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SUMMARY OF THE DOCTORAL THESIS

Fires extinguishing management that occurs in enclosed spaces by streamlining water jets

Managementul stingerii incendiilor în spații închise prin eficientizarea jeturilor de apă

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Abstract

The thesis „Fires extinguishing management that occurs in enclosed spaces by streamlining water jets” is an applied research aimed at identifying parameters that favorably influence the extinguishing of fires that occur in confined spaces, following water discharge using different techniques. In particular, this paper investigates water discharge using the letters technique „T”, „Z” and „O”, compared to other discharge techniques, both in terms of water distribution analysis, as well as in terms of its influence on extinguishing fires.

The main objectives of the thesis are:

(i) The development of experimental procedures for water discharge in the absence, respectively in the presence of combustion:

- ✓ *manually - using the letters technique „T”, „Z”, „O” and maintaining the nozzle fixed, inclined at an angle of 45° to the horizontal plane, the conical angle of the jet taking, in turn, the value of 30°, respectively 45°;*
- ✓ *automatically – using the fixed sprinkler and water mist installation;*

(ii) Performing numerical simulations on free combustion of four wood cribs to quantify the influence of natural ventilation on the variation in temperature recorded in a room over time;

(iii) Performing experimental water discharge tests, in the absence of combustion, inside a room, manually, using a fire nozzle, and automatically, using the fixed sprinkler and water mist installation, to know how water will act through its fire extinguishing mechanisms; seven scenarios will be used in this regard;

(iv) Performing experimental water discharge tests, in the presence of combustion, in a room manually, using a fire nozzle, and automatically, using the fixed sprinkler and water mist installation, to identify parameters that significantly influence the extinguishing of a fire in an enclosed space; seven scenarios will be used in this regard.

The first chapter represents an introduction to the topic of the thesis and presents the current stage of knowledge in the field, both experimentally and numerically, of extinguishing fires using different water discharge techniques, as it appears from the literature.

In chapter 2 of the thesis are presented the main characteristics of the fires in enclosed spaces, the mechanisms of the fire extinguishing water, the energy balance of a fire compartment, the fundamental parameters underlying the efficiency of the extinguishing process, basic methods of extinguishing fires using water, the concept of fire control, as well as the analysis of the results obtained from a numerical simulation using the

PyroSim program, compared to experimental tests performed on a natural scale of a wood crib free burning.

Chapter 3 describes the mathematical equations that underlie the processes of burning and extinguishing fires within the FDS program.

Chapter 4 of the thesis presents the following: the experimental stand, the intervention device, the equipment used for the measurement and their accuracy classes. Test procedures within a room are also described in: (a) analysis of water distribution following discharge in the absence of combustion; (b) free burning of four wood cribs; (c) extinguishing four wood cribs. Procedures for analyzing water distribution and extinguishing involve the use of seven scenarios (S1 – S7), following manual water discharge, using the fire nozzle (water discharging using the letter technique „T" (S1), „Z" (S2) and „O" (S3) and water discharge by maintaining a fixed and inclined fire nozzle at 45 °, conical jet angle taking in turn the values of 30 ° (S4) and 45 ° (S5)), and automatically, using fixed sprinkler installations (S6) and water mist (S7).

Chapter 5 presents the pyrolysis models used in the PyroSim program and the numerical simulation of the free burning of four wood cribs.

Chapter 6 interprets the results by: (A) analysis of water distribution inside the test room, in the absence of combustion, within the seven water discharge scenarios (S1 – S7); (B) free combustion of four wood cribs; (C) comparative analysis between experimental test and free burning simulation of four wood cribs; (D) extinction after manually water discharging, using the fire nozzle (S1 – S5), and automatically, using fixed sprinkler installations (S6) and water mist (S7) of four burning wood cribs.

Thus, it is found that the efficiency of extinguishing the fire is obtained following the reduction of the temperature inside the fire compartment, of the water discharged volume, of the time necessary for the fire control, as well as reducing the heat released rate per unit area. The main parameters that influence the extinction efficiency process are: the discharge direction of the water jet, the water flow, the density of the water distribution, the conical angle of the jet, the discharge technique used and the water discharge method in terms of continuity.

Chapter 7 presents the concept of fire control, which is the basis for the operational management of extinguishing fires indoors.

Chapter 8 ends the thesis by presenting the conclusions extracted from the analysis of the results obtained, of the original contributions brought by this paper, respectively the perspectives of subsequent research.

Keywords: *letters technique, experimental test, numerical simulation, fire control, extinction efficiency.*

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Chapter 1. INTRODUCTION

1.1. The context of this paper

The dynamics of the fires that manifest in residential buildings has undergone significant changes following the development of the building construction field, which led to: much faster fires spread, reducing the evacuation time of people, releasing large amounts of smoke and toxic gases, as well as rapid changes in the manifestation of the fire by the appearance of particularly dangerous phenomena such as flashover or backdraft [26].

Thus, there is a need for in-depth knowledge of the impact of different water discharge techniques on the dynamics of fires that are manifested in enclosed spaces both on the safety and health of firefighters, respectively, of the occupants of the building surprised by the fire, as well as on the resistance structure of the construction.

Water discharge maneuvering the nozzle in the form of „T ", „Z", „O" letters is a discharge technique studied both theoretically and practically. However, as regards practical studies, they were not carried out by discharging water on a fire, in order to analyze the influence of the use of the letters technique on the dynamics of the fire in an enclosed space. The „T", „Z", „O" letters technique was used in experimental tests performed on a natural scale for study, on the one hand, of the volume of air driven by the discharge water jet [42] and, on the other hand, in order to analyze the water distribution inside a testing room [43].

In this respect, the impact of the „T ", „Z", „O" letters technique use compared with other water discharge techniques of the dynamics of a fire that manifests itself in an enclosed space is an important subject of study that needs to be exploited.

1.2. Purpose and objectives of the paper

Doctoral thesis „Fires extinguishing management that occurs in enclosed spaces by streamlining water jets" is an applied research aimed at identifying parameters that favorably influence the extinguishing of fires that occur in enclosed spaces, following water discharge using different techniques. In particular, this paper investigates water discharge using the „T", „Z" and „O" letters technique, compared to other discharge techniques, both in terms of water distribution analysis, as well as in terms of its influence on extinguishing fires.

The aim of the paper is to identify the main parameters that significantly influence the efficiency of extinguishing a fire process that manifests itself in an enclosed space, comparatively analyzing the results obtained from water discharge using different techniques.

The main objectives of the thesis are:

(i) Development of experimental procedures for water discharge in the absence respectively in the presence of combustion:
   - ✓ manually - using the „T ", „Z", „O" letters technique and maintaining the nozzle fixed, inclined at an angle of 45° to the horizontal plane, the cone angle of the jet taking, in turn, the value of 30° respectively 45°;
   - ✓ automatically – using the fixed extinguishing system with sprinklers and water mist;

(ii) Performing numerical simulations on free combustion of four wood cribs to quantify the influence of natural ventilation on the variation in temperature recorded in a room over time;

(iii) Performing experimental water discharge tests, in the absence of combustion, in a room manually, using the nozzle, and automatically, using the fixed sprinkler and water mist installation, to know how water will act through its fire extinguishing mechanisms; in this regard seven scenarios will be used;

(iv) Performing experimental water discharge tests, in the presence of combustion, in a room manually, using the nozzle, and automatically, using the fixed sprinkler and water mist installation, to identify parameters that significantly influence the extinguishing of a fire in an enclosed space; in this regard seven scenarios will be used.

1.3. Organizing the thesis on chapters

The doctoral thesis is organized in 8 chapters and ends with the bibliography. The chapters are presented in a certain order for the purpose to highlight the evolution of the research carried out, starting from theoretical, experimental aspects, respectively numerical simulations and continuing with comparative analyzes of the obtained results.

Chapter 2. CURRENT STAGE OF THE FIELD KNOWLEDGE

2.1. The fire characteristics that manifest in enclosed spaces

Fires that occur in confined spaces are influenced by the type, quantity and arrangement of combustible materials, geometry and existence of the fire compartment ventilation respectively, by the ignition source. The type and arrangement of combustible materials influence the characteristics of the increase in fire, while the total amount of combustible materials and the characteristics of the ventilation influence the intensity and duration of the fire.

The phases of a fire, represented in Fig. 2.1., are: ignition, growth, generalized combustion and regression. If the flashover phenomenon occurs, the fire is characterized by the pre-flashover stage, which includes ignition and fire growth, respectively the post-flashover phase, which includes generalized combustion and regression [15].

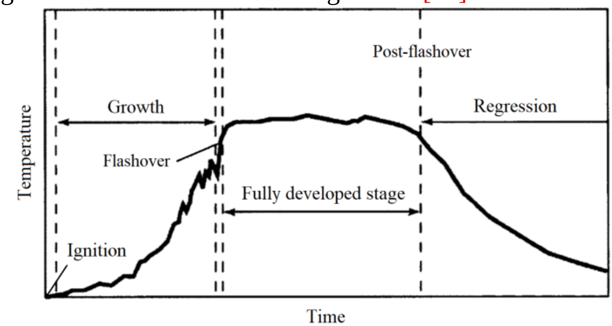


Fig. 2.1. The stages of fire development [15]

The main parameters that define the fire models, namely fires which are representative of those which may occur in a building and which are used to assess the performance of the building in terms of fire protection, are the heat release rate - HRR, the temperature recorded in the room and the toxic gas production rate [5]. The heat release rate of the fire represents the speed at which a fire releases thermal energy, being measured in J/s or W [14], being a parameter closely related to the fire load. Fire load is the total value of the heat flux that can be released by the complete combustion of all combustible materials inside a fire compartment and is measured in MJ, being an important input parameter in fire modeling [32].

2.2. The importance of water in streamlining the fire extinguishing process

Water is an important fire extinguishing agent [3]. Two of the most important physical properties of water are its ability to increase its volume by turning it into steam at 100 °C and the ability to absorb heat, being in both liquid and gaseous forms [12]. The unique properties of water are volumetric expansion and heat absorption capacity, which can be divided into three categories: specific water heat, latent vaporization heat, specific heat of water vapor. Depending on how the water is discharged, manually, using nozzles, respectively automatically, through fixed water mist and sprinkler extinguishing systems, water develops different fire extinguishing mechanisms [7]. Fire extinguishing water mechanisms using nozzles, according to Fig. 2.2., are: heat absorption, reduction of oxygen concentration, cooling effect / surface shielding, reduction of thermal radiation, blowing effect.

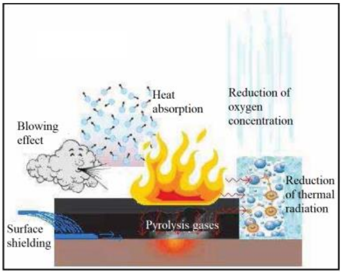


Fig. 2.2. Fire extinguishing water mechanisms using nozzles [19]

Fire extinguishing water mechanisms using the sprinkler system are: cooling effect and suppression effect.

Fire extinguishing water mechanisms using the water mist installation [1, 7, 17], fall into two categories: primary (absorption of heat released from flame and hot gases, burning materials and objects near the outbreak, reduction of oxygen concentration, thermal radiation blockage) and secondary (dilution of the mixture between air and vapor of burning combustible materials, respectively kinetic effects of the water mist on flames).

2.3. The energy balance of a fire compartment

Within a fire compartment, equipped with a door type opening, an energy balance takes place, as follows: in case of free burning of a wood crib, between the thermal energy released and the resulting heat losses; following water discharge, on the burning wood crib; following water discharge, in the upper layer of smoke and hot gases [38]. Most of the thermal energy released after burning the wood crib inside the compartment leads to the heating of the fire compartment edges, by radiative heat transfer and by convection, about 54% of the total amount of energy released being absorbed by its walls. Approximately 25% of the thermal energy is released by convection by door type ventilation opening of the fire compartment, about 16% of the total energy lead to heating the gases inside it, and about 5% of the total energy is dissipated by door type ventilation opening in the form of radiation [14].

2.4. The main parameters underlying the efficiency of the fire extinguishing process

Following the discharge of water over a fire, two efficiency coefficients are used to call the efficiency coefficient of heat absorption by water, k_w, respectively the efficiency coefficient of heat produced by a fire that manifests itself in a building, k_{foc}. The value of the efficiency coefficient of heat produced by a fire, k_{foc}, varies between 10% and 50% [2]. The recommended value of the coefficient k_w is 50%, for extinguishing a fire being sufficient an absorption included in the range of 30% - 60% of the total heat released [44]. The remaining 50% represents water losses caused by the protection of neighboring buildings, leaks, strong wind or discharge in order to cool the flue gases and hot surfaces [2].

