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STUDY OF THE INFLUENCE OF GAS EXCHANGE ON THE EFFICIENCY OF FIRE EXTINGUISHING USING CARBON DIOXIDE

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The purpose of the research of this work is to study the effectiveness of extinguishing a fire using carbon dioxide, taking into account changes in gas exchange. An analysis of the use of neutral gases in automatic fire extinguishing systems, which provide a three-dimensional method of extinguishing. The analysis shows that the rate of elimination of combustion will depend on the gas exchange in the room, ie the number and location of vents, doors, windows, etc. To study the effect of gas exchange on the efficiency and rate of cessation of combustion, an installation was developed, the camera of which simulates a real room and a computer model of the same room for simulation. The created installation allows to apply qualities of a phlegmatizer – carbon dioxide, nitrogen, argon, etc. The structural components of the installation are substantiated so that the phlegmatizer enters the combustion chamber from the pressure chamber, which is equipped with two openings: the first for removal of combustion products from the chamber, the second for input of phlegmatizer and two openings that simulate ventilation and inlet passage. in the cell. The amount of phlegmatizer supplied to the combustion chamber is regulated by a reducer. A thermocouple is built into the chamber to control the temperature in the combustion zone. A computer model of a combustion chamber similar to a full-scale experiment has been created. A computational experiment was performed. A full-scale experiment was conducted. It is established that the effect of open ventilation ducts on the rate of cessation of combustion is most significant at low inert gas flow rates. The relative deviation of the results of mathematical modeling from the experimental data is calculated. The results of the study show the effectiveness of modeling of thermal processes for further studies of the effect of gas exchange on the rate of fire extinguishing in closed volumes.

Key words: *fire extinguishing, inert gases, fire extinguishing substances, computer simulation.*

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Introduction. In Ukraine, as always, the problem of fighting fires and their consequences is acute. According to the results of the analysis of fires and their consequences in Ukraine in 2020 trends that indicate an increase in the number of fires and material losses from them, people injured in fires compared to 2018 are revealed. Substances, which are conventionally called fire extinguishers are used to fight fires.

Traditionally, all substances used to stop burning are conventionally divided into 4 types (H. I. Yelahin et al., 2020; V.O. Duniushkin et al., 2011; V.O. Borovykov et al., 2000; A.V. Antonov et al., 2001; V.O. Borovykov et al., 2001; A.V. Antonov et al., 2003; T.Ie. Kisil et al., 2003; A.V. Antonov et al., 2006; N. M. Koziar et al., 2007; A. I. Turchyn et al., 2008; A.V. Antonov et al., 2010; A.V. Antonov, 2012; A.V. Antonov, 2013; A.V. Antonov et al., 2007):

– those that dilute substances in the combustion reaction zone are mainly neutral gases: nitrogen (N_2), carbon dioxide (CO_2), water vapor (H_2O), helium (He), argon (Ar) and some others;

– those that cool the reaction zone or combustible substances are mainly water, powder, sand and others;

– those that insulate substances (combustibles or oxidants) from the combustion zone are sand, fire-extinguishing powders, foam (air-mechanical, chemical);

– those that inhibit the combustion reaction (chemical active inhibitors) are some types of chemical powders and liquids that contain chemical elements of group 7 of the periodic table, – halides such as carbon tetrachloride (CCl_4), methylene bromide (CH_2Br_2), ethyl bromine (C) , tetrafluorodibromoethane ($C2Br_2F_4$) and many others.

At first glance, such a conditional division is almost unquestionable. The conditionality and relativity of such a division, that the extinguishing agent acts on the process of cessation of combustion by a combination of its physical and chemical properties, is described in many works (A.V. Antonov, 2017; A. G. Tropinov et al., 1990, A.V. Antonov, 1993; A.V. Antonov, 1995; A.V. Antonov et al., 2000; A.V. Antonov et al., 2001; Yu. B. Tsapko, 2002; D. M. Derevynskyi et al., 2004; A.V. Antonov et al., 2005; V. M. Balaniuk et al., 2006; B. B. Kovalyshyn et al., 2013; A.V. Antonov, 2013; V. O. Duniushkin et al., 2014; S. Ohurtsov, 2014; Y. Cai et al., 2015; J. G. Gatsonides et al., 2015; M. Trevits et al., 2010; Ju. V. Capko et al., 2001; DSTU 3958: 2000). For example, neutral gases, when introduced into the combustion zone, dilute the molecules of combustible substance and oxidant; their collision becomes less probable, the oxidation reaction slows down, the combustion intensity decreases, the heat release is weaker, and at a certain concentration of inert gas it stops altogether. As a result, the burning stops and the fire goes out.

