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Experimental Study of Combustion Characteristics of Typical Material in a Non-Hermetic Room

POSPELOV Boris[1,a], RYBKA Evgeniy[1,b], MELESHCHENKO Ruslan[1,c], POLKOVNYCHENKO Dmytro[1,d] and KORNIIENKO Ruslan[1,e]

[1]National University of Civil Defence of Ukraine, 94, Chernyshevska str., Kharkiv, 61023, Ukraine

[a]pospelov@nuczu.edu.ua, [b]rybka@nuczu.edu.ua, [c]mel@nuczu.edu.ua, [d]polkovnychenko@nuczu.edu.ua, [e]kornienkoruslan56@gmail.com

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Abstract. The results of experimental study of combustion peculiarities of typical materials (alcohol, paper, wood and textiles) in a small-sized unsealed chamber are presented. By the method of exponential filtering of measurements by traditional fire sensors of temperature, smoke density and carbon monoxide concentration of the gaseous medium in the ceiling area of the experimental chamber, the combustion peculiarities of these materials were revealed. It is established that the dynamics of temperature, smoke density and gas medium concentration in the ceiling area of the chamber during the ignition of alcohol, paper, wood and textiles has a complex and non-stationary character. This character of dynamics is caused by complex and invisible mechanisms of interaction at the molecular and macroscopic levels of combustion materials with the gas medium of the chamber. It was found that the beginning of combustion of materials is characterized by the signs of appearance of the trend of growth and increase of fluctuations of temperature, smoke density and carbon monoxide concentration of the gas medium. These signs are representative, which allows recommending them for current detection of material ignition in order to prevent fire in the premises.

1 Introduction

Buildings are a major part of any infrastructure and play a key role in the socio-economic development of a country. Recently, with the rapid development of the world, the fire hazards of buildings have undergone significant changes and have gained special importance and relevance. In the last two decades (1993–2015), 86.4 million fires caused more than one million deaths [1], and the total annual fire damage in the world is about 1% of the world GDP [2] (approximately 857.9 billion dollars) [3]. On average, 3.8 million fires caused 44,300 deaths annually in both developed and developing countries of the world [1]. From 2010–2014, developed countries like USA accounted for the maximum number of fires (600000–1500000 per year) and the second highest number of fire deaths in the world (1000-10000 per year) [4]. Meanwhile, developing countries like India and Pakistan suffered the highest number of fire deaths (10000–25000 per year) and ranked second in the number of fires (100000-600000 per year) [4]. Therefore, in order to reduce the negative effects of fires, it is important to provide the necessary fire safety for buildings. The existing fire protection measures lead to an insufficient level of fire safety of buildings, provide minimal strategies for reducing fire risk and do not solve the current problems of fire safety reduction. The sources of indoor fires are combustible materials that burn in the presence of oxygen in the ambient air. The duration and rate of heat release in such a fire depend mainly on the type of material and the level of natural ventilation in the room [5–7]. The spread of fire is a function of the heat energy released over time, causing the temperature in the room to rise. The release of heat during a fire results in complex phenomena. The most prominent of these is the plume, which reflects the upward flow of gases observed above the hearth of the fire and is driven by buoyancy forces caused by the density difference between the hot gases produced by burning material and the surrounding cold air [8]. The hot gases, rising upwards, create a rarefaction around the combustion hearth, which causes a flow of ambient air to the hearth. This makes it possible to maintain combustion

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of the material until it is completely burned out. Studying the characteristics of fire in a leaky room is of great practical importance. Researchers are interested in experiments more than in numerical simulations of fire behavior to better understand its mechanisms. Fires in leaky rooms have been investigated theoretically and by numerical modeling [9–13]. These studies have revealed the features of complex combustion behavior of materials in airtight spaces [14–17]. The features of fire behavior under natural ventilation are usually classified by the ventilation coefficient [15, 18]. This coefficient takes into account the size of the openings in relation to the total size of the room during a fire [19]. This ventilation coefficient, as well as parameters affecting the fire behavior, allows calculating, for example, the mass flow rate of incoming cold air or escaping hot gases leaving the room through openings [20–22]. Studying the recurrent diagrams of carbon monoxide concentration at early ignitions in premises and development of a method to improve the performance speed of maximal fire detectors done on [23, 24]. Design of fire detectors capable of self-adjusting by ignition and examining the learning fire detectors under real conditions is contained in [25, 26]. Development of the correlation method for operative detection of recurrent states gas medium studying on [27]. Short-term fire forecast based on air state gain recurrence and zero-order Brown model on modification of the Brown's zero-order model done on [28, 29]. Peculiarities of amplitude spectra of the third order for the early detection of indoor fires and defining the features of amplitude and phase spectra of dangerous factors of gas medium during the ignition of materials in the premises studying on [30, 31]. Revealing the peculiarities of average bicoherence of frequencies in the spectra of dangerous parameters of the gas environment during fire and a method for assessing the reliability of fire detection in premises done on [32, 33]. Comparison of bicoherence on the ensemble of realizations and a selective evaluation of the bispectrum of the dynamics of dangerous parameters of the gas medium during fire is being considered in [34]. Empirical cumulative distributions function of the characteristic sign of the gas environment during fire done on [35]. Assessment of improvement of ecological safety of power plants by arranging the system of pollutant neutralization and development of the method for encoding service data in crypto compression image representation systems done on [36, 37].

