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Skin temperatures of a pre-cooled wet person exposed to engulfing flames

Torgrim Log

Western Norway University of Applied Sciences, Haugesund, Norway

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ABSTRACT

In a television show, a wetted bare-skinned person slid through engulfing kerosene pool fire flames. The 0.74 s flame exposure resulted in pain and light sun burns. The heat and mass transfer involved in this dangerous stunt have been analyzed in order to evaluate whether or not the thin water layer represented an important heat protection measure. It is estimated that the wetted person was exposed to heat fluxes in the range of 80–90 kW/m^2. Analytical solutions of the heat equation were used to evaluate water-spray pre-cooling, heating during flame exposure and post-flame relaxation of skin temperature gradients. It is shown that the water layer carried on the skin into the flames represented limited heat protection. The 30 s cold water-spray pre-cooling prior to the flame exposure was the most important heat protection mechanism. Larger flames of higher emissivity, longer period of flame exposure, warmer pre-cooling water or shorter pre-cooling period would most likely have resulted in severe skin burns.

1. Introduction

1.1. Life on the Line

Some television shows generate excitement by exposing individuals to near-harmful conditions. One such show is the series, *Life on the Line* (*Med livet som innsats*), presented by the Norwegian Broadcasting Corporation, www.nrk.no. This particular series takes physics and science out of the textbooks and into the real world through rather dangerous stunts. The TV host performs the stunts himself, and the premise is that proper consideration of the physics will protect him during the exercise. The program is comparable to other popular TV series such as *MythBusters* [1]. While the latter works hard on several safety procedures, *Life on the Line* relies strongly on understanding and accounting for the physics involved in order to assure safety. Flames and skin exposure represent a situation in which the physics involved may not be as straightforward as at first assumed.

Prior to one of the episodes, named "Grilled Alive", the Western Norway University of Applied Sciences (WNU) was contacted by the producer (Bulldozer Film Inc., Norway). The idea was to prove that a thin layer of water can protect naked skin during short periods, i.e. less than one second, of exposure to engulfing flames. A WNU laboratory engineer agreed to participate in the TV show to warn about flame exposure, the need for breathing air and protective clothing during firefighting, etc. The laboratory engineer asked the author of the present paper for an opinion on the concept. Based on estimates of thermal dose unit damage [2] and the dangers involved, it was concluded that such exposure to flames was potentially very dangerous. The author strongly recommended abandoning the stunt. The producer did, however, proceed without scientific assistance and constructed water-cooled rails on which the bare-skinned TV host decided to travel through fully-covering kerosene flames. A short video for the international audience is shown at: http://youtu.be/mQVlOXfegsA.

1.2. Thermal exposure of skin

After World War II, a series of significant studies on the effects of thermal skin injury was published in *The American Journal of Pathology*. These articles included heat transport to, and through porcine skin, as well as the temperatures achieved [3]. Also studied was the importance of time and surface temperature in causing cutaneous burns [4], in addition to the pathology and pathogenesis of cutaneous burns on pigs [5]. Most research in heat exposure to people lately has been on protective clothing. Full manikin-scale test facilities have therefore been built for research and testing [6]. A recent review of this work is given by Zhai and Li [7].

It is generally agreed that a temperature >44 °C will give burns, with the degree depending on the temperature and exposure time. Recently, more research has been conducted on burns and burns treatment [8,9]. Skin simulators have also been built for studying heat transfer and comparing the developed models to recorded "skin" temperatures during controlled cone calorimeter heat flux exposure [10]. Fu et al. [8] showed that the dermis blood perfusion rate, the epidermis and dermis conductivity and heat capacity, had little influence on skin damage. Following

E-mail address: torgrim.log@hvl.no.

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heating of the skin's surface, Van de Sompel et al. [11] found that the reduction in Arrhenius damage integrals near the skin's surface during fast cooling was too small to be physiologically relevant.

Wieczorek and Dembsey [12] present a comprehensive review of the effects of thermal radiation on people. The benefit of low skin temperatures prior to radiant heat exposure is briefly discussed, and they conclude that this may help considerably in preventing skin overheating. No research was identified regarding pre-cooled wet human skin exposed to flames.

1.3. The present work

The work by Wieczorek and Dembsey [12] serves as a basis for parts of the present study. Extensions needed for pre-wetted (pre-cooled) skin, including water layer heating and evaporation was introduced. In addition to studying TV footage, the methods include interviewing personnel involved in the TV show, engineering and analytical solutions of heat and mass transfer. For the proofing process, a water layer thickness (A) that does not evaporate completely during flame exposure is selected. The theoretical behavior of this water layer is compared to photographical evidence regarding the actual behavior of the real water layer (thickness B). Ensuring that A > B makes it possible to demonstrate limitations in heat protection by the real water layer, and the influence of the pre-wetting and pre-cooling is outlined. The novelty of the work includes the heat and mass transfer involved when wet pre-cooled skin is exposed to flames and the use of analytical solutions in this respect. A potential lesson from the study could be its possibility to act as a warning to others about participating in such dangerous stunts.

