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The influence of ventilation conditions of heat release rate variation over time

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***Abstract*— The heat release rate (HRR) is an important parameter in the description of fire evolution. In this paper, the significant influence of ventilation conditions of HRR variation over time is emphasized. This was achieved by: i) performing seven experiments to burn a wood crib on a natural scale, in a confined space using different ventilation scenarios; ii) validation of a fire model by framing the mean value of the HRR parameter error between the results obtained from an experimental test and those obtained from the simulation using the Pyrosim program, in the range of ± 15 % to ± 20 %, within the same ventilation scenario. It has been found that both surface values and types of ventilation opening configurations significantly influence the variation of HRR over time. Thus, both the maximum surface value of the ventilation openings and the use of two types of openings configurations, located diametrically opposite, lead to a maximum value of the HRR. The use of ventilation openings with a low surface value leads to a minimum value of the HRR.**

***Keywords* — experiment, heat release rate, numerical simulation, Pyrosim software, ventilation**

I. INTRODUCTION

To assess the fire performance of buildings to a fire representative models are used. The common variables in the description of a fire model are: the heat release rate (HRR), the size of the fire (including the length of the flame), the fire effluent volume, the hot gas temperature, and the time until key events such as the flashover occur. Fire models are often expressed according to the HRR parameter, which is important to quantify the increase and spread of the fire inside of a compartment.

The novelty of this work consists in the analysis of the influence of ventilation on the HRR parameter following the combustion of a wood crib in a closed space within 7 ventilation scenarios. It is experimental determined the HRR parameter based on the mass loss of the wood crib, and a numerical simulation using the Pyrosim program is performed to compare the results obtained.

A. The role of HRR parameter in fire classification

Using HRR, fires are characterized in three ways, depending on the rate of fire growth, ventilation and fire phases.

Fires characterized by the rate of growth, are called "time-dependent" fires, and are defined in their time evolution by three phases: growing, steady-state and decay (burnout) fire, as presented in Fig. 1.

The increase phase of the fire involves increasing the value of HRR parameter over time, the volume of available air being higher than the volume of air required to burn the released combustible gases. Fires in this phase will continue to increase until they are limited by the mass of fuel material available or the volume of air available for combustion. During the fire equilibrium phase (steady-state fire), the value of the HRR parameter remains relatively constant over time. The fire decay, also called burnout, assumes that there is enough air available to support combustion, but the value of the HRR decreases because the fuel material is consumed.

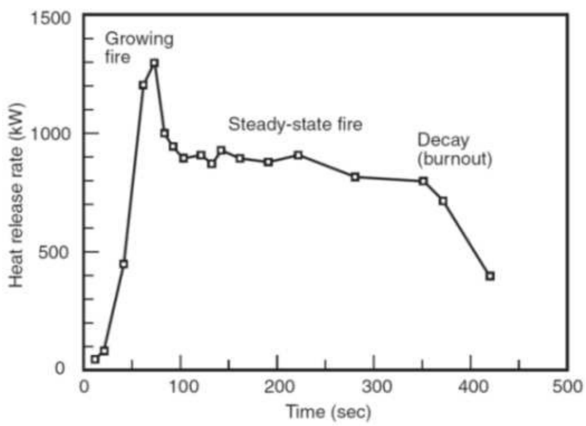

Fig. 1. Fires defined by the rate of growth [1].

The growing rate of fires that usually occur in residential or office buildings is directly proportional to the square of time. These types of fires are also called "t^2" fires and can be characterized by the equation:

$$\dot{Q} = \alpha t^2, \quad (1)$$

where: $\dot{Q}$ represents HRR at a certain time [kW]; α – fire growth constant (represents the cumulative effects of fuel configuration and chemistry of the fire increase characterized by the relationship „t^2") [kW/s^2]; t – time [s].

Fires „t^2" can be classified according to the α parameter as follows: slow fire ($\dot{Q} = 0.00293t^2$), medium fire ($\dot{Q} = 0.01172t^2$), fast fire – usual for burning upholstered furniture ($\dot{Q} = 0.0469t^2$) and ultrafast fire – usual for burning of flammable liquids ($\dot{Q} = 0.1876t^2$) [2].

According to ventilation conditions fires can be classified as:

- fires controlled by the mass of fuel available for combustion. These fires occur outdoors or inside a compartment where fires are in the initial stages of development. In both cases the volume of air required for combustion is in excess compared to the fuel vapors produced;
- controlled ventilation fires, where the fuel material inside a fire compartment is sufficient and the ventilation openings are controlling the volume of air available for combustion. In this case, more fuel vapors are produced than can be consumed by the air available inside the compartment. The effect of ventilation on the HRR parameter is influenced by the dimensions of the ventilation opening [3] and the equation is:

$$\dot{Q} \approx A\sqrt{h} \tag{2}$$

Where: A represents the surface of the ventilation opening [m^2]; h - the height of the ventilation opening [m].

According to their phases, fires are classified as: fires in the early phase (smoldering fire), fires in the growth phase (increase in the value of the HRR parameter over time, fire being controlled by fuel), fires in the steady-state (the HRR parameter value is relatively constant, and fire can be controlled by either fuel or ventilation) and fires in the decay phase (decrease in the HRR parameter over time either due to fuel consumption or available oxygen). In this classification it is considered the energy released within each phase.

In the event of changing room conditions, such as breaking a window, giving way to a wall or opening a door, the fire may return to the growth phase and reach the equilibrium phase depending on the presence of fuel material mass or ventilation conditions.

B. Determination of the HRR parameter

The HRR parameter can be determined by using experimental methods (the oxygen consumption calorimetry technique, respectively by measuring mass loss) and computer modeling and fire simulation methods [4].

The technique of oxygen consumption calorimetry is highly accurate and involves measuring the composition of the gases resulting from the burning of the analyzed material, collected in a hood of a calorimeter. The HRR parameter can be measured using large scale calorimetric cone (room corner fire test [5], furniture calorimeters [6]) and intermediate scale (ICAL test [7]), obtaining maximum values of the order of tens of megawatts. Using the small scale calorimetric cone method (for example OSU apparatus [8], fire propagator [9], calorimetric cone [10, 11], or single burning item test [12]), samples of material tested are used in the range of 100 mm to 1 m, and quantitative values of the HRR parameter are obtained.

The method of mass loss involves to determine the HRR parameter as the product between the speed of mass loss, the heat of the material burning and the efficiency of burning. When the value of the combustion heat is known, the HRR parameter can be estimated using the mass loss rate obtained by measurements. In this paper the mass loss method is used to determine the HRR parameter after the wood crib combustion.

Computer modelling and fire simulations are another method of determining the HRR parameter. The accepted difference between HRR predictions from the use of the Fire Dynamic Simulation (FDS program) and results from natural-scale experimental tests shall be within $\pm 15\,\%$ - $\pm 20\,\%$ [13, 14].

The common element of the determination of the HRR parameter using the mathematical model and the calorimetric cone is represented by the heat released following the combustion of the wood crib. Thus, if in the first case the HRR value is obtained as a result of the product between the heat of combustion and the rate of mass loss of the crib, in the second case, it is taken into account that the value of the heat of combustion is directly proportional to the mass of oxygen needed for combustion.

C. Purpose and objectives of the paper

The purpose of this paper is to analyze the influence of ventilation conditions on the HRR parameter time variation in case of burning a wood crib in a confined space.
This goal realises by achieving the following objectives:

- making a fire pattern using the Pyrosim FDS program characterized by burning a stack in a closed space, the ventilation scenario used being represented by opening the door of the test room;
- performing seven experimental fire tests on burning a pine wood crib in a closed space, under different ventilation conditions;
- validation of the fire model characterized by burning a wood crib inside a test room, which is provided with the door open.

II. NUMERICAL SIMULATION USING THE PYROSIM PROGRAM

The simulation was performed using Pyrosim software. The Pyrosim program is an interface of the Fire Dynamics Simulator (FDS) program, developed by the National Institute of standards and Technology (NIST). This program was used to predict the variation in HRR over time following the burning of a wooden crib, the ventilation scenario used being characterized by the opening of the test room door.

II.1. Numerical Method

Fire Dynamics Simulation is a computational fluid dynamics software based on large eddy simulation that solves low Mach number combustion equations. Combustion is determined based on a turbulence model based on the Eddy dissipation concept in which the mixture of fuel and oxygen is represented by a single step reaction.

In the simulation carried out in this study, the combustible material is represented by a wood crib. The one-dimensional heat conduction equation is used to solve the heat transfer in a solid fuel material according to equation 3 [15]:

$$\rho_s c_s \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial x}\left(k_s \frac{\partial T_s}{\partial x}\right) \quad (3)$$

where: ρ_s is the wood crib density [$\mathrm{kg/m^3}$]; k_s – wood crib conductivity [$\mathrm{W/mK}$]; c_s – specific heat of the wood crib [$\mathrm{J/kgK}$]; T_s – stack temperature [K].

