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

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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

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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

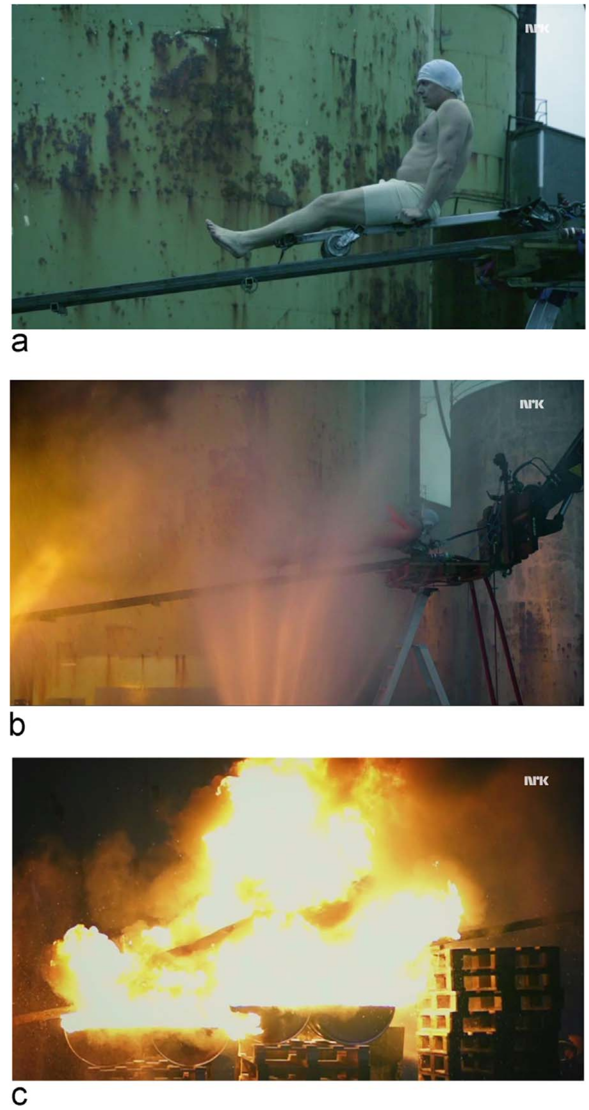

Fig. 1. a) TV host mentally preparing for pre-wetting prior to final flame exposure b) TV host during the 30 s pre-wetting period c) TV host engulfed in flames on the way towards the water pool. (Bulldozer Film Inc., Norway). Reproduced with permission.

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:

Fig. 2. Soot marks on arms (photo by Andreas Wahl). Reproduced with permission.

$$\dot{q}_h'' = \frac{k_a}{\delta_a}\cdot(T_F - T_S) = h\cdot\Delta T, \quad (1)$$

where the first equation defines a transition layer, δ_a (m), from the skin surface to the flames and hot gases at temperature T_F (K), k_a (W/m K) is the thermal conductivity of air, $h=\frac{k_a}{\delta_a}$ (W/m^2 K) is the convective heat transfer coefficient and $\Delta T=T_F - T_S$. The heat flux by thermal radiation in engulfing flames is given by:

$$\dot{q}_{rad}'' = \varepsilon_f\cdot\sigma\cdot(T_F^4 - T_S^4), \quad (2)$$

where ε_f is the resulting emissivity, σ (5.67·10^{-8} W/m^2 K^4) is the Stefan Boltzmann constant and T (K) is the absolute temperature of the radiating object. For flames and hot gases, the emissivity is given by:

$$\varepsilon_f = 1 - e^{-K\cdot L}, \quad (3)$$

where K (1/m) is the extinction coefficient and L (m) is the optical thickness of the flame/hot gas, i.e. from the edge of the flame to the exposed object. The resulting emissivity is given by:

$$\varepsilon_r = \left(\frac{1}{\varepsilon_f} + \frac{1}{\varepsilon_s} - 1\right)^{-1}, \quad (4)$$

where ε_s is the emissivity of the exposed object, i.e. the skin.

For 0.3 m diameter kerosene pool fires, Rasbash et al. [19] recorded an extinction coefficient of 2.6 1/m. Gaydon and Wolfhard [14] recorded time-averaged flame temperatures of 990 °C for similar pool fires. Close to the fuel surface, the flame temperature is expected to be lower, due to less mixing of fresh air. The average flame temperature was therefore most likely in the range of 900–1000 °C, with 950 °C being a fair estimate.

The convective heat transfer coefficient in the flames depends on the gas velocities. Using the engineering fire plume relations developed by Heskestad [20] gives about 5 m/s vertical flame speed at body impact. Given 3.9 m/s speed of travel through the flames, at approximately 100° angle to the upwards flame velocity vector, an apparent flame speed of about 6.4 m/s is obtained. The convective heat transfer coefficient can be estimated based on a Nusselt number versus a Reynolds number correlation for airflow across circular cylinders [21]. The selection of a cylindrical diameter of 0.1 m to represent arms and legs, and a film temperature of 800 K, leads to a value of 24.4 W/m^2 K.

At a flame temperature of 950 °C, about 2–3% of the radiation will be reflected by a water film [22]. The emissivity of human skin is about 0.98 [23]. These factors reduce the incident radiation by about 4–5% (Eq. (4)). Assuming now that the average skin surface temperature is about 30 °C, and the average flame thickness from the surface of the body to the edge of the flame is 0.3 m, the heat flux by radiation is ~ 63 kW/m^2. The convective heat flux is ~ 23 kW/m^2, i.e. the total average heat flux to the body is ~ 86 kW/m^2. This is close to the 84 kW/m^2 heat flux value presented in the ISO13506 [24] and ASTM F1930-13 [25] standards for testing heat protective clothing. Using the height of the person (1.93 m) for metric scaling, it may be estimated from Fig. 1c that the length of the flame zone in the direction of travel was about 2.9 m. Given a speed of 3.9 m/s, the exposure time, t_e, was about 0.74 s. This was also confirmed by a study of the TV footage.

5. Water layer evaporation

The heat flux required to heat a water layer from the initial skin surface temperature, $T_{s,0}$, to the final temperature, $T_{w,max}$, during the flame exposure may be expressed by:

$$\dot{q}_{CpW}'' = \delta_w\cdot\varrho_w\cdot C_{Pw}\cdot(T_{s,0} - T_{w,max})/t_e, \quad (5)$$

where C_{Pw} is the specific heat of water (4180 J/kg K), δ_w (m) is the water layer thickness, and ϱ_w is the water density (1000 kg/m^3). Assuming a water layer thickness of 0.1 mm (referred to as thickness A in the Introduction), heated from e.g. 20–50 °C for 0.74 s, this requires a heat flux, $\dot{q}_{CpW}''$ = 17 kW/m^2. Assuming now that the protective water layer evaporates completely during the period of flame exposure, the heat flux consumed by evaporation is given by:

$$\dot{q}_{vap}'' = \delta_w\cdot\varrho_w\cdot\Delta H_{vap}/t_e, \quad (6)$$

where ΔH_{vap} (2382 kJ/kg) is the evaporation heat of water at 50 °C. The water evaporation flux is, however, governed by Fick's law of diffusion [26]:

$$\dot{m}'' = -D_{aw}\cdot dC/dx, \quad (7)$$

where D_{aw} (m^2/s) is the intermolecular diffusion coefficient of water vapor in air, and dC/dx (kg/m^3 m) is the concentration gradient. The diffusion coefficient at 20 °C (273 K) is 25·10^{-6} m^2/s [27], and the general temperature dependency is given by [26]:

$$D_{aw(T)} = \gamma\cdot T^{3/2},\ i.\ e.\quad D_{aw(T)} \approx 4.\ 8\cdot 10^{-9}\cdot T^{3/2} \quad (8)$$

The heat transfer coefficient (Eq. (1)) can be used to estimate the distance from the skin surface to virgin flames, i.e. the diffusion layer thickness:

$$\delta_D \approx \frac{k_a}{h} \quad (9)$$

At a film temperature of 800 K, the thermal conductivity of air, k_a, is 0.057 W/m K [21]. In combination with a heat transfer coefficient of 24.4 W/m K, this gives δ_D = 0.00234 m. At 800 K, the diffusion coefficient, D_{aw}, is ~1·10^{-4} m^2/s. Since the TV host did not suffer severe burns, we may assume that the water layer temperature did not exceed 50 °C. The saturated vapor pressure of the water layer may be calculated by a three-parameter equation [28]:

$$P_{sat} = \left(\frac{101325}{760}\right)\cdot 10^{(8.07131 - 1730.63/(-39.724+T))}, \quad (10)$$

where T (K) is the absolute temperature. The corresponding water vapor concentration at the water surface may be calculated by:

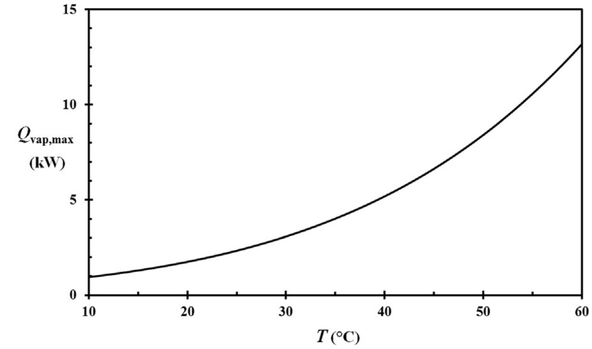

Fig. 3. Maximum water evaporation heat flux as a function of temperature for a 2.34 mm thick diffusion layer.

$$C_w = \frac{P \cdot M_w}{R_g \cdot T} \tag{11}$$

where P (101 325 N/m^2) is the atmospheric pressure, M_w (0.01802 kg/mol) is the molar mass of water, and R_g (8.314 J/mol K) is the molar gas constant. The corresponding heat flux for the water evaporation is given by:

$$\dot{q}''_{vap} = \dot{m}'' \cdot \Delta H_{vap} \tag{12}$$

Assuming that there is no water vapor in the bulk phase of the flames, the heat flux consumed by evaporation as a function of water temperature and diffusion layer thickness is shown in Fig. 3. Given a diffusion distance of 2.34 mm and a maximum temperature of 50 °C, the evaporation heat loss just at the exit of the flame zone is about 8.4 kW/m^2. A 0.1 mm thick water layer heated from 15 °C to 50 °C and evaporating during the flame exposure is finally capable of absorbing at most 17 kW/m^2 (heating) + 8 kW/m^2 (evaporation) = 25 kW/m^2. This is much less than the 86 kW/m^2 received from the flames, i.e. a 0.1 mm thick water layer could only constitute a minor contribution to heat protection.

The soot marks shown in Fig. 2 indicate that, at several locations, all the water had evaporated. The evaporation heat flux of at most 8 kW/m^2, compared to the heat flux needed to evaporate a 0.1 mm water layer in 0.74 s, i.e. 322 kW/m^2 (Eq. (6)), indicates that the real water layer thickness (referred to as B in the Introduction) must have been thinner than 0.1 mm at some locations. At other locations, such as flat surfaces facing upwards, the water layer may have been thicker. Assuming an average water layer thickness of 0.1 mm (referred to as A in the Introduction), i.e. complying with the requirement A > B, the next step may then be to check what temperatures may be expected in skin that is exposed to the remaining heat flux, $\dot{q}''_{net}$, of 61 kW/m^2.

6. Skin temperatures during flame exposure

In the case of a flat body, such as the back of a person, the heat conducted in one dimension is described by Fourier's law:

$$\dot{q}''_k = -k \cdot \frac{\partial T}{\partial x}, \tag{13}$$

where k (W/m K) is the thermal conductivity of the skin. The corresponding heat equation is given by:

$$\frac{\partial T}{\partial t} = a \cdot \frac{\partial^2 T}{\partial x^2}, \tag{14}$$

where t (s) is the time and a (m^2/s) is the thermal diffusivity given by:

$$a = k/(\rho \cdot C_P), \tag{15}$$

where ρ (kg/m^3) and C_P (J/kg K) represent the skin density and specific heat capacity, respectively. If this semi-infinite solid at temperature T_0 for $0 < t \le t_e$ is exposed to a constant surface heat flux, the temperature distribution is given by [29]:

$$T - T_0 = \frac{2\dot{q}''_{net}\sqrt{at}}{k} ierfc\left(\frac{x}{2\sqrt{at}}\right) \tag{16}$$

where x (m) is the distance into the solid. The integral error function is defined by:

$$ierfc(\xi) \equiv -\xi erfc(\xi) + \exp(-\xi^2)/\sqrt{\pi} \tag{17}$$

and the complementary error function is defined by:

$$erfc(\varphi) \equiv 1 - \frac{2}{\sqrt{\pi}} \int_0^{\phi} e^{-\eta^2} d\eta \tag{18}$$

Assuming that this object from $t > t_e$ is completely insulated, the temperature distribution during this time period (before entering the water pool) may be described by:

$$T - T_0 = \frac{2\dot{Q}''_{net}\sqrt{a}}{k} \left\{ \sqrt{t} \cdot ierfc\left(\frac{x}{2\sqrt{at}}\right) - \sqrt{(t - t_e)} \cdot ierfc\left(\frac{x}{2\sqrt{a \cdot (t - t_e)}}\right) \right\} \tag{19}$$

Representative values for the thermal properties of the skin are taken from Wieczorek and Dembsey [12], i.e. thermal conductivity k = 0.5878 W/m K, and volumetric heat capacity ρC_P = 4,186,800 J/m^3 K. This gives a thermal diffusivity, $a = 1.4 \cdot 10^{-7}$ m^2/s (Eq. (15)). The temperature of an idealized skin with these thermal properties, exposed to the 61 kW/m^2 net heat flux for 0.74 s and then thermally insulated, is shown in Fig. 4. Adding these temperatures to 32.5 °C, referred to as the normal skin temperature [12], gives temperatures, which far exceed the threshold value for skin burns and pain, i.e. 44 °C and 44.8 °C, respectively. As an example, the temperature at 0.1 mm depth peaks at 32.5 °C + 28.4 °C = 59.9 °C.