2. Set-up and flame exposure

The television show set-up consisted of a 12 m long sloping water-cooled steel rail, passing over a pool fire and terminating in a water pool. A trolley was fabricated for the purpose of acceleration and guidance through the flames. The rails were first tested without fire and with a dummy of a similar size and mass to that of the TV host (1.93 m tall, 100 kg). The inclination was adjusted to give a speed of 14 km/h (3.9 m/s), as measured by the local police force using their speed-recording radar unit. The fire pool had a length (along the rails) of 2.24 m and a width of 0.86 m. It was partly filled with water and topped with kerosene. Based on successful test runs, the TV host decided to undergo the final flame exposure wearing only underwear, consisting of woolen shorts, and a woolen head cloth, as shown in Fig. 1a. The arrangement for the 30 s pre-wetting is shown in Fig. 1b, while the flame exposure is shown in Fig. 1c.

Soot marks on the skin were evident, as seen in Fig. 2. These soot marks indicate that parts of the skin had experienced complete drying during the flame exposure. About 10 min after the flame exposure, the TV host started feeling burns, similar to light sunburn, on most of the back (~40 cm by 60 cm), as well as on the forearms, calves and the lower parts of the thighs (each ~5 cm by 30 cm). The light burns did, however, vanish completely after 24–36 h, leaving no permanent marks or scars on the skin surface.

The TV host later reported having experienced a short bout of pain just before, or just as, he hit the surface of the water-cooling pool. He did feel surprisingly warm after exiting the water pool, describing this later as follows: "I got a feeling of warmth spreading through the body". He further explained that this could have been the normal sensation of warmth following a short swim in cold water, ice bathing, etc., but he could not exclude the possibility that the feeling of heat was emanating from deeper within the skin, or a combination of these factors.

3. Risks involved

Inhalation of hot gases at 1000 °F (538 °C) will immediately result in heat injury to the upper airways above the carina [13]. According to

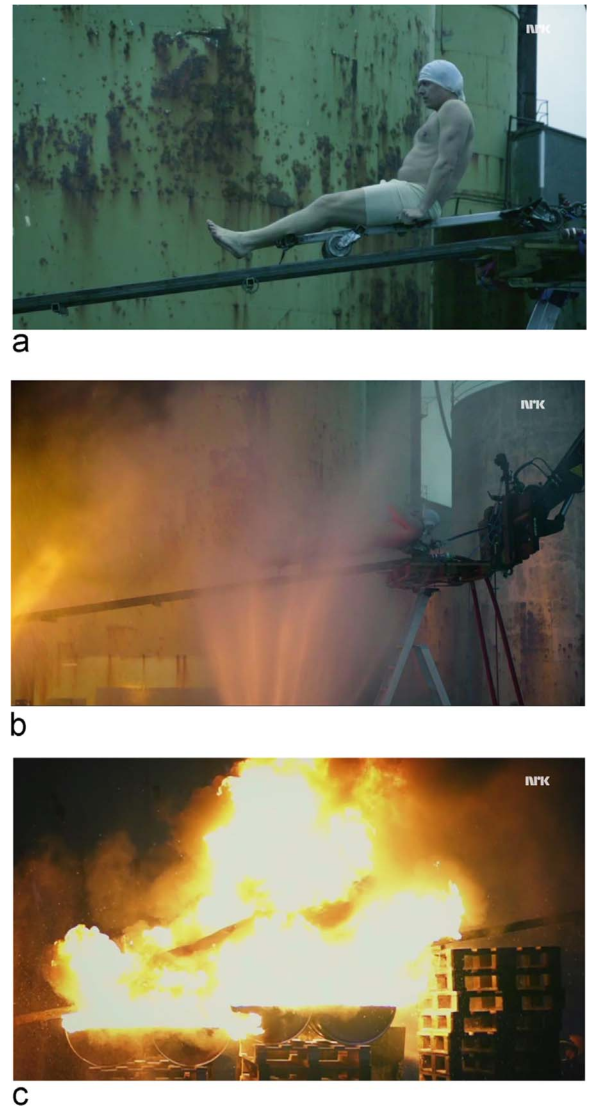

Fig. 1. a) TV host mentally preparing for pre-wetting prior to final flame exposure b) TV host during the 30 s pre-wetting period c) TV host engulfed in flames on the way towards the water pool. (Bulldozer Film Inc., Norway). Reproduced with permission.

Gaydon and Wolfhard [14], the average flame temperature is expected to be about 990 °C. Fortunately, the TV host avoided inhalation until safely deposited in the water-cooling pool.

The other major issue is the risk of skin burns. Pain receptors are located at a depth of approximately 0.1 mm, and the pain temperature threshold is 44.8 °C [15,16]. However, skin injury starts to develop when the skin temperature is greater than 44 °C due to the onset of protein breakdown [17,18]. Skin damage is a function of temperature and time period above this threshold temperature. An Arrhenius type of damage development is often assumed, i.e. the damage increases considerably with excess temperature [12]. Flame temperatures close to 1000 °C represent a significant threat also for short periods of exposure. The light burns received by the TV host indicate that this may have been a narrow escape. Further investigation into the heat and mass transfer involved is therefore of scientific interest.

4. Heat flux from flames to the skin

Two principal heat transfer modes exist when heat is transferred from hot gases and flames at temperature T_F (K) to the surface of an exposed object, such as skin, at temperature T_S (K), i.e. convection and radiation. The heat flux by convection may be expressed by: