Determination of the Lightning Current from its Thermal Effects

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Abstract—**Lightning accidents are random events whose electrical magnitudes are difficult to be measured or estimated. However, analyzing its consequences, some of its parameters, such as its possible trajectory to earth and current waveform and amplitude, can be reconstructed. This paper presents a methodology applied to estimate the lightning current based on both its thermal effects on a conducting material and on the burns left on a victim. The thermal effects are reconstructed by studying the skin burns left by a stainless steel pearl-like necklace wore by a soldier, which conducted an indirect lightning current. The current amplitude is estimated through Joule heating simulations in Comsol Multiphysics of a section of the metallic necklace. Analysis of results shows feasible lightning current amplitudes and waveforms, which could have impacted the victim. The methodology used here to reconstruct and to evaluate the lightning current could be of interest for further studies on understanding lightning accidents. Furthermore, the reconstructed lightning current amplitude could be a reference value for the future protection systems of population at risk in similar conditions.**

Keywords- Lightning; lightning accidents; lightning current; lightning heating

I. INTRODUCTION

Colombia is one of the countries with the largest lightning density in the world [1] mainly due to its geographical and climatic conditions. For this reason, a large number of lightning accidents are expected every year. Specifically, lightning accidents involving military population are very frequent in the country [2], leaving fatal and nonfatal victims depending on several local conditions [2-3]. Lightning accidents previously reported, in which metallic necklaces were involved [3], presents the accident scenarios but without analyzing the thermal effects of the lightning current on the victim's skin.

In this investigation, a methodology to estimate the lightning current starting from its thermal effects is proposed. This methodology is based on numerical simulations of Joule heating performed in Comsol Multiphysics and was applied to a particular case presented in [3], where a soldier in declined sitting posture on a military shelter was struck by lightning. Lightning hit the shelter structure passing through the high resistance sandbag wall, reaching the soldier personal

identification metallic necklace (ID dog tag in ball chain) that he was wearing around his neck, entering by the nape zone. The current of the indirect lightning strike flowed throughout the soldier necklace, overheating and melting a part of it, and burning his nape skin as it can be seen in Fig. 1. To determine the lightning current amplitude, a reconstruction study based on the soldier necklace characteristics and on the estimation of the temperature which could burn the soldier skin was performed.

II. BACKGROUND

Lightning discharges correspond to electrical discharges generated in the Earth's atmosphere due to several causes [4]. In the simulations performed in this paper, it is suggested that the current is of negative polarity as a consequence of a cloud-to-ground discharge, mainly because it has been established that the polarity ratio of lightning discharges is 10% positive and 90% negative [5]. Moreover, lightning current is defined as the current flowing at the point of strike and is characterized by different parameters, like time and amplitude [5]. The lightning current consequences depend on the previously mentioned two parameters and are directly related to the lightning current shape and its thermal effects on a conducting material, which in this case corresponds to the soldier necklace.

A. Lightning current expression

The lightning current impulse is defined in [5] as the time function presented in (1), where I is the peak current, k is the

Figure 1. Soldier's neck burn marks caused by the skin contact with the pearl-like spheres of his necklace heated by the lightning current.

correction for the peak current, t is the time, T_1 is the front time constant and T_2 is the tail time constant.

$$i(t) = \frac{I}{k} \times \frac{(t/T_1)^{10}}{1 + (t/T_1)^{10}} \times \exp(-t/T_2) \qquad (1)$$

These parameters may be adjusted to obtain the desired impulse shape, as the characteristic times for the first negative impulse in protection level I, which are 1 μs and 200 μs for rise-time and time-to-mean-value respectively, according to the IEC standard [5] and as it is shown in Fig. 2.