7. Skin temperatures during the pre-wetting period

During the 30 s pre-wetting period, applying cold water spray at temperature T_w to the skin gave convective surface cooling where the temperature development may be described by [29]:

$$T = T_0 + (T_w - T_0) \left\{ erfc\left(\frac{x}{2\sqrt{at}}\right) - \exp\left(\frac{x \cdot h_w}{k} + \frac{at}{\left(\frac{k}{h_w}\right)^2}\right) \cdot erfc\left(\frac{x}{2\sqrt{at}} + \frac{\sqrt{at}}{\left(\frac{k}{h_w}\right)}\right) \right\}, \tag{20}$$

where h_w (W/m^2 K) is the convective heat transfer coefficient of the water spray. Estimating this convective heat transfer coefficient is not a

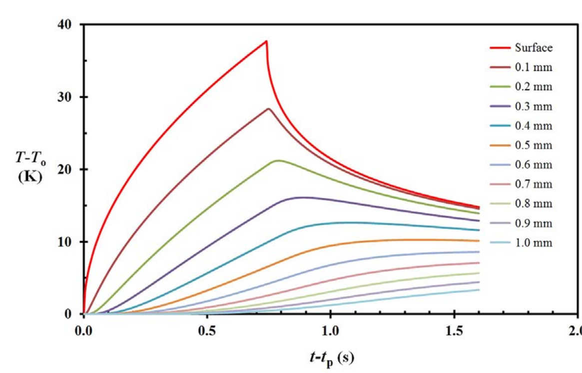

Fig. 4. Temperature increase of the idealized skin (k =0.5878 W/m K and a =1.4·10^{-7} m^2/s) when exposed to a net heat flux of 62 kW/m^2 for 0.74 s and then thermally insulated.

straightforward process. A naked human body immersed in stagnant water is expected to show a heat transfer coefficient between 100 and 200 W/m^2 K [30]. A convective spray heat transfer coefficient higher than this value could be expected during the pre-wetting period. According to the local fire brigade (Melbu), two Akron nozzles (RB 101, Rosenbauer Inc.), connected to 38 mm hoses, were used to produce the pre-wetting water spray, one nozzle at ground level at the start location and one nozzle at ground level under the rails towards the flame zone. The firetruck pump was adjusted to give the rated 7 barg water pressure at the nozzles. The RB 101 (at position 2) water flow rate is about 230 l/min. According to Fig. 2, the spray diameter was about 3 m at the height of the TV host. This gives a water spray flux of about 0.54 kg/s m^2 at the downward facing skin surface. The specific heat capacity of 4180 J/kg K results in a maximum theoretical spray cooling rate of 2257 W/m^2 K. If one assumes that the water hits the body surface at the most exposed area, i.e. the back, with efficiency in the range of 10–20%, this gives a convective heat transfer coefficient in the range of 220–440 W/m^2 K. A value of ~300 W/m^2 K was confirmed in a cooling test in a similar spray arrangement tested by the author, wearing a 0.5 mm diameter type K thermocouple taped to the arm, i.e. not scientifically recorded but sufficient for an estimate. For the calculations, a heat transfer coefficient of 300 W/m^2 K is taken as a representative and conservative value. It has not been possible to obtain the exact temperature of the water spray, but as the tests were conducted on May 9th at Melbu, Norway, at 68.5 N, just after the ice had thawed on the lake, from which the water was taken, the water temperature was probably in the range of 4–6 °C. Using a skin surface temperature of 32.5 °C, k = 0.5878 W/m K, a = 1.4·10^{-7} m^2/s, T_w = 5 °C and h_w = 300 W/m K, the temperature development of the outer 1 mm of the skin during the pre-wetting period is shown in Fig. 5.

Numerical modelling showed that the temperature at a depth of 0.1 mm will only increase from 17.0 °C to 18.5 °C during a 0.75 s internal relaxation period. Taking the relaxed temperature at 0.1 mm depth, i.e. 18.5 °C, and adding the peak temperature at this depth, i.e. 28.4 °C (Fig. 4), gives 46.9 °C. Compared to the previously calculated maximum temperature of 59.9 °C, it may be concluded that the pre-cooling was very important in preventing severe skin burns.

