Review of the study of relation between the thermal protection performance and the thermal comfort performance of firefighters’ clothing

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Abstract

This paper reviews the current evaluation methods of thermal protection performance and thermal comfort performance for fabric and clothing from standard and non-standard tests. The test environment includes thermal radiation, thermal convection, flash fire, and so on. The research of this paper will promote the formulation and improvement of the new standard of Fire clothing. The future researches on thermal protection performance, and thermal comfort performance should be closer to the real fire environment. At the same time, the study of relation between the thermal protection performance and the thermal comfort performance of fire-fighters’ clothing is reviewed. The shortcomings of current researches and the focus of future researches are expounded. This study not only provides guidelines and suggestions for the research, development, design and selection of fire-fighters’ clothing, but also helps to better understand the relationship between thermal protection performance and thermal comfort performance of fire fighter clothing. Meanwhile, it provides a reference for improving the testing methods and establishing the testing standards of fire fighter clothing.

Keywords

Thermal protection performance, thermal comfort performance, firefighters’ clothing, evaluation methods, standard and non-standard test

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Introduction

The firefighters’ clothing is not only an indispensable equipment for firefighters to carry out fire rescue, but also an important safeguard for firefighters’ life safety. The firefighters’ clothing should prevent external thermal damage, including radiation, flame, smoke, toxic gases, high temperature, high wet steam, and other hazards intrusion into the human body.1–5 Therefore, many scholars began to study the thermal protection performance of fire fighters’ clothing. On the one hand, what factors affected the thermal protection performance were discussed, and how to improve the thermal protection performance of the firefighters’ clothing. On the other hand, some scholars studied how to test and evaluate the thermal protection performance of the firefighters’ clothing.

As functional clothing, the thermal protection performance of firefighters’ clothing is the most important, followed by thermal comfort performance. When firefighters wear heavy fire suits to carry out fighting fire and rescue tasks...
in the fire scene, they will inevitably be subjected to the thermal stress exerted by the fire environment, and produce a strong sense of discomfort. This will affect the work efficiency of firefighters, and even threaten their life safety. Therefore, the thermal comfort of fire-fighters’ clothing is particularly important.

How to make the firefighters’ clothing not only ensure the thermal protection performance, but also have excellent thermal comfort performance has become the research hotspots of most scholars. It can be seen that most studies hope to find a more optimal matching scheme by balancing the thermal protection and thermal comfort of fabrics. However, the relationship between the thermal protection performance and its thermal comfort performance is rarely reported.

This paper reviews the current evaluation methods of thermal protection performance and thermal comfort performance for fabrics and clothing from standard test and non-standard test. At the same time, the study of relation between the thermal protection performance and thermal comfort performance of firefighters’ clothing is reviewed. The shortcomings of current researches and the focus of future researches are expounded. The review structure is shown in Figure 1.

### Evaluation of thermal protection performance for fire-fighting fabrics

The thermal protection properties of fabric mainly include fabric flame resistance and heat transfer properties. The evaluation methods of flame retardant properties are vertical combustion method, 45° Slope method and limit oxygen index method. Although these test methods can evaluate the flame retardant ability of the fabric and the performance of most flame retardant fabric. With the development of new materials, it is difficult to evaluate the fabric flame retardant test under the same circumstances.

#### Standard test

Behnke\(^6\) noted that the early flame resistance tests for quality control of fabric resistance were not sufficient to assess the grade of protection and proposed to test the thermal transfer performance using a thermal protection (thermal protective performance, TPP) test device based on the Stoll burn guidelines on secondary burns in human skin.\(^7,8\) With the application of the TPP test method,\(^9\) a series of standard tests are developed, and common standard test methods are shown in Table 1 below.

As can be seen from the above table, most of the evaluation indicators are obtained by calculating the time of second-degree burns or the minimum heat exposure time multiplied by the heat flow density using the skin burn model. There are also some indicators to evaluate the thermal protection performance of the fabric, such as with the time required for the penetration of energy or a certain increase of sensor temperature.