B. Joule Heating

Thermal effects linked to the lightning current are related to the resistive heating caused by the current flow across a conducting material [5]. This heating phenomenon describes the process where the energy of the electric current is converted into heat [6] and it is analytically approached as presented in (2), when it is considered as an adiabatic process [5].

$$\Delta\theta = \frac{1}{\alpha} \times \left[\exp\left(\frac{\frac{W}{R} \times \alpha \times \rho}{q^2 \times \gamma \times C_w} \right) - 1 \right] \qquad (2)$$

According to this expression, the temperature rise ($\Delta\theta$) depends of the specific energy of the lightning current (W/R) and some material properties: temperature coefficient (α), specific ohmic resistance at ambient temperature (ρ), density (γ), thermal capacity (C_w) and the considered cross-sectional area (q). Furthermore, the specific energy (W/R) is determined as

$$\frac{W}{R} = \int i^2(t)\, dt \qquad (3)$$

Applying (2) and (3) with the current impulse of the Fig. 2 on a piece of stainless steel with a cross-sectional area of 4,52 mm^2, based on the necklace characteristics, a temperature rise of 4832 K and a specific energy of 1,4 MJ/Ω are obtained. This specific energy is taken as a reference value for the lightning
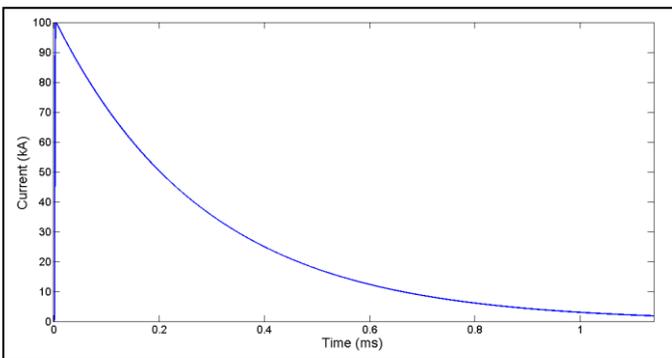
current of the studied case.

C. Current impulse shape

The estimated lightning current in the analyzed accident depends on the current shape used for calculations. Several currents shapes are taken into account in order to find the most possible lightning current involved in the accident, according to the observable consequences. The rise-time and time-to-mean-value of the current shapes employed, was 1,2/50 μs, 8/20 μs, 1/200 μs and 0,25/100 μs, which agree with the current shapes suggested by [5] and [7]. The first two correspond to most typical lightning shape representations, while the last two correspond to standard values of negative lightning current impulses of a single lightning return stroke. Multistroke lightning discharges are not considered in this paper. Therefore, further investigations considering an appropriate discharge duration and the specific energy of every single stroke (first and subsequent) applied to the necklace must be performed.

III. METHODOLOGY

To obtain the lightning current characteristics, both the temperature reached by the soldier necklace heated by the lightning current and the burns left in the soldier skin due to the overheated metallic chain are separately considered. Finally, the lightning current amplitude is determined from a superposition of both results: skin burn temperature and temperature reached by the metallic necklace.

A. Necklace model and temperature analysis

To obtain the temperature rise of the soldier ID necklace, a Joule heating calculation in a typical necklace section was performed using Comsol Multiphysics. This calculation method allows the possibility of evaluating the temperature rise in the varying cross-sectional area, considering external conditions as the reference ambient temperature. The employed ID necklace computational model shown in Fig. 3, was built using the actual dimensions of the Colombian army identification necklaces. It was considered that the necklace metallic hollow pearl-like spheres and joint cylindrical pins were made of stainless steel.

Keeping in mind the lightning current trajectory showed in Fig. 4 [3], some assumptions were needed to perform the simulations:

- All the lightning current flowed across the metallic

Figure 2. Lightning current impulse with a front time of 1 μs and a tail time of 200 μs [5].
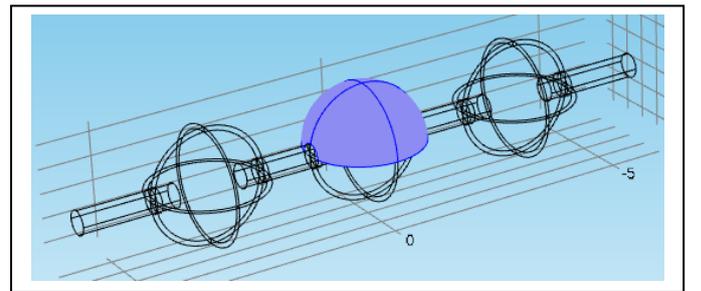