Fuel ignition occurs when the cell surface temperature reaches a specified value. The fuel mass flow is controlled by an initially specified heat release behaviour.

The mass of the fuel in a cell is then determined by multiplying the density by the volume of the cell. The combustible material containing cell is transformed into the gas phase when equation 4 is fulfilled [15]:

$$\int_0^t \dot{m}_f'' A_{cel}\, dt > \rho_s V_{cel} \quad (4)$$

where: $\dot{m}_f''$ is the combustible material mass flux [$\mathrm{kg/sm^2}$]; A_{cel} – surface cell [$\mathrm{m^2}$]; V_{cel} – cell volume [$\mathrm{m^3}$].

II.2. The wood crib burning simulation

Using the Pyrosim program was represented the test room, located in the Fire Officers Faculty, the dimensions of the construction being shown in Fig. 2. The test room used in numerical simulation model is the same as the room used in experimental study.

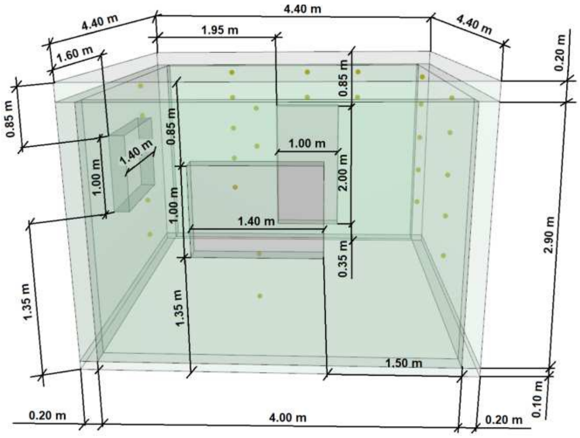

Fig. 2. Pyrosim presentation of the test room dimensions [16].

The wooden crib under analysis was placed in the middle of the room, at a height of 0.60 m from the floor. It has the shape of a cube with a side of 0.60 m, consisting of 12 layers of pine wood sticks, arranged orthogonal. On each layer of the wood crib are placed 6 sticks with a length of 0.60 m and the cross-section area of 0.0025 $\mathrm{m^2}$. The distance between each stick, at the level of each horizontal layer, is 0.06 m.

The input parameters used are: the pin heat of combustion - 17900 kJ/kg [17, 18] and heat release rate per unite area (HRRPUA) of the wood crib - 175 $\mathrm{kW/m^2}$ [18] (experimental value extracted from the literature [19, 20]), respectively of the burner – 535,6 $\mathrm{kW/m^2}$ (experimental value obtained by the first author of this paper on the basis of mass loss resulting from the burning of 2 L of ethanol). Using the ventilation scenario characterized by the opening of the door, it was found that the growing rate of the temperature values recorded inside the fire compartment following the experimental test was higher compared to the numerical simulations performed [16]. Therefore, in this simulation, the burner was activated at $t = 60$ s from the experimental test, where the wood crib was lit at $t = 0$ s.

Following the use of calculation application <u>*dstar-calculator_v1_1*</u> [21], three values of the optimal size of the grid mesh were determined, namely approximately 0.2 m, 0.08 m and 0.04 m. To reduce the simulation time, the value used was 0.2 m for the calculation cells related to the burner and wood crib range, where high accuracy of the calculation is required, and for the rest of the range the size of 0.4 cm was used.

III. EXPERIMENTAL STUDY – SEVEN VENTILATION SCENARIOS

Using seven ventilation scenarios, the time variation of the HRR parameter resulting from the free burning of a stack placed in the middle of a test room at a height of 0.60 m from the floor was analyzed.

The experimental test room is equipped with a door and two windows, the seven ventilation scenarios (each of them named S) being characterized by the opening of the following elements: S1-door; S2-door and window located on the right-hand side; S3-door and window located on the wall diametrically opposite the door; S4-door, window located on the right-hand side and window located on the wall diametrically opposite the door; S5-window located on the right-hand side; S6-window located on the wall diametrically opposite the door, open; S7-window located on the right-hand side and window located on the wall diametrically opposite the door, open.

A. Presentation of the experimental stand

The experimental tests were carried out on a natural size within a testing room located within the Fire Officers Faculty, the dimensions of which are shown in Fig. 3. The test room has a length of 4 m, a width of 4 m and a height of 2.9 m. The room walls, made by aerated concrete blocks, and the ceiling, made of reinforced concrete, have a thickness of 0.20 m, and the floor, made of reinforced concrete, has a thickness of 0.10 m.

