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CALORIMETRIC MEASUREMENT OF ARC FLASH INCIDENT ENERGY

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ABSTRACT

Live working is permissible under the provision that there is a protection against the thermal hazards of an electric arc caused by an arc fault. The determination of arc flash thermal energy exposed on the human skin behind protective clothing (incident energy) is carried out on the base of calorimetric measurements using copper calorimeters in the standards for testing protective clothing. The accuracy of the estimation of arc flash thermal energy based on the calorimetric measurement using copper calorimeters is discussed in the paper.

Index Terms - live working, arc fault, incident energy, copper calorimeter, protective clothing

1. INTRODUCTION

In case of arcing faults in electric power installations, among others, particularly the thermal hazards of an electric arc are of high risk for persons especially when live working. The human tissue tolerance to heat is characterized by the Stoll curve (warming time > 1 s) and the Privette one (warming time < 1 s) of thermal energy density (heat flux or incident energy respectively) and time [1, 2, 19 - 21]. The determination of arc flash thermal energy exposed on the human skin behind protective clothing (incident energy) is carried out on the base of calorimetric measurements using copper calorimeters [3, 4, 17-23]. The principle construction of a copper calorimeter as used in the box test [4] is shown in Fig. 1.

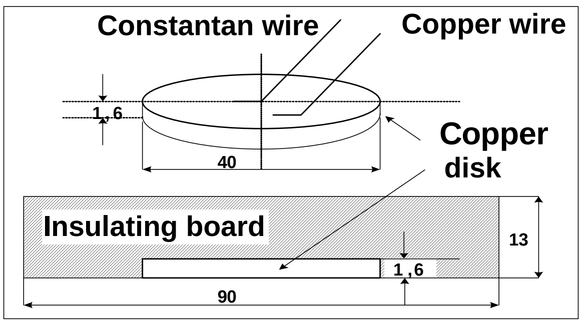


Figure 1 Construction of a copper calorimeter with copper-constantan thermocouple

The ***incident energy*** is calculated by multiplying the measured *delta peak temperature* dT_{max} (difference between the maximum temperature and the initial temperature of the sensor during the arc test exposure time) by the *sensor constant* 5,52 kJ/m² °C based on the mass, the specific heat and the surface area of the copper disk: $E_i = 5{,}52\ dT_{max}$ [4]. It means that the measurement of the temperature dT, and especially of the maximum value, is important for the correct estimation of the personal risk and the protective behavior of the PPE (e.g. clothing) under arc test conditions.

It must be noted that the arcing time in the arc tests (in the box test 500 ms) is comparable with the time constant of the copper calorimeter. Fig. 2 illustrates this. Because of it the measured temperature-time behavior during the arc burning can be erroneous. On the other hand the thermal exposure time (observation time) during the arc test is 30 s and much longer than the arcing time. The measured delta peak temperature dT_{max} is usually achieved 4-6 s after the test beginning (firing of the arc) in cases of direct arc exposure. After 30 s the temperature is only reduced by 10 –15 %. That means that the arc flash incident energy conserved in the copper disk and in the its environment (air) is measured using the copper calorimeter. Depending on the sample, the time to delta peak temperature is still longer in case of textile material and clothing testing.

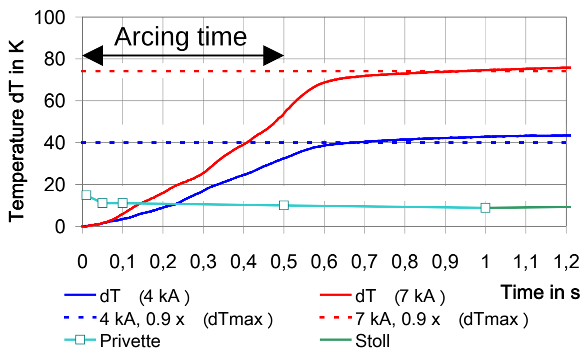


Figure 2 Temperature time courses measured by copper calorimeters

For assessing the physiological skin effects (Stoll or Privette criteria) the incident energy has to be determined, meaning the delta peak temperature but not the exact temperature time course. The principle measurement error in case of material or clothing testing will be small for this reason. The correctness of the estimation of arc flash thermal energy based on the temperature measurement using copper calorimeter is further discussed in the following. Main focus is the direct arc exposure measurement.

2. THEORETICAL CONSIDERATIONS FOR THE ARC FLASH HEAT FLUX ESTIMATION

Heat flux is the thermal intensity of an electrical arc indicated by the amount of energy transmitted per unit area and time.

The heat from an electric arc to its environment (air) and to the copper calorimeter is transferred by radiation, convection and conduction. There are different estimations of the relative parts of the heat transfer mechanisms mentioned above.

According to [5 - 9] the relative part of the radiation heat transfer from an electric arc is less than 20% of full arc power. On the other hand in [10 – 12] is stated that up to 95% of the energy released from an arc is delivered in the form of radiation.

Experimental calorimetric measurement of the incident energy is a possible way to verify theoretical considerations.

The theoretical estimation of the arc flash heat flux at a certain distance from the arc under study was based on the incident heat flux calculation made for the arc furnace vessel [10].

Figure 3 shows the simplified schema for the determination of the radiant heat flux on the vessel wall at the point A. l_{arc} is the length of arc, d_{arc} is the diameter of the arc.

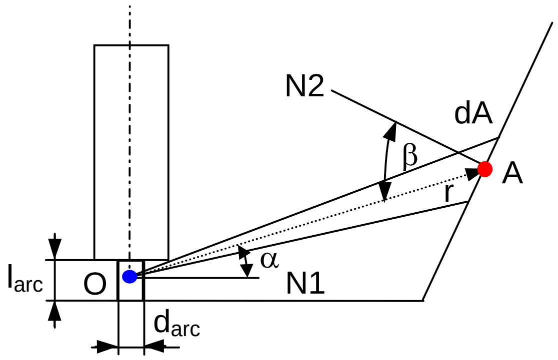


Figure 3 Schema for the calculation of an incident heat flux for electric arc furnaces

The point O is the position of the equivalent heat source on the axis of the electric arc under study. There are two main approaches for the representation of an electric arc as a heat source: 1) representation as an infinitesimal sphere or 2) representation as an infinitesimal cylinder. Respectively there are two different equations for the case under study: ***Keppler***'s formula (for spherical heat source)

$$q = \frac{P_{arc} \cos\beta}{4\pi r^2} \quad (1)$$

and ***Makarov***'s formula (for cylindrical heat source)

$$q = \frac{0{,}9 P_{arc} \cos\alpha \cos\beta}{4\pi^2 r^2} \quad (2)$$

where P_{arc} – electric arc active power

r – distance from the arc axis

β – angle between the direction to the heat source and the direction of the normal N2 to the surface under consideration

α – angle between the direction to the point under study and the normal N1 to the arc axis.

In relation to the box test conditions [2] the schema described above is transformed into that one shown in Figure 4:

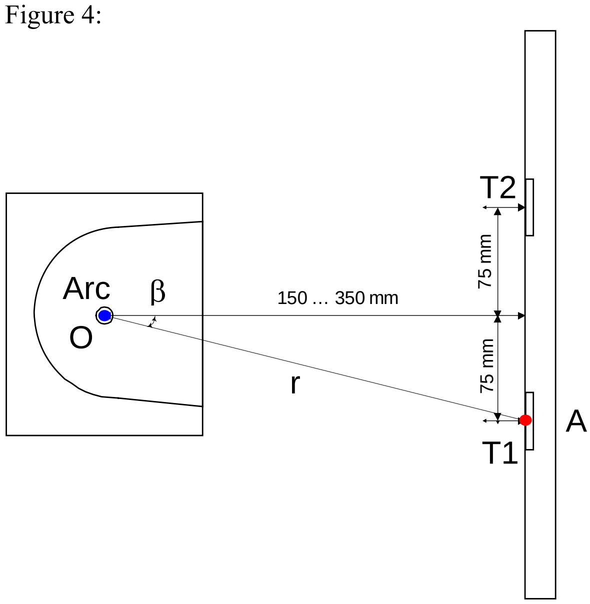


Figure 4 Schema for the calculation of incident heat flux under box test conditions

There are two copper calorimeters in Figure 4 (T1 and T2) for the registration of the incident heat flux in the schema Figure 4. The direct distance to the test plate with the calorimeters is a = 300 mm in the box test set-up. This distance was also varied between 150 and 350 mm in the following considerations for analysis reasons.

The arc power is calculated from the instantaneous arc voltage values multiplied by the instantaneous arc current values, and performing the arithmetic mean value over the arc duration. The arc power values for (1) and (2) are so determined over the full arcing time.

3. BASIC MEASUREMENT RESULTS

A typical temperature-time curve measured during the box test (direct exposure without sample) is shown in

Figure 5. From Figure 5 can be seen that the curve of dT can be divided into several characteristic parts. It can be assumed that the first practically linear part of the curve dT characterizes the absorbed electric arc radiation. It is known that radiation of constant heat flux will cause a linear temperature increase measured by a copper calorimeter [13].

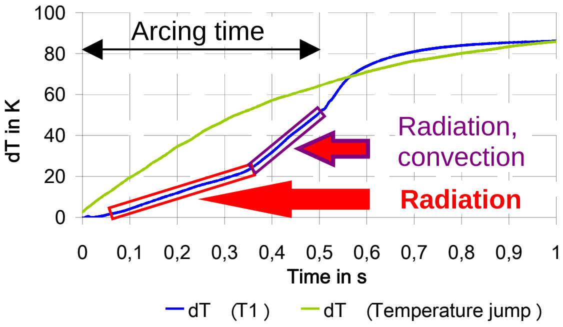


Figure 5 Typical temperature curves measured by copper calorimeters in case of a box test (dT (T1)) and in case of a temperature jump

Taking into account that radiant heat flux is transferred by electromagnetic waves, it may be expected that the heat flux will be measured practically immediately after the arc ignition.

The second part of the measured temperature curve which can be linearized, too, and showing a stronger slope, can be explained by, first of all, an additional heat transfer by convection (hot plasma and gas cloud) and the reflection of the electromagnetic waves from the box wall, construction elements and equipment.

For comparison Figure 5 shows also the temperature curve measured with a temperature jump caused by fast moving a copper calorimeter from ice into boiling water. There is a different temperature rise character compared to that with arc exposure.

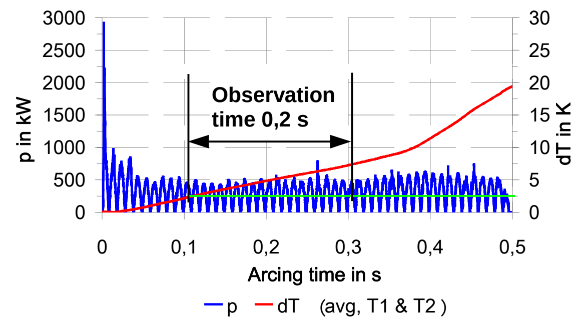


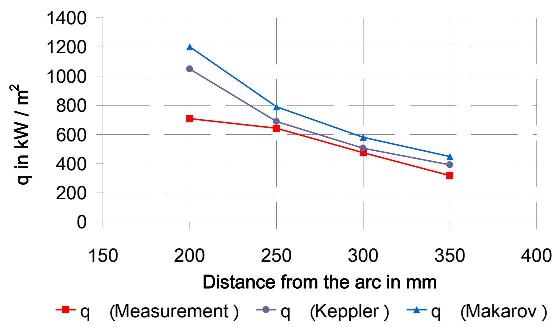
Figure 6 Choice of the data interval from measured temperature curve

Figure 6 illustrates the selection of the data interval used for the following estimation of the electric arc heat flux on the base of the analysis of the measured temperature curve. This observation time interval of the heat flux estimation was chosen taking into account a linear character of the measured temperature curve after the arc ignition. For the minimization of the influence of non-stationary transient processes directly after the arc ignition this observation interval is counted from the moment when the measured temperature values exceed dT = 2,5 K. The temperature value of 2,5 K is marked by the green line in Figure 6. The duration of the observation time was chosen by 0,2 s.

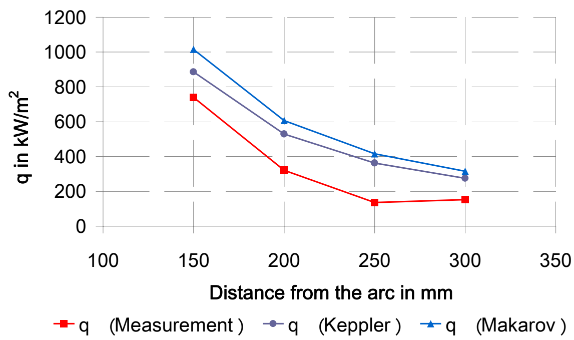
The chosen data interval of temperature values dT was used for the determination of the incident energy rise $e_{i0}(t)$ by multiplying the values dT with the sensor constant 5,52. The determined values of e_{i0} were linearized. The linearized values e_{i0lin} were used for the calculation of the heat flux values q as follows:

$$q = \frac{\Delta e_{i0lin}}{\Delta t} \qquad (3)$$

where Δt - the time interval from the beginning of the observation time until the time point under consideration. Figures 7 a) and b) show the heat flux values determined out of the measurement results by (3) and the theoretical values calculated by (1) and (2) for the two box test classes (test current 4 kA and 7 kA) [4] for different distances to the arc.



a)



b)

Figure 7 Heat flux values

a) class 2 (test current 7 kA)

b) class 1 (test current 4 kA)

The measured heat flux values presented in Figure 7 are the average temperature values of the two copper calorimeters T1 and T2 (s. Figure 4).

It can be seen from the Figures 7 a) and b) that the character of the heat flux changes measured is well described by the both theoretical formulas (1) and (2). The numerical values of the heat flux experimentally determined have a better accordance to the theoretical values calculated by Keppler's formula those of the Makarov one.

The best approximation of the measured values by the calculated ones is, as to be seen from Figure 7 a), for the test condition with r = 300 mm and a test current 7 kA. The difference between the measured and the theoretical heat flux value is less than 6,2 % in this case. The biggest difference between the measured and a calculated heat flux value is 62,5% for r = 250 mm and a test current 4 kA. But those large deviation or scattering ranges are typically for the stochastic arc processes.

From the statistically confirmed direct exposure incident energy ranges for box test conditions [4]

Test current	Mean value E_{i0} kJ/m^2 (%)	Triple standard deviation ± 3 σ kJ/m^2 (%)
Class 1: 4 kA	135 (100)	± 84 (± 62,2)
Class 2: 7 kA	423 (100)	± 117 (± 27,7)

and the statistical distribution of the incident energy values measured for LV arcs according to [14] showing deviations from -100% until +62% in comparison with theoretical values, can be concluded that the differences between experimental and theoretical dependences presented in Figures 7 a) and b) are result from the electric arc behavior, and do not mean a insufficient approach.

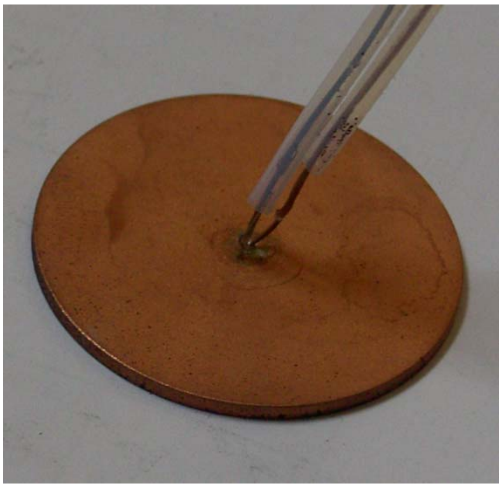
4. VERIFICATION OF MEASUREMENT RESULTS

The measurement results discussed above were received using the conventional copper calorimeters according to Figure 1 [1, 2]. For the verification of the correctness of the heat flux estimation measurements based on a changed copper calorimeter construction were carried out. Copper discs with the thickness of 0,5 mm instead of 1,6 mm were used for this measurement series.

