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MODEL INVESTIGATIONS OF THE IMPACT OF OVERHEATED AIR TERMINATION CONDUCTORS ON FLAMMABLE ROOFINGS

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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 air terminal conductors overheated by lighting discharges on flammable roofings causes different effects for different roofing materials. The most dangerous result of this action is their combustion, which may set entire buildings on fire.

The problem of the protection of flammable roofings against possibility of combustion caused by lightning strokes was reflected in former Polish technological regulations concerning lightning protection having been in force by the year 2009 [1]. As per these regulations it was required that separation distance between above mentioned (meshed) conductors and all kinds of flammable roofings had to be increased (in relation to distance applied for non-flammable coverings) to at least *40* cm, but without proving results obtained by the means of investigations. New international regulations [2] being in force in Poland at present have implemented the requirement of much shorter minimal distance between roofings made of flammable materials and air terminal conductors. It is to be equal to *10* cm which, in the author's opinion, is also groundless.

The author came to conclusions about above mentioned uncertainties of Polish regulations [1] and [2] (standards) after finding out the lack of respective data in available technical literature which would enable competent estimation of limiting distance in question.

Laboratory tests carried out as a stage preparatory to writing this article opened up the possibility of ve-reifying these conclusions for roofings made of straw, reed and wooden shingle.

2. Theoretical motivation of investigations

Thermal action of overheated air termination conductors on flammable roofings after lightning discharges 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:

$$W_1 = h \cdot U \cdot Q, \qquad (1)$$

where h is a heating coefficient (equal to 0.6÷0,7 [5,6]); U is a voltage drop (usually assumed as equal to 15÷20V [7,8]).

Q is lightning electric charge calculated as:

$$Q = \int_0^t i \cdot dt, \qquad (2)$$

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

$$W_1 = V \cdot g \cdot \left(C_1 \cdot \Delta T_1 + C_2\right), \qquad (3)$$

where V is a volume of melted metal; g is metal density; C_1 is specific heat; C_2 is heat of fusion; ΔT_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:

$$V = \frac{h \cdot U \cdot Q}{g \cdot \left(C_1 \cdot \Delta T_1 + C_2\right)}. \qquad (4)$$

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 $h = 0,7$ and $U = 20\,\mathrm{V}$ in typical range of electric charges $Q = 10 \div 10^2\ \mathrm{A \cdot s}$ (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

Parameter	Unit	Value
γ	$\mathrm{g \cdot mm^{-3}}$	$78 \cdot 10^{-4}$
C_1	$\mathrm{J \cdot g^{-1} \cdot {}^oC^{-1}}$	$47 \cdot 10^{-2}$
C_2	$\mathrm{J \cdot g^{-1}}$	272
ΔT_1	$\mathrm{{}^oC}$	$15 \cdot 10^{-2}$
α	$\mathrm{{}^oC^{-1}}$	$52 \cdot 10^{-4}$
ρ	$\Omega \cdot \mathrm{m}$	$12 \cdot 10^{-5}$

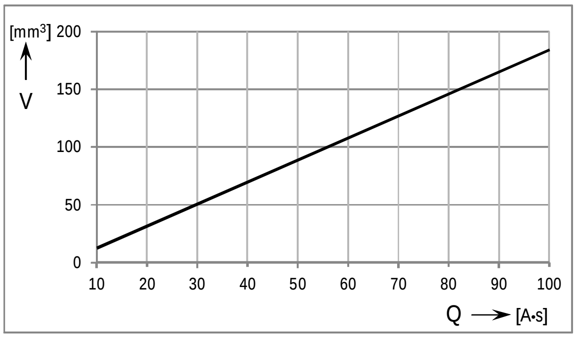

Fig. 1. Relationship between V (steel volume melted out from air termination conductor) and Q (flash charge).

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:

$$R = \frac{r \cdot l \cdot a \cdot \Delta T_2}{S \cdot \ln\left(l + a \cdot \Delta T_2\right)}, \qquad (5)$$

where r is metal resistivity; l is the length of the conductor; a is a temperature coefficient of resistance; ΔT_2 is the rise of conductor temperature caused by energy W_2; S is a cross-sectional area of conductor.

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

$$W_2 = R \cdot w, \qquad (6)$$

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

$$w = \int_0^t i^2 dt\ . \qquad (7)$$

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

$$W_2 = 1 \cdot S \cdot g \cdot C_1 \cdot \Delta T_2 . \qquad (8)$$

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

$$\Delta T_2 = \frac{1}{a} \cdot \left[\exp\left(\frac{r \cdot a \cdot w}{g \cdot C_1 \cdot S^2} \right) - 1 \right]. \qquad (9)$$

In Fig. 2, graphic interpretation of (9) is represented in the form of relationship $\Delta T_2 = f(S)$ for $w = 0,5 \cdot 10^7, 10^7$ and $2 \cdot 10^7\ \mathrm{A^2 \cdot s}$ 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]).

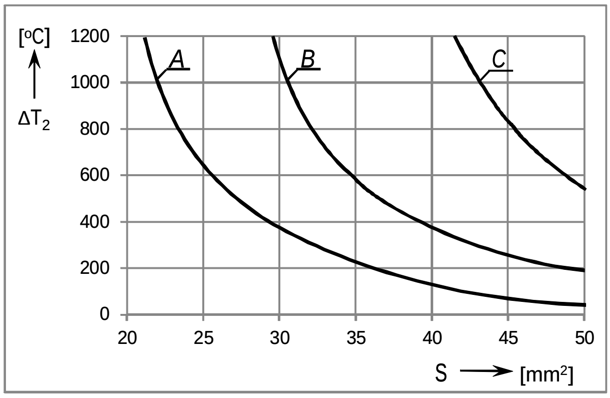

Fig. 2. Relationship between temperature rise DT_2 of air termination conductors and their cross-sectional area S, for three different values of specific energy of lightning discharge: A – 0,5 x 10^7 A^2 x s, B – 10^7 A^2 x s, C – 2 x 10^7 A^2 x s.