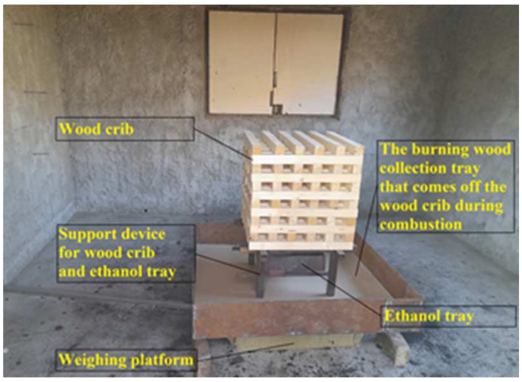

Fig. 3. Presentation of the experimental stand [16].

According to Fig. 4, inside the test room the experimental stand consists of:

- weighing platform, with a maximum capacity of 300 kg and a division of 50 g, used to measure the mass loss of the wood crib during its burning;
- a sheet metal device of 1.20 x 1.20 x 0.20 m in size and 2 mm in thickness, used to collect burning wood material from the wood crib during combustion to measure the mass loss of the wood crib;
- a support bracket for the wood crib and the liquid fuel tray (2 L of ethanol) required to ignite the wood

crib, having the outer dimensions of 0.695 m and the height of 0.34 m;

- a wood crib, shaped like a cube with 0.6 m side, consisting of 12 layers of sticks, arranged orthogonal, on each layer being piled 6 sticks, each of them having a length of 0.6 m and the cross section area of 0.05 m.

B. Determination of the HRR parameter based on the mass loss of the wood crib

The mass loss method was used to determine the HRR parameter.

The HRR parameter is directly proportional to the rate of mass loss (fuel consumed mass/unit time) with the fuel heat of combustion (available energy/unit mass) and the efficiency of combustion (mass fraction converted into energy). Following the seven experimental tests to burn a pine wood crib, the HRR parameter was obtained using the formula:

$$\dot{Q} = MLR \times \Delta H_c \times \chi \tag{5}$$

where: MLR represents the mass loss rate [kg/s]; ΔH_c – pine heat of combustion [J/kg]; $\chi = 0{,}85\ \%$ – combustion efficiency [13].

The mass loss rate (MLR) was obtained by the ratio of the wood crib mass loss resulting from its measurement and the unit of time.

The pine heat of combustion used during the seven experimental tests was obtained by using the calorimetric bomb [22, 23] with the value of 17.66 MJ/kg.

According to Table I, the average values of the HRR parameter in the seven scenarios are close, ranging from 362.15 kW to 372.40 kW. The maximum value of the HRR parameter is obtained in the case of S4 (the area of the ventilation openings is maximum) and S7 (the area of the ventilation openings is medium, the window located on the wall to the right of the door, respectively the one located on the wall diametrically opposite the door being open). In the case of S5 and S6 (the area of the ventilation openings is minimal), the value of 600.44 kW and 575.42 kW respectively is obtained. In the case of S5 and S6 scenarios, characterized by a minimum ventilation opening surface value, the maximum HRR is obtained during the longest time, i.e. 1020 s and 1110 s.

TABLE I. MAXIMUM AND AVERAGE HRR VALUES FOR THE SEVEN VENTILATION SCENARIOS

Scenarios / Phases of HRR time variation	S4	S7	S3	S1	S2	S5	S6
	a	*c*	*b*	*d*	*b*	*e*	*e*
The surface of the openings [m²]	4.80	2.80	3.40	2.00	3.40	1.40	1.40
Average HRR [kW]	363.79	362.15	371.99	365.43	372.40	365.02	368.30
Peak HRR [kW]	675.50	675.50	650.48	600.44	600.44	600.44	575.42
The time to reach peak HRR [s]	390.00	420.00	510.00	360.00	300.00	1020.0	1110.0

Fig. 4 shows the variation in time of the HRR parameter, finding that within the seven scenarios the obtained curves have similar shapes.

