Abstract. The article concerns laboratory tests simulating practical situations in which roofings considered as flammable are hazarded by the increase of temperature of the air termination conductors after lightning discharges. The main part of the paper deals with motivation for undertaking tests, determination of assumptions for their execution, characteristics of testing system and presentation of results obtained by the author. The article is summarized with conclusions drawn from the above mentioned results.

Key words: flammable roofing, hazard, temperature increase, air termination conductor, lighting discharge, thermal action, testing system.

1. Introduction

Thermal action of overheated air terminal conductors over heated by lightning discharges on flammable roofings can be considered as follows [3, 4]:

– action of falling down conductor particles (metal drops) melted out at the places of lightning strokes and caused by conversion energy $W_1$ described by formula (1) and

– action of heated conductors (as linear heat sources), whose temperature is connected with energy $W_2$ described by formula (6).

Energy $W_1$ is determined as:

$$W_1 = \eta \cdot U \cdot Q,$$

where $\eta$ is a heating coefficient (equal to $0.6 \div 0.7$ [5, 6]); $U$ is a voltage drop (usually assumed as equal to $15 \div 20$V [7, 8]).

$Q$ is lightning electric charge calculated as:

$$Q = \int_{0}^{\tau} i \cdot dt,$$

where $i$ is a momentary current value; $t$ is time; $\tau$ is flash duration, as well as by the formula:

$$W_2 = V \cdot \gamma \cdot (C_1 \cdot \Delta T_1 + C_2).$$

where $V$ is a volume of melted metal; $\gamma$ is metal density; $C_1$ is specific heat; $C_2$ is heat of fusion; $\Delta T_1$ is the rise of metal temperature causing fragmentary melting of the conductor.

On the basis of (1) and (3) volume $V$ can be determined by the following relationship:

$$V = \frac{\eta \cdot U \cdot Q}{\gamma \cdot (C_1 \cdot \Delta T_1 + C_2)}.$$
Function \( V = f(Q) \) for steel which is almost the main material commonly used for construction of air termination conductors (parameters of steel used for calculations are given in Table 1) is illustrated in Fig. 1. This function is worked out for \( \eta = 0.7 \) and \( U = 20 \text{ V} \) in typical range of electric charges \( Q = 10 \pm 10^2 \text{ A} \cdot \text{s} \) (because of rectilinear character of relation in question, its extrapolation for the charges higher or lower than those given in Fig. 1 can be done without difficulty).

Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma )</td>
<td>( \text{g} \cdot \text{mm}^{-3} )</td>
<td>( 78 \times 10^{-4} )</td>
</tr>
<tr>
<td>( C_1 )</td>
<td>( J \cdot \text{g}^{-1} \cdot \text{°C}^{-1} )</td>
<td>( 47 \times 10^{-2} )</td>
</tr>
<tr>
<td>( C_2 )</td>
<td>( J \cdot \text{g}^{-1} )</td>
<td>( 272 )</td>
</tr>
<tr>
<td>( \Delta T_1 )</td>
<td>( \text{°C} )</td>
<td>( 15 \times 10^{-1} )</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>( \text{°C}^{-1} )</td>
<td>( 52 \times 10^{-2} )</td>
</tr>
<tr>
<td>( \rho )</td>
<td>( \Omega \cdot \text{m} )</td>
<td>( 12 \times 10^{-5} )</td>
</tr>
</tbody>
</table>

The value of aforementioned energy \( W_2 \) is determined by the formula:

\[
W_2 = R \cdot w,
\]

where \( w \) is specific energy of discharge, defined as follows:

\[
w = \frac{\beta}{0} \int t^2 dt.
\]

On the other hand, energy \( W_2 \) can be estimated from the relationship:

\[
W_2 = 1 \cdot S \cdot \gamma \cdot C_1 \cdot \Delta T_2.
\]

On the basis of (6) and (8), taking into account (5), the following relation is obtained [7]:

\[
\Delta T_2 = \frac{1}{\alpha} \left[ \exp \left( \frac{\rho \cdot \alpha \cdot w}{\gamma \cdot C_1 \cdot S^2} \right) - 1 \right].
\]

In Fig. 2, graphic interpretation of (9) is represented in the form of relationship \( \Delta T_2 = f(S) \) for \( w = 0.5 \times 10^7 \text{ A}^2 \cdot \text{s} \) and \( 2 \times 10^7 \text{ A}^2 \cdot \text{s} \) in the case of steel conductor (the latter of aforementioned values of specific energy \( w \) is higher than maximum value of this parameter obtained in European conditions in a case of positive discharge [11]).

Parameters of steel used for determination of air conductor resistance \( R \) (formula (5)), as well as functions \( V = f(Q) \) (4), \( \Delta T_2 = f(S) \) (9) and \( w = f(S) \) (10) (Fig. 1, 2, and 5) are calculated according to [3].

As it can be concluded from the experimental data [9, 10], the particles of melted steel can cause thermal destructions of flammable materials in direct contact with them even after covering relatively long distances through the air.

Energy \( W_2 \) appears as a result of the presence of air termination conductor resistance \( R \) determined by the following formula:

\[
R = \frac{\rho \cdot l \cdot \alpha \cdot \Delta T_2}{S \cdot \ln (l + \alpha \cdot \Delta T_2)},
\]

where \( \rho \) is metal resistivity; \( l \) is the length of the conductor; \( \alpha \) is a temperature coefficient of resistance; \( \Delta T_2 \) is the rise of conductor temperature caused by energy \( W_2 \); \( S \) is a cross-sectional area of conductor.
termination conductors (which act as linear heat sources) on inflammable roofings located beneath were examined in laboratory conditions, above all else for fragmentary verification of Polish lightning protection regulations which (as per author's opinion) determine too long distances between air termination conductors and flammable roofings (i.e., as it has been already mentioned, at least 40 cm in former Polish standard [1] being in force to the year 2009 and no less than 10 cm in international standard [2] being in force in Poland at present).

3. Method of research

For the research a testing system shown in Fig. 3 was used. Heavy current transformer 2 is the main part of this system. It enables receiving currents up to 4 kA in the electric circuit including electric conductor simulating air termination conductor. The ordinary power mains 1 (220 V/50 Hz) is applied here. Regulation of current value was performed in the testing system by the change of number of coils of regulating inductor 3 and by displacing the core of this inductor.

![Fig. 3. Diagram of principal part of testing system applied for generation of high alternating currents: 1 – power mains, 2 – heavy current transformer, 3 – regulating inductor, A – transformer operating terminals, B – voltage control terminals, C – current control terminals.](image)

The testing system can be used in two different experiments. The first one is intended for the preparation of drops of melted steel (falling down onto tested models of roofings from different heights) by means of electric arc between two electrodes made of steel and of carbon.

The electric arc was initiated by creating a contact between these electrodes and then drawing them apart gradually. High temperature of the electric arc (several thousand degrees Centigrade) made it possible to melt out steel drops of various volumes (within the range taken into account in Fig. 1 and considered to be typical).

While producing drops of melted steel with the use of electric arc, the author caused their falling down onto the models of flammable roof coverings from various heights within the range 5–80 cm typical for real conditions [3]; the possibility of thermal destruction of these models by heat from the electric arc was eliminated.

The second variant of the testing system application was used for fast heating up the whole steel conductor simulating the air termination conductor to high temperatures. The main problem of the experiment was to select the appropriate range of variability of temperature increase ΔT₂. The author has paid attention to the conclusions resulting from the publication [3], derived from the analysis of data included in various professional articles and papers. Taking them into account, it was assumed that this increase should be within the range 2 \( \times 10^2 \)–5 \( \times 10^2 \)°C. The temperature of air conductor model was measured by a thermocouple.

In Fig. 4 the functions \( w = f (S) \) are presented. They are obtained for minimum and maximum values of temperature increase ΔT₂ for steel conductors with the use of the following formula

\[
 w = \frac{C_1 \cdot \gamma \cdot S^2 \cdot \ln (1 + \alpha \cdot \Delta T_2)}{\rho \cdot \alpha},
\]

resulting from the transformation of relationship (9).

![Fig. 4. Relationships between specific energy of lightning discharge \( w \) and air termination conductor cross-sectional area \( S \) for minimum and maximum values of \( \Delta T_2 \):

\( A - \Delta T_2 = 500 \degree C \), \( B - \Delta T_2 = 200 \degree C \).](image)
It should be noted that, as it can be seen in Fig. 4 (as well as in Fig. 2), in the case of the highest value of \( w = 2 \cdot 10^7 A^2 \cdot s \) taken into consideration, the temperature increase \( \Delta T_2 \) on the commonly used steel air termination conductor with cross-sectional area equal to 50 mm\(^2\) [2] is not very likely to exceed 500 °C.

Linear heat source (heated conductor) acted on the models of flammable roofings while being moved up to them when the test system was under voltage, then the conductor was immobilized, after 1 s the power supply was disconnected and the conductor began to cool down (see Fig. 5).

Taking into consideration that in Europe duration \( \tau \) practically does not exceed 1 s [4] and that during this time the increase \( \Delta T_2 \), determined by (9), does not occur continuously in real conditions, it can be assumed that method of research applied in the second experiment assures slight, but motivated margin of safety in drawing inferences concerning disadvantageous action of hot air termination conductors onto flammable roofings.

It should be added, that since maximum value of specific energy \( w \) registered in Europe is lower than \( 2 \cdot 10^7 A^2 \cdot s \) (what was stated in part 2 of this article), the air termination conductors with the cross-sectional area equal to \( S = 50 \text{ mm}^2 \) (or more) cannot be practically destroyed by lightning stroke while such destruction should be definitely eliminated for buildings with flammable roofings (which nowadays are mainly located in open-air museums).

4. Results of laboratory tests

The author attached great importance to extremely disadvantageous results of action of the models of hot air termination conductors on models of flammable roofings (Table 2).