The data given in Fig. 2, as well as these presented in [12] are leading to preliminary conclusion that flammable roofings can be destroyed by thermal action, but only when they are very close to incandescent air termination conductors.

Real effects of steel drops melted out from air termination conductors and the incandescent air 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.

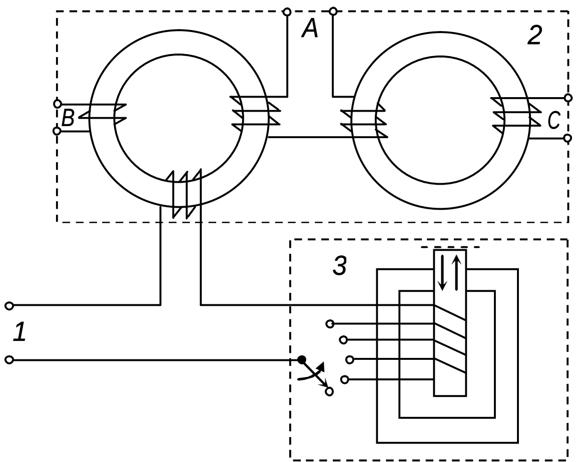

Fig. 3. Diagram of principal part of testing system applied for generation of high alternating currents: 1 – power mains, 2 – heavy current transformer, 3 – regulating inductor, A – transformer operating terminals, B – voltage control terminals, C – current control terminals.

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 $5 \div 80$ 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 ΔT_2. 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 $2 \times 10^2 \div 5 \times 10^2$ °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 ΔT_2 for steel conductors with the use of the following formula

$$w = \frac{C_1 \cdot g \cdot S^2 \cdot \ln\left(1 + a \cdot \Delta T_2\right)}{r \cdot a}, \qquad (10)$$

resulting from the transformation of relationship (9).

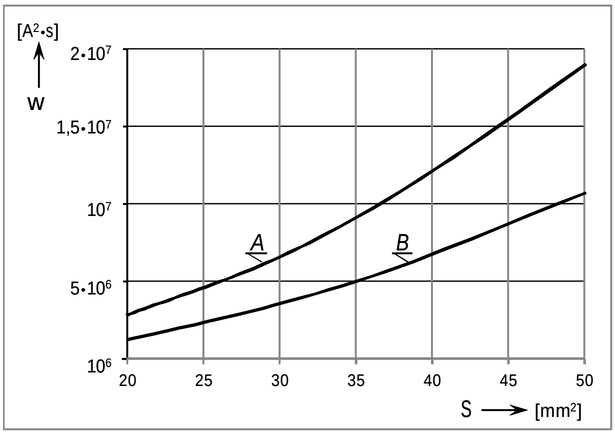

Fig. 4. Relationships between specific energy of lightning discharge w and air termination conductor cross-sectional area S for minimum and maximum values of ΔT_2 *:*
$A - \Delta T_2 = 500\ °C$, $B - \Delta T_2 = 200\ °C$.

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 ΔT_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 ^{o}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).

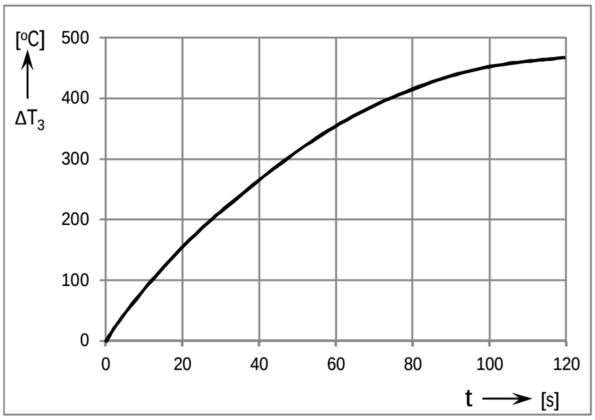

Fig. 5. Relationship between drop ΔT_3 of temperature rise $\Delta T_2 = 500°C$ and time t, during cooling down of air termination conductor model.

Taking into consideration that in Europe duration *t* practically does not exceed *1* s [4] and that during this time the increase ΔT_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 $S = 50$ 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).

Table 2

Influence of models of overheated air termination conductors on models of flammable roofings.

Kind of a test	Material of roof covering		
	1	2	3
A	I	I	II
B	III	III	IV

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:

$$P_{F\bar{V}} = \frac{N_{F\bar{V}}}{N_{\bar{V}}}, \qquad (11)$$

where $N_{F\bar{V}}$ is a number of steel drops (from the sample of steel drops of average volume $\bar{V}$) causing combustion of roofing model; $N_{\bar{V}}$ 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 $P_{F\bar{V}}$ (the author assumed that $N_{\bar{V}} \geq 30$ [13, 14]).

The probability $P_{F\bar{V}}$ 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 $P_{F\bar{V}}$.

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 DT_2 is within the range 400÷500 °C.

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

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 $S \geq 50$ mm^2) 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.

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

Піотр 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 дослідів.

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