Thus, the dynamics of fire development in a leaky room has peculiarities depending on a number of parameters, which are unknown in advance and change significantly in time at the initial phase of fire development. The most important of them are the rate of energy release by the hearth (ignition material), the presence, as well as the physical and chemical properties of the combustion material. In this regard, the aim of the present work is to experimentally study the combustion features of typical materials in an unsealed room. This will allow a deeper study of the complex mechanism of fire initiation at the initial phase of fire occurrence in order to use the features of combustion of materials for early fire detection.

2 Main Part

The essence of combustion is the heating of a combustible material by an ignition source until it begins to decompose. When the combustible material decomposes, it emits carbon and hydrogen vapors which, combining with oxygen in the combustion reaction, form carbon dioxide, water and generate a lot of heat. In addition, carbon monoxide is formed as a product of incomplete combustion of carbon (the main poisonous substance called carbon monoxide) and smoke.

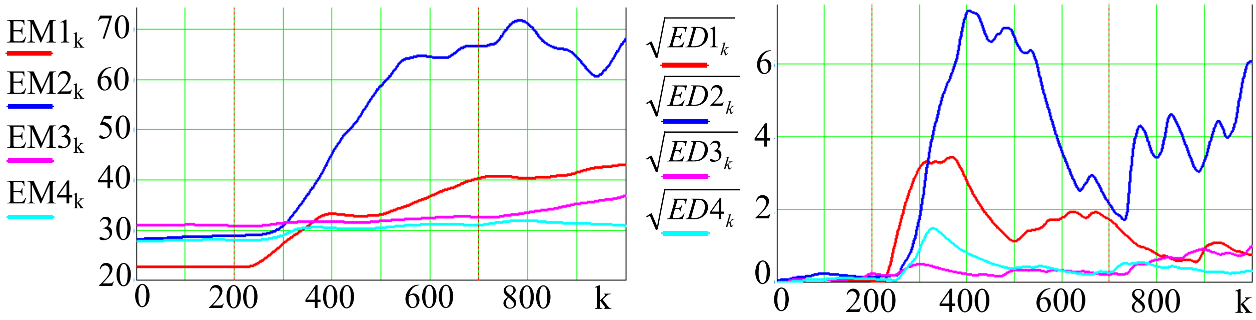
The experimental study of material combustion is based on the fact that any material ignition in a room generates both changes in the physical parameters of the material itself and in the gas environment of the room. At the initial stage, a convective flow occurs above the ignition source of the material, carrying combustion products and heat to the ceiling of the room. As a consequence of this transfer, the parameters of the environment below the ceiling change. Usually, the transfer of excess enthalpy to the ceiling of the room leads to an increase in temperature and turbulence of the gas medium in the ceiling region. Therefore, the features of ignition of materials in the room can be studied on the basis of changes in the parameters of the gas medium in the ceiling region. However, it is difficult to theoretically study the features of indoor material ignition based on the changes in the turbulence characteristics of the gas medium in the ceiling region. For this reason, the study of the peculiarities of material ignition in the room is carried out experimentally. For this purpose, an experimental laboratory chamber simulating a non-hermetic room of reduced size was created. The external view of the experimental chamber is shown in Fig. 1. The chamber has dimensions of 1500 cm x 1000 cm x 500 cm. In the ceiling area of the chamber above the focus of ignition of the material were placed measuring sensors of temperature, smoke density and carbon monoxide concentration. Such placement of measuring sensors in the chamber allowed studying the peculiarities of combustion of materials in the area of jet flow of heat and gases from the hearth of ignition in the ceiling area [38]. It is the features of the beginning of combustion of materials in the room that turns out to be poorly studied, but practically important for preventing a fire with losses. The TPT-4 sensor (Ukraine) [39], the IPD-3.2 sensor (Ukraine) [40], and the Discovery sensor (Switzerland) [41] were used as a sensor to measure the temperature of the gas medium, to measure the smoke density, and to measure the concentration of carbon monoxide.