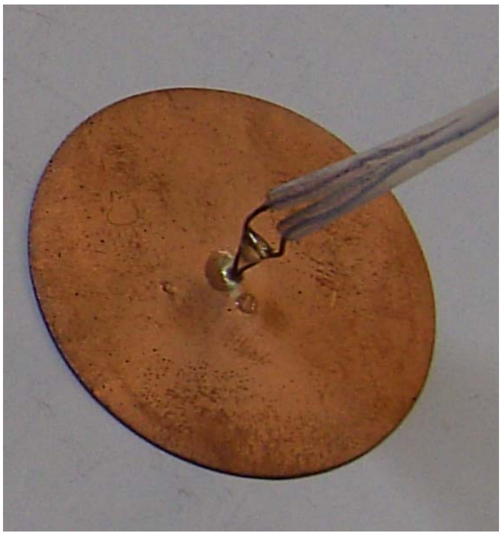
Figures 8 a) and b) show the conventional (a)) and the changed (b)) construction of copper calorimeters. In both calorimeter constructions copper-constantan thermocouples type T (according to IEC 60584-1 [15]) were used. The copper calorimeters were embedded in an insulating board (s. Figure 1). The surface area of the copper disc intended for heat receiving was covered by a thin layer of optical-black colour.

Before the embedding into the insulating board each copper calorimeter was calibrated by a temperature jump reached by taking the calorimeter from a vessel with ice into an other one containing boiling water, adjusting two stationary temperatures T = 0 °C and °C and T = T_{BP} (near to 100 °C; the actual boiling temperature of water is depending on the air pressure; the air pressure was determined for the calibration place and the boiling water temperature was exactly calculated and measured [16]).

After the embedding into the board each calorimeter was exposed to a fixed radiant energy source (halogen lamp 35 W) for 30 s. It was checked that no one calorimeter response varied more than 5% from the long term average of a reference calorimeter.



a)



b)

Figure 8 Copper calorimeters for the heat flux estimation

a) Copper disc 1,6 mm
b) Copper disc 0,5 mm

Figure 9 shows temperature time curves of the 2 calorimeters S1 and S2 measured in a direct exposure class 1 box test (constrained and directed electric arc, test current 4 kA, distance 300 mm, without sample) by both copper calorimeters types described above.

It can be seen from Figure 9 that the delta peak temperatures measured by the copper calorimeters with the thin disc (0,5 mm) are significantly higher in comparison with the case of the use of conventional copper calorimeters (copper disc 1,6 mm). The time to delta peak temperature is less than 1 s.

This difference can be explained by the higher measurement dynamics of the copper calorimeters with thin discs.

The *time constant* of a copper calorimeter is, first of all, depending on the copper disc behaviour (its own thermal time constant). The time constant of the copper calorimeters with a thin disc is shorter than the time constant of a conventional copper calorimeter. For this reason the copper calorimeter with thin disc is able measure rapid short-term temperature changes which can not be detected by a conventional copper calorimeter.

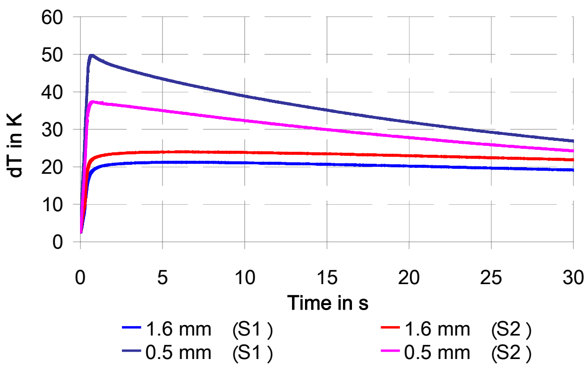


Figure 9 Temperature- time behaviours in box tests (test current 4 kA) measured by different copper calorimeters

There are two measured temperature curves presented in Figure 9 for each type of copper calorimeter. Sensor 1 (S1) is calorimeter T1 and sensor 2 (S2) is calorimeter T2 in the measuring construction of Figure 4. The measurements were carried out simultaneously for the both calorimeters of each calorimeter type.