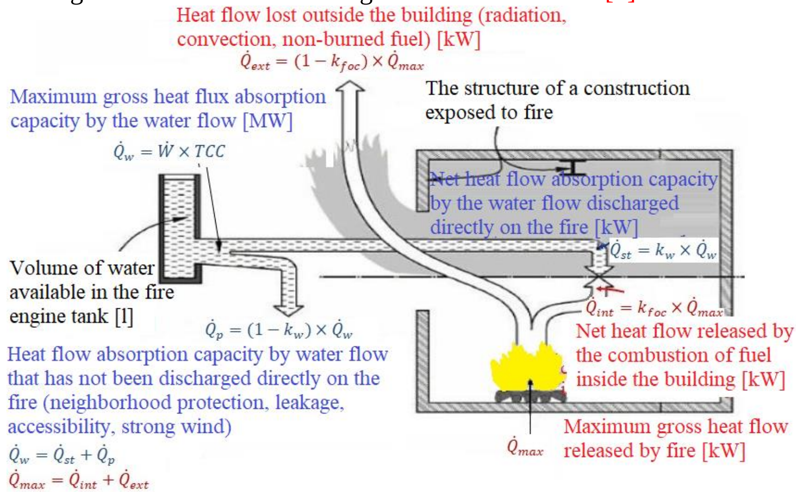


Fig. 2.3. Energy balance on the capacity of the water flow absorption of the heat flow and the capacity of the fire to produce the heat flow [2]

In Fig. 2.3. the energy balance is presented on the capacity of the water flow absorption of the heat flow and the capacity of the fire to produce the heat flow.

The main parameters underlying the fire extinguishing process are: flow and volume of water discharged (the mathematical methods for determining the two parameters have as common element the total fire load of the fire compartment), the size of water droplets (the smaller their diameter, the larger the total surface of the droplets that come into contact with the flames), the distribution density of the discharged water (influences the decrease of the time necessary to extinguish the fire), the water discharge pressure, the cone angle of the jet and the inclination of the water jet towards the horizontal plane.

2.5. Extinguishing methods using water discharge nozzles

There are several main methods used to extinguish fires that occur indoors, namely, the method of direct attack, the method of indirect attack, the method of combined attack, and a complementary method, „ 3D water fog ”, used for cooling the upper layer of smoke and hot gases. The method of direct attack consists in the discharge of water directly on the burning materials that burn, at the base of the outbreak, in order to cool them to the temperature at which the pyrolysis process no longer takes place, more precisely below the ignition temperature [20]. The method of indirect attack consists in the discharge of water on the door or window, from the outside of a room with temperatures above 537 °C at the ceiling [16]. The combined attack method consists of water discharge inside the fire compartment using the „T”, „Z”, „O”, „U inverted” letters technique. Thus, both the transformation of water into steam is carried out on its contact with the hot surfaces of the room, as well as the discharge of water on the burning materials, resulting in the cooling of the upper layer of smoke and hot gases, of surfaces and fire [20]. According to Fig. 2.4., using the letters technique, the starting point is from top to bottom. This technique is used for rooms with a floor area of up to 10 m^2, in the case of the „T” letter, 10-20 m^2, in the case of the „O” letter, respectively 20-30 m^2, in the case of the „Z” letter [4].

Fig. 2.4. Water discharge using the „T” [4], „Z”, „O” and „inverted U” [42] letters technique

The distribution of water discharged inside a room using the letters technique is influenced by the angle formed by the discharge nozzle and the horizontal plane. By discharging the water on the door, using the letter technique, in the middle of the ceiling, the water accumulated, especially in the middle of the room, in the plane away from the discharge position, maximum values being recorded near the diametrically opposite wall of the door. Discharging the water on the diametrically opposite wall by the door, according to Fig. 2.5., water accumulated in its immediate vicinity, the maximum values being recorded in the extremities of the wall.

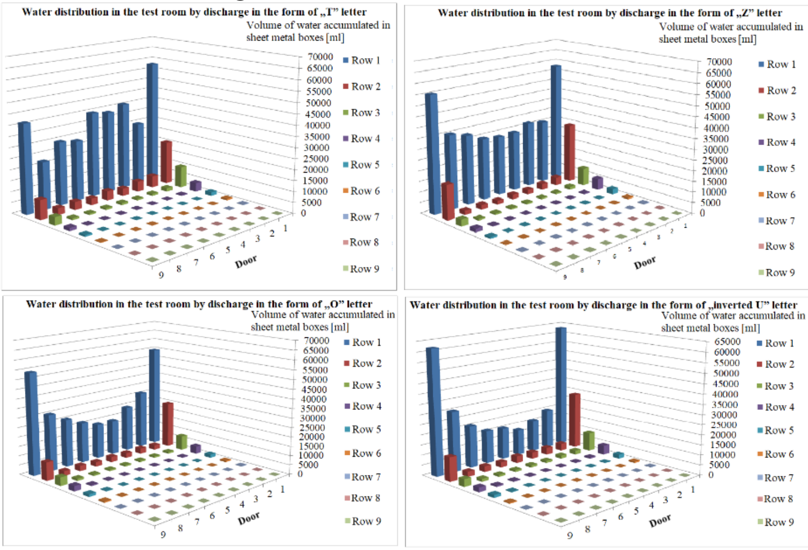


Fig. 2.5. Water distribution after discharge on the opposite diametrically wall [8]

The „3D water fog" method consists of discharging water into the smoke and hot gases in the form of short pulses, in order to increase the security and efficiency of firefighters, by creating the necessary conditions for their break-in and water discharge directly on the fire.

2.6. Fire control, a basic principle of fire extinguishing management in buildings

The operation of extinguishing a fire is based on two key factors, namely: the operational factor, which includes the initiation, coordination and application of intervention procedures, respectively the control factor, which implies the ability to meet the common goal of the firefighters at the site of intervention [39]. A vital condition for fire control is given by access to fire information. The central place in this aspect that characterizes the fire control is the human factor, represented by the intervention commander.

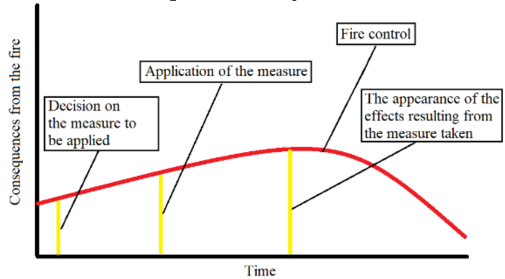


Fig. 2.6. The influence of the period between the decision-making and the effects of it on the consequences of a fire [40]

According to Fig. 2.6., there is a period of time between the time of the decision on the measures to be applied during the firefighting and the effects of these measures [40]. This period is directly proportional to the sum of the resulting consequences.

2.7. Mathematical models

Fires can be defined based on mathematical models, an example being the fire model „t^2", characterized by the evolution over time of the HRR parameter.

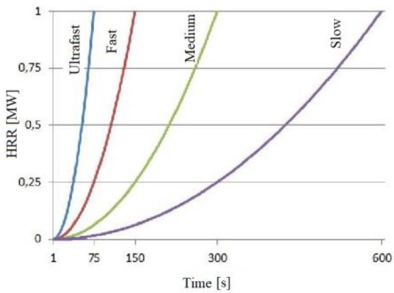


Fig. 2.7. Heat release rate for the fire model „**t^2**" [18]

According to Fig. 2.7., the fire growing (developement) can be classified [34], based on the equation „t^2", as ultra fast ($\propto_g$= 0.1874 kW/s^2, t_{1MW} = 75 s), fast ($\propto_g$= 0.0466 kW/s^2, t_{1MW} = 150 s), medium ($\propto_g$= 0.0117 kW/s^2, t_{1MW} = 300 s) and slow ($\propto_g$= 0.00293 kW/s^2, t_{1MW} = 600 s), $\propto_f$ representing the fire growth coefficient (kW/s^2), and t_{1MW}, the time measured from the moment of ignition until HRR reaches 1 MW.

If the fire compartment is naturally ventilated, a statistical, dimensionless correlation [28] has been developed, obtained from performing more than 100 experiments, based on the principle of energy conservation, to determine the temperature of the hot gas layer based on the HRR parameter

$$\Delta T_g = 6{,}85\left(\frac{\dot{Q}^2}{A_v\sqrt{h_v}A_T h_k}\right)^{\frac{1}{3}} \tag{2.1}$$

where

$\Delta T_g = T_g - T_{amb}$ represents the increase in the temperature of the flue gases in the upper layer located at the level of the ceiling[K];

T_{amb} - ambient air temperature [K];

$\dot{Q}$ - heat flow released by fire [kW];

A_v - ventilation opening area [m^2];

h_v - height of the opening [m];

h_k - the effective heat transfer coefficient [$\mathrm{kW/m^2K}$];

A_T - the total area of the compartment covering the edges of the surface, excluding the surface of the ventilation openings [m^2].

2.8. Results obtained by numerical simulation compared to experimental tests following free burning of a wood crib

Analyzing the results obtained from the numerical simulation compared to those obtained from the experimental combustion test of a pine wood crib, in a test room provided with the open door, according to Fig. 2.8., the variation of the HRR parameter over time was validated, by obtaining the accepted value of the average error equal to 15% [30].

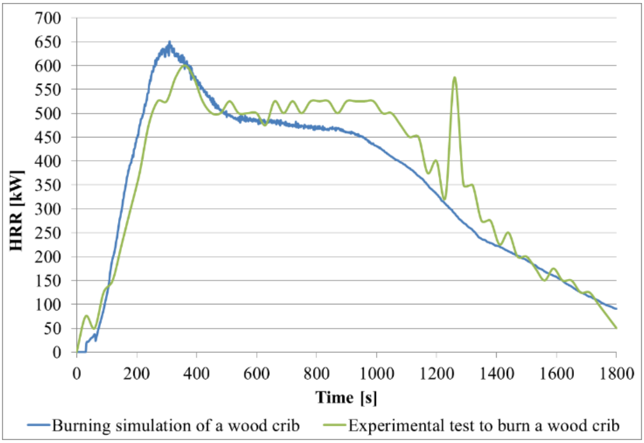


Fig. Error! No text of specified style in document.**.8.** Comparative analysis of HRR variation over time based on the results obtained in the experimental test and simulation using the PyroSim program to burn a wood crib [11]

Also, the variation in temperature recorded by thermocouples located at 2.80 m was validated, according to Fig. 2.9., and 2.40 m from the floor (arranged on the midline of the ventilation openings, respectively on the wall which is not provided with openings), the accepted values of the average error being less than or equal to 10 %.

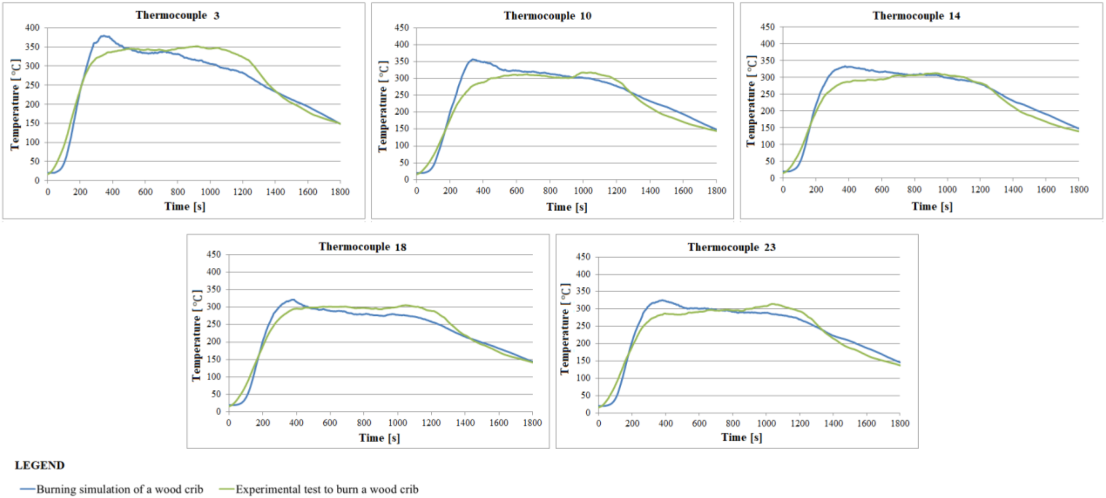


Fig. 2.9. Comparative analysis of the variation in temperature recorded by the thermocouples of layer 1, located at 2.80 m from the floor, based on the results obtained in the experimental test and the numerical simulation using the PyroSim program for burning a wood crib [9]

According to Fig. 2.9., the average value of the error was calculated, this being equal to 9.57% (Thermocouple 3), 10.41% (Thermocouple 10), 9.47% (Thermocouple 14), 9.67% (Thermocouple 23). Thus, the time variation of the temperature recorded by these thermocouples was validated because the value of the temperature error in the range of 0% and ± 10 % [30] is accepted for most experimental fire tests performed on a natural scale.

Chapter 3. MATEMATIC MODELING THEORETIC ELEMENTS

Fire Dynamics Simulator (FDS), the fire model based on Computational Fluid Dynamics, is an open source program, developed by the National Institute of Standards and Technology and the VTT Technical Research Center of Finland, widely used by a large number of fire safety engineers and professionals for fire simulation due to its unique characteristics.

The fire modeling program, FDS, is characterized by a series of equations and a general methodology for solving them, which is practical for simulations „of" thermally induced flows, as is the case with fires. The options of the FDS model were selected based on the results obtained from wide ranges of validation experiments [30].

The governing equations of Fire Dynamics Simulator are represented by: a) the gasodynamic model (the mass conservation equation, also called the continuity equation, the momentum conservation equation, the equation of state and the Poisson equation, the gas species conservation equation), b) heat transfer model (conduction, convection and radiation), c) pyrolysis model and d) combustion model based on the mixing of gas species.

3.1. Gasodynamic model

The FDS program numerically solves the Navier-Stokes equations, written in a form suitable for low-speed, thermally-driven flow, emphasizing the transport of heat and smoke from the fire. The central algorithm is an explicit predictor-corrector scheme, with a second-order accuracy in space and time. Turbulence is treated by means of Large Eddy Simulation (LES), being possible to perform a Direct Numerical Simulation (DNS) if the numerical mesh is fine enough. Consequently, the LES method is the main mode of operation.

The gasodynamic model is characterized by the fact that a series of mathematical sub-models are used in FDS, such as the turbulence model of Large Eddy Simulation, which was developed into a time-dependent three-dimensional flow pattern. The density is determined from the continuity equation, while the momentum equation and the state equation are used in determining the speed and temperature values [29].

The following are used in the gasodynamic model: the mass conservation equation, also called the continuity equation; momentum conservation equation; state equation; Poisson's equation; conservation equation of gas species.

3.2. Heat transfer model

The heat transfer model is represented by the use of mathematical equations characteristic of heat transfer by conduction, convection and radiation.

3.3. Pyrolysis model

In the case of pyrolysis reactions, Arrhenius equation [29] can be used

$$k_{reac} = A_{fpe} e^{\frac{-E}{RT}} \tag{3.1}$$

where

k_{reac} – reaction speed [s^{-1}];
A_{fpe} – the pre-exponential factor [s^{-1}];
E – activation energy [$kJmol^{-1}$];
R – universal gas constant [J/molK];
T – temperature [K].

Under the FDS program, the reaction speed model is based on a slightly different form of the Arrhenius function, characterized by an oxidation function that takes into account the local oxygen concentration.

3.4. Mixing-controlled combustion model

The FDS program uses a mixing-controlled chemical reaction, in a single-stage, characterized by three „lumped species" (so named because it represents a group of gas species) , namely air, fuel and combustion products. Under the mixing-controlled method, single-fuel gas species, containing primarily C, H, O and N, reacts with oxygen in a single stage controlled by the mixture to form H_2O, CO_2, soot and CO, the reaction between fuel and oxygen being considered infinitely rapid. The FDS program uses semi-empirical rules to determine the rate of oxygen-fuel mixing within a given cell network at a given time step. Each calculation cell can be considered as an area where only mixed compositions can react [29].

3.5. Mathematical model of extinguishing fires following water discharge within the FDS program

Under the FDS program, water droplets are represented using Lagrangian particles. The FDS program uses Lagrangian particles to represent three main categories, namely, massless tracking particles, water droplets and other elements. In the Lagrangian description, the position and physical properties of the particles are described according to the material or the reference and time coordinates. A particle is considered to be Lagrangian when it moves as if it were a fluid element. The movement of Lagrangian particles over a step of time is calculated using an analytical solution and remains stable regardless of the time step used by the flow solver. If the particles move along the width of several mesh cells in a single time step, the momentum transferred between particles and gases cannot be allocated accordingly to all cells involved. To prevent this problem, the FDS program divides the time step of the gas phase based on the speed of each particle. Thus, if the particle crosses two cells in one time step, then its trajectory is calculated by dividing the time step by two [29].

Regarding the distribution of the size of the discharged water droplets, the average volume diameter of the droplet is used, $D_{v;0,5}$. The cumulative volume distribution of the water jet is a combination of normal logarithmic distribution and Rosin-Rammler distribution [6].

To make the prediction of extinguishing the fire within the FDS program, there are two options based on the concept of critical flame temperature, namely extinguishing based mainly on oxygen concentration, and extinguishing based on both fuel and oxygen. The critical flame temperature is based, within the FDS program, on the limiting oxygen index (LOI), the oxygen volume fraction in the oxidant stream at the point of flame extinction. The criterion of extinguishing based on both fuel and oxygen presupposes that the combustion of a computing mesh cell, at a certain time step time, is suppressed, if the potential heat released by the reactants cannot raise the cell temperature above the empirical value of the critical flame temperature.

The absorption of thermal radiation by the discharged water droplets takes place following the conservation of energy and the transformation of thermal radiation into internal energy of water droplets.

Regarding the reduction of the pyrolysis production rate following water discharge, the suppression of the fire is found to be exponential in nature [29].

Chapter 4. EXPERIMENTAL TESTS

4.1. Experimental stand

Test room, presented in Fig. 4.1., is a construction that has the walls made of BCA, and the resistance pillars, floor and ceiling are made of concrete. It has two windows and a door.

Fig. 4.1. Test room

Having a simple structure and a combustion behavior close to the real development of the fire inside a compartment, the wood cribs were chosen as a source of ignition in the realization of this thesis. Wood cribs are also characterized by the fact that they have a high value of the exposed surface of the fuel material within their structure, and the cross-thermal radiation released by the baguettes of the wood cribs allows their combustion to be sustained in the absence of an external heat flux [33]. Considering that the test room destination is bedroom and knowing the value of the total heat released following a fire (following the product between the surface of the room floor, 16 m^2, and the mean fire load density for one bedroom, 780 MJ/m^2 [36]) and the total heat released from the combustion of a wood crib, it is found that, by equating the value of the fire load of a bedroom with pine wood cribs, 15.22 stacks are required. To reduce the costs of the large number of experimental tests that need to be performed, which will consist of both the free burning of the wood cribs, respectively their burning and then extinguishing with water, four wood cribs will be used for each experimental test. The four wood cribs represent approximately the equivalent of a quarter of the fire load density of a bedroom, 204.98 MJ/m^2. This value is also found in reality, in the case of rooms having the destination of the hospital room, being 230 MJ/m^2 [36].

According to Fig. 4.2., the four wood cribs are arranged in a row, at a distance of 0.32 m from the diametrically opposite wall of the door.

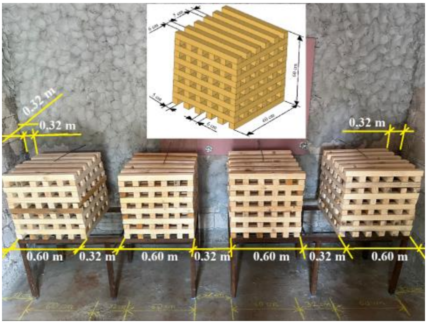


Fig. 4.2. Location of the 4 wood cribs that are the ignition source

The intervention device consists in the use of the 2-ton Volvo FLL 4x2 fire engine with water and foam, with a low-pressure step flow of 2000-2500 L/min at 8-10 bar and high pressure step flow of 200-250 L/min at 35-40 bar [27].

The water was discharged both manually, using the FlowMatic Compact nozzle (the discharge flow value range is 0 – 500 l/min at a pressure of 6 bar) and automatically, according to Fig. 4.3. a) and b), using the fixed sprinkler and water mist installation. Tyco type TY3251 sprinkler heads used are characterized by: activation temperature is equal to 68 °; the color of the liquid inside the bulb being red (the bulb was broken before the start of the experimental tests); the maximum operating pressure is 12.1 bar; K=5,6 $\frac{l}{min}/(bar)^{1/2}$ [45]. The discharge nozzles of the Tyco water mist type ULF AM29 Automatic have the following characteristics: the operating pressure takes values in the range of 7 - 12 bar; discharge coefficient K=8,5 $\frac{l}{min}/(bar)^{1/2}$ [46].

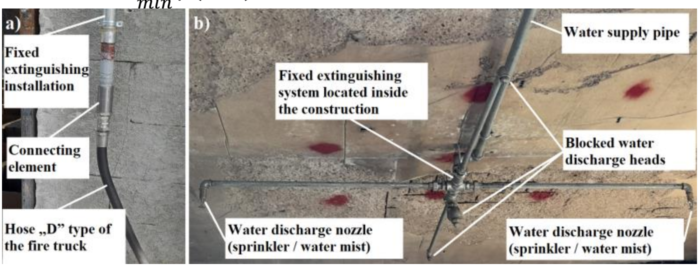


Fig. 4.3. Fixed extinguishing system located: a) outside the test room, perpendicular to the wall with the door; b) inside the test room, at the ceiling

In Fig. 4.4. the types of jets used in the experimental tests are presented: the jet is compact, the pipe being kept fixed, inclined at 45° from the horizontal plane (a), respectively the conical angle jet equal to 30° (b) and 45° (c).

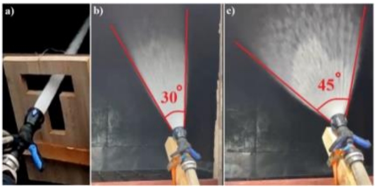


Fig. 4.4. Types of jets used in experimental tests

For water discharge by maintaining the fixed nozzle, inclined at 45° from the horizontal plane, according to Fig. 4.5., a wooden support, inclined at 45° from the ground surface, was used, the hose and discharge nozzle being provided by the wooden support by using two clamping straps.

Fig. 4.5. Device for fixed maintenance of the discharge nozzle inclined at 45 °

For water discharge using the „T", „Z", „O" letters technique, according to Fig. 4.6., 3 wooden models were made, following experimental water discharge tests [10].

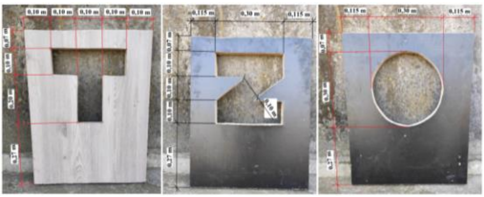


Fig. 4.6. The „T", „Z", „O" models by which water is discharged

The intervention device used for water discharge inside the test room using the discharge nozzle is made of: ***a fire engine with a capacity of 2000 l*** (the discharge pressure is 4 bar); ***a hose line type „C"*** (the inner diameter is equal to 52 mm and the length is equal to 20 m); ***flow meter; manometer; a hose type „C"*** (length is equal to 3 m); ***discharge nozzle***.

In the case of water discharge using the fixed sprinkler and water mist installation, the intervention device is made of: ***a fire engine with a capacity of 2000 l*** (the discharge pressure is 12 bar); ***a „D" type hose*** that supplies ***the fixed extinguishing system with sprinklers / water mist*** mounted at the level of the test room.

4.2. Measuring equipment

The recorded temperature collection system inside the test room consists of 55 thermocouples type K (0 - 1200 °C), with a length of 40 cm (47 pcs., T1 – T29, T38 – T55) and 180 cm (8 pcs., T30 – T37), data acquisition unit, (compensation cables connect thermocouples to the data acquisition unit) and a PC. The 55 thermocouples (T1 - T55) are arranged, according to Fig. 4.7., on 5 layers.

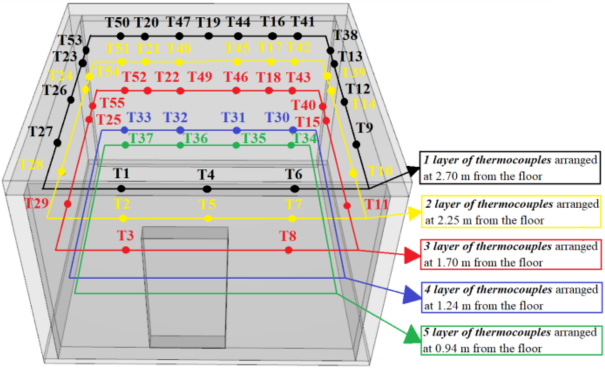


Fig. 4 Error! No text of specified style in document.**.7.** Layered arrangement of the 55 thermocouples inside the test room

In Fig. 4.8. the location of the thermocouples is presented.