Fig. 1. External view of the experimental chamber and combustion center

Materials of the study. The study materials included the output signals of sensors measuring temperature, smoke density and carbon monoxide concentration of the gaseous medium in the experimental chamber when test materials were ignited. The first material to be studied was alcohol (burnout rate 33.0 kg m^{-2} s^{-1} 10^3, lower heat of combustion 13400 kJ kg^{-1}). The second material was crumpled paper (burn rate 8.0 kg m^{-2} s-1 10^3, lower heat of combustion 27200 kJ kg^{-1}). The third material was wood chips (burn rate 14.0 kg m^{-2} s^{-1} 10^3, net calorific value 13800 kJ kg^{-1}). The fourth material was textile in the form of a staple fiber fragment (burnout rate 6.7 kg m^{-2} s^{-1} 10^3, lower heat of combustion 13800 kJ kg^{-1}). The source of forced ignition of the above selected combustible materials in the chamber was a lighter. The area of the ignition hearth for all investigated materials was chosen to be the same (circular) and amounted to approximately 38 cm^2. The height of the flame from the base of the combustion hearth for the investigated materials was approximately 20–30 cm. Analysis of the results of measurements obtained by sensors indicates that the dynamics of temperature, smoke density and carbon monoxide concentration in the gas medium of the chamber during combustion of the considered types of materials is non-stationary and has signs of trend and random fluctuations.

Research methods. Time-continuous measurements of temperature, smoke density and carbon monoxide concentration of the gas environment, obtained at the output of the corresponding sensors, were subjected to temporal discretization with an interval of 0.1 seconds. Discrete measurements of each of the studied parameters of the gas environment were stored in a personal computer (PC) for their subsequent thematic processing. For thematic study of the trend features and random fluctuations of temperature, smoke density and carbon monoxide concentration of the gas environment in the absence and presence of burning materials, the corresponding discrete measurements were subjected to preliminary exponential filtering with a fixed smoothing parameter equal to 0.02. Such a value of the smoothing parameter ensured representativeness of the current estimates of both the trend and fluctuations of the studied changes in temperature, smoke density and carbon monoxide concentration over the entire observation interval defined by 100 seconds. Forced ignition of all materials was carried out approximately at the interval of 20 – 30 seconds after the beginning of measurements of gas environment parameters.

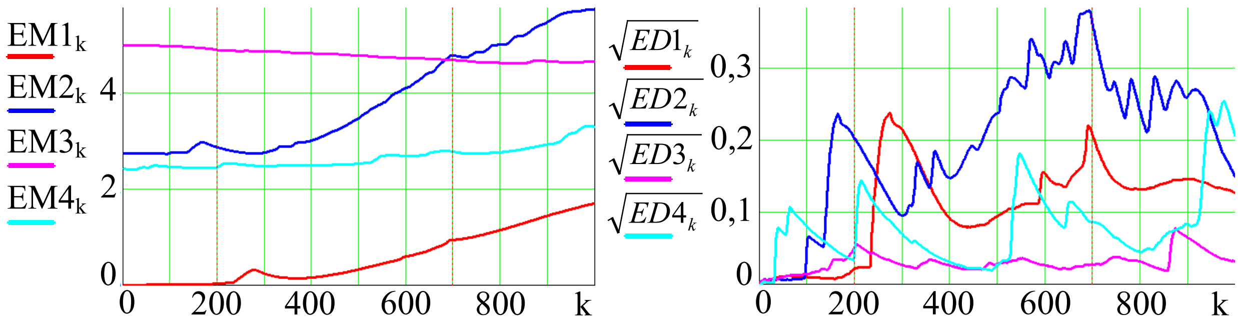
The results of the study. The results of the study of the trend and fluctuations (mean square deviation – MSD) of the gas medium temperature in the chamber over the whole observation interval for 4 types of the tested ignition materials ($EM1_к$ and $\sqrt{ED1_k}$ – alcohol, $EM2_к$ and $\sqrt{ED2_k}$ – paper, $EM3_к$ and $\sqrt{ED3_k}$ – wood chips, $EM4_к$ and $\sqrt{ED4_k}$ – textile) are presented in Fig. 2, where k is the number of the current discrete measurement.



a) b)

Fig. 2. Peculiarities of gas medium temperature dynamics in the chamber: a – trend; b – MSD