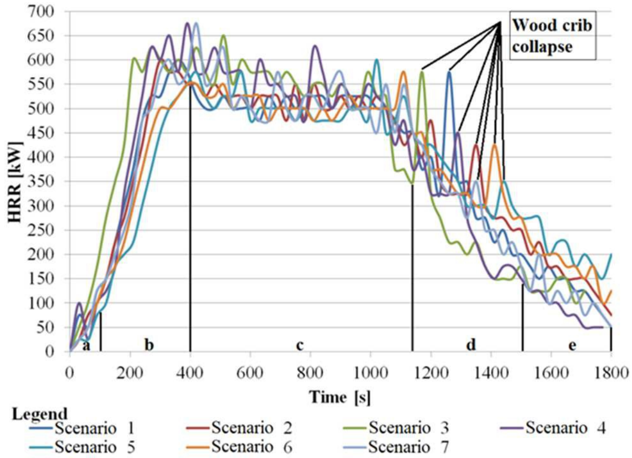

Fig. 4. Time variation of HRR for the seven ventilation scenarios.

According to Fig. 4, the time variation of HRR can be divided into 5 phases:

(a) the ignition phase: lasts from the moment of ignition in the moment of time equal to 100 s; the wooden sticks are heated, lit and start to burn, and the value of the HRR parameter increases rapidly.

(b) the growth phase: lasts from 100 s to 400 s; the HRR value increases rapidly to the maximum value;

(c) steady-state burning phase: lasts from 400 s to 1100 s; the wood crib maintains a stable burning state, the HRR parameter reaching high values, without large differences between the 7 scenarios;

(d) the collapse phase: lasts from 1100 s to 1440 s; the value of the HRR parameter begins to decrease at the same time as the wood crib collapse;

(e) regression phase: lasts from 1440 s to 1800 s; the value of the HRR parameter continues to decrease until the tests are completed.

Table II shows the time periods during which the wood crib collapse under the seven ventilation scenarios, ranging from 1140 s to 1470.

TABLE II. MAXIMUM HRR VALUES IN CASE OF WOOD CRIB COLLAPSE UNDER THE SEVEN VENTILATION SCENARIOS

Scenarios / Phases of HRR time variation	S1	S3	S4	S2	S6	S5	S7
	d	*b*	*a*	*b*	*e*	*e*	*c*
The surface of the openings [m²]	2.00	3.40	4.80	3.40	1.40	1.40	2.80
Wood crib collapse time interval [s]	1230–1290	1140–1230	1260–1320	1320–1380	1380–1440	1410–1470	1320–1380
Peak HRR [kW]	575.42	575.42	450.33	425.31	425.31	350.26	350.26

Also, under scenarios S3 (door and window located on the wall opposite the open door) and S1 (open door), the collapse of the wood crib occurs the fastest, namely in the intervals 1140 – 1230 s, respectively 1230 – 1290 s. The maximum HRR values compared to the other scenarios shall also be recorded in these time intervals. In scenerios S5, characterized by the lowest ventilation opening surface value, the wood crib collapses at the latest, with the HRR recorded during this time interval being minimal.

IV. VALIDATION OF NUMERICAL SIMULATION IN CASE OF SCENARIO 1. RESULTS AND DISCUSSIONS

In the ventilation scenario characterized by the opening of the test room door (scenario S1), the time variation of the HRR parameter was determined using two methods: the numerical simulation method, performed by the Pyrosim program and the mass loss method, the HRR parameter being obtained by calculation. Calculation of the HRR parameter was possible because it is directly proportional to the rate of mass loss of the wood crib, which resulted from the measurement of mass loss.

Figure 5 shows the time variation of the HRR parameter resulting from the simulation using the Pyrosim program, drawn with a blue line, respectively the one resulting from the calculation, following the measurement of the mass loss of the wood crib, drawn with a green line. Based on the results of the HRR parameter time variation obtained from experimental tests compared to numerical simulations, the mean value of the error was calculated, and is equal to 15.04 %. In general, the error value of the HRR parameter in the range ± 15 % and ± 20 % [13, 14] is accepted for most experimental fire tests carried out on a natural scale.

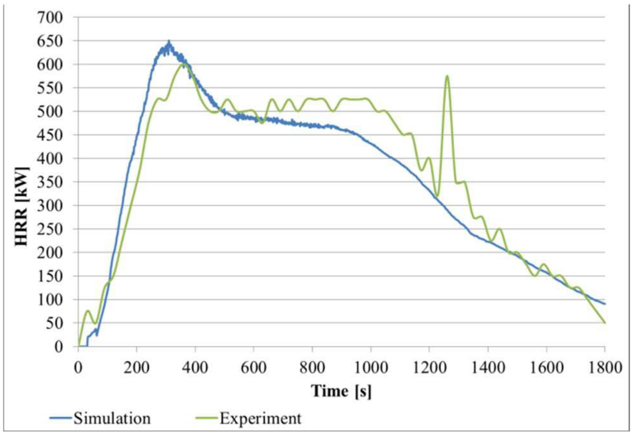

Fig. 5. The time variation of HRR in the simulation compared to that in the experimental test

According to Fig. 5, the shape of the time variation of the HRR parameter curve obtained from the simulation using the Pyrosim program is similar to that obtained from the experimental test carried out on a natural scale.