It is known from the physics of combustion and explosion that when the volume concentration of oxygen in the combustion zone decreases less than 14%, kinetic (and diffusion) combustion stop. But if it is only a matter of mechanically diluting the molecules of the combustible substance with the oxidant, then it seems that it does not matter what to dilute with – nitrogen, carbon dioxide, helium, water vapor and so on. However, studies (I. M. Abduragimov, 2012) have shown that this is not the case. And the efficiency of extinguishing fires with inert gases is significantly affected by their thermophysical properties.

The dependence of the required concentration of different inhibitors and phlegmatizers for methane dilution is shown in work (I. M. Abduragimov, 2012) (Fig. 1). The figure shows that the most effective are inhibitors (halogenated hydrocarbons) and phlegmatizers (carbon dioxide and water vapor).

However, neutral gases are mainly used in automatic fire extinguishing systems, which provide a three-dimensional method of extinguishing. It is clear that the rate of fire elimination will depend on the gas exchange in the room, ie the number and location of vents, unlocked doors, windows and so on. Research in this direction, both in Ukraine and in the world is almost not conducted, so the purpose of this work is relevant.

Materials and Methods. The basics of the theory of diffusion flame extinguishing are presented in particular in the work (V.O. Dunjujushkin et al., 2014). It is proved that the cessation of combustion in a gas diffusion flare occurs when at the moment of supply of extinguishing agent the rate of chemical reaction in the flame front localized in the stoichiometric composition circuit becomes insufficient for chemical conversion at given fuel and oxidant velocities. The phlegmatizer can be supplied with both oxidizer and fuel.

There are many works devoted to the determination of the minimum fire-extinguishing concentration (limiting concentrations of phlegmatizer for supply to the oxidant zone) (see, (Y.Cai et al., 2015; J. G. Gatsonides et al., 2015; M. Trevits et al., 2010; Ju.V.Capko et al., 2001). In works (Y.Cai et al., 2015; J. G.Gatsonides et al., 2015; M.Trevits et al., 2010; Ju. V. Capko et al., 2001) the effect of synergism when applied to the oxidant zone by phlegmatizers of different chemical nature (for example, chemically inert and those with inhibitory action) was revealed. Based on the use of synergistic effects, new highly effective fire extinguishing compositions have been proposed (M. Trevits et al., 2010). The influence of agents of different chemical nature on the extinguishing of the diffusion flame during their supply together with the oxidant was studied in (M. Trevits et al., 2010; Ju.V.Capko et al., 2001). Thus chemical mechanisms of suppression of combustion of hydrocarbons by means of fluorinated agents are revealed.

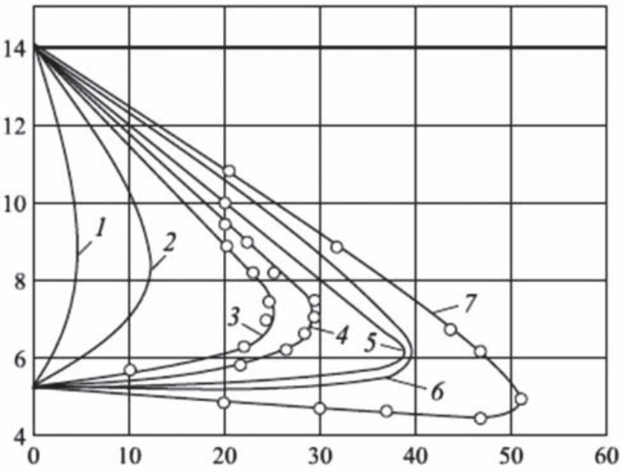


Fig. 1. Dependence of methane concentration in the mixture on the phlegmatizer content in the atmosphere: 1, 2 – halogenated hydrocarbon type $C_2Br_2F_4$; 3 – carbon dioxide CO_2; 4 – water vapor H_2O; 5 – nitrogen N_2; 6 – helium He; 7 – argon Ar.

