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Review

Prediction methods of skin burn for performance evaluation of thermal protective clothing

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ABSTRACT

Most test methods use skin burn prediction to evaluate the thermal protective performance of clothing. In this paper, we reviewed different burn prediction methods used in clothing evaluation. The empirical criterion and the mathematical model were analyzed in detail as well as their relationship and limitations. Using an empirical criterion, the onset of skin burn is determined by the accumulated skin surface energy in certain periods. On the other hand, the mathematical model, which indicates denatured collagen, is more complex, which involves a heat transfer model and a burn model. Further studies should be conducted to examine the situations where the prediction methods are derived. New technologies may be used in the future to explore precise or suitable prediction methods for both flash fire tests and increasingly lower-intensity tests.

Contents

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1. Introduction

Workers in high-risk occupations, such as firefighters, are likely to be exposed to thermal hazards, especially extreme heat induced by flame, which may result in skin burn [1]. Thermal protective clothing will reduce the rate of heat absorbed by human skin in order to minimize skin burn [2].

Over the past decades, inherent flame-retardant fibers, such as Nomex and polybenzimidazole (PBI) [3], have been developed. They provide better protective performance compared with modified fibers and fabrics. Unlike the traditional test methods for most functional clothing, human tests are never used due to the potential risk to the human body. Initially, in order to determine the burn prevention performance of nonflammable fabrics, the US Army Aeromedical Research Laboratory (USAARL) used the porcine cutaneous bioassay technique [4]. However, this technology is difficult and expensive to conduct. Therefore, various test methods were developed, which use a physical thermal sensor to measure the heat flux, such as benchtop tests [5], cylindrical device tests [6], and manikin tests [7]. Most test methods use skin burn predictions to simulate the potential burn and determine the protective performance of the sample [8].

In the early 1960s, Stoll [9] used surface temperature over a thermal manikin to determine the potential burn. Since then, various burn prediction methods have been developed. Most of the benchtop tests use the temperature rise of a calorimeter and the Stoll criterion [10], while the manikin test uses the surface heat flux and a more complex mathematical model [11,12]. In recent years, many researchers have pointed out the limitation of traditional burn prediction methods, such as the uncertainty of the prediction results due to various skin properties in different body locations [13,14]. Moreover, the Pennes bio-heat transfer equation seems insufficient to simulate the heat transfer of human skin [15]. Thus, some researchers have tried new methods vastly different from those suggested in the test standards [16,17].

The aim of this paper was to review burn prediction methods in detail, and to discuss the relationship or differences between various prediction methods. For a more efficient comparison, we divided the prediction methods into two categories: prediction based on the empirical criterion and prediction using a mathematical model. The former is actually derived from the skin burn studies conducted by Stoll et al. [18–20]. However, the clinical data were used in different methods over the years. As to the mathematical model, different heat transfer models of skin, burn models, and influencing factors are discussed. The newly developed methods and models are also involved in the review as well as some further research suggestions.

2. Prediction based on the empirical criterion

2.1. Stoll criterion and Stoll curve

2.1.1. Stoll criterion

Previously, it was believed that the total skin damage is dependent only on the total cumulative dosage, and equal doses produce equal injury [21]. The thermal damage is described as follows:

$$\Omega = \int_0^t q dt \tag{1}$$

where Ω is the measure of thermal damage and q is the heat flux.

However, Stoll found that a thermal burn was dependent not only on the total energy but also on the exposure time. She conducted a series of human or animal tests to investigate the relationship between exposure level (0.1–0.4 cal/cm^2 s, 4–16 kW/m^2) and human tolerance time to particular thermal damage [18]. Then mathematical models were used to predict the tolerance time for a larger range of radiation intensity (0.4–1.2 cal/cm^2 s, 16–48 kW/m^2) [19,22]. Using these data, the tolerance time to second-degree burns was predicted for different incident heat fluxes.

Considering the often-confused names such as "Stoll criterion" [22,23] and "Stoll curve," [24,25] in this paper, we suggest the following definition for the Stoll criterion. The Stoll criterion is the relationship between the heat flux and tolerance time to second-degree burns, which is based on Stoll's research data. Obviously, the criterion developed by Stoll is for a limited heat flux level. These data are represented by scatters in Fig. 1. Later, the American Society for Testing and Materials (ASTM) D4108 used the following formula

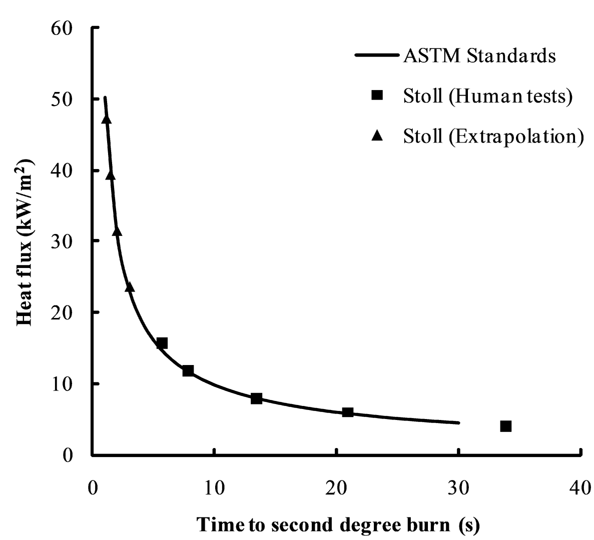

Fig. 1 – Stoll criterion developed by Stoll [20] and expanded by ASTM standards. [26].