Figure 3. Geometric model of the necklace section for simulation, emphasizing the lightning input area.
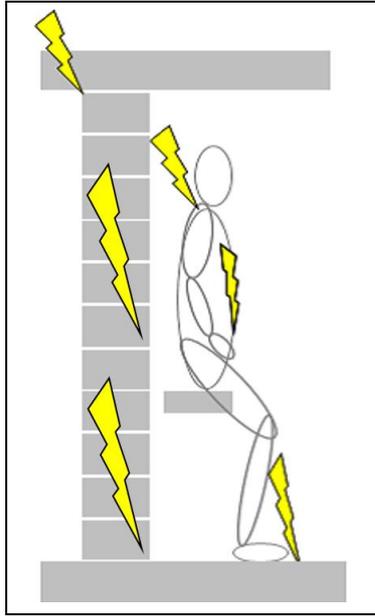
Figure 4. Lightning current trajectory scenario [3].

necklace and no current flowed through the victim's body.

- A little section of the necklace was considered in the simulations, which corresponds to three metallic pearl-like spheres and four joint cylindrical pins. The central sphere placed in the soldier´s nape was the lightning current entry point.

- The lightning current flowing across the necklace section is divided in two equal parts.

In a first stage of the study, a DC current was applied during 50 µs to the central sphere of the necklace section shown in Figs. 3 and 6. This current shape was chosen as a simple way to reduce the simulation time and to obtain the specific energy applied to the necklace. Several simulations with different current magnitudes allow to establish a numerical relationship between the temperature of the skin contact area with the necklace and the current flowing through it.

B. Skin burns analysis

Skin burns are related basically to the relation between two contact characteristics: temperature and exposition time [8]. The contact time was taken as the current duration assumed in the first stage of the study (50 µs). This assumption was made considering the accident consequences, where the joint cylindrical pins were melted and the necklace's spheres disassembled after the current flow. Therefore, the contact temperature is the temperature that could burn the skin in this short time period and it is calculated based on the human skin thermal injury tables [8].

Moreover, a simulation of heat transfer to the skin were performed in Comsol Multiphysics, using the reference temperature values able to burn the skin, as it is shown in Fig.

5. In the model employed, the necklace section was set to the contact temperature during the exposition time required to burn the skin. The results of these simulations show that the highest temperature appears at the skin surface and that the penetration depth is not very large. This result is coherent with the superficial burns observed in the victim's injuries shown in Fig. 1.

C. Equivalent current impulse

The equivalent DC lightning current is estimated by using the contact temperature found in the skin burns analysis and the numerical relationship between temperature and current flowing across the necklace. The different lightning current impulse shapes are obtained by matching the specific energy of the mentioned DC current, calculated using (3), and the chosen standard lightning impulses. The specific energy and the peak current values are presented as the final results of this study.

IV.   RESULTS

A. Necklace thermal behavior

The necklace thermal simulations under different current magnitudes allowed the determination of the necklace final temperature. Fig. 6 shows the temperature behavior for an applied DC current of 8 kA during 50 µs. These simulations show that the highest temperature is observed at both ends of the pearl-like sphere where the lightning current is injected, while the lowest observed temperature occurs in the air inside the hollow spheres. Because of the difference in the cross-sectional area of the pearl-like spheres and the joint cylindrical
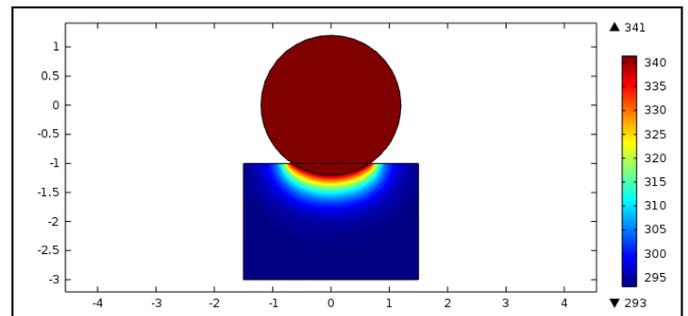