From the perspective of test standards, TPP and RPP (Radiant Protective Performance) evaluation methods are simple and widely used by most scholars. But there are some deficiencies, such as the metal copper sheet sensor, whose accuracy will decrease with the heat exposure time increasing; the external heat source density is constant, the
exposure time period, and which cannot evaluate the accumulated heat released by the fabric in the cooling stage. The SET (Measuring the Transmitted and Stored Energy of Firefighter Protective Clothing Systems) test method evaluates the thermal accumulation properties of the fabric and gives minimum exposure times for second-degree burns.

Non-standard test

In the process of developing fire service thermal protection performance testing standards, some scholars have designed and built fabric thermal protection performance testing devices, and established many non-standard testing methods.

Zhu et al.18 used the independently developed three-dimensional cylindrical test device to measure the thermal protection performance and combined with the skin biological heat transfer model to compare the results of the plate experiment and the cylindrical experiment.

Xin et al.19 measured the thermal protection of the fabric under dynamic air layer conditions by improving the TPP test device. Liu et al.,20 Murtaza,21 and Su and Li22 developed small-scale bench testing equipment with horizontal placement to study the thermal protection properties of fabrics under high-temperature steam conditions. Mandal et al.23 and Lu et al.24 designed test equipment to study the thermal protection properties of fabrics under high-temperature liquid exposure. Mandal et al.25 set a standard the thermal protection performance under thermal surface contact exposure by building a thermal contact platform.

Table 1. Common international standard thermal protection performance evaluation method of fabrics.

| Standard name | Test device | Heat source type | Sample size (cm) | Evaluation indicators |
|---------------|-------------|------------------|------------------|----------------------|
| ISO1749210    | TPP Tester  | Convection 50% Radiation 50% (80 kw/m²) | 15 × 15 | HTI |
| ASTM F2700-200811 | TPP Tester | Mixed (84 kw/m²) | 15 × 15 | HTP |
| ASTM F2703-200812 | TPP Tester | Convection 50% Radiation 50% (84 kw/m²) | 15 × 15 | TPE |
| NFPA1971-200713 | TPP Tester | Convection 50% Radiation 50% (84 kw/m²) | 15 × 15 | TTP |
| NFPA197714    | RPP Tester  | Radiation 100% (84 kw/m²) | 25 × 10 | RPP |
| ASTM1939-200815 | RPP Tester | Radiation 100% (84, 21 kw/m²) | 23 × 80 | RHR |
| ISO6942-200216 | RPP Tester  | Radiation 100% (80, 5–10, 20–40 kw/m²) | 152 × 152 | Time of second-degree burns, minimum heat exposure time |

evaluation of thermal protection performance of fire fighters’ clothing

In the production process of fire fighters’ clothing, the clothing style design, structural design, type design, size, sewing process, and other aspects will affect the thermal protection performance of the fire fighters’ clothing, so the fabric system level test cannot truly reflect the thermal protection performance of the fire fighters’ clothing. Therefore, it is necessary to carry out the thermal protection performance research of fire fighters’ clothing research. The current international universal is the burning dummy law.26

The corresponding criterion is that ISO13506, ASTM F1930-2011, this method evaluates the second-degree burn time of the skin in combination with the Pennes heat transfer model and the Henriques burn integral model, giving the percentage of skin burn grade and burn area. Burning manikin makes the fire fighters’ clothing exposed to high heat flow density for short time and damages the clothes. However, the working environment of firefighters is mostly under the condition of low heat radiation. Skin burns occur when the fire suit is not damaged.

Based on this, Watson27 has built the radiation manikin, which can realize the thermal protection performance test of forest firefighters under the radiation intensity of 5–21 kw/m². Radiation manikins are not widely used and no relevant criteria are set.

Studies have shown that firefighters mostly have been burned in harmful thermal environments, Such as low levels of thermal radiation 0.42–8.37 kw/m².51 Rossi and Bolli28 used a manikin to assess the radiation thermal protection performance of the fire jacket, but the manikin was simply a static model made from PVC.

Havenith et al.29 studied the effect of radiation on Newton manikin heat loss at different wind speeds, but the lower radiation levels were only 0.325 and 0.45 kw/m². The thermal protection properties of protective clothing were not explored.

Stroup et al.30 used desktop instruments and a full size manikin to study the thermal protection performance of fire suits at different low levels. However, like the model used by Rossi, the full-size manikin has no power control system and cannot sweat, ignoring the role of firefighters in using them.

There are many heat protection performance factors of fire fighters’ clothing, fabric performance, heat exposure strength and type, wind speed, which would affect the thermal protection performance of fire fighters’ clothing, while the air layer under the fire fighters’ clothing will hinder heat transmission.34
There are many factors affecting the thermal insulation performance of fire fighters’ clothing, such as fabric performance, heat exposure strength and type, wind speed, and so on. The air layer under the fire fighters’ clothing will hinder heat transmission, a large amount of sweat and water in the external environment are absorbed by the fireproof clothing, which changes the thermal conductivity and specific heat capacity. The energy change of water will affect the heat transfer process in the fire fighters’ clothing, thus affecting the heat protection performance of the fire fighters’ clothing.

To sum up, it can be found that the evaluation of thermal protection performance of fire fighters’ clothing is becoming more and more perfect from fabric level to clothing level and from standard test to non-standard test. However, the existing evaluation methods still have shortcomings, such as ignoring the effects of dynamic conditions, water, exposure time, exposure heat source type and other factors on the thermal protection performance of Fire fighters’ clothing.

In the near future, the development trend of thermal protection performance test and evaluation method of fire fighters’ clothing is to simulate the working environment of firefighters more truly, from experimental evaluation to damage-free numerical simulation evaluation.

### Evaluation of thermal comfort of firefighting fabrics

Clothing comfort is a complex concept, which mainly evaluates the comfort of the body to clothing. It includes thermal comfort, sports comfort, skin contact comfort, and so on. The structure of clothing itself and the external environment are the two main factors affecting comfort. For the comfort of fire fighters’ clothing, the most important is thermal comfort performance.

Thermal comfort mainly refers to the thermal and wet comfort performance of fabrics. The thermal and wet comfort performance of clothing refers to the continuous exchange of heat, water and gas between the human body wearing clothing and the environment under different climatic environment and human activity level. When the exchange reaches a balance, the human body feels comfortable and satisfied with a certain status.

Thermal comfort performance evaluation methods can be divided into two categories: subjective evaluation and objective evaluation. The subjective evaluation method evaluates the thermal comfort of clothing through the subjective feelings of the wearer. Objective evaluation methods include physical methods, physiological methods, psychological methods, and warm body dummy methods. Currently, the five-level comprehensive analysis method is widely used internationally.

The thermal comfort performance evaluation indicators of the fabric include heat resistance, moisture resistance, moisture transmission index, total heat loss, evaporation, and heat dissipation efficiency. The proposal of clo value and wet transmission index laid the foundation for the evaluation of thermal and wet comfort.

### Heat resistance

In 1941, Gagge, a physiologist, proposed a general quantitative unit of clothing thermal resistance. Measuring the heat resistance of clothing with clo value can not only reflect the characteristics of clothing materials and process production, but also reflect the physiological state of thermal balance regulation in the human body. The concept of clo value not only creates a new era of clothing thermal and wet comfort research, but also provides a unified index for clothing thermal and wet comfort.

### Moisture resistance

The moisture resistance of clothing affects the comfort of clothing. The vapor pressure difference between skin and environment is the driving force of latent heat transmission. Sweat on the skin evaporates on the skin surface and passes to the environment through clothing. This moisture transfer resistance is called clothing moisture resistance. For typical clothing, the greater the wet resistance is, the greater the resistance to the wet transmission is, the worse the moisture permeability of the clothing is.

### Moisture transmission index

In 1962, American clothing scientist woodcock wrapped the test fabric in a wet cylinder to determine the surface temperature of wet fabric. Based on these test data, he proposed a physical quantity of 1, as a measure to evaluate the comfort of clothing under thermal environmental conditions. The evaporation heat dissipation efficiency considers the heat transfer, evaporation heat transfer and the wet transmission index and the dry heat resistance between the wet transmission index and the heat resistance. In terms of determining the evaporative heat transfer of the clothing system, the evaporative heat dissipation efficiency represents the maximum evaporation cooling share when the environment is not windy, so that expectations can be made about whether the evaporation heat dissipation amount of the clothing under the given environmental conditions can meet the needs.