![Fig. 5. Relationship between drop \( \Delta T_3 \) of temperature rise \( \Delta T_2 = 500 \text{°C} \) and time \( t \), during cooling down of air termination conductor model.](image)

**Table 2**

<table>
<thead>
<tr>
<th>Kind of a test</th>
<th>Material of roof covering</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>I</td>
</tr>
<tr>
<td>B</td>
<td>III</td>
</tr>
</tbody>
</table>

Designations: 1 – straw, 2 – reed, 3 – shingle, A – steel drops falling down onto the model of roofing, B – hot air termination conductor located close to the model of roofing, I – combustion of roofing model, II – local thermal destruction of roofing model without combustion, III – combustion of roofing model but only in direct contact with the conductor, IV – local thermal destruction of roofing model without combustion, but only in direct contact with the conductor.

It should be noted that the height from which melted steel drops were falling had no visible impact on frequency of straw and reed inflammation. This frequency was estimated by means of a formula:

\[
P_{F,V} = \frac{N_{F,V}}{N_{V}},
\]

where \( N_{F,V} \) is a number of steel drops (from the sample of steel drops of average volume \( V \)) causing combustion of roofing model; \( N_{V} \) is a number of steel drops formed in testing system, having similar volumes \( V \) and average volume \( \bar{V} \) which were taken into consideration in the evaluation of probability \( P_{F,V} \) (the author assumed that \( N_{V} \geq 30 \) [13, 14]).

The probability \( P_{F,V} \) depends not only on the volume \( \bar{V} \) (growing with its increase), but also (and significantly) on the compression (squeezing) of the straw or reed forming roofings. For loose arrangements of these materials the probability of combustion is near to 1, however, for tightly compressed (squeezed) materials it is about 0. Lack of precise criteria for the determination of how tightly straw or reed is compressed is an obstacle to comprehensive interpretation of a parameter \( P_{F,V} \)
Combustion of straw and reed takes place only when these materials are in direct contact with the model of the heated air termination conductor, they are loosely packed and temperature rise ΔT2 is within the range 400±500 °C.

Thermal destruction of shingle consists, in extreme cases, in local wood charriages.

5. Conclusions

1. Steel drops melted out from air termination conductors after lightning discharges falling down onto flammable roofings made of straw or reed can cause combustion of these materials, which is highly probable if they are arranged on the roofs loosely (without tight squeezing); possibility of combustion does not depend on distance between air termination conductors and roofing in the range 5±80 cm.

2. Simulation of bringing the air termination conductors (as linear heat sources characterized by increases of their temperatures to 200±500 °C) closer to models of thatches proved that their combustion after lightning discharges is possible in practice only in cases when roofings materials are packed loosely and have direct contacts with mentioned conductors which are heated to dangerous temperature rising to 400±500 °C; it should be added that if possibility of thermal destruction of air termination conductors is eliminated (what is guaranteed for S ≥ 50 mm²) and if the lightning protection systems are made carefully, the aforementioned contacts are impossible.

3. Direct contacts of roof coverings made of flammable (from the point of view of fire protection) wooden shingle with melted steel elements of air termination conductors (because of lightning discharge) and with some sections of these conductors having temperature 200±500 °C can cause, in extreme cases, practically insignificant local thermal destructions of wood in the form of charred stains.

4. In connection with above remarks 1±3, minimal distance between flammable roofings and air termination conductors required by Polish lightning protection regulations as equal to 40 cm (in former standard [1], having been in force to the year 2009) and 10 cm (in present standard [2]) are groundless if it is assumed that thatch combustion caused by hot gases surrounding lightning channel is impossible. Therefore, the only requirement concerning the considered problem should come to the conclusion that mentioned conductors and roofings mustn’t touch each other.

References

МОДЕЛЬНЕ ДОСЛІДЖЕННЯ ВПЛИВУ ПІДВИЩЕННЯ ТЕМПЕРАТУРИ У ПОВІТРЯНИХ КАНАЛАХ РОЗРЯДУ БЛИСКАВКИ НА ЗАЙМИСТІ ПОКРІВЛІ

Піotr Стружевські

Розглянуто лабораторні дослідження, що моделюють реальні ситуації, коли покрівлі, виготовлені із займистих матеріалів піддаються загрозі внаслідок підвищення температури у повітряному каналі, створеному під час розряду блискавки. У головній частині статті описано проведені досліди, визначено допущення під час їхнього проведення, характеристики лабораторної устави та аналіз результатів, які отримав автор. Подано висновки, отримані на підставі проведених досліджів.

Piotr Struzewski – electrical engineer, graduated from Warsaw University of Technology, Warsaw, Poland in 1974 and received his PhD in 1977. The theme of his PhD thesis was “Estimation of the lighting protection effectiveness of lighting rods using Monte-Carlo method”.

Member of Polish Lighting Protection Committee. Published more than 75 articles, predominantly on problems of lighting protection.