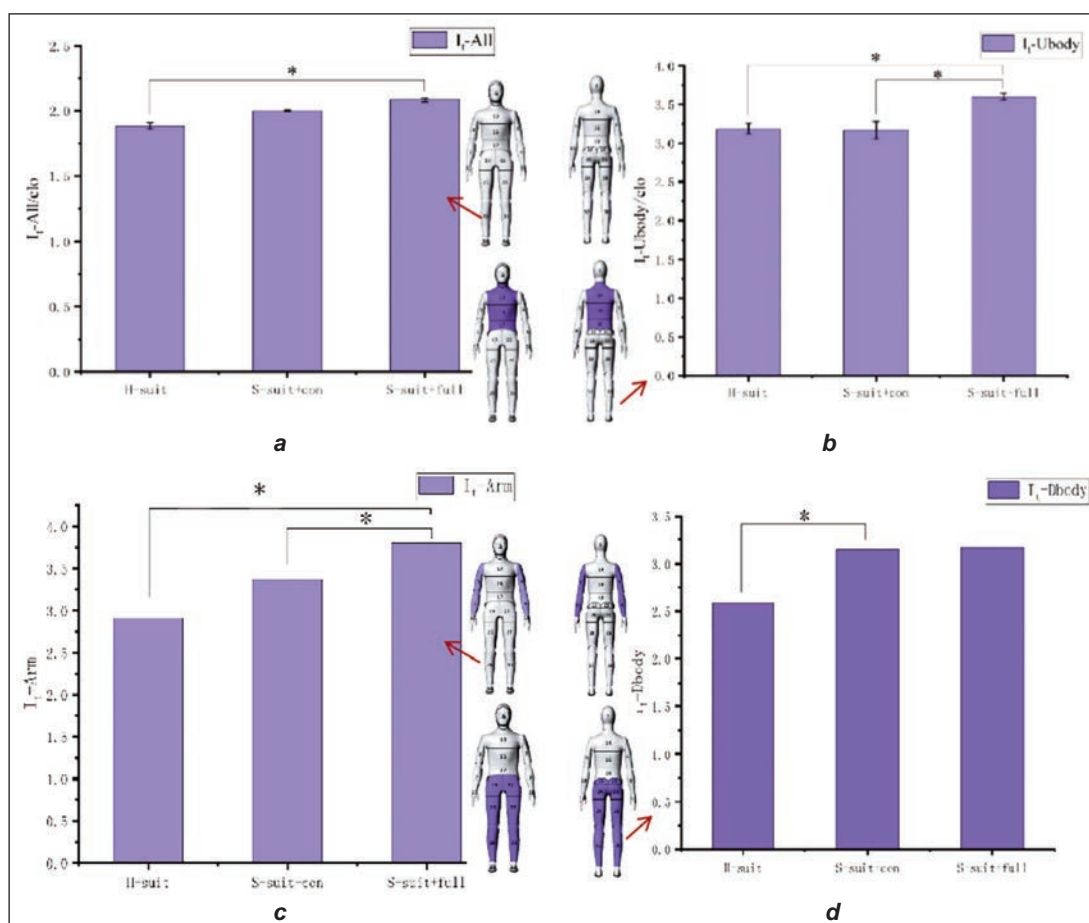


Fig. 6. Graphical representation of: *a* – total thermal resistance of H-suit and S-suit and thermal resistance of H-suit and S-suit in section; *b* – upper body (Ubody); *c* – arm; *d* – the lower part of the body (Dbody)