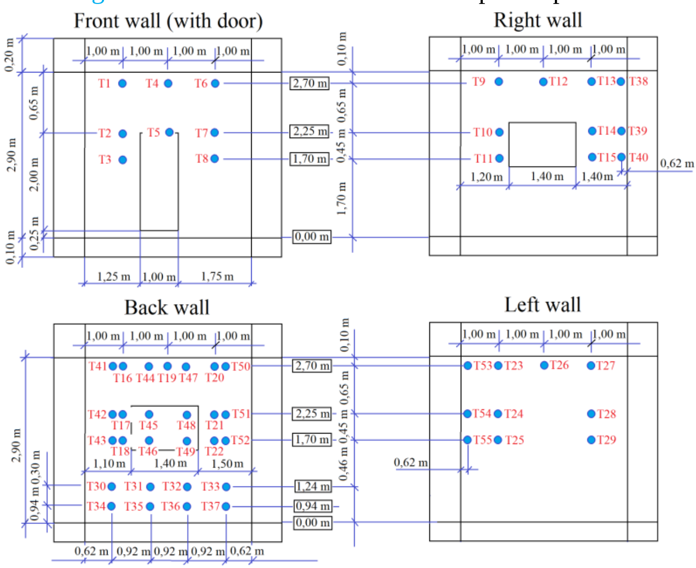


Fig. 4.8. Location of thermocouples – view from outside the test room

The 8 thermocouples with a length of 1.80 m are located in the center, respectively in the middle of the upper surface of the 4 stacks, and the rest of the thermocouples at a distance of 0.15 m from the surface of the wall on which they are arranged. The accuracy of the measurements is 10 %.

The SBG01 flow meter, presented in Fig. 4.9., is used for measuring the heat flux released both after free combustion and after extinguishing the 4 wood cribs during experimental tests, taking values in the range of 5 - 50 kW/m^2. It is placed on a tripod so that the sensor is arranged at the door level at the entrance to the test room, at a height of 1.50 m from the ground surface. The accuracy of the measurements is 2-3%.

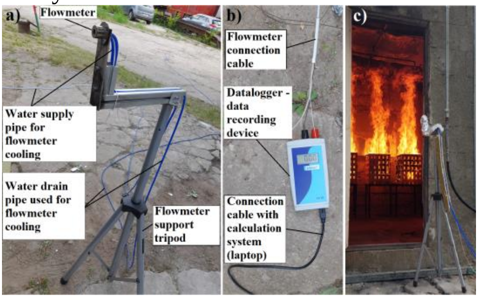


Fig. 4.9. The SBG01 type flow meter: a) Flowmeter; b) Datalogger; c) location mode.

The Flir T420 thermal imaging camera is used during experimental tests both in terms of free combustion and in terms of water extinguishing of the four wood cribs. It is located at a distance of 2 m from the test room, respectively at a height of 2 m from the ground. The main characteristics of the thermal imaging camera are: the recorded temperature range is -20 ... + 1200 ºC; the field of view (FOV) is narrower than 26º x 20º, which offers the possibility to see details at a distance; the resolution of the infrared detector is at least 320 x 240 physical pixels. The accuracy of the measurements is ± 2 ℃ or ± 2 % of the indication.

The Style 9301 AkroFlow electromagnetic flow meter is used to measure the flow and volume of water consumed, the measurement range being 38 – 2270 l/min. The accuracy of the measurements is ± 1 %.

The AKRON line manometer, type HLGK-25NST-16, ISO 9001 certified, is used to control the water discharge pressure, the measuring range being 0 – 1100 kPa.

In order to measure the volume of water accumulated in the test room, according to Fig. 4.10., a), were placed 81 sheet metal boxes (40 sheet metal box assemblies, equipped with two compartments, according to Fig. 4.10. b), and a sheet metal box, the dimensions of which are equal to those of a single compartment). Each sheet metal box has a maximum volume value equal to 64 l.

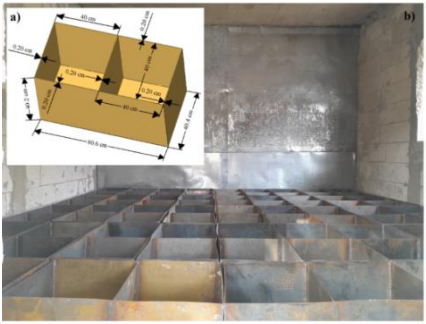


Fig. 4.10. Location of the 81 sheet metal boxes intended for accumulating discharged water: a) dimensions of a set of boxes; b) the location of the sheet metal boxes

4.3. Test procedure

The test procedure is drawn up for three categories of experimental tests, namely: (a) water distribution analysis; (b) free combustion; (c) fire extinguishing. In case of water distribution analysis and fire extinguishing, according to Fig. 4.11., seven scenarios are used: i) water discharge, in the middle of the ceiling, maneuvering the nozzle in the shape of letters „T” - S1, „Z” – S2 and „O” – S3, respectively maintaining the fixed discharge nozzle, inclined at 45° from the horizontal plane, the cone angle of the jet being equal to 30° - S4 and 45° - S5; use of fixed sprinkler installations – S6 and water mist - S7.

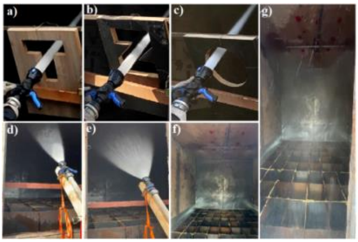


Fig. 4.11. Water discharge using: a) letter technique „T”; b) letter technique „Z”; c) letter technique „O”; d) discharge nozzle inclined at 45°, cone angle being equal to 30°; e) discharge nozzle inclined at 45°, cone angle being equal to 45°; f) sprinkler installation; g) water mist installation.

The test procedure involves:

(a) ***analysis of water distribution in the absence of combustion***, following water discharge manually, using the discharge nozzle, and automatically, using fixed sprinkler and water mist installations:

- the water was discharged by performing three experimental tests for each of the 7 scenarios;
- the duration of each experimental test was the discharge of a water volume equal to 640 l;
- in order to measure the volume of water accumulated in the test room, 81 sheet metal boxes were placed, each box having the volume value equal to 64 l;
- the water was extracted using two types of water pumps.

(b) ***free burning of four wood cribs:***

- the 4 wood cribs were located near the diametrically opposite wall of the test room door, at a height of 0.64 m from the floor; the distances between the wood cribs, between the wood cribs and the side walls, respectively between the wood cribs and the diametrically opposite wall of the door are equal to 0.32 m;
- each of the 4 wood cribs was lit with 2 l of ethanol; the fuel liquid was placed in sheet metal trays, arranged under each wood crib, centrally; the distance between the upper limit of the fuel tray and the lower surface of the wood crib is 0.10 m;
- fuel trays were removed 120 s after the ethanol was ignited;
- the duration of the experimental test was 1800 s.

(c) ***extinguishing four wood cribs that burn*** following water discharge manually, using discharge nozzle, and automatically, using fixed sprinkler and water mist installations, in 7 scenarios:

- the 4 wood cribs were located near the diametrically opposite wall of the test room door, at a height of 0.64 m from the floor; the distances between the wood cribs, between the wood cribs and the side walls, respectively between the wood cribs and the diametrically opposite wall of the door are equal to 0.32 m;
- each of the 4 wood cribs was lit with 2 l of ethanol; the fuel liquid was placed in sheet metal trays, arranged under each wood crib, centrally; the distance between the upper limit of the fuel tray and the lower surface of the wood crib is 0.10 m;
- fuel trays were removed 120 s after the ethanol was ignited;
- the initiation of the extinguishing process was made 600 s from the ignition;
- water was discharged in the 7 scenarios, S1 – S7;
- the duration of the experimental tests is equal to or less than 1800 s if, during the tests, at a height of 1.70 m, the temperature value is found to fall below 60 ℃; this is based on the fact that, in the performance-based model of fire safety engineering, the temperature recorded at a height of 1,80 m should be less than 60 ℃ [24, 31].

Chapter 5. ANALYSIS OF THE MODELING AND NUMERICAL SIMULATION COMBUSTION PROCESS

5.1. Pyrolysis models used in PyroSim

Within PyroSim, three methods defined by different pyrolysis models can be used to simulate the combustion of a wood crib: a) model of complex chemistry - the model of burning the wood crib behaving similarly to a real combustion; b) simple chemistry model – defines the HRRPUA of the wood crib, within the surface properties of each baguette in the wood crib structure; c) simple chemistry model – defines the HRR of the wood crib, this being considered a cubic object [13, 21]. The running time and accuracy of the simulation results are maximum when using the first method, respectively minimum when using the third method. Thus, within the thesis it was decided to use the second method.

5.2. Free burning simulation of four wood cribs

Using the PyroSim program, the free burning simulation of four wood cribs was performed, the duration of the simulation being 1800 s. The dimensions of the room are presented in Fig. 4.2., and the wood cribs have a cubic shape, the length of a side being equal to 0.60 m. The wood cribs consist of wooden baguettes arranged orthogonally, having a length of 0.60 m, and the cross-section, square, having a side equal to 0.05 m. According to Fig. 4.5., the distances between the wood cribs and between the wood cribs and the side walls of the room are equal to 0.32 m. The height at which the wood cribs are arranged in relation to the floor is equal to 0.64 m. The ventilation scenario used during the burning of the wood crib is represented by the opening of the room door, the surface of the ventilation opening being equal to 2 m^2, its height being equal to 2 m. Below each wood crib is placed a burner, the distance between the upper surface of the burners and the lower surface of the wood cribs being equal to 0.10 m.

The following parameters were used in the simulation: a) pine wood heat of combustion, its value equal to 17.66 MJ/kg, being obtained experimentally [23, 25]; b) HRRPUA of the wood crib, the maximum value of this parameter being 175 kW/m^2, this being obtained from the literature [22, 35, 41]; c) HRRPUA of the burner (ethanol), the maximum value of this parameter, equal to 535.60 kW/m^2, being obtained experimentally.

Chapter 6. DISCUSSIONS AND INTERPRETATION OF RESULTS

6.1. Water distribution analysis

Following the analysis of the water distribution inside the test room, in the absence of combustion, using the S1 – S7 scenarios, it is found that it is influenced by the following parameters: discharge direction, flow, water distribution density and the cone angle of the jet.

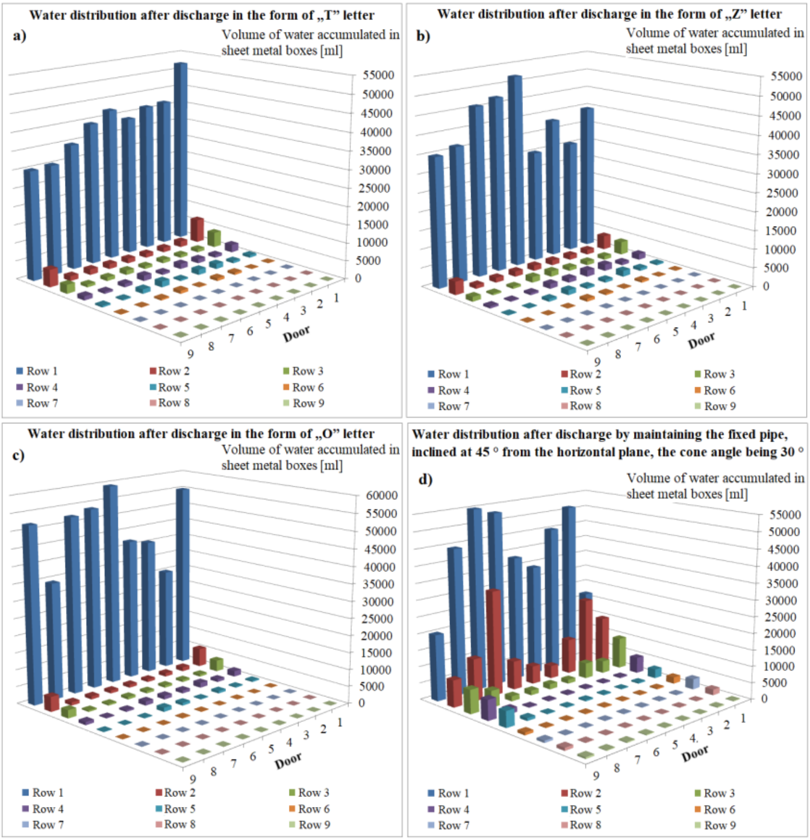


Fig. 6.1. Water distribution after discharge inside the test room at the door: a) using the „T” letter technique; b) using the „Z” letter technique; c) using the „O” letter technique; d) maintaining the fixed pipe, inclined at 45° from the horizontal plane, the cone angle of the jet having the value of 30°.