Figure 5. Heat transfer on a skin burn with a contact temperature of 341 K (68 °C) and a contact time of 1 s, as presented in [8].
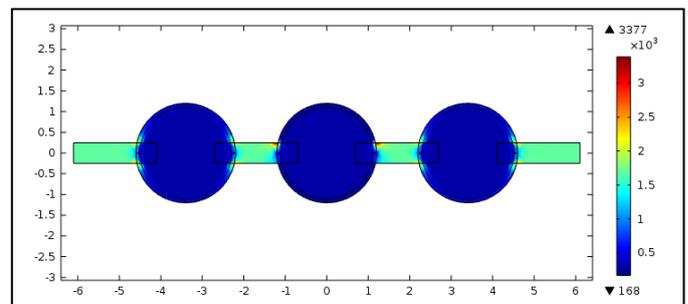

Figure 6. Temperature, in Kelvin, in the cross section of the necklace for a lightning current of 8 kA. Notice that joint cylindrical pins temperature (1675 K) is much higher than the pearl-like spheres temperature (397 K) in the contact area with the victim's skin.

pins, the temperature in the later is much higher than in the spheres surface. Furthermore, the variation in the temperature rise as a function of the cross-sectional area may be observed in the pearl-like spheres, where the temperature at the joint cylindrical pins contact points is higher than the temperature in the central zone.

By simulating applied DC currents between 1 kA and 20 kA to the necklace and evaluating the surface temperature in the pearl-like spheres, corresponding to the contact area with the skin (observed in Fig. 5), a numerical relationship between current and temperature is obtained, as showed in Fig. 7.

The calculated values presented in Fig. 7 were approximated to the quadratic relationship in (4), which allows to calculate the skin contact temperature, in K, for any applied DC current, in kA. It also permits to determine the required current for a desired reached temperature.

$$T = 1{,}6294 \times i^2 - 0{,}0115 \times i + 293{,}15 \qquad (4)$$

B. Skin burns temperature

Fig. 8 shows the skin burns temperature values as a function of exposition time, obtained from reported values of thermal injury studies [8]. Additionally, in Fig. 8 the red curve is a numerical approach of the blue curve and its numerical representation is given in (5).

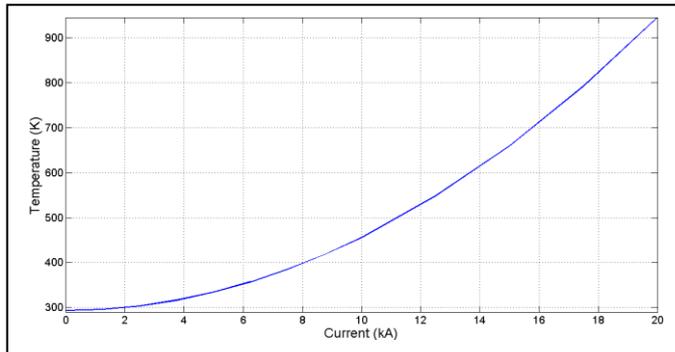$$T = 66{,}591 \times t^{-0{,}057} + 293{,}15 \qquad (5)$$

Figure 7. Contact temperature between the necklace and the skin as a function of the lightning current injected.
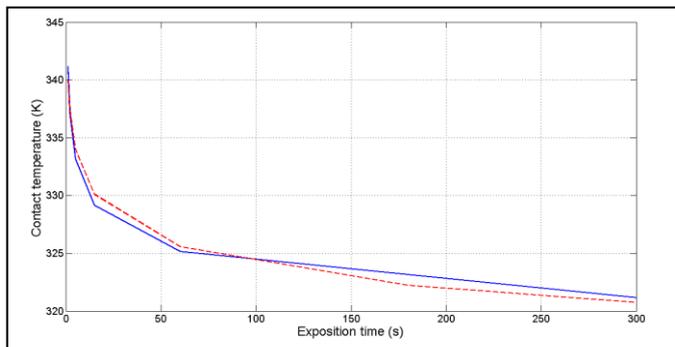

Figure 8. Skin burn temperature. In blue, temperature and time for skin burns reported in [8]. In red, the numerical approximation of these reported values, used to estimate the burns temperature for the lightning duration (50 µs).

By extrapolating equation (5) in Fig. 8, it was found that the average temperature in the contact area, for an exposition time of 50 µs, is 410 K. The simulation results for this necklace heating and current duration is shown in Fig. 9. Despite of the limited temperature penetration observed in the calculation for 50 µs, compared with the temperature calculations for 1 s shown in Fig. 5, the superficial skin temperature is enough to produce superficial burns.

C. Lightning current

8,5 kA is the calculated equivalent DC current, when the previously calculated temperature of 410 K is replaced in (4). The specific energy associated to this current shape, calculated by using (3), is 3,6 kJ/Ω. For this current value, the temperatures reached by the necklace pearl-like spheres and the joint cylindrical pins are 410 K and 1846 K respectively.

From that specific energy, a calculation of the peak value for different current shapes with the same characteristic was performed. The equivalent lightning shapes for all the considered cases are presented in Fig. 10. The peak values of the lightning current for each shape are summarized in Table I. As it was expected, the current shapes with a longer stroke duration have a smaller peak value to keep the same dissipated energy.

In Fig. 11 is presented the Comsol Multiphysics simulation performed with an 8/20 µs current shape, used to compare the temperature reached by the 8,5 kA DC current and the 17,3 kA 8/20 µs lightning current impulse. By comparing Figs. 6 and
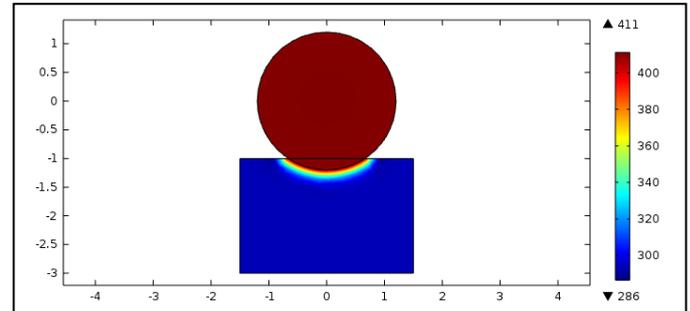

Figure 9. Heat transfer to the skin with a contact temperature of 410 K and a contact time of 50 µs.
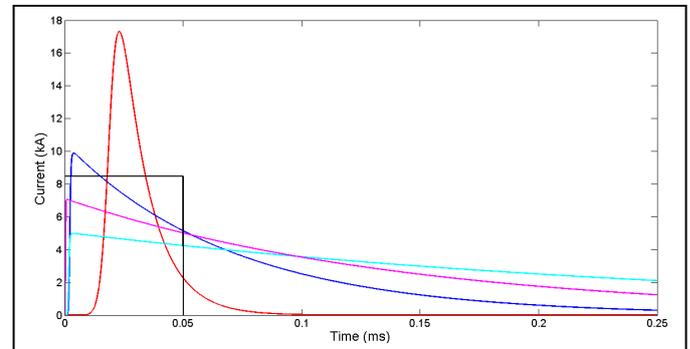

Figure 10. Lightning current shapes obtained for the specific energy applied to the necklace that rise its temperature to produce the effects in the skin. In black the original DC current obtained, in blue the equivalent 1,2/50 µs shape, in red the equivalent 8/20 µs shape, in cyan the equivalent 1/200 µs shape and in magenta, the equivalent 0,25/100 µs shape.

11, it was found an excellent coincidence between the calculated temperature values in different parts of the necklace section in both figures. This result indicates that the temperature rise on the necklace depends on the specific energy associated with the lightning current and not on the lightning current wave shape.

Current Shape	Current Peak Value (kA)
1,2/50 µs	9,9
8/20 µs	17,3
1/200 µs	5,0
0,25/100 µs	7,1

V. DISCUSSION

The specific energy of the estimated lightning current in the accident (3,6 kJ/Ω) is very small compared to the calculated specific energy of the first negative impulse at protection level I (1,4 MJ/Ω) considered in the IEC standard [5]. This result could be explained by considering that just a fraction of the total lightning current flowed across the soldier ID pearl-like necklace. The lightning current path in Fig. 4 shows that in this accident the most important part of the lightning current flowed directly to the ground across the sandbag wall of the military sentry box. Moreover, another current split was assumed in the necklace itself. In symmetrical conditions, half of the lightning current should flow across each necklace side, i.e., just 4,25 kA in each section side. According to these results, if the whole calculated current (8,5 kA) should flow across the necklace section, without division, the temperature rise would be four times higher.