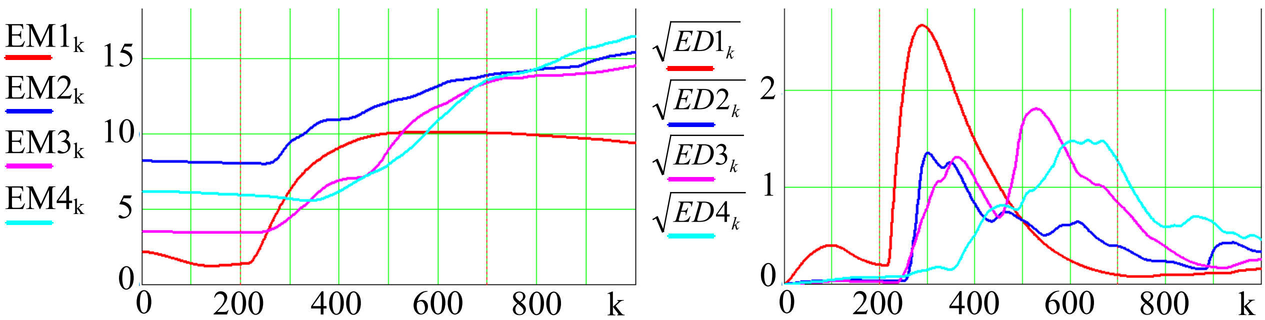
Similar results of the study of the features of the trend dynamics and MSD of the smoke density of the gas medium in the chamber over the entire observation interval for 4 types of the tested ignition materials are presented in Fig. 3.



a) b)

Fig. 3. Peculiarities of the dynamics of the smoke density of the gaseous medium in the chamber: a – trend; b – MSD

The results of the study of the features of the trend dynamics and MSD of the carbon monoxide concentration of the gas medium in the chamber over the entire observation interval for the 4 types of ignition materials tested are presented in Fig. 4.



a) b)

Fig. 4. Features of the dynamics of carbon monoxide concentration of gaseous medium in the chamber: a – trend; b – MSD

From the analysis of the results presented in Fig. 2 – Fig. 4, it follows that the dynamics of temperature, smoke density and carbon monoxide concentration in the absence and presence of ignition of materials in a leaky chamber is random and non-stationary. In this case, the experimental study of the peculiarities of combustion of materials allows us to take into account the complex and unknown mechanism of mutual influence of temperature, smoke density and carbon monoxide concentration of the gas medium at the micro and macro level. It is not possible to develop mathematical models that take into account such mutual influence due to its complexity. The boundaries of the interval characteristic of ignition of materials in Fig. 2 – Fig. 4, are indicated by vertical dashed lines corresponding to 200 and 700 readings.

In this case, the dynamics of the trend of temperature, smoke density and carbon monoxide concentration during the ignition of materials is smoother compared to the dynamics of MSD. Taking into account that MSD characterizes the dispersion of current values relative to the trend, it can be argued that the increase of MSD of temperature, smoke density and carbon monoxide concentration is caused by the violation of stability of their dynamics. Therefore, an important practical feature of material ignition is the violation of the initial stability of dynamics of temperature, smoke density and carbon monoxide concentration in the presence of ignition of materials.

3 Conclusion

As a result of the experimental study of combustion peculiarities of alcohol, paper, wood and textiles in the laboratory chamber it is shown that different chemically different materials burn differently. Combustion of chemically complex liquid and solid combustible materials (alcohol, paper, wood and textiles) proceeds in two stages: 1) decomposition, the processes of which are not accompanied by flame and light emission; 2) combustion proper, characterized by the presence of flame or smoldering. This confirms that complex materials do not burn themselves, but the products of their decomposition do. In this case, a feature of combustion of chemically complex materials is the formation of carbon monoxide flames and smoke. Flames are formed by luminous gases, vapors and solids, in which both stages of combustion take place. Smoke is a complex mixture of combustion products containing solid particles. It is confirmed that the tested materials, depending on their composition, complete or incomplete combustion, emit different amounts of heat, carbon monoxide and smoke. It has been experimentally established that at ignition of alcohol, paper, wood and textile the dynamics of temperature, smoke density and concentration of gas medium in the ceiling area of the chamber as a whole has a complex and non-stationary character. At the same time, the beginning of combustion of tested materials is characterized by the signs of appearance of growth trend and increase of fluctuations of temperature, smoke density and gas medium concentration. These signs, unlike mathematical models (if they can be obtained at all), are representative and take into account complex invisible mechanisms of interaction between combustion and gas medium, both at molecular and macroscopic levels. For this reason, the obtained results and attributes can be used for current detection of material ignitions in order to prevent indoor fires based on the use of traditional fire sensors.

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