If the discharge direction of the water jet is perpendicular to the floor, according to the scenarios S1 (Fig. 6.1. a)) and S2 (Fig. 6.1. b)), the water was uniformly distributed over the entire surface of the test room. According to the S5 scenario (Fig. 6.2. e)), the water was distributed on about 3/4 of the total surface of the room, in a plane far from the discharge position, especially perimeter, along the walls parallel to the direction of discharge. Instead, discharging water from the door at a certain angle to the ceiling, according to scenarios S1 - S4 (Fig. 6.1. a)-d)), the water was distributed mainly near the diametrically opposite wall of the door, but also along the walls parallel to the direction of the jet, in the middle of the room located in a distant plane from the discharge position.

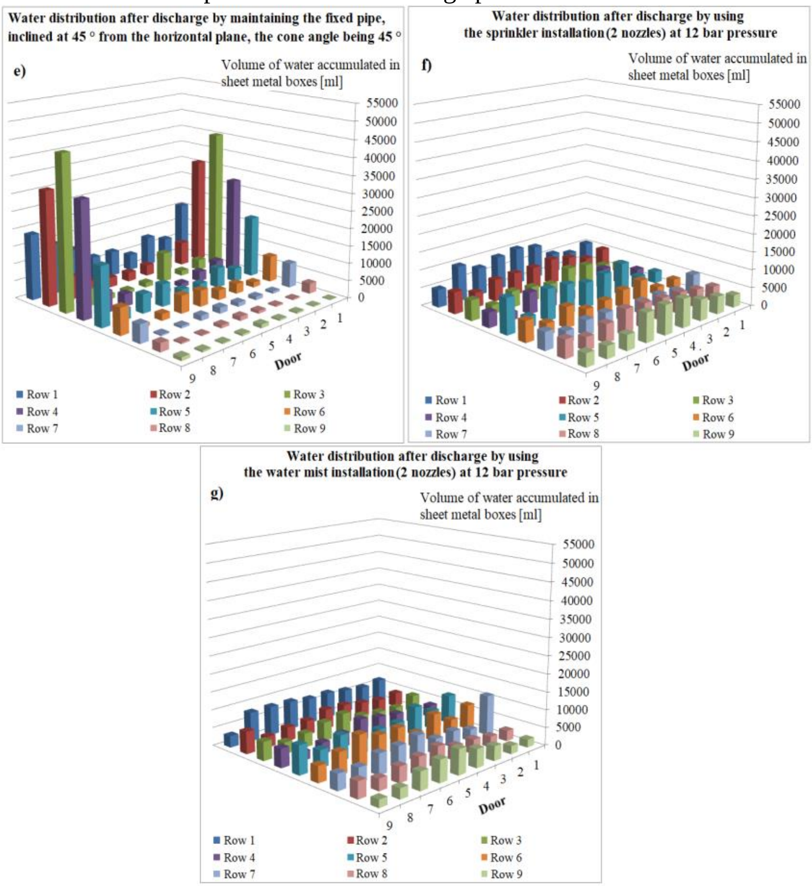


Fig. 6.2. Water distribution after water discharge inside the test room: e) keeping the pipe in front of the door, in a fixed position, inclined at 45° from the horizontal plane, the cone angle of the jet having a value of 45°; f) using the sprinkler installation; g) using the water mist installation.

Increasing the water distribution flow and density values leads to improved distribution of discharged water. Thus, at a pressure of 12 bar, the water distribution is better in the case of the S6 scenario (Fig. 6.2. f)) compared to S7 (Fig. 6.2. g)). In the case of water discharge at a pressure of 4 bar, the water is more evenly distributed in the S4 scenario (the flow rate being about 394 L/min, and the water distribution density 0.41 $(l/s)m^{-2}$)), compared to S1 scenarios – S4 (the flow rate being about 376 L/min, and the water distribution density 0.39 $(l/s)m^{-2}$).

Also, when using the discharge nozzle, an increase in the value of the cone angle of the jet in the case of scenario S5 (45 °) compared to S4 (30 °) and S1 - S3 (0 °) leads to a better water distribution.

6.2. Free burning of four wood cribs

Following the free burning of four wood cribs was analyzed the variation of the temperature in time, the snapshots made normally and in infrared, respectively the variation in time of HRRPUA.

Analyzing the variation of the temperature over time is found, according to Fig. 6.3., the fact that the increase in temperature values is directly proportional to the increase in the height of the test room both at the level of the inner perimeter area of the test room and at the level of the wood cribs, in the height range 1.70 m – 2.70 m.

According to Fig. 6.4., unlike these areas, in the middle of the upper surface of the wood cribs and in the center of the wood cribs, higher temperature values are recorded, the maximum values being obtained in their center.

The time to reach the maximum temperature average values recorded by thermocouples located at the same height is inversely proportional to the height of the room.

The maximum temperature values in the height ranges of 1.70 m - 2.70 m and 0.94 m - 1.24 m were recorded above, respectively at the level of the two centrally located wood cribs.

Because it was found that at a height of 2.70 m from the floor, the average temperature value suddenly increases to about 750 °C at 600 s from the ignition, there is a slow increase to about 850 °C at 1200 s from the ignition, it was established that the moment of initiating water discharge in the seven experimental tests should be 600 s from the lighting of the wood cribs.

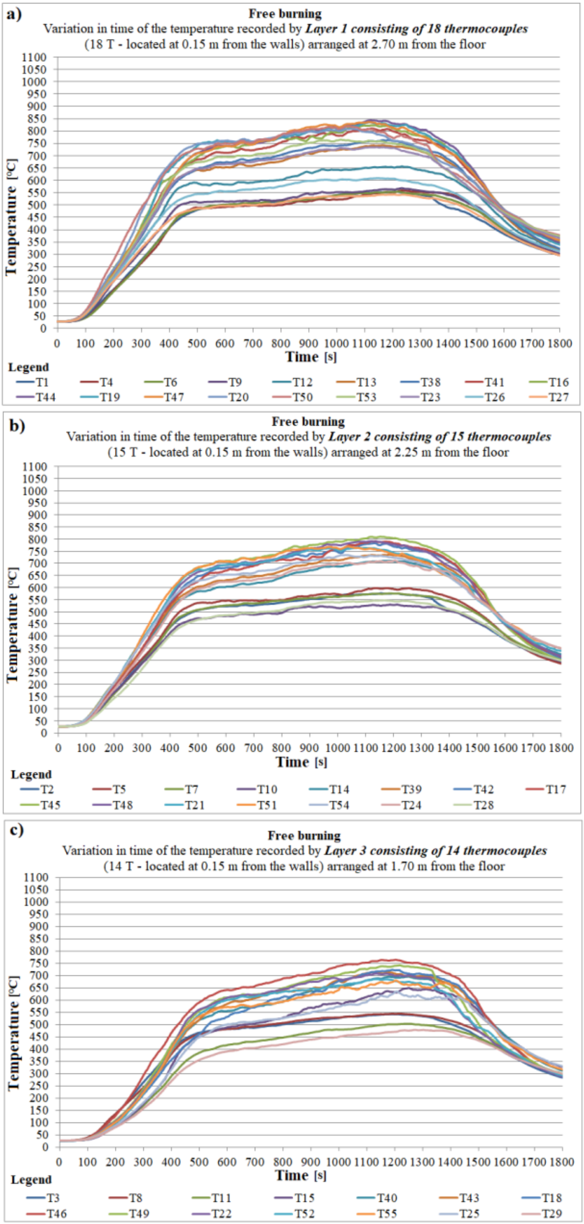
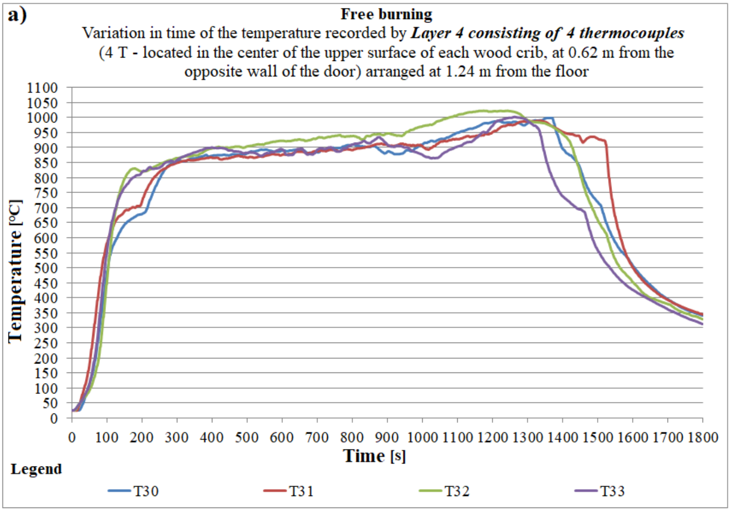


Fig. 6.3. Temperature values recorded by thermocouples arranged in layers, located perimeterly, inside the test room, compared to the floor at: a) layer 1 - 2.70 m; b) layer 2 – 2.25 m; c) layer 3 - 1.70 m.



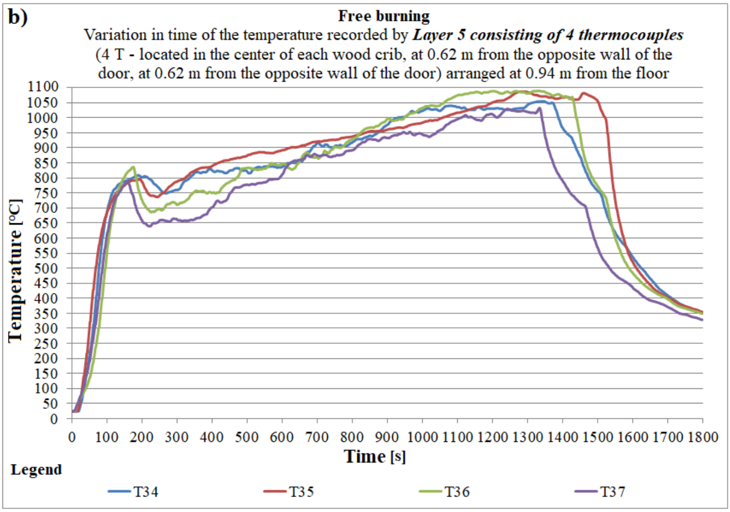


Fig. 6.4. Temperature values recorded by thermocouples arranged in layers, located in the stack area, relative to the floor, at: a) layer 4 – 1.24 m; b) layer 5 – 0.94 m.

As can be seen in Fig. 6.5., according to the snapshots made with the thermal imaging camera, both infrared and normal, within the time intervals in which the maximum temperature average values recorded by thermocouples arranged at the same height were recorded, corresponding to the height range 0.94 m – 2.70 m, it is found that the wood cribs did not collapse.

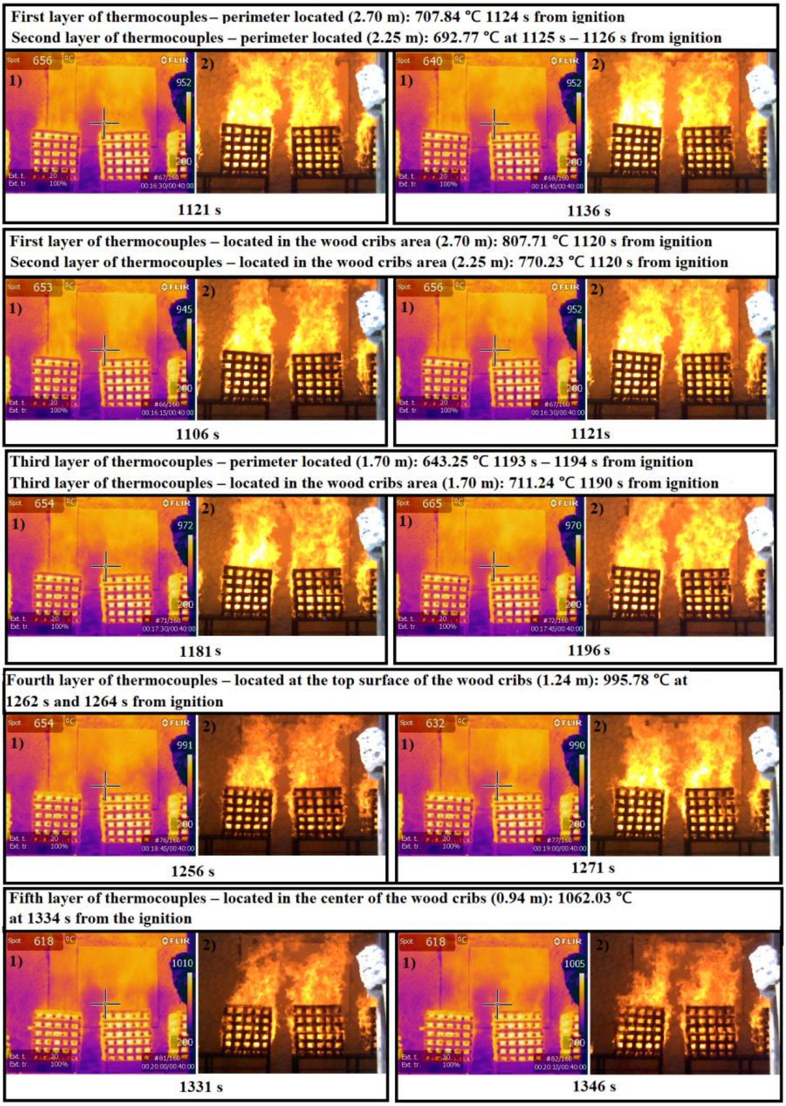


Fig. 6.5. Snapshots made when reaching the maximum temperature average values recorded by thermocouples on each layer: 1) infrared image; 2) normal image.