The main difference is observed in the time interval 1230 s - 1290 s. Thus, the shape of the curve obtained in the simulation is downward, the HRR value decreasing from 331.55 kW, to about 1231 s, to 290 kW, to 1290 s. In contrast, in the case of the experimental test, the curve of the variation over time has an ascending shape, the HRR value suddenly increasing, due to the loss of mass of the wood crib, from 325.07 kW, to about 1229.40 s, to 574.59 kW, to about 1258 s, then suddenly decreasing to 342.11 kW, to 1260 s.

The shape of the Gauss bell obtained in the curve resulting from the experimental test is explained by the fact that, in the time interval 1230 – 1290 seconds, the collapse of the wood crib almost completely takes place.

Thus, according to Fig. 6, from the time of 1230 s measured since the wood crib ignites, a large part of the wood crib center collapses due to the sudden increase in the wood crib mass loss, which leads to an increase in the HRR value.

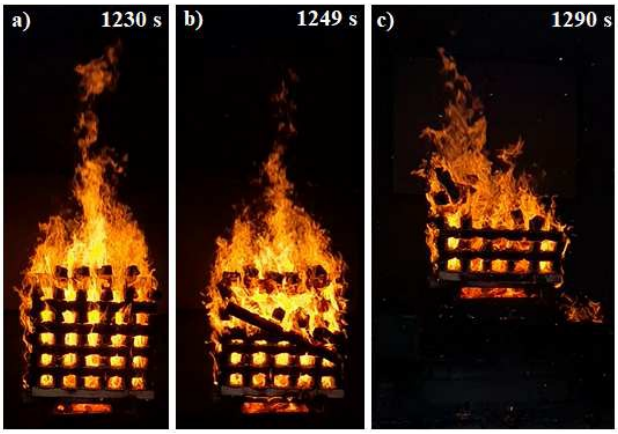

Fig. 6. The moments of wood crib collapse in the case of Scenario 1 - door open: a) the sudden rise of HRR begins; b) the HRR suddenly increases, the maximum value is reached and the wood crib collapses; c) the HRR suddenly drops, and the wood crib continues to dismember [24].

Starting with the time of 1249 s, the wooden sticks that form the outside of the wood crib begin to collapse and the HRR value decreases due to the burning of a large mass of the wood material.

V. CONCLUSIONS

Following seven experimental tests on burning a pine wood crib in a confined space under different ventilation conditions, it was found that these conditions influence the variation in time of the HRR parameter, as follows:

- Achieving the maximum value of the HRR parameter is influenced both by the maximum surface value of the ventilation openings (S4 - 4.80 m^2) and by their type and arrangement (S7 - 2 windows, with a total area of 2.80 m^2, which are arranged on adjacent walls); although in the case of S4 the thermal energy released outside the room was higher compared to S7 due to the larger area of the ventilation openings, the higher oxygen intake in the case of S4 resulted in equal maximum values of the HRR parameter.
- The minimum value of the HRR parameter was reached in the case of S5 and S6, characterized by the minimum value of the ventilation opening area (1.40 m^2).
- The increase in the surface value of the ventilation openings is inversely proportional to the time during which the maximum value of the HRR parameter is obtained due to the higher oxygen intake needed to sustain the combustion.

Five phases of HRR time variation were also identified during wood crib burning: ignition phase, HRR growth phase, steady-state combustion phase, wood crib collapse phase and regression phase.

The time intervals during which the wood cribs collapse under the seven ventilation scenarios are between 1140 s and 1470 s.

Following the comparative analysis of the results obtained in the numerical simulation using the Pyrosim program and the results obtained from the experimental test of burning a wood crib in a confined space, in both methods using the ventilation scenario characterized by the opening of the door, the validation of the fire model was performed. This was achieved by obtaining the mean value of the error of the HRR parameter equal to 15.04 %, the error value of the HRR parameter within ± 15 % and ± 20 % [13, 14] being accepted for most experimental fire tests carried out on a natural scale.

Knowing the variation in time of the HRR parameter is important because it can provide information on the magnitude and intensity of the fire, the speed of its increase, the available evacuation time of construction users and the impact of the fire suppression system.

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