Being directly proportional to the mass of copper disc, there are different values of sensor constants for both constructions of used copper calorimeters. The sensor constant for the copper calorimeter with the thin disc is

$$1{,}725 = 5{,}52 \times \frac{0{,}5}{1{,}6} \qquad (4)$$

This means if the same temperature was measured by both calorimeter types there would have been different incident energies. For determining the incident energy and incident energy rise from the temperature rises measured by the calorimeter type with the thin disc this sensor constant has to be used.

That also means that the comparison with the Stoll limits may not be done on the base of the temperature values indicated in [3] and [4] but in principle for the incident energy values because the corresponding values of [3] and [4] are found and valid for a calorimeter with a sensor constant of 5,52.

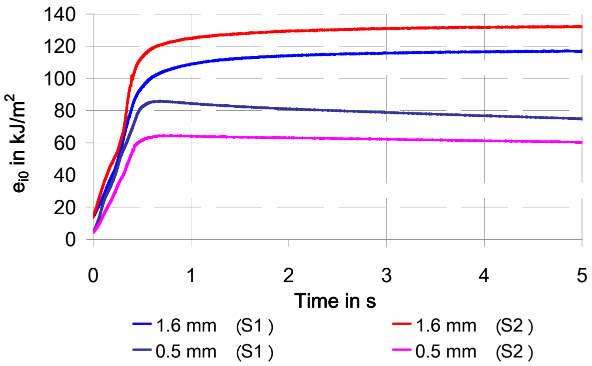
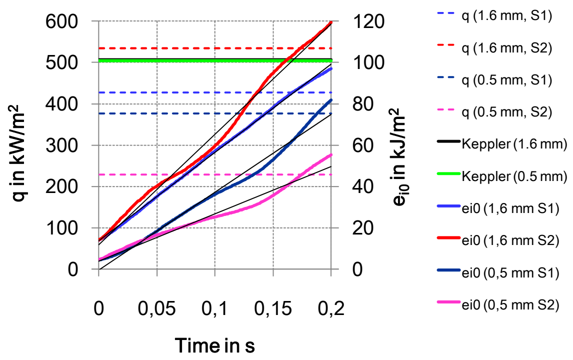
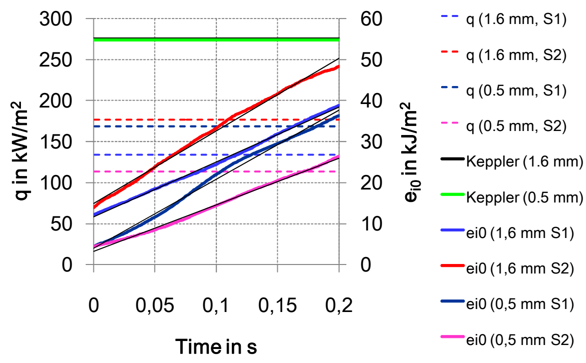


Figure 10 Incident energy rise values in box tests (test current 4 kA) resulting from different copper calorimeters



a)



b)

Figure 11 Heat flux values (300 mm distance from the measuring board to the arc axis)
a) Test current 7 kA
b) *Test current 4 kA*

Figure 10 shows the incident energy rise values of the different copper calorimeters, resulting from the measurements in the box tests considered above (test current 4 kA). It can be seen that there is a significant difference not only between the results received by using different copper calorimeter types, but also between the values determined for each of the both calorimeters of the same type. The differences last mentioned can be explained by the asymmetry of the electric arc radiation and, respectively, the asymmetrical heat flux spreading.

The incident energy E_{i0} is the maximum value of the energy rise curve $e_{i0}(t)$ (according to the delta peak temperature of the dT(t) curve to be multiplied by the sensor constant). The following Table gives an overview about the incident energy values result from the measurements considered.

Test	Disk	Sensor	dT_{max} K	E_{i0} kJ/m^2	t_{max} s
7 kA	1,6 mm	S1	90,8	503	4,52
		S2	101	559	4,23
	0,5 mm	S1	146	253	0,6
		S2	113	196	1,39
4 kA	1,6 mm	S1	21,3	118	6,05
		S2	24,1	133	6,03
	0,5 mm	S1	49,9	86,5	0,72
		S2	37,3	64,4	0,83

The incident energy is significantly smaller in case of using the calorimeters with the thin disc. Because of the smaller time constant the temperature maximum is not only reached faster but there is also a faster disc cooling down after the heat source is not more existing due to heat transfer to the surrounding. In case of the standard calorimeter with a 1,6 mm disc the cooling effect will become efficient after the full heat flux was received so that the copper disc maximum temperature gives a better equivalent of the thermal energy density resulting from the arc.