The necklace simulation model considers perfect contacts between the pearl-like spheres and the joint cylindrical pins. Nevertheless, in actual necklaces the placement of the necklace in the soldier´s neck could cause a variation in the impedance and therefore in the current flow. Moreover, an imperfect contact could generate a higher temperature at the contact points of the e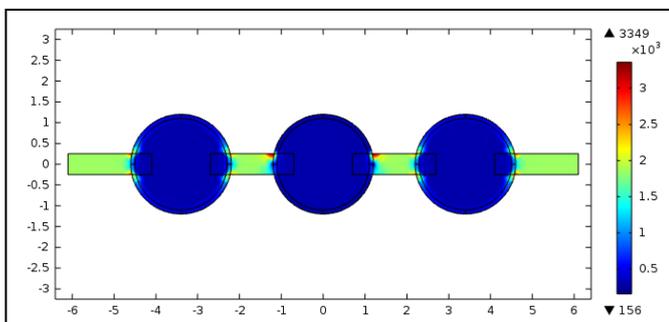lements which compose the necklace, but it does not change the temperature of the central zone caused by the current flow.

As the temperature rise does not depend on the current shape but only on the specific energy applied to the material, the presented methodology may be applied to different problems and not just for the lightning current determination. However, the conditions and consequences of the evaluated case must be determined in every particular situation, since different conditions will lead to different results.

VI. CONCLUSIONS

The calculated lightning current amplitudes are consistent with the observed victim's injuries and the melting temperature of the necklace's joint cylindrical pins reported in a lightning accident. With the calculated current, both conditions are reached: 1-the skin burn temperature in the victim's skin caused by the overheated necklace pearl-like spheres and 2- the melting temperature of the joint cylindrical pins used to connect the metallic spheres.

Numerical simulations related to the present investigation indicates that burns marks in the soldier's neck were only superficial due to the short time period of the skin contacting the overheated metallic pearl-like spheres of the necklace.

The results of this investigation could be used as a reference to understand lightning accidents and to improve lightning protection studies of human beings.

REFERENCES

[1] N. Navarrete-Aldana, M.A. Cooper, R. L. Holle, "Lightning fatalities in Colombia from 2000 to 2009," in International Conference on Lightning Protection (ICLP). Shanghai, China, 2014.

[2] F. Roman, F. Vega, "Lightning accidents in Colombia: Lightning threats in the Colombian army," in American Electromagnetics Conference (AMEREM)). Albuquerque, New Mexico, USA, 2014.

[3] J. A. Cristancho, C. Rivera, J. J. Pantoja, F. Román. "Nonfatal Lightning Injuries in Colombia: Case Reports," in International Symposium on Lightning Protection (XIII SIPDA), Balneário Camboriú, Brazil, 2015.

[4] V. Cooray. Lightning protection. London, UK: The Institution of Engineering and Technology IET, 2010, pp. 15-35.

[5] International Standard IEC 62305-1. "Protection against lightning – Part 1: General principles". Edition 2.0, 2010-12.

[6] Comsol multiphysics cyclopedia, "The Joule heating effect" [online] 2016, https://www.comsol.com/multiphysics/the-joule-heating-effect (Accessed: 26 may 2015).

[7] IEEE Power Engineering Society. IEEE Standard C62.45. "IEEE Recommended practice on surge testing for equipment connected to low-voltage (1000V and less) AC power circuits". New York, USA, 2003.

[8] A. R. Moritz, F. C. Henriques, "Studies of thermal injury: II. The relative importance of time and surface temperature in the causation of cutaneous burns", The American Journal of Pathology, vol. 23(5), pp. 695-720, 1947.

Figure 11. Necklace temperature simulation with the 8/20 µs lightning current impulse applied. Notice that joint cylindrical pins temperature (1846 K) is higher than the melting steel temperature (1773 K) and the pearl-like spheres reach the burn temperature (410 K) in the skin contact area.