Analyzing the variation of the HRRPUA parameter over time, it is found that the maximum value of 16.55 kW/m^2 is recorded at 1466 s from the ignition, after reaching the maximum value of the average temperature in the center of the wood cribs, obtained at 1334 s from the ignition.

6.3. Comparative analysis between the experimental test and the free burning simulation of four wood cribs

According to Fig. 6.6., following the simulation of the free burning of four wood cribs using the PyroSim program, it is found that the shape of the temperature variation curve over time is similar to that obtained from the experimental test.

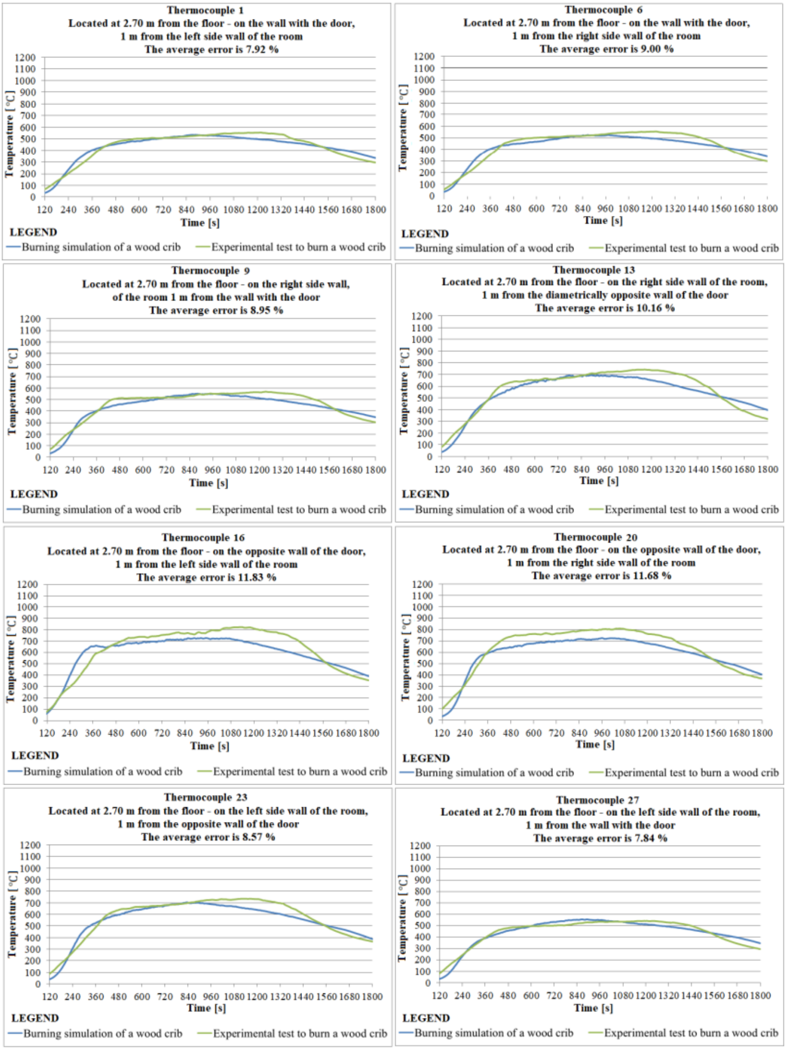


Fig. 6.6. Time variation of the temperature obtained from the experimental free combustion test of four wood cribs compared to the simulation using the PyroSim program

Following the comparative analysis between the experimental test and the free combustion simulation of four wood cribs, it is found that the average temperature error is less than or equal to 10% in the case of 24 thermocouples, the other 31 thermocouples having the average error values in the range of 11% - 30.09 %.

Thus, given that the SDS model overestimates the measured temperature value by 10% [30], only 24 thermocouples fall within the accepted values of the average error.

The analysis was performed for the time interval 121 s – 1800 s in which the wood cribs burned in the absence of ethanol trays. The time interval 0 s – 120 s, in which the stacks were pre-burned, namely the ethanol combustion, was not subjected to analysis.

6.4. Extinguishing with water manually, using the discharge nozzle, and automatically, using fixed sprinkler and water mist installations, of four burning wood cribs

In case of extinguishing with water manually, using the discharge nozzle (S1 – S5), and automatically, using fixed sprinkler installations (S6) and water mist (S7) of four burning wood cribs, it was found that the process of streamlining the extinguishing of fires in confined spaces consists in reducing the temperature of the fire compartment, the consumption of the discharged water, the time required to control the fire and the heat flow released by the fire per unit area taking into account the significant influence of parameters such as:

- the direction of discharge of the water jet;
- flow rate and density of the distribution of the discharged water;
- cone angle of the water jet;
- discharge technique;
- how to discharge water in terms of continuity.

Analyzing the efficiency of extinguishing fires based on the temperature reduction inside the fire compartment, the following are found:

➢ following water discharge, the situation of the temperature variation over time curve profile, on areas, at different heights, is as follows:

- ❖ both at the level of the test room, according to Fig. 6.7., as well as in the wood crib area, at 2.70 m, 2.25 m and 1.70 m from the floor, is similar in the case of S1 – S5 scenarios, respectively in the case of S6 - S7 scenarios; however, compared to S1 - S5 scenarios, in the case of S6 - S7 scenarios the temperature reduction is achieved in a longer time, especially in the case of S7;

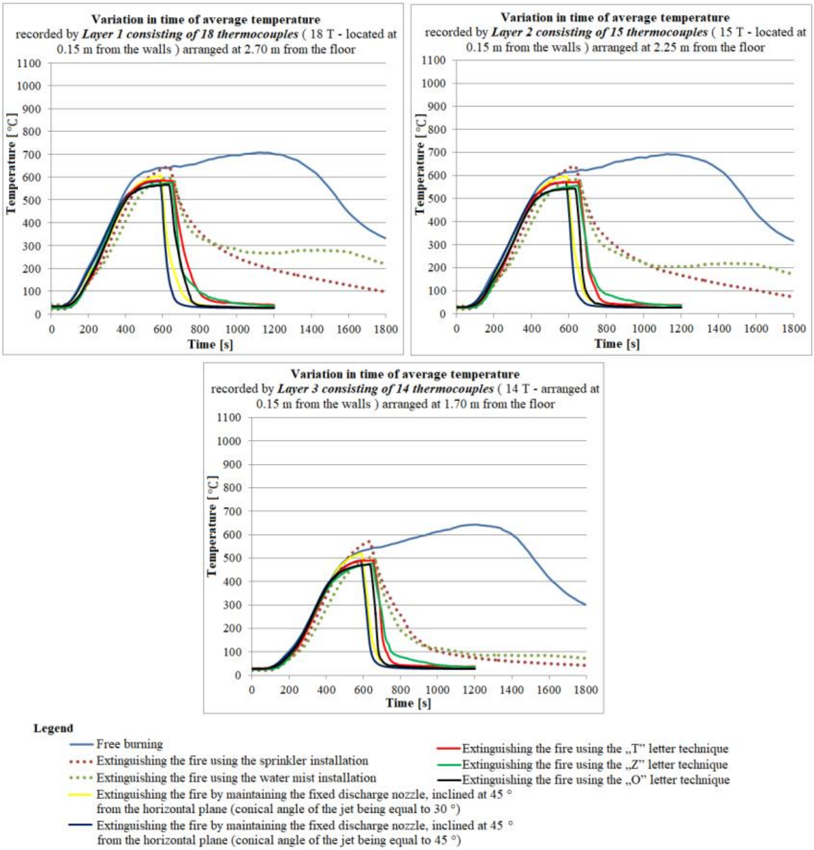


Fig. 6.7. Variation in time of the average temperature recorded in the test room of the thermocouples of layers 1, 2 and 3

❖ at the level of the upper surface of the wood cribs, according to Fig. 6.8., temperature reduction is slower in the case of S2, S6 and S7; thus, a slower temperature reduction is found in the case of scenarios S2, S6 and S7 for wood crib 1, S2 and S7 for wood crib 2, S2, S6 and S7 for wood crib 3 and S1, S2 and S7 for wood crib 4;

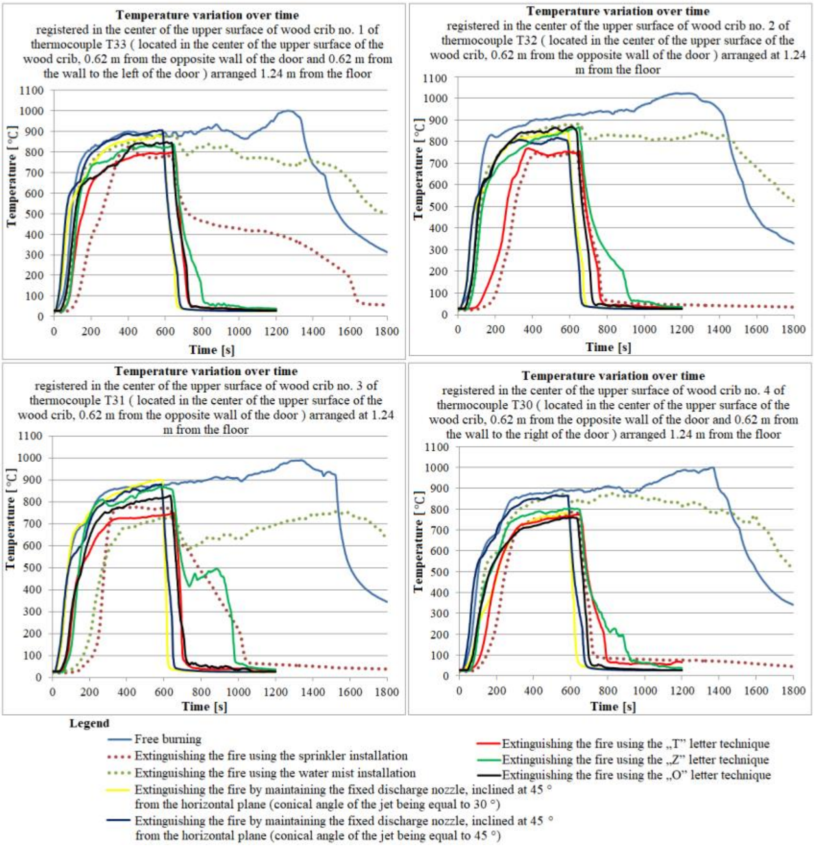


Fig. 6.8. Time variation of the temperature recorded in the middle of the upper surface of the wood crib by thermocouples of the layer 4

❖ in the center of the wood cribs, according to Fig. 6.9., temperature reduction is slower in the case of S2, S6 and S7; regarding the center of the wood cribs, the slower temperature reduction is found in the case of S2 scenarios, S6 and S7 for wood crib 1, S2 and S7 for wood crib 2, S2, S6 and S7 for wood crib 3, respectively S1, S2, S6 and S7 for wood cribs 4;