### Total heat loss

The heat dissipation of the human body mainly includes the heat dissipation of the human body to the external environment in the dry state, the heat dissipation brought by sweating and evaporation, and the heat exchange of the internal and external environment and the environment. In addition
Table 2. Calculation formula.

| Calculation formula | Equations number |
|---------------------|------------------|
| \( Q = \frac{10^\circ C + 3.57kPa}{R_{cf} + 0.04 - R_{cf} + 0.0035} \) | (1) |
| \( R_{cf} = R_{ct} - R_{cbp} \) | (2) |
| \( R_{cf} = R_{ct} - R_{cbp} \) | (3) |
| \( R_{ct} = \frac{(T_s - T_a)A}{H} \) | (4) |
| \( R_{ct}^A = \frac{(P_s - P_e)}{H - (T_s - T_a)A} \) | (5) |

The thermal comfort evaluation method of standards of Countries\(^5\) is obviously the same. The US takes the total heat loss as the evaluation index, the European Union takes the wet resistance as the evaluation index, the United States and the European Union are based on multi-layer fabric as the test object. At present, The China takes the moisture permeability of waterproof and breathable single layer as the evaluation index to evaluate the thermal comfort performance of fire fighters’ clothing.

**Evaluation of fire fighters’ clothing**

The thermal comfort performance of fire fighters’ clothing is also affected by multiple factors, like the thermal protection performance of fire fighters’ clothing. At present, the thermal comfort performance assessment method of fire fighters’ clothing mainly includes dress human body test method and thermal manikin method.

**Dress human body test method**

The dress human body test directly evaluated the thermal and wet comfort of the clothing through the subjective response of the subjects. Dress human body test can be divided into psychology test evaluation method and physiological test evaluation method. Psychology test evaluation method is that present different reactions according to different thermal and wet comfort states of human physiological parameters, so as to judge the thermal comfort performance of clothing. Physiological test evaluation method judges the thermal comfort performance of clothing based on the change of human physiological parameters with the thermal and wet comfort state.

Some representative test parameters include core temperature, skin temperature, skin humidity, heart rate, metabolic heat yield, and oxygen consumption. Psychological test evaluation method is the subjective sensory evaluation method.

Subjective feeling is a quantitative evaluation ruler containing evaluation items such as heat feeling, wet feeling and stuffy feeling. Subjects score each evaluation item. The commonly used subjective evaluation rulers are seven-level scale and five-level scale. The other subjective feeling is through the EEG component analysis method, according to the nerve endings will respond differently to cold and hot stimulation, through collecting the EEG of the dressed body can judge the hot and wet comfort.

**Thermal manikin methods**

Thermal manikin is a simulated test equipment with human body size and structure characteristics. It can simulate human sweating with a certain metabolic heat production and skin temperature.
It is an important part of the performance test and evaluation of hot and wet comfort. In 1946, the world’s first thermal manikin, developed by the American Quartermaster Institute, was used to test the clo value of clothing in copper and non-walking. It was known as the first generation thermal manikin. Then scholars began to develop a second generation of walking thermal manikin. At present, the more mature is the third generation of sweating thermal manikin, which can simulate human sweating, such as Walter, Newton, Tore.

With the progress of science and technology, the thermal physiological sweating thermal manikin with active body temperature regulation opened the prelude to the fourth generation of thermal manikin.44 The development of thermal manikin has experienced the process from static to dynamic, from drying to sweating, from single section to multi-section, from manual to automatic control. The development of thermal manikin also improves the testing and evaluation system of clothing thermal and moisture properties.

The overall total heat loss (THL) value of the firefighters’ clothing can be assessed by the sweat thermal manikin system. Ross45 selected fire fighters’ clothing for the sweat thermal manikin as an intermediate tool to compensate for the gap between the sweating heat plate instrument and physiological tests, while trying to predict the heat stress generated during the use of the fire suit. However, since the THL values measured by the thermal manikin were obtained based on THL of fabric, which was measured in two different environments, the total heat loss of the sweating thermal manikin is predicted rather than actually measured.

Alternatively, this calculation ignores the effects of moisture condensation, absorption and fabric type variation in various environmental conditions, but is useful for direct comparisons of clothing thermal comfort, as it considers the complete individual surface area and morphology, as well as the structure and design of 3-D clothing.

In conclusion, the dress human body test method can obtain accurate and reliable test results, but the repeatability is poor and the test environment is limited. The dress human body is not suitable for clothing in some extreme environments, which limits the thermal comfort assessment of fire fighters’ clothing. In addition, the current physiological test and evaluation methods lack evaluation standards, and cannot quantitatively evaluate the thermal and wet comfort performance of clothing.

The development of the fourth generation of thermal physiological sweating thermal manikin will break through the traditional thermal manikin which does not have the function of active heat regulation, and will undoubtedly push the thermal and wet comfort performance of clothing to a new stage. The evaluation index of thermal comfort performance of fire fighters’ clothing is not yet mature, so it is necessary to formulate new evaluation indexes to improve the test and evaluation system of thermal and wet comfort performance of clothing.

The study of relation between the thermal protection performance and thermal comfort performance of firefighters’ clothing

The research of fire fighters’ clothing by scholars at home and abroad focuses on the thermal protection performance aspect of fire fighters’ clothing, relatively little research on the thermal comfort performance of fire fighters’ clothing, and less research on the study of relationship between the two performance relations of fire fighters’ clothing.

Research status

Cui46 tested the thermal protection performance and clothing performance of each layer of fabric in fire fighters’ clothing. The three-layer composite system of fire fighters’ clothing is simulated with the orthogonal combination of the outer fabric, waterproof fabric and heat insulation fabric by using the mixed orthogonal design method.

The experimental results were analyzed with ANOVA. The results show that the performance of the outer layer material determines the thermal protection performance of the composite fabric system to a great extent, and the waterproof layer material mainly determines the moisture permeability of the composite fabric system.

Zhou47 combined the existing fire service fabrics, established the relationship between TPP and THL indicators and the basic performance of the fabric through testing and analysis, and used the fabric to find the optimal components with high values by comprehensive balance method. This study only obtains the theoretical formula highly related to the index to be measured through the physical parameters.

Zhang46 determined the heat and humidity resistance, the total heat loss (THL) and the heat protection time under the heat storage conditions by using a sweat heat plate instrument and a fabric storage heat test device. Based on the thermal and wet comfort of the fabric system, the comprehensiveness of the fabric system is analyzed and evaluated. The results show that the relationship between the thermal and wet comfort and its thermal protection performance, and the optimal component and optimal thickness of air layer are obtained. This study did not consider the influence of humidity on the thermal comfort and thermal protection properties. Which only considering the qualitative research, and ignoring quantitative study of thermal accumulation, that is the heat storage of the fabric.

Xin46 studied the relationship between thermal protection performance and comfort of fire fighters’ clothing fabric system, and constructed the thermal protection performance and thermal comfort performance of multi-layer fabric system.
and the gray correlation system of single-layer fabric material characteristics and basic properties. Finally, a comprehensive index which can effectively combine thermal protection performance and thermal comfort performance was established. It can use a single quantitative index to comprehensively evaluate the thermal protection performance and thermal comfort of fireproof clothing fabric system.

**Research shortages**

Most of the researches are based on the thermal protection performance and thermal comfort performance of fabric systems, based on which the two properties are balanced to find the optimal fabric combination scheme. However, there are still some differences between the performance of fabric system and the performance of fire fighters’ clothing. The thermal protection performance and thermal comfort performance of fabric system cannot truly reflect the thermal protection performance and thermal comfort performance of fire fighters’ clothing.

The factors affecting the thermal protection performance and comfort performance were not fully considered, and the comprehensive impact of these factors on the thermal protection performance and thermal comfort performance was not discussed. The use environment of fire fighters’ clothing involves multiple factors occurring at the same time, and the accuracy of the thermal protection performance and thermal comfort performance of fire fighters’ clothing alone needs to be verified.

