Determining the smoke-generating ability of modern cable products needed to model fires in energy facilities

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Abstract. A comparative analysis of methods of carrying out fire tests was carried out in order to obtain the value of smoke formation coefficient required for simulation of fire dynamics at power engineering facilities. A new method of carrying out fire tests to determine smoke-forming ability of substances and materials is proposed. Results of measurements of radiant heat flux density and gas medium temperature inside combustion chamber at different distances from heating element are presented. The effect of the sample area, the density of the heat flow incident on the sample and the temperature inside the combustion chamber on the value of the smoke formation coefficient is shown. For modern types of cable products used at power engineering facilities, values of smoke formation coefficient under different modes have been determined. Dependence of smoke formation coefficient on sample area and on distance from heating element inside combustion chamber is obtained. A comparative analysis of the results obtained at different facilities with the values given in the database of typical fire load was carried out. It was found that the experimental value of smoke formation coefficient differs significantly from the values obtained in the standard ГОСТ12.1.044 facility. The results were analyzed.

1. Introduction

Mathematical modeling of fire thermogasodynamics allows to estimate the degree of danger of human presence in the territory of the energy object where the fire can occur. According to works [1–4], in most cases the decrease visibility in smoke reaches critical values earlier than other dangerous fire factors. The accuracy of the visibility reduction calculation depends significantly on the amount of smoke-generating ability of the substances and materials obtained experimentally.

In Russia, the database of typical fire load [2] is used in mathematical modeling of fire at energy facilities. However, for most modern substances and materials, such data are not available. In addition, the values of the smoke generation coefficient obtained on the standard method [5] used for certification differ significantly from the values in the given database [2], so improving the quality of fire tests to determine the smoke-generating ability of substances and materials, reliability of measuring equipment and methods of processing the obtained results is a pressing and rather difficult scientific task.

2. Experimental facility

Method [5] is used to determine the smoke formation coefficient of construction and finishing materials. However, this method has a number of significant disadvantages [7]. Therefore, we use a new experimental facility [7, 8], the scheme of which is shown in Figure 1.
Figure 1. Scheme of the modified experimental facility [7, 8]:
1 - combustion chamber; 2 - adapter hose; 3 - exposure chamber; 4 - laser module;
5 - thermocouples; 6 is a gas extraction probe; 7 – fan; 8 is a photosensitive member;
9 - electronic scales; 10 - sample holder; 11 - electric heating emitter;
12 - recording equipment

Smoke formation coefficient was determined by formula [5]:

$$D_m = \frac{V}{L \cdot m} \ln \frac{I_0}{I_{\text{min}}},$$

Where $D_m$ is specific smoke formation coefficient of combustible material, Np·m²/kg; $V$ - volume of exposure chamber, m³; $L$ - path length of light beam in smoke medium, m; $m$ is the weight of the sample, kg; $I_0, I_{\text{min}}$ - respectively values of initial and final light transmission, %.

3. Comparison of fire test results on a new experimental and the standard facility

Experiments were carried out on a standard facility [5] and on a new experimental facility [7, 8]. The fire tests were carried out under the same conditions. Samples of wood of coniferous breeds had the sizes of 40×40×3 mm and mass of 3±0.2 g. Density of a heat flux on the exhibited surface of samples on both facility was 35 kW/m², length of a way of a ray of light in the smoke-filled environment in both cases was 80 mm.

Experimental values of smoke formation coefficient are shown in Figure 2. It can be seen from Figure 2 that the values obtained in different facilities differ by an order of magnitude.

The arithmetic mean of the smoke formation coefficient of three tests in the experimental facility [7, 8] was $D_m = 47.7$ Np·m²/kg, while the standard method [5] produced $D_m = 495.7$ Np·m²/kg.

The values obtained in the facility [7, 8] were close to the values in base of date [2]: wood $D_m = 57$ Np·m²/kg, coniferous wood materials $D_m = 61$ Np·m²/kg, hardwood - $D_m = 53$ Np·m²/kg.

This difference between the values obtained in the considered facilities may be due to the difference in the configuration of these facilities, as well as the nature of the thermal impact on the sample during the firing tests [1].
One of the main fire loads at energy facilities is cable products. Database [2] have values for only six cables. Values of their smoke-generating ability vary from 407 to 850 Np·m²/kg, which has a rather large variation and shows the need to determine smoke-generating ability for modern types of cable products of different design and chemical composition, which are used at power engineering facilities.