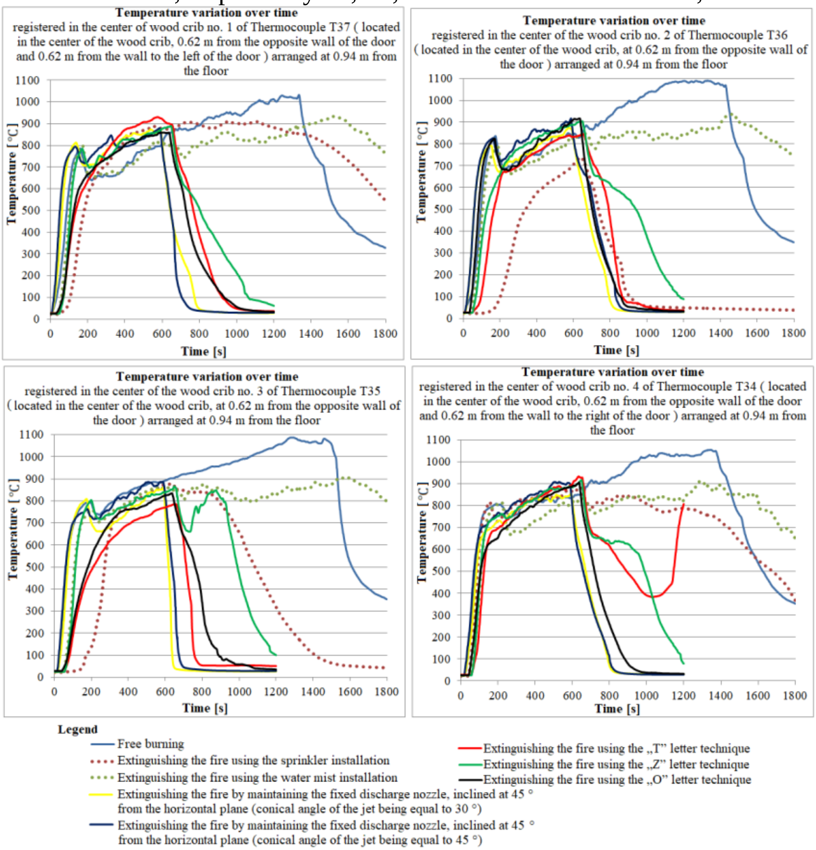


Fig. 6.9. Variation in time of the temperature recorded in the center of the wood crib by thermocouples of the layer 5

- the average temperature reduction rate in the extinguishing scenarios S1-S7, depending on the analyzed area and the height from the floor, presented in descending order, is as follows:
  - test room / 1.70 m – 2.70 m : S1, S2, S3, S4, S5, S6, S7;
  - wood cribs area / 0.94 m – 2.70 m : S3, S2, S1, S4, S5, S6, S7;
  - wood cribs surface / 1.24 m : S2, S3, S1, S5, S4, S6, S7;
  - center of wood cribs / 0.94 m : S3, S2, S5, S4, S1, S6, S7.

Analyzing the efficiency of extinguishing fires based on the minimum volume of discharged water, within the two fire control criteria, the following are found:

Depending on the minimum volume of water discharged in order to reduce the temperature, according to the two fire control criteria:

- below 60 °C, inside the test room, at a height of 1.70 m from the floor (the first fire control criterion), the following scenarios are recommended: S5 (408.05 L), S4 (609.27 L), S3 (647.01 L), S1 (772.89 L), S6 (1298.48 L), S2 (1476.14 L); in the case of scenario S7 no temperature reduction below 60 °C is obtained before the end of the experimental test;
- below 100 °C, in the center of the wood cribs, at a height of 0.94 m from the floor (the second fire control criterion), the following scenarios are recommended: S4 (1143.17 L), S5 (1316.30 L), S3 (1815.40 L), S2 (2912.12 L); in the case of S1, S6 and S7 scenarios, do not achieve a temperature reduction below 100 °C in the center of the wood cribs before the end of the experimental tests.

Analyzing the efficiency of extinguishing fires based on the shortest time in which the two fire control criteria are met, the following are found:

Depending on the time when water is discharged in order to reduce the temperature, according to the two fire control criteria:

- below 60 °C, inside the test room, at a height of 1.70 m from the floor (the first fire control criterion), according to Fig. 6.10., the following scenarios are recommended: S5 (62 s), S4 (97 s), S3 (103 s), S1 (152 s), S2 (294 s), S6 (783 s); it is thus found that in the case of scenario S7 no temperature reduction below 60 °C is obtained before the end of the experimental test;
- below 100 °C, in the center of the wood cribs, at a height of 0.94 m from the floor (the second fire control criterion), according to Fig. 6.11., the following scenarios are recommended: S4 (182 s), S5 (200 s), S3 (289 s), S2 (580 s); in the case of S1, S6 and S7 scenarios do not achieve a temperature reduction below 100 °C in the center of the wood cribs before the end of the experimental tests.

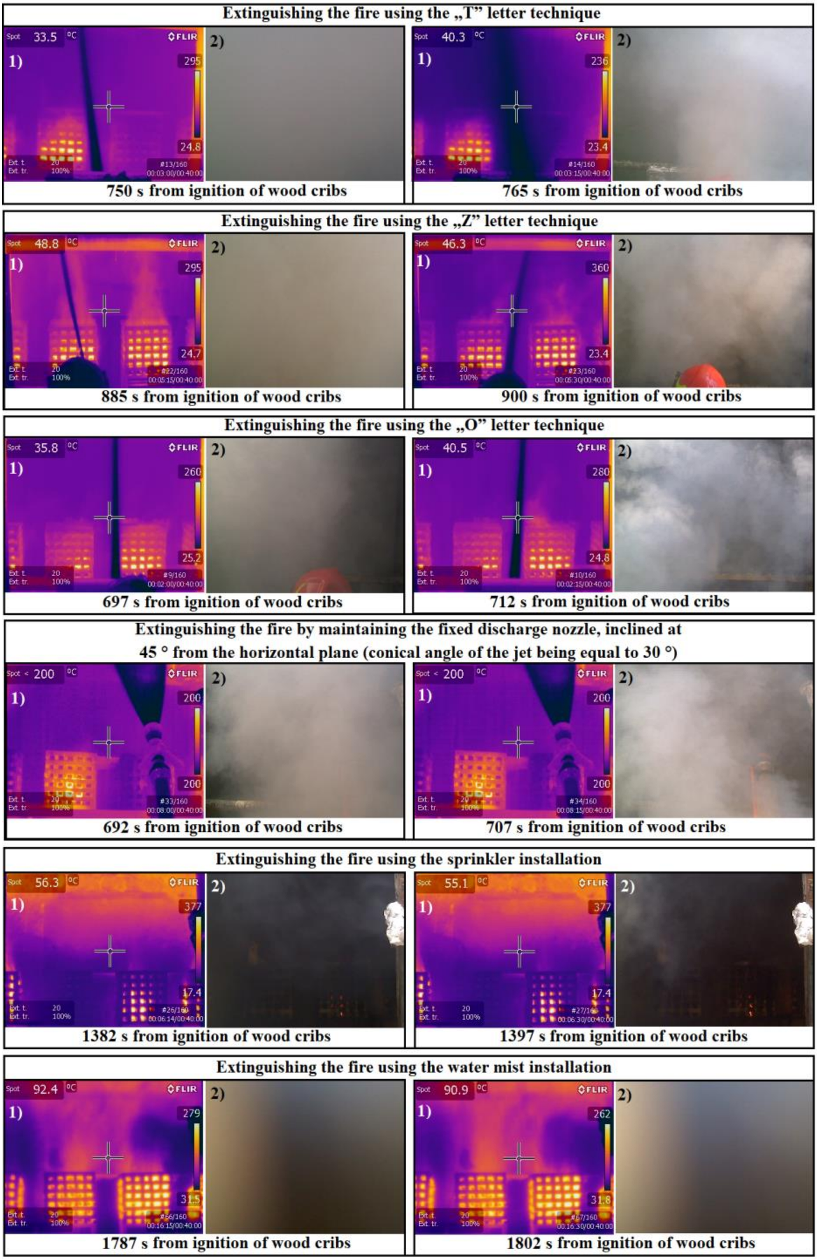
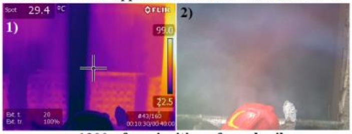


Fig. 6.10. Snapshots made at the time of temperature drop below 60 °C at a height of 1.70 m from the floor: 1) infrared image; 2) normal image.

Extinguishing the fire using the „T" letter technique

The average temperature in the center of the 4 wood cribs is 232.85 °C at 1200 s from the ignition

The average temperature in the middle of the upper surface of the 4 wood cribs is 42 °C at 1200 s from the ignition



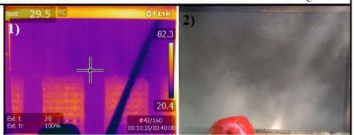
1200 s **from ignition of wood cribs**

Extinguishing the fire using the „Z" letter technique

The average temperature in the center of the 4 wood cribs is 99.70 °C at 1180 s from the ignition

The average temperature in the middle of the upper surface of the 4 wood cribs is 37.63 °C at 1180 s from the ignition

1170 s **from ignition of wood cribs**



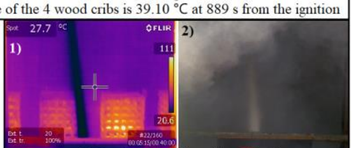
1185 s **from ignition of wood cribs**

Extinguishing the fire using the „O" letter technique

The average temperature in the center of the 4 wood cribs is 99.68 °C at 889 s from the ignition

The average temperature in the middle of the upper surface of the 4 wood cribs is 39.10 °C at 889 s from the ignition

877 s **from ignition of wood cribs**

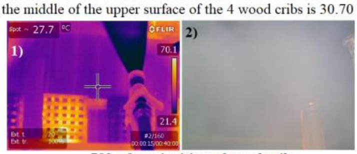


892 s **from ignition of wood cribs**

Extinguishing the fire by maintaining the fixed discharge nozzle, inclined at 45 ° from the horizontal plane (conical angle of the jet being equal to 30 °)

The average temperature in the center of the 4 wood cribs is 96.15 °C at 782 s from the ignition

The average temperature in the middle of the upper surface of the 4 wood cribs is 30.70 °C at 782 s from the ignition

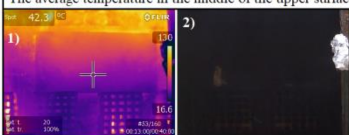


782 s **from ignition of wood cribs**

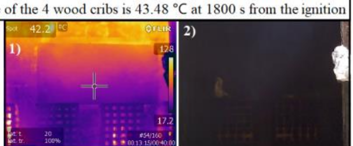
Extinguishing the fire using the sprinkler installation

The average temperature in the center of the 4 wood cribs is 248.48 °C at 1800 s from the ignition

The average temperature in the middle of the upper surface of the 4 wood cribs is 43.48 °C at 1800 s from the ignition



1787 s **from ignition of wood cribs**



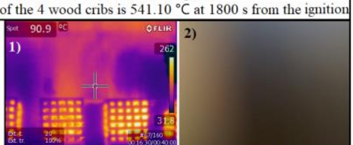
1802 s **from ignition of wood cribs**

Extinguishing the fire using the water mist installation

The average temperature in the center of the 4 wood cribs is 740.68 °C at 1800 s from the ignition

The average temperature in the middle of the upper surface of the 4 wood cribs is 541.10 °C at 1800 s from the ignition

1787 s **from ignition of wood cribs**



1802 s **from ignition of wood cribs**

Fig. 6.11. Snapshots made at the time of decreasing the average temperature of the four stacks below 100 °C in their center: 1) infrared image; 2) normal image.

Analyzing the efficiency of extinguishing fires based on the reduction of the heat flow released by the fire on the surface unit, the following are found:

According to Fig. 6.12., the variation over time of HRRPUA in the use of the fixed water mist installation (S7) is greater compared to other extinguishing techniques, the profile of the variation curve being similar in the case of S1– S6 scenarios.