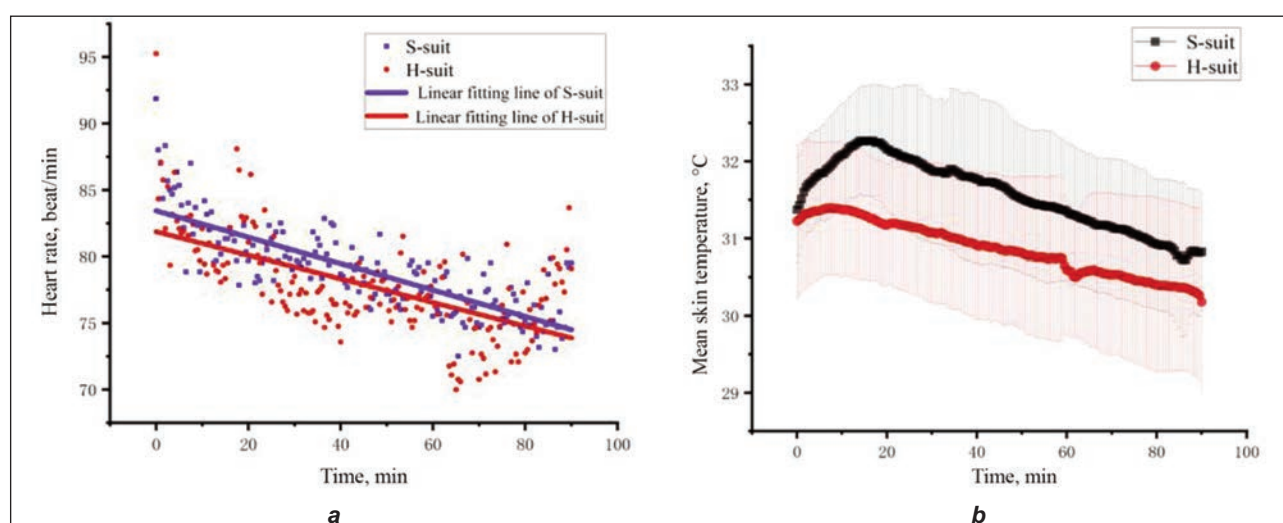


Fig. 7. The change of: *a* – heart rate; *b* – mean skin temperature of subjects in S-suit and H-suit

suits, including comfort, warmth, and humidity, while wearing them underwater. The results were shown in figure 8. From the evaluation results, the subjective scores for the S-suit were higher than those for the H-suit. The subjects wearing the S-suit remained in a state of thermal neutrality or above throughout the experiment, with a cold-hot score of 0.16 at the end of the experiment, while those wearing the H-suit felt

colder after 20 minutes of the experiment, with a cold-hot score of -1, indicating that the S-suit had better cold protection (figure 8, *a*). As shown in figure 8, *b*, the subjects wearing the S-suit remained dry for 0–60 min, and then began to feel wet, with a score of -0.17. The subjects wearing the H-suit remained dry in 0–45 min, and then gradually began to feel wet, with a score of -0.33. Furthermore, as shown in

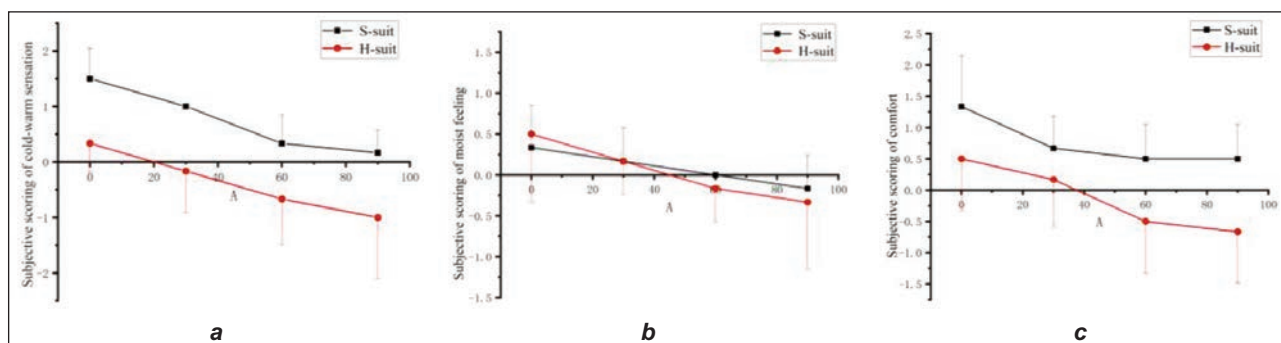


Fig. 8. Subjective scoring of: a – cold-warm sensation; b – moisture feeling; c – comfort

figure 8, c, the subjective scoring of comfort of S-suit was always positive and the end value was 0.51, while after 40 minutes, the scoring of H-suit was negative and the end value was -1.14.

CONCLUSION

In this work, based on human ergonomics, the function, style, and structure of a new type of inflatable anti-immersion suit were designed and produced. A multi-functional new type of inflatable anti-immersion suit was designed, and the protective performance and comfort of the anti-immersion suit were subjectively and objectively evaluated. The test results showed that adding airbag patches to the inner layer

of the suit can provide some buoyancy to the suit. When fully inflated, the inherent buoyancy is 200.6 N, and after 24 hours of immersion, the buoyancy is 197.6 N, with a buoyancy loss of 1.4%. It can also improve the thermal insulation performance of the anti-immersion suit: after soaking in low-temperature water for 1.5 hours, the average skin temperature decreases from 31.37°C to 30.82°C, with a temperature decrease of only 0.55°C.

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