Analysis of the results of the fire tests of the PVC insulated & sheathed bare (coverless) reduced fire hazard rating cable “ВВГнг” in Russian showed that the values of smoke-generating capacity differ significantly from the values obtained according to GOST 12.1.044-89 and are proportional to the values from the database of typical fire load (Fig. 3).

\[ D_{m}, \text{Np} \cdot \text{m}^2/\text{kg} \]

**Figure 2.** Value of the smoke formation coefficient for three fire tests in different facilities

**Figure 3.** Histogram of smoke-generating ability values from the database of typical fire load [2] and averaged values obtained in the new experimental facility [7.8] and facility as per GOST 12.1.044-89
4. Experimental studies of the effect in combustion chamber parameters on smoke-generating ability

4.1. Influence of the distance between the sample and the electric heating element

The experimental facility [7, 8] allows to change the distance from the heating element to the sample surface, unlike the standard facility [5]. Diagram of combustion chamber of this facility is shown in Figure 4.

Figure 4. Combustion chamber diagram of experimental facility:
1 - heat insulation layer; 2 - a water cooling chamber; 3 - electric heating emitter;
4 - the outer wall of the combustion chamber;
5 - sample holder; 6 - electronic scales; 7 - is a system for adjusting the distance from the electric heating emitter to the test sample; 8 - is quartz glass; 9 - low inertia thermocouple; 10 - sample for test

In calibration experiments, in the absence of combustion of the sample, heat flux density measurements were performed at different distances from the electric heating emitter using a water-cooled sensor of type “Гордон ФОА-013” in Russian with an error not exceeding ± 8%. Temperature measurements on the inner surface of the heating element and the sample surface were carried out using thermoelectric converters of type “ТПК-005” in Russian with a measurement range of -40 to 1000 °C with an error of not more than 6%.

Table 1 shows the results of calibration experiments where the q-density of the radiant heat flux incident on the sample surface, kW/m²; \( t_n \) is adjustable temperature on an internal surface of a heating element, °C.

| \( q \), kW/m² | \( t_n \), °C | \( t_n \), °C | \( t_n \), °C | \( t_n \), °C | \( t_n \), °C | \( t_n \), °C | \( t_n \), °C |
|---------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 65            | 809         | 793         | 777         | 764         | 746         | 733         | 719         | 708         |
| 60            | 792         | 774         | 757         | 742         | 727         | 715         | 702         | 693         |
| 55            | 775         | 756         | 737         | 722         | 707         | 696         | 684         | 675         |
| 50            | 758         | 738         | 718         | 702         | 688         | 677         | 666         | 658         |
| 45            | 736         | 716         | 697         | 681         | 667         | 657         | 646         | 638         |
| 40            | 711         | 693         | 675         | 660         | 646         | 635         | 624         | 616         |
| 35            | 685         | 667         | 650         | 635         | 621         | 610         | 599         | 591         |
| 30            | 659         | 641         | 623         | 608         | 593         | 581         | 569         | 560         |
| 25            | 624         | 605         | 587         | 572         | 557         | 546         | 535         | 526         |
| 20            | 582         | 563         | 544         | 529         | 516         | 506         | 496         | 488         |
| 15            | 532         | 513         | 494         | 479         | 466         | 457         | 447         | 440         |
| 10            | 462         | 446         | 430         | 417         | 405         | 396         | 386         | 379         |
| 5             | 351         | 340         | 329         | 320         | 313         | 309         | 304         | 300         |

\( L_e \), mm | 70 | 65 | 60 | 55 | 50 | 45 | 40 | 35
The use of the data in Table 1 allows more precise determination of the density of the heat flux incident on the exposed surface of the test sample, which increases the reliability of the experimental data obtained.

Based on this, a series of fire tests were performed on this installation with a given heat flux density of 25 and 35 kW/m$^2$, and with different distances between the sample and the heating element (35, 55 and 70 mm). Coniferous wood with a size of 30×30×3 mm and a weight of 1.23±0.02 g was used as samples.

The obtained relations of the smoke formation coefficient with the distance between the sample and the electric heating element are shown in Figure 5.

Results of these tests are in more detail presented in table 2 in which the following designations: $q$ - density of the falling heat flux, kW/m$^2$; $l$ - distance between a surface of a sample and a heating element, mm; $t_0$ is temperature on a surface of a sample, °C.

From Figure 5 and Table 2, it can be seen that the smoke formation coefficient depends substantially on the distance between the sample and the electric heating element and the burning mode (burning or smoldering).