8. Discussion

The bare-skinned man-through-flame television stunt was based on the assumption that a thin water layer could protect the skin from the hot flames. It has been shown that a water layer of 0.1 mm thickness (referred to as A in the Introduction) could not have evaporated completely during the flame exposure. The soot deposits indicate that the water layer (referred to as B in the Introduction) at several downward facing areas had evaporated completely. In these areas, the real water layer thickness must therefore have been less than 0.1 mm, i.e. B < A.

For a 10° inclined glass plate, supplied with a water flux of 0.24, 0.48 and 0.58 kg/s m^2, Colina-Marquez et al. [31] recorded a water film depth of 0.8, 1.2 and 1.3 mm, respectively. The water flux hitting the upward-facing surfaces of the TV host may have comprised 10–20% of the spray flux from below, i.e. 0.054–0.18 kg/s m^2. In the case of skin, the surface roughness and body hair will prevent water run-off to a larger degree than in the case of plain glass. It is therefore unlikely that the thickness of the water layer on upward-facing skin was much less than 0.2–0.3 mm when entering the flame zone. This conclusion is supported by the lack of soot marks on upward-facing skin surfaces.

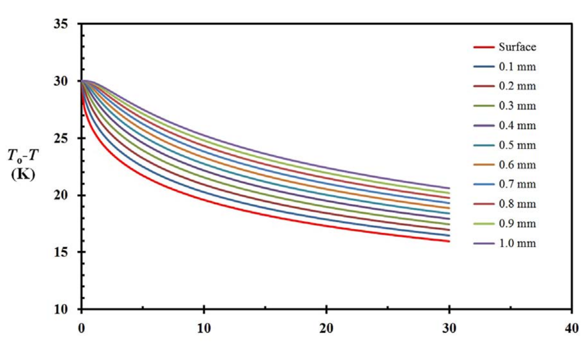

Fig. 5. Skin temperatures according to Eq. (20) during the 30 s pre-wetting period.

In the case of downward-facing surfaces, pendant droplets develop. While growing, these droplets quickly drain the surrounding skin surface, and gravity overcomes the capillary forces for a droplet mass of about 0.12 g [32]. Any shaking movement of the trolley might also have resulted in the detachment of smaller droplets. After detaching, any residual water "droplet" will still be influenced by gravity and continue to deplete the surrounding area. This results in limited water layer thickness close to pendant and recently detached droplets. The depletion may reach the limit of fully wet skin, with a water film thickness of ~14 µm [33]. Some water may, however, be retained by capillary bridges [34] and between skin and body hair (of typical diameter 50 µm). In the TV stunt, dry skin areas got direct flame contact and soot deposits, while wet areas remained clean. White spots surrounded by soot-marked areas, as seen in Fig. 2 for downward-facing skin surfaces, indicate pendant droplets or the remains of detached droplets, which have not completely dried. The clean tracks indicate draining channels for water from higher-elevation skin surfaces. The uneven distribution of the water layer by pendant droplets added unforeseen risk.

In the TV stunt, the 30 s pre-wetting (pre-cooling) period contributed to skin protection in two principal ways. It resulted in temperature depletion well into the depth of the skin, as well as a colder water layer being carried into the flames. It therefore seems reasonable to conclude that the 30 s pre-cooling period was the most important parameter protecting the TV host from severe skin burns. There are uncertainties regarding the water temperature and the associated water spray heat transfer coefficient. These uncertainties may influence the absolute temperature depletion. The main conclusion, however, is not altered by changing these parameters within reasonable limits, i.e. the 30 s pre-cooling was the most important heat protection mechanism. The length of this pre-wetting period was not considered prior to the flame exposure. It is most likely that a shorter pre-wetting period or warmer pre-wetting water would have resulted in severe burns.

9. Conclusions

It is demonstrated that the heating and evaporation of a thin water layer contributed only to a minor extent to the protection of the exposed skin against the high heat flux during the presented flame exposure. Analytical solutions of the heat equation were used to evaluate the pre-cooling of the skin before flame exposure, heating during flame exposure and post-flame relaxation of skin temperature gradients. It is shown that the 30 s pre-cooling by cold (~5 °C) water was the most significant parameter preventing major burns. The importance of this pre-cooling period, pendant water droplet dynamics and radiative heat flux levels was not evaluated prior to the TV stunt. A longer period of flame exposure, warmer pre-cooling water or a shorter pre-cooling period would most likely have resulted in severe burns.

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