At the same time, the analysis of literature sources in which the extinguishing of the flame diffusion torch by feeding the phlegmatizer together with the fuel was studied (G. E. Golinevich et al., 1991). One of the first works in this direction is the work (G. E. Golinevich et al., 1991), which investigated the concentration limits of diffusion combustion of the mixture H_2 + He in the air. Along with this, the study of the conditions of stabilization of diffusion flares of mixtures of hydrogen and methane with various inert solvents should be noted (Golinevich, G.E. et al., 1991).

To study the effect of gas exchange on the efficiency and rate of combustion cessation, an installation was developed (Fig. 2), the chamber of which simulates a real room and a computer model (Fig. 3) of the same room for simulation.

The closest analogue to the technical essence of the device is a gas fire extinguishing system (O.A.Derevianko et al., 2018), which contains a cylinder with a gas extinguishing agent, shut-off valves, pipelines and outlets. However, this installation does not provide for the possibility of regulating the flow of extinguishing agent and changing the number of open armholes.

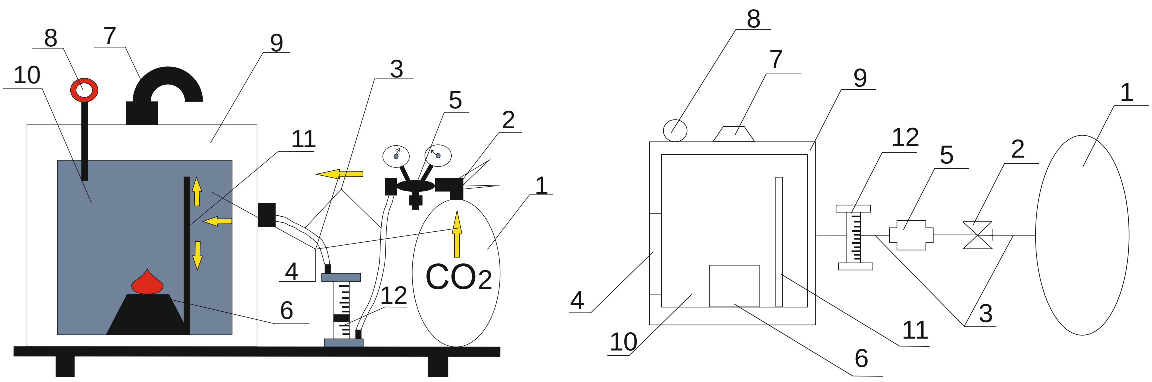
Results. The installation (Fig. 2) works according to the following scheme. From the pressurized tank the phlegmatizer comes to the combustion chamber (simulation room), equipped with two (working) holes: the first to remove combustion products from the chamber, the second to enter the phlegmatizer and two holes that simulate ventilation and inlet and allow to change gas exchange in the chamber. The amount of phlegmatizer supplied to the combustion chamber is regulated by a reducer. A thermocouple is built into the chamber to control the temperature in the combustion zone.

When introducing a neutral gas into the combustion zone, in addition to reducing the concentration of the components of the combustible mixture, there is also a loss of heat for heating this diluent from the initial temperature to the temperature of the combustion zone. The installation allows to use as a phlegmatizer – carbon dioxide, nitrogen, argon, etc..

During our research (Fig. 4), carbon dioxide was chosen as the phlegmatizer (CO_2). A paraffin candle was chosen as the source of combustion. The experiment was conducted in two modes: 1 – all armholes are open, 2 – all armholes are closed. The temperature change was recorded using a DT-838 multimeter complete with thermocouples. During the research, the time from the beginning of the supply of carbon dioxide to the combustion zone to the cessation of combustion was recorded. To correlate the results, 2 experiments were performed.

The study was conducted at carbon dioxide feed rates of 60, 80 and 100 l / min.

The results of the research are presented in the graph (Fig. 5). They show that the cessation of combustion with closed vents (gas exchange mode № 1) occurs faster than with open vents (gas exchange mode № 2). So at a feed rate of carbon dioxin equal to 40 l / min it happens 4 s faster, which is more than 40% faster; at a carbon dioxide feed rate of 60 l / min this happens 3.5 s faster, which is more than 35% faster; at a carbon dioxide feed rate of 80 l / min this is 3.3 s faster, which is more than 35% faster; at a carbon dioxide feed rate of 100 l / min 1.9 s, which is more than 25% faster.



а б

Fig. 2. Installation for the study of cessation of combustion by phlegmatization (a); constructive scheme of installation (b):
1 – container with phlegmatizer under pressure; 2 – the valve; 3 – flexible pipeline; 4 – an opening for air inflow with a latch, 5 – a reducer; 6 – combustible substance; 7 – hole for removal of combustion products; 8 – temperature sensor; 9 – isolated camera; 10 – heat-resistant glass; 11 – screen; 12 -rotameter.

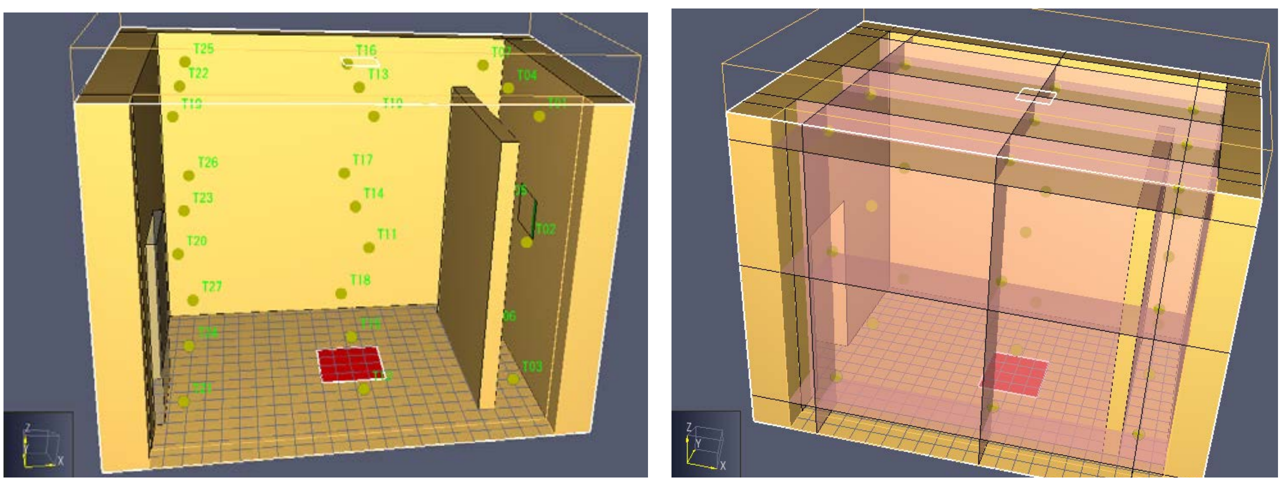


Fig. 3. The view of the model of the simulation room, which was used for the computational experiment (yellow dots show the places of calculation of temperatures)

Fig. 4. Conducting experimental studies to determine the effect of gas exchange on the rate of extinguishing a fire with carbon dioxide

From this we can conclude that the effect of open ventilation ducts (window doors) on the rate of cessation of combustion is most significant at low inert gas flow rates. And also that increasing the speed of flow rate of phlegmatizers in a burning zone extinguishing time decreases.

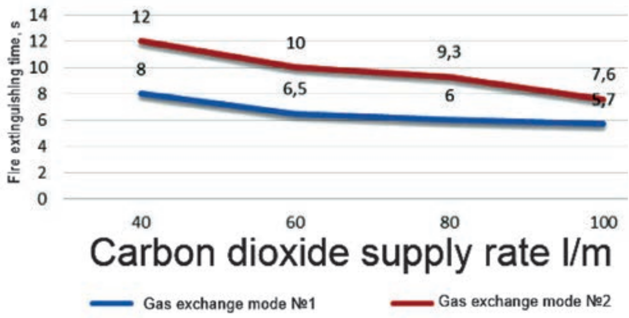


Fig. 5. Graph of the dependence of time (from the moment of the beginning of supply of carbon dioxide to the cessation of combustion) on the mode of gas exchange and the rate of supply of extinguishing agent

To conduct a computational experiment using the created mathematical model of the model room (Fig. 3) for testing the following sequence of calculation procedures was used.

1. With the help of CAD program the geometric configuration of the model room of the necessary sizes is created. Inside, models of partitions, openings for the exit of combustion products and places of air support are created. The geometric model is imported into the environment of the FDS calculation complex.