The overall thermal comfort test and evaluation system of fire fighters’ clothing needs to be improved. The present test and evaluation indicators are established under dry conditions, ignoring wet fire fighters’ clothing.

**Future trend**

It can be seen from the study of thermal protection performance and comfort performance, from fabric to clothing, test environment from a single radiation heat flow to flash fire, experimental methods from experimental research to numerical simulation, non-standard test research, to promote the formulation and improvement of more new standards. The future research of thermal protection performance and thermal comfort performance should be operated in more practical scenario, the test method should be more simulated, and the test environment is used to simulate in the fire operation environment.

The future researches can be studied in the following aspects:

The relationship between the overall thermal protection performance and thermal comfort performance of fire fighters’ clothing will be studied. Fire fighters’ clothing is multi-layer clothing. In the process of making clothing, due to the clothing style design, structural design, number design, size, sewing process and other factors will have a more complex and comprehensive impact on the overall thermal protection performance and thermal comfort performance of fire fighters’ clothing.

It is in order to deeply study the important factors affecting the thermal protection performance and thermal comfort performance of fire fighters’ clothing that discuss the impact of different states (static, dynamic), water, air layer, thermal exposure conditions, length of exposure time, and temperature and humidity conditions on the overall thermal protection performance and comfort performance of fire fighters’ clothing, and establish the relationship between the overall thermal protection performance of fire service and the comfort performance of fire fighters’ clothing.

A new thermal comfort performance evaluation index of fire fighters’ clothing will be built. Now the general thermal protection performance and thermal comfort performance evaluation index are established under dry conditions. However, the use environment of fire fighters’ clothing inevitably has external environment water and human sweat. Therefore, establishing the evaluation index under wet conditions is helpful to improve the thermal protection performance and comfort performance evaluation system of fire fighters’ clothing.

A multi-dimensional mathematical model of “human-clothing space-fire fighters’ clothing-environment” was established to explain the overall thermal and wet transmission texture of fire fighters’ clothing, and verify the effectiveness of the experimental results, providing a theoretical basis for quantifying the thermal protection performance and thermal comfort performance of fire fighters’ clothing.

**Conclusion**

This paper reviews the current thermal protection performance and thermal comfort performance evaluation methods of fabric and clothing from standard and non-standard tests. Research on thermal protection performance and comfort performance of fire fighters’ clothing, from fabric to clothing, the test environment from a single thermal radiation, thermal convection to flash fire and other environments, experimental methods from experimental research to numerical simulation, non-standard test research, which promote the formulation and improvement of more new standards. The future research of thermal protection performance and thermal comfort performance should be tested in more practical scenario, the test method should be more simulated, and the test environment is simulated in the more truly fire operation environment. At the same time, the study of relation between the thermal protection performance and thermal comfort performance of fire-fighters’ clothing is reviewed. The current research shortage and future scope are expounded.

Most of the research is based on the thermal protection performance and thermal comfort performance of fabric
system to find the best fabric combination scheme; the influence of thermal protection performance and comfort performance is incomplete, and the comprehensive impact of these factors on thermal protection performance and thermal comfort; the overall thermal comfort test and evaluation system of fire service need to be improved.

The study future scope of relationship between the overall thermal protection performance and thermal comfort performance of the fire fighters’ clothing was proposed, which based on the current situation of the relationship; discussing different states, water, air layer, thermal exposure conditions, exposure time, temperature and humidity conditions; constructing new thermal comfort performance of fire fighters’ clothing; establishing a multi-dimensional mathematical model of “human-clothing space-fire fighters’ clothing-environment,” and verifying the overall thermal and humidity transmission texture with the experimental results to provide a theoretical basis for quantifying the thermal protection performance and thermal comfort performance of fire fighters’ clothing.

The study of relationship between thermal protection performance and fire comfort performance not only provides effective guidance and advice for the production, production and selection, but also helps to fully understand the overall thermal protection performance and comfort performance and influencing factors, and provides reference to improve and develop relevant test methods and test standards, and in the field of protection to enhance protection and comfort, reduces operation risk, but also for the country, social, personal public property safety, which is of great significance and value.

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