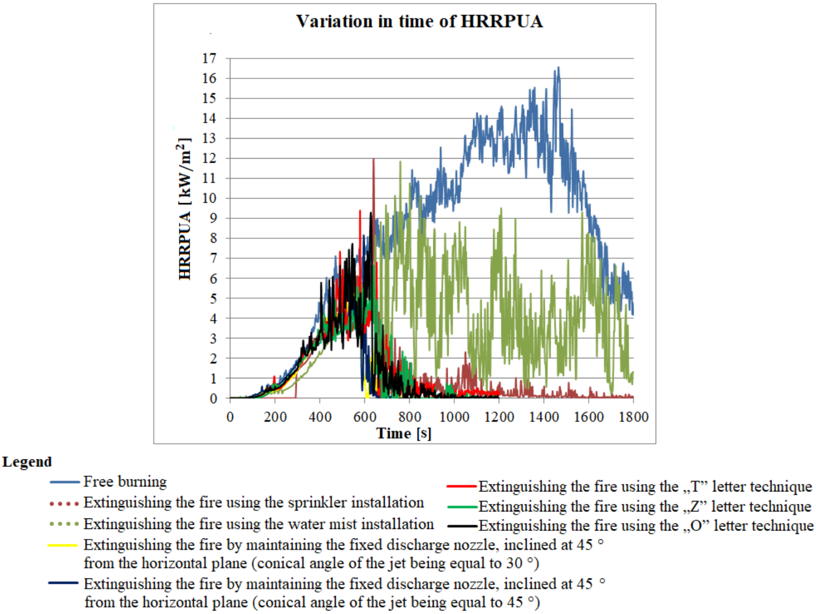


Fig. 6.12. Variation in time of HRRPUA

After analyzing the HRRPUA parameter reduction speed values, it is recommended to use the following scenarios: S4 (56.22 W/(m^{2}s)), S5 (45.09 W/(m^{2}s)), S3 (29.22 W/(m^{2}s)), S2 (19.72 W/(m^{2}s)), S1 (16.37 W/(m^{2}s)), S6 (4.68 W/(m^{2}s)), S7 (2.68 W/(m^{2}s)).

Chapter 7. OPERATIONAL MANAGEMENT OF EXTINGUISHING FIRES IN CONFINED SPACES

The main objective in the case of a fire extinguishing action is to obtain and maintain control over the fire.

Within this thesis, two fire control criteria were established, both based on reaching a certain temperature value, namely:

- the first fire control criterion is to reduce the temperature inside the test room below 60 °C to a height of 1.70 m from the floor;
- the second fire control criterion consists in reducing the average of the temperature values recorded in the center of the four wood cribs at which the combustion is manifested below 100 °C at a height of 0.94 m from the floor.

According to the first control criterion, the fire control time and the total volume of the discharged water are directly proportional to the density of the water distribution; thus, it is observed that minimum values of the two parameters are obtained for the value of 0.41 $(l/s)m^{-2}$ of the water distribution density, in the case of scenario S5.

According to the second control criterion, the fire control time and the total volume of the discharged water are directly proportional to the density of the water distribution up to 0.39 $(l/s)m^{-2}$, increasing to 0.41 $(l/s)m^{-2}$ of the density of water distribution; thus, it is observed that minimum values of the two parameters are obtained for the value of 0.39 $(l/s)m^{-2}$ of the water distribution density, in the case of scenario S4.

The results of experimental tests performed on a natural scale may form the basis for further research into the management of intervention actions and fire control.

The analysis of the experimental data obtained in this thesis can be performed taking into account the hypothesis that the effects resulting from the use of the seven different water discharge techniques can be represented using exponential functions.

According to Fig. 7.1., the effects of different firefighting procedures (such as opening a door, opening a window, using forced ventilation with positive pressure, the use of a certain water discharge flow value) used during an intervention may be represented as the sum of exponential functions [39].

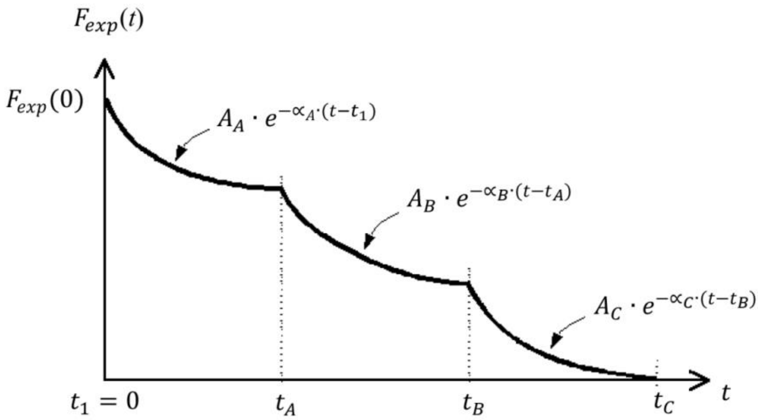


Fig. 7.1. Graphic representation of firefighting procedures used during an intervention in the form of the sum of exponential functions [39]

Exponential functions are characterized by amplitudes A_A, A_B, A_C and frequencies α_A, α_B, α_C, characteristic of each time interval in which certain intervention procedures are applied. The parameters t_1, t_A și t_B represent the moment of applying certain intervention procedures, and the parameter t_C represents the moment of completion of the experimental fire extinguishing test.

Obtaining high frequency values leads to faster reduction of temperature values recorded in the fire compartment. This implies that appropriate intervention procedures have been chosen, resulting in the efficiency of extinguishing the fire [39].

Mathematical representation using exponential functions is a method often used in engineering applications. It can also be used in the case of firefighting operations, in order to identify representative water discharge techniques in terms of firefighting efficiency.

Chapter 8. CONCLUSIONS AND CONTRIBUTIONS

The main purpose of the research carried out within this doctoral thesis was to streamline the extinguishing of fires by investigating and analyzing different water discharge techniques in an enclosed space.

This was done by analyzing the results obtained after extinguishing a fire outbreak, represented by four pine wood cribs, following water discharge using the „T", „Z", „O" letters technique, compared to other techniques such as: a) water discharge while maintaining a fixed discharge nozzle, inclined at 45 ° from the horizontal plane, the cone angle of the jet being equal to 30 ° respectively 45 °; b) water discharge using the fixed sprinkler and water mist installation.

Thus, the main parameters that significantly influence the efficiency of the fire extinguishing process were identified.

The doctoral thesis emphasizes the need for continuous research of how water discharge techniques have a major impact on fire extinguishing given the complexity of fire dynamics that occur in confined spaces.

8.1. Original contributions

This paper makes a number of original contributions to the experimental and numerical study of water discharge in confined spaces, as follows:

- performing an analysis of the current stage of theoretical, numerical and experimental studies on fire extinguishing in enclosed spaces published in the literature lately (Cap. 2.1. – 2.7., Cap. 3., Cap. 5.1.);
- validation of a set of numerical results on the variation of the HRR parameter over time following the burning of a wood crib in a closed space (Cap. 2.8.);
- creation of the experimental stand (Cap. 4.1. – 4.2.);
- preparation of test procedures for: (a) analysis of water distribution in the absence of combustion; (b) free burning of four wood cribs; (c) extinguishing four burning wood cribs after discharging water manually, using the discharge nozzle, and automatically, using fixed sprinkler and water mist installations (Cap. 4.3.);
- calculation of the maximum HRRPUA value of ethanol based on the results obtained from the experimental combustion test of 2 l of ethanol for 1800 s (Cap. 5.2.4.);

➢ numerical simulation on burning four wood cribs using the PyroSim program (Cap. 5.);

➢ performing a set of experimental tests on:

❖ performing 21 experimental tests on water discharge inside the test room, in the absence of combustion, 3 tests for each of the seven scenarios (Cap. 6.1.);

❖ performing an experimental free combustion test of four wood cribs to determine when water discharge is initiated in experimental extinguishing tests (Cap. 6.2.);

❖ comparative analysis between experimental test and simulation using the PyroSim program of four wood cribs free combustion (Cap. 6.3.);

❖ extinguishing four burning wood cribs, using different water discharge techniques in seven scenarios (S1 – S7): S1 – water discharge using the „T" letter technique; S2 – water discharge using the „Z" letter technique ; S3 – water discharge using the „O" letter technique; S4 – water discharge by keeping the nozzle fixed, inclined at 45° from the horizontal plane, the cone angle of the jet being equal to 30°; S5 – water discharge by keeping the nozzle fixed, inclined at 45° from the horizontal plane, the cone angle of the jet being equal to 45°; S6 – water discharge using the fixed sprinkler installation; S7 – water discharge using the fixed water mist installation (Cap. 6.4.);

➢ obtaining data concerning, on the one hand, the distribution of water discharged inside a room, and on the other hand, extinguishing the fire, using different water discharge techniques (Cap. 6.);

➢ identification of elements leading to the efficiency of extinguishing fires in confined spaces, namely the reduction of the temperature of the fire compartment, the consumption of the discharge water and the heat release rate per unit surface taking into account the significant influence of parameters such as the discharge direction of the water jet, flow rate and density of the distribution of the discharged water, cone angle of the water jet, discharge technique, respectively the water discharge mode in terms of continuity (Cap. 6. – 8.).

8.2. Perspectives for further development

Fundamental research on the dynamics of fires in enclosed spaces can be deepened by developing studies on:

➢ extinguishing fires using the „inverted U" letter technique;

- comparative analyzes of water discharge results using the „T”, „Z”, „O” and „inverted U” letters technique following the use of different values of flow and pressure of the discharged water;
- measuring the volume of water actually remaining after discharge on the fire in order to estimate the volume of water represented by losses as a result of infiltration at the room level, evaporation following contact with room surfaces, respectively evaporation following the heat released by fire;
- mathematical representation using exponential functions based on the results obtained from performing experimental tests;
- numerical simulation using the PyroSim program and fire extinguishing validation using fixed sprinkler and water mist installations;
- water discharge in the form of „T”, „Z”, „O” and „inverted U” letters on the fire by means of a robot.

8.3. List of publications

1. *Anghel, I., Chiojdoiu, A. F.*, Fire Behavior In Corner Tests Of Interior Finish Materials Under Natural Conditions, Acta Technica Napocensis-Series: Applied Mathematics, Mechanics, And Engineering, 65(1), pp. 57-64, ISSN 1221-5872, https://atna-mam.utcluj.ro/index.php/Acta/article/view/1781, Impact Factor: 0,3; 2022.
2. *Anghel, I., Chiojdoiu, A. F., Petrache, M. A., Vrabie, S.*, The Influence Of Wood Cribs Shape On The Mass Loss And Temperature Variation In Enclosed Spaces, Acta Technica Napocensis-Series: Applied Mathematics, Mechanics, And Engineering, 65(2), pp. 195-204, ISSN 1221-5872, https://atna-mam.utcluj.ro/index.php/Acta/article/view/1806, Impact Factor: 0,3; 2022.
3. *Chiojdoiu, A. F., Anghel, I., Enciu, V., Mocioi, I. A., Tudor, E. F.,* Influența performanțelor la foc ale plăcilor din așchii de lemn (PAL) asupra dezvoltării unui incendiu simulat la scară naturală, într-un spațiu închis, Revista Română de Inginerie Civilă, vol. 12, Iss. 1, pag. 105-125, 2021.
4. *Chiojdoiu, A. F., Anghel, I., Panaitescu, N. V.,* Analiza comparativă a influenței principalilor parametri asupra eficientizării stingerii cu apă a incendiilor, Revista Romana de Inginerie Civila, 12(2), 329-350; 2021.
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Applied Mathematics, Mechanics, and Engineering, vol. 64, Issue I, March, pag. 113 – 122, 2021.
7. *Chiojdoiu, A.-F., Anghel, I., Safta, C. A., Simion, A.,* Influence of water discharge using the „T”, „Z”, „O” and „inverted U” letters technique on its distribution in a confined space, Acta Technica Napocensis-Series: Applied Mathematics, Mechanics, And Engineering, 66(3), pp. 397-406, ISSN 1221-5872, https://atna-mam.utcluj.ro/index.php/Acta/article/view/2190, Impact Factor: 0,3; 2023
8. *Chiojdoiu, A.-F., Anghel, I., Dima, Safta, C.-A.,* The influence of ventilation on the temperature variation resulting from burning a wood crib inside a confined space, În curs de publicare în cadrul Buletin Științific, Universitatea Națională de Știință și Tehnică Politehnica București.
9. *Chiojdoiu, A.-F., Anghel, I.,* The procedure for performing discharge tests using the letter technique (TZO) for water distribution analysis, Scientific Conference „Provocări și Strategii în Ordinea și Siguranța Publică”, Bucharest, Romania, 2023.
10. *Chiojdoiu, A.-F., Anghel, I, Dragne, H., Dragomirescu, A., Safta, C.-A.,* The influence of ventilation conditions of heat release rate variation over time, Technium, col. 14, pp. 109-114, ISSN: 2668-778X, www.techniumscience.com, 2023.
11. *Neamtu, C., Anghel, I., Chiojdoiu, A. F., Buna, Z., Trofin, A., Dragomir, D.,* Automatic Fire Extinguishing System Using „T”„Z”„O” Letters Technique Based On A Parallel Structure, Acta Technica Napocensis-Series: Applied Mathematics, Mechanics, And Engineering, 62(3), pag. 389 – 396, 2019.
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Chapter 9. BIBLIOGRAPHY EXTRACT

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