The Figures 11 a) and b) show the linearized parts of the incident energy rise values (determined from the temperature measurements) and their linear trend lines as well as the heat flux values calculated from the electrical arc parameters by the Keppler formula on the one hand, and from the linearized incident energy rise values on the other hand.

It can be seen from Figures 11 a) and b) that the heat flux values may differ relatively wide from each other. The reason has to be seen again mainly in the electric arc stochastic since the calorimeters of the same type show also relatively large deviations, too. However, those sensors of different type which lie closest together (e.g. sensors S1 – 0,5 mm and S2 – 1,6 mm, 4 kA test), have only small differences (4,7%). This means that the temperature characteristic recorded is similar, independent on the dynamic of the calorimeter in the initial period mainly determined by radiation absorption, too.

Summarizing, as a first estimation it may be concluded that the arc flash incident energy can be correctly determined by using copper calorimeters in general and the conventional ones in particular.

The analyses have to be continued for finding final conclusions. For this, the results of a larger number of similar measurements (repetitions series) have to be compared to confirm the above statements. Furthermore, the heat flux characteristics in the second part of the temperature curve and for the full temperature rise period until dT_{max} shall be considered.

5. SUMMARY

The analyses carried out confirm the correctness of the arc flash incident energy estimation by using copper calorimeters.

The heat flux is a more informative parameter for the characterization of thermal impact of an arc flash in comparison with the temperature rise and the incident energy usually considered. However the incident energy is the parameter characterizing the total heat absorbed by the skin and used for the Stoll assessment as well as the ATPV classification. The measurement of the incident energy by conventional copper calorimeters is sufficiently exact, particularly in case of measuring the transferred incident energy behind the textile material as done in the tests standardized. The temperature curves (time course) measured in case of direct exposure (without material) may have differences to the actual temperature rises especially in case of very high arc energies and arc durations but the delta peak temperatures obtained from the temperature curves measured by the conventional calorimeters (being proportionally to the incident energy) are sufficiently correct.

It was confirmed that the initial heat flux caused by an arc flash to a point at a certain distance to the arc and measured there by the calorimeters is delivered mainly by radiation.

The analyses have to be continued.

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7. REFERENCES

[1] Stoll, A. M.; Chianta, M. A.: Method and Rating System for Evaluation of Thermal Protection. Aerospace Medicine Vol. 40 (1969) 11, pp. 1232...1238

[2] A. Privette: Progress Report for ASTM Burn Study. Duke Power Company, June 10, 1992.

[3] IEC 61482-1-1, Ed. 1: Live working – Protective clothing against the thermal hazards of an electric arc – Part 1: Test methods – Method 1 – Determination of the arc rating (ATPV or EBT) of flame resistant materials for clothing

[4] IEC 61482-1-2 Ed.1 Part 1: Test methods – Method 2 –Determination of arc protection class of material and clothing by using a constrained and directed arc (box test)

[5] И.А.Кринберг. К теории столба дуги, горящей в условиях естественной конвекции. Журнал Технической Физики, 1964, вып.5, с.492.
I. A. Krinberg. To the theory of the arc column burning under conditions of natural convection. Technical Physic Journal, 1964, vol. 5, p. 492 (in Russian)

[6] N. A. Rubtsov, N. M. Ogurechnikova. Radiative-Convective Heat Transfer in Discharge Chamber at Turbulent Gas Flow. Contrib. Plasma Phys. SS (1988) 1, 17-25

[7] A. Lefort, M. J. Parizet, S. Jellouli, and R. Bessege. Heat Transfer from an Electric Arc to Insulating Wall. IEEE Trans. on Plasma Science. Vol. 21, No 5. Oct. 1993, pp. 593 - 597

[8] Чувствительность дуговой защиты. Учебное пособие курсу семинара: «Монтаж, пуско-наладочные работы и эксплуатация УДЗ «ОВОД-МД»
Arc protection sensitivity. Tutorial for the seminar „Montage, precommissioning and exploitation UDZ "OVOD-MD" (in Russian)

[9] Steinhorst P. Simulation des instationären Wärmetransports durch Hitzeschutztextilien. Diplomarbeit TU Chemnitz, 2003

[10] А. Н. Макаров. Теория и практика теплообмена в электродуговых и факельных печах, топках, камерах сгорания. Часть I. Основы теории теплообмена излучением в печах и топках. Тверь 2007.
A. N. Makarov. The theory and practice of heat exchange in electric arc and torch furnaces, fireboxes, combustion chambers. Part I. Bases of the theory of heat exchange by radiation in furnaces and fireboxes. Tver' 2007 (in Russian)

[11] D. Guo, G. A. Irons. Modeling of radiation intensity in an EAF. 3rd Intern. Conf. on CFD in the Minerals and Process Industries. CSIRO, Melbourne, Australia. 10-12 Dec. 2003

[12] R. H. Lee. The Other Electrical Hazard: Electric Arc Blast Burn. IEEE Industry Applications Society Annual Meeting. Philadelphia, Oct. 5 – 9, 1981

[13] R.L. Barker, H. Hamouda, I. Shalev, J. Johnson. Review and Evaluation of Thermal Sensors for Use in Testing Firefighters Protective Clothing. North Carolina State University, Center for Research on Textile Protection and Comfort, College of Textiles. Raleigh, NC, Annual Report, March 1999

[14] Chet Davis, P.E.; Conrad St. Pierre; David Castor, P.E.; Robert Luo; Satish Shrestha. Practical Solution Guide to Arc Flash Hazards. ESA, Inc., 2003

[15] DIN EN 60584-1. Thermopaare. Teil 1: Grundwerte der Thermospannungen (IEC 584-1:1995) Deutsche Fassung EN 584-1:1995. Oktober 1996

[16] U. Elßner. Durchführung und Bewertung kalorimetrischer Messungen für Prüfungen zum Personenschutz. Studienarbeit TU Ilmenau 2009

[17] Schau, H. Störlichtbögen - Schutz vor thermischen Gefahren. Berlin: ep Elektropraktiker 62 (2008), Heft 8, S. 687 – 691

[18] Schau, H. Testing of personal protective equipment against the thermal hazards of an electric fault arc. VI Scientific Conference ELECTRICAL POWER NETWORKS (SIECI 2008), September, 10-12, 2008, Wroclaw/Polen, Konferenzband S. 501 -506 (CD-ROM)

[19] Schau, H. Gefahren durch Störlichtbögen
Thermische Wirkungen von Störlichtbögen – Stand der Normung zum Personenschutz
13. Vortragsveranstaltung ELEKTROTECHNIK, 30/31. Mai 2006, Nürnberg, Tagungsband, S. 39...45 (+CD-ROM)

[20] Schau, H. The new standard IEC 61482 and experiences with the box test method for testing of protective clothing against the thermal hazards of an electric arc. 8th International Conference on Live Maintenance ICOLIM 2006, 7.-9. Juni 2006, Prag/Tschechien, Tagungsband, 11 S. (CD-ROM)

[21] Schau, H. Arc protection – Protection against the thermal hazards of an electric arc. Health & Safety International Journal, Heft Juli 2005, S. 75…81.

[22] Schau, H.; Beier, H. Practice-oriented test standard for the evaluation of protective clothing against the risks of an electric arc – CLC/TS 50354 Box Test. International Conference on Research and Standardization in the Field of Development and Use of Personal Protective Equipment, Krakow/Polen, 12.-14. Sept. 2005, S. 312...320.

[23] Schau, H.; Haase, J. Messung und Bewertung der kalorimetrischen Lichtbogenwirkungen. 48. Internationales Wissenschaftliches Kolloquium der TU Ilmenau (IWK), 22.-25.Sept. 2003, Ilmenau/Thür., Tagungsband S.486.