![Figure 5. Graph of change of smoke formation coefficient value from distance between sample and electric heating element.](image)

**Table 2.** Effect in combustion chamber conditions on the specific smoke formation coefficient of wood

| Test No. | $q$, kW/m$^2$ | $l$, mm | $t_0$, °C | $t_s$, °C | $D_{sm}$, Np·m$^2$/kg | Test mode   |
|----------|---------------|---------|-----------|-----------|------------------------|-------------|
| 1        | 35            | 70      | 685       | 309       | 56.9                   | burning     |
| 2        | 35            | 70      | 685       | 309       | 42.8                   | burning     |
| 3        | 35            | 70      | 685       | 309       | 44.8                   | burning     |
| 4        | 35            | 55      | 635       | 282       | 33.6                   | burning     |
| 5        | 35            | 55      | 635       | 282       | 29.5                   | burning     |
| 6        | 35            | 55      | 635       | 282       | 23.2                   | burning     |
| 7        | 35            | 35      | 591       | 273       | 22.1                   | burning     |
| 8        | 35            | 35      | 591       | 273       | 26.4                   | burning     |
| 9        | 35            | 35      | 591       | 273       | 30.4                   | burning     |
| 10       | 25            | 70      | 624       | 239       | 100.9                  | smoldering  |
| 11       | 25            | 70      | 624       | 239       | 134.5                  | smoldering  |
| 12       | 25            | 70      | 624       | 239       | 120.5                  | smoldering  |
| 13       | 25            | 55      | 572       | 224       | 85.7                   | smoldering  |
For comparison, the same samples were tested according to standard method [5], the results of which are shown in Table 3.

Table 3. Results of fire tests obtained in standard facility [5]

| Test No. | \( q \), kW/m\(^2\) | \( l \), mm | \( t_{in} \), °С | \( D_m \), Np m\(^2\)/kg | Test mode      |
|---------|-----------------|---------|-------------|-----------------|-------------|
| 1       | 35              | 60      | 766         | 290             | burning (burner) |
| 2       | 35              | 60      | 766         | 775             | smoldering   |
| 3       | 25              | 60      | 700         | 560             | smoldering   |

From Tables 2 and 3 it can be seen that the values of smoke formation coefficient depend significantly on the design features of the facility [7,8] and test conditions.

4.2. Effect of sample area and mass on smoke formation coefficient value

In addition to the external conditions, the smoke generation coefficient is affected by the sample area [6] and mass, respectively [7]. However, in the fire test of standard method [5], when the minimum value of light transmission is outside the operating range or near its limits, it is allowed to change the dimensions of the sample. The mass of the sample, which is taken into account in formula (1), will also change. Therefore, the values of the coefficient for one material with different weight and size of samples should be equal to or different within the measurement error, which at confidence of 95% should not exceed 15% [5]. However, changing the sample area can result in a significant difference in the value of smoke formation coefficient.

For this effect demonstration, experimental fire tests were conducted to determine the smoke formation coefficient on samples with different burning areas in the standard facility [5]. Polyvinyl chloride, which is used for insulation of modern cable products at power facilities, was used as a material for fire test.

The relationships of the smoke formation coefficient to the surface area and weight of the samples are shown in Figure 6.

![Figure 6. Dependence of smoke formation coefficient on sample area and mass of polyvinyl chloride in the standard facility [5]](image)

This divergence can be caused both by the uneven distribution of heat flux density over the sample area and by the disproportionate relationship between the variation in area (mass) and the variation in smoke density, as the volume of the exposure chamber remains constant.
5. Discussion

According to the experiments carried out (Tables 2 and 3) during wood combustion, the values of smoke formation coefficient obtained in the standard facility [5] are significantly higher than the values of this coefficient, which are used as the initial data for fire simulation [2]. However, the values obtained from the experimental facility [7, 8] are commensurate with them.

This difference between the values obtained in different facilities is caused by different structures of the facilities and different organization of thermal impact on the sample during fire tests [7].

Measurement of heat flux density at different distances from the electric heating emitter showed that at equal density, the temperature on the sample surface is different and depends on the distance to it.

The results of the fire tests of wood at a different distance from the heating element show that there is a relationship between the smoke formation coefficient and the distance between the surface of the sample and the heating element, provided that the value of the heat flux density in the center of the sample remains unchanged.

The results of fire tests of insulation of modern cable products showed that the value of smoke formation coefficient is significantly affected by the sample area. The reasons for this are the uneven distribution of heat flux density over the sample area and the non-proportionality between the variation in sample area (mass) and the variation in smoke density due to the constant volume of the exposure chamber.

6. Conclusion

The existing method of determining the smoke formation coefficient [5], as opposed to the proposed [7, 8], gives overestimated values compared to the value of data used as the initial data in fire modeling [2].

The design features of the experimental facility and the test conditions for determining the smoke-generating ability of modern cable products used at energy facilities, in particular the selection of the surface area and mass of the sample, as well as the distance between the electric heating emitter and the sample, have a significant effect on the smoke-forming coefficient.

It is necessary to further study the effect of the combustion chamber conditions on the smoke-generating ability of substances and materials during fire tests, which will allow to increase the accuracy of measurement of this parameter, as well as to justify the possibility of its application in modeling fires in full-scale premises.

7. References

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