2. The initial parameters of modeling are entered, as it is impossible to change in the course of calculation: initial temperature of the environment, support of air on the one hand, necessary time of burning, etc..

3. The combustion process is initiated in the middle part of the room. For this purpose the fire center is modeled.

4. During the calculation, the temperature of the respective points in the room and the temperature gradient are monitored online.

In order to control the temperature regime by means of the computer complex FDS 27 places of its control were created (yellow dots of fig. 3).

After completion of the computational experiment, temperature data were obtained at each control point for verification.

Discussion. In fig. 6, 7 there are graphs of the average temperature in the middle of the model room during the computational experiment.

As a result of calculations of cessation of combustion in the model room with closed vents with a carbon dioxide supply rate of 40, 60, 80 and 100 l / min. we obtained the following time intervals for cessation of combustion – 8.2; 6.7; 6.3 and 5.8 seconds.

As a result of calculations of combustion cessation in the model room with open vents with a carbon dioxide supply rate of 40, 60, 80 and 100 l / min. we obtained the following time intervals for cessation of combustion – 12.4; 10.3; 9.6 and 7.8 seconds.

Analyzing the comparison of the results of mathematical modeling of the heat transfer process (Fig. 7) in case of fire in the model room and experimental data, it can be stated that the relative deviation averages 5.6%, which shows the efficiency of modeling thermal processes for further studies of gas exchange on fire extinguishing rate in closed volumes.

Conclusions. This work investigates the effect of gas exchange on the efficiency of extinguishing fires with carbon dioxin by conducting experimental studies on a specially designed installation and by computational experiment using the software package CFD Fire Dynamics Simulator 6.2. The efficiency of modeling of thermal processes for further research of the influence of gas exchange on the rate of extinguishing fires in closed volumes is proved. To achieve this goal, the following tasks were performed:

1. A mathematical model of the model room, similar to the full-scale experiment was created. A computational experiment was performed. A full-scale experiment was conducted.

2. It is established that the influence of open ventilation ducts (window doors) on the rate of cessation of combustion

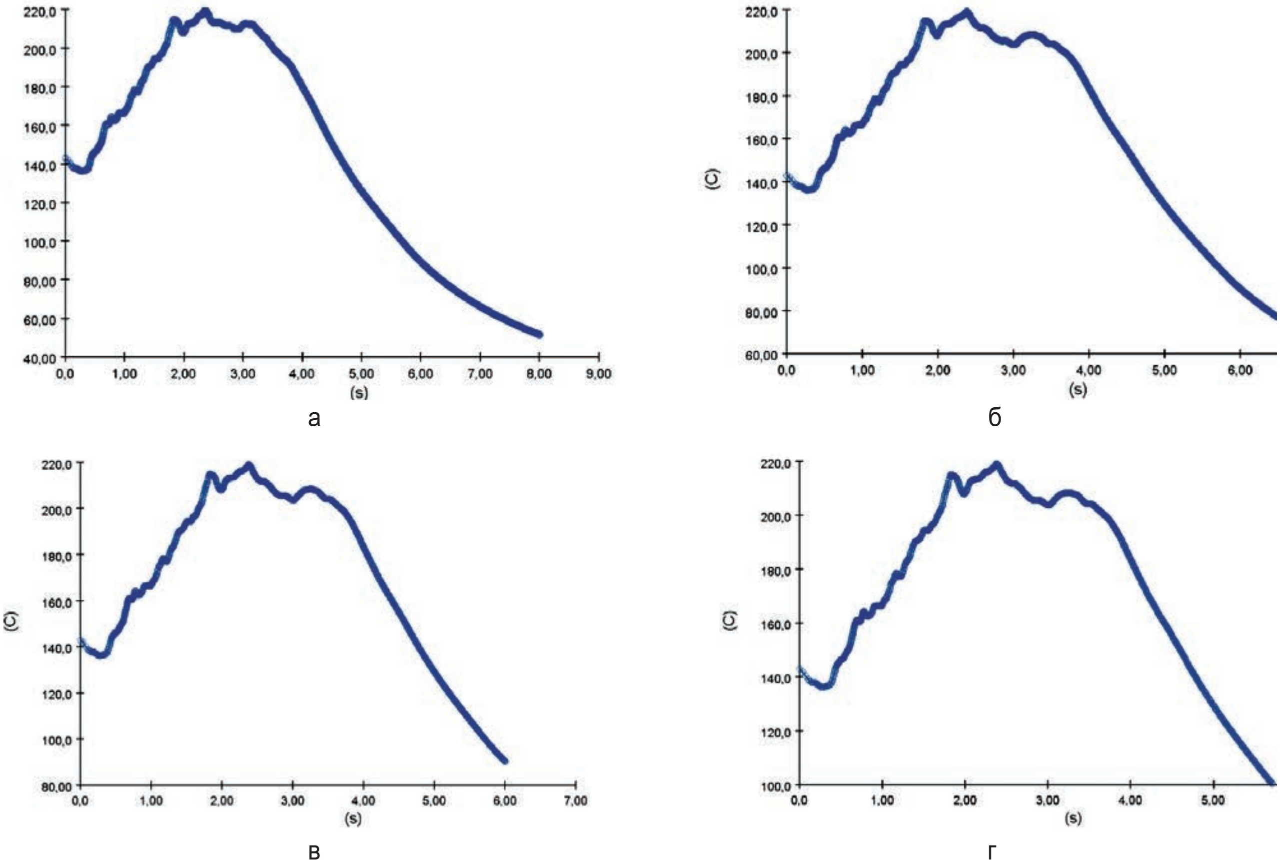


Fig. 6. Change of average temperature in a model room at the closed ventilating apertures and various speeds of supply of carbon dioxide (а – 40 l / min., б – 60 l / min., в – 80 l / min., г – 100 l / min)

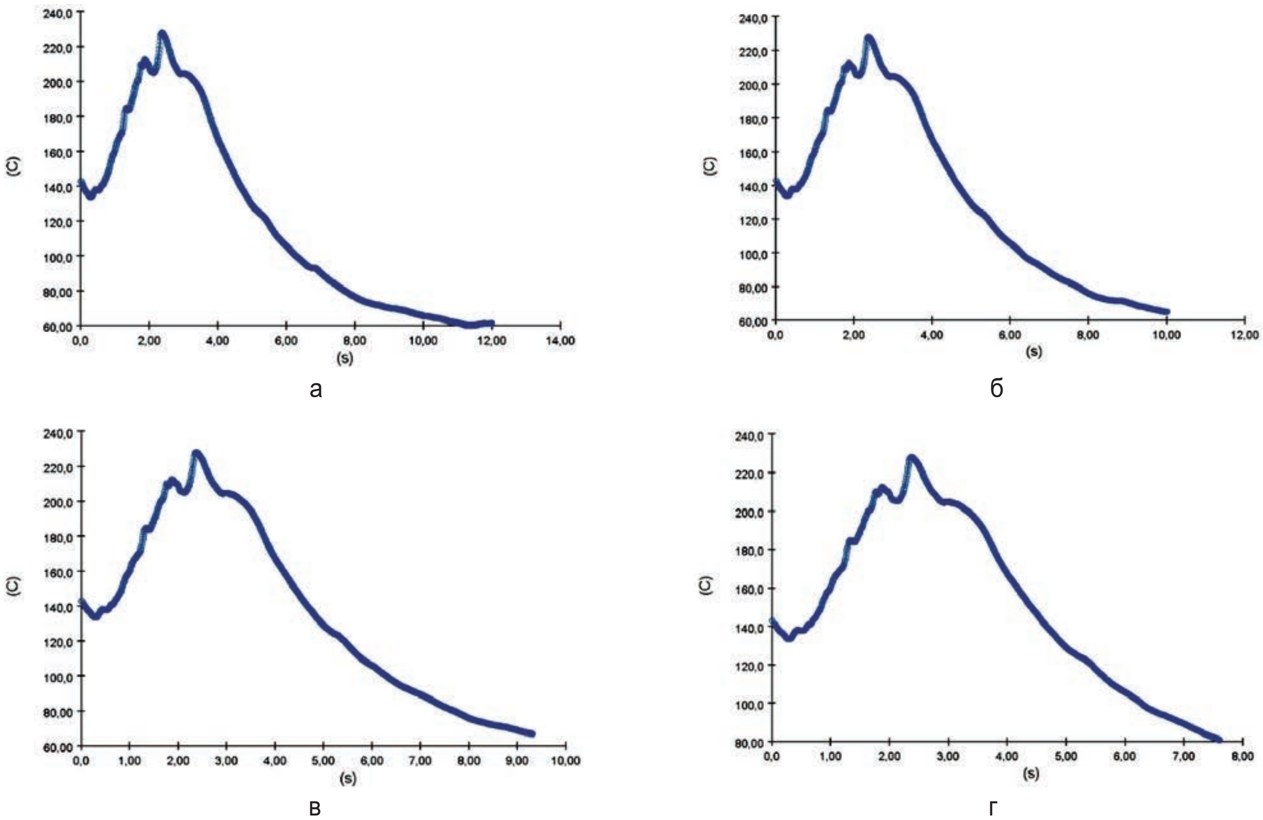


Fig. 7. Change of average temperature in a model room at open ventilating apertures and various speeds of supply of carbon dioxide (а – 40 l / min., б – yu 60 l / min., в – 80 l / min., г – 100 l / min)

is most significant at low velocities of inert gases. It is also established that with increasing speed of phlegmatizers entering the combustion zone, the extinguishing time decreases and the cessation of combustion with closed vents occurs faster than with open vents. So at a feed rate of carbon dioxin equal to 40 l / min it happens 4 s faster, which is more than 40% faster; at a carbon dioxide feed rate of 60 l / min this happens 3.5 s faster, which is more than 35% faster; at a carbon dioxide feed rate of 80 l / min this is 3.3 s faster, which is more than 35% faster; at a carbon dioxide feed rate of 100 l / min 1.9 s, which is more than 25% faster.

3. The relative deviation of the results of mathematical modeling from the experimental data, which is 5.6%, is calculated.

4. The results of the study show the effectiveness of modeling of thermal processes for further studies of the effect of gas exchange on the rate of fire extinguishing in closed volumes.

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Дослідження впливу газобміну на ефективність гасіння пожеж діоксидом вуглецю

Метою дослідження є вивчення ефективності гасіння пожежі діоксидом вуглецю з урахуванням зміни газообміну. Проведено аналіз застосування нейтральних газів у системах автоматичного пожежогасіння, що передбачають об'ємний спосіб гасіння. Під час аналізу встановлено, що швидкість ліквідації горіння залежатиме від газообміну у приміщенні, тобто від кількості та місць розташування вентиляційних отворів, дверей, вікон тощо. Задля дослідження впливу газообміну на ефективність і швидкість припинення горіння розроблено установку, камера якої імітує реальне приміщення і його комп'ютерну модель для проведення моделювання. Створена установка дозволяє застосовувати як флегматизатор діоксид вуглецю, азот, аргон тощо. Обґрунтовано структурні компоненти установки таким чином, що із ємності під тиском надходить флегматизатор до камери для спалювання, обладнаної двома отворами: перший отвір служить для відведення продуктів горіння із камери, другий – для введення флегматизатора через два отвори, які імітують вентиляцію і вхідний прохід, дозволяючи змінювати газообмін у камері. Кількість флегматизатора, що подається до камери спалювання, регулюється редуктором. У камеру вмонтовано термопару для контролю температури у зоні горіння. Створено комп'ютерну модель камери для спалювання, аналогічну натурному експерименту. Комп'ютерну модель приміщення із заданими геометричними конфігураціями і розмірами створено за допомогою CAD-програми. Усередині також було створено моделі перегородок, отвору для виходу продуктів згоряння і місця підпору повітря. Геометричну модель імпортовано у середовище розрахункового комплексу FDS для подальшого проведення обчислювального експерименту. Проведено обчислювальний експеримент. Із метою відслідковування зміни температурного режиму під час обчислювального експерименту засобами комп'ютерного комплексу FDS створено 27 місць її контролю. Після завершення обчислювального експерименту отримано показники температури за кожним місцем контролю для проведення верифікації. Проведено натурний експеримент. Установлено, що вплив, який чинять відкриті вентиляційні канали на швидкість припинення горіння, є найсуттєвішим за низьких швидкостей подачі інертних газів. Розраховано відносне відхилення результатів математичного моделювання від експериментальних показників. Результати проведеного дослідження свідчать про ефективність моделювання теплових процесів під час подальшого вивчення впливу газообміну на швидкість гасіння пожеж у закритих об'ємах.

***Ключові слова:** пожежогасіння, інертні гази, вогнегасні речовини, комп'ютерне моделювання.*

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