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# An Innovative System for the Evacuation of Smoke and Heat

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## ABSTRACT

*The purpose of this work is to describe an innovative active fire protection device, consisting of a smoke and heat exhaust system. The system consists of a window-wall with openings at the base and at the top, respectively the first for the entry of fresh air and the second for the evacuation of the smoke and heat produced by the fire. This system allows timely intervention before flashover, significantly reducing the risk of personal injury and material damage and increasing visibility and time available for evacuation and rescue operations.*

*The behavior of the smoke and heat exhaust system above mentioned has been studied, both with fire engineering calculation procedures and with an experimental test, in which the system has provided for the evacuation of the combustion products generated by a test fire, consisting of a pile of wood.*

*The system seems to have better performance than traditional ones and it is fully restorable if not damaged by fire.*

*The system covered by this article, while already providing unquestionable positive results, is still in the testing phase and will be subject to future development, carrying out further experimental tests, if necessary.*

**Keywords: Active fire prevention, Natural Smoke and Heat Exhaust Systems, Smoke and Heat Evacuators (EFC)**

## 1. INTRODUCTION

Fire risk assessment is a process by which the level of risk in a workplace is de-fined and the actions and measures to minimize it. In this context, the definition of active protections that make it possible to bring the risk to an acceptable level assumes considerable importance. Active protection devices include Smoke and Heat Evacuators (EFCs). An EFC is an equipment that ensures, in the event of a fire and from a certain moment, the evacuation of the smoke and the hot gases produced by combustion, with predetermined capacity and automatic and/or manual operation [1]. An EFC allows facilitating the exodus of the people present and the action of the rescuers making their operations more effective. It is able to protect, in addition to people, also structures and goods against the action of smoke and hot gases, reducing the risk of collapse of the supporting structures. Finally, it delays or even avoids the fire in full development (flashover). Generally, EFCs are used in combination with fire detection systems and based on the exploitation of the natural upward movement of the masses of hot gas generated by the fire, which, by means of openings on the roof or on the walls, are evacuated to the external. The EFC is composed of base and fixing elements to the roof, mobile closing elements, opening devices. The installation of EFCs is made in such a way as to ensure, in the event of a fire, the escape of smoke and heat to prevent the room from being full of smoke. During a fire, the operation of the EFCs should ensure also that a smoke-free area is maintained for a time sufficient to evacuate the occupants. This smoke-free area must be close to the floor, with a height of at least half of that of the room and in any case not less than 2.5 m, in accordance with Italian technical standard UNI EN 9494.

The purpose of this article is to describe an innovative Natural Smoke and Heat Exhaust System (NSHES), covered by an international patent, installed in a closed construction module, in which, in the event of a fire, a sensor controls the activation of the system. When the NSHES is activated, its windows are opened simultaneously, both those located in the upper part, for the evacuation of smoke and heat, and those located in the lower part, for the introduction of air from the outside. A sensor placed on the ceiling detects the temperature and, when it reaches 64°C, unlocks an electromagnetic lock and activates a mechanism, capable of sliding the two windows of the frame-wall, both the lower and the upper one.

With this system you will get the opening of the lights of the two compartments corresponding to the two translated parts, through which cold air can flow from the bottom and at the same time hot air will flow from the top, together with the gases and smoke that in the propagation phase piled high. The behavior of this smoke evacuation system was studied, first, with the methods of fire engineering, then with a simulation software for confined fires and, finally, through an experimental test, carried out with the assistance of the Italian Fire and Rescue Service. In this test, the system evacuated the combustion products generated by fire of a standard pile of wood.

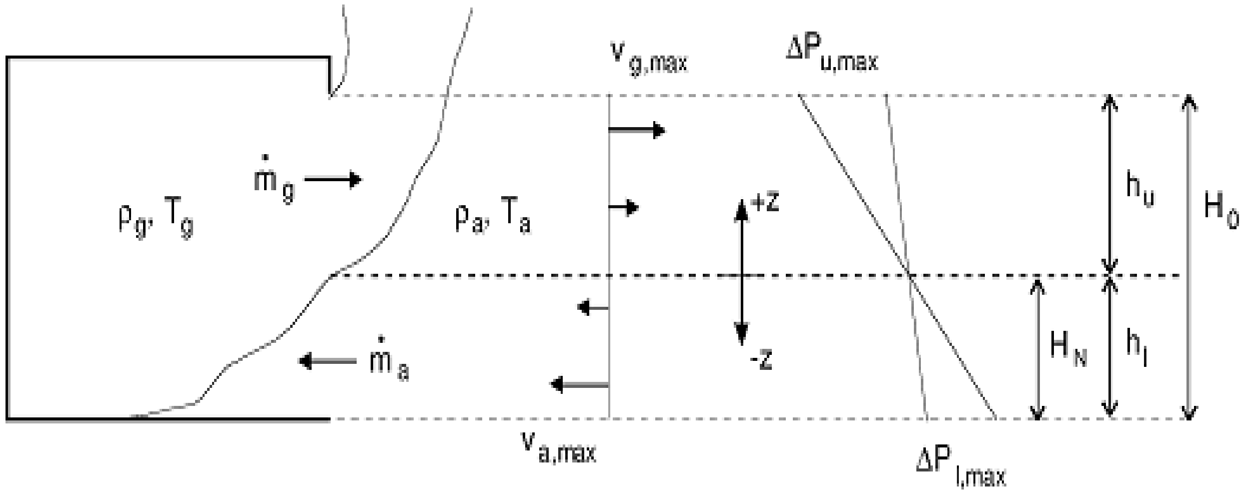


**Figure 1: Fluid dynamic description of system operation from flashover onwards**

The system studied in this work allows to intervene promptly, before the flashover occurs, reducing the risk of personal injury and material damage, increasing the time available for evacuation and for rescue operations. It also prevent the glass windows from exploding, since the internal temperature will not reach 400°C and facilitating the action of the rescuers, since the immediate entry of cold air will present the rooms not full of smoke and therefore visible. After carrying out the described function, if there have been no structural changes, the system can also be restored independently, simply having to return the elements to their original position.

The device allows ensuring the presence of openings in the lower part of the room, essential to ensure the flow of fresh air and, therefore, the correct functioning of the NSHES. This creates a fluid dynamic balance that stabilizes the height of the neutral plane, with a consequent increase in its height compared to the floor (see Figure 1). This effect, which has been verified, has evident beneficial consequences in the exodus phase. Other systems available for creating the same openings, such as the presence of sub-windows and curtains, do not appear to be as efficient as the innovative system under consideration.

## 2. SYSTEM DESCRIPTION

The object of the experimental test was a modular product in steel sections (see Figure 2), equipped with the previously illustrated NSHES, of dimensions 3.60x3.60x3.00 m, whose walls and ceiling are made up of a double layer of fire-proof plasterboard panels.

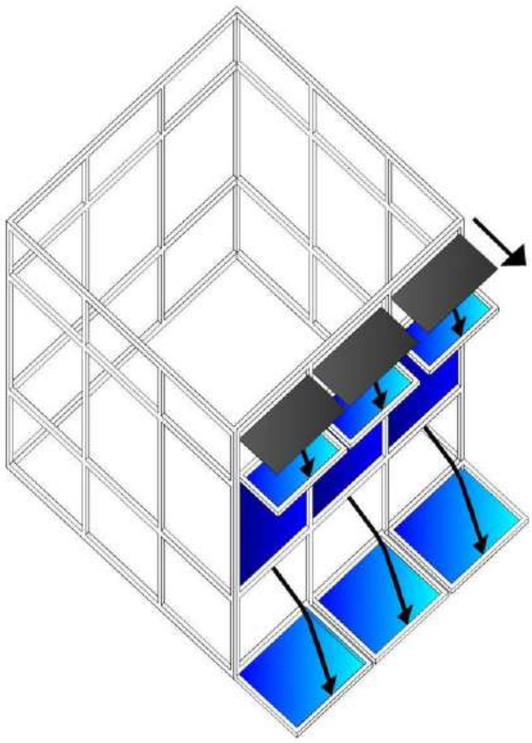

**Figure 2: The proposed smoke and heat evacuation system**

At the center of the floor of the building is piled a $g_{tot}$ quantity of wood [2], equal to about 85 kg and having a lower calorific value H = 17.5 MJ/kg.

The woodpile is of the type according to Italian technical standard UNI EN 3-7 and the resulting fire can be assimilated to the fire of a sofa [3].

The ventilation openings, part of the NSHES and present only on the facade, consist of:

- three openings 1.01x0.35 m in size, all with the sill placed 2.60 m above the ground;
- three openings 1.01x0.81 m in size at ground level.

## 3. EXPERIMENTAL TESTS AND CALCULATIONS

The experimental test was carried out using as sensors: 1 thermocouple for measuring the external temperature and 20 type K thermocouples mounted on two vertical pylons placed near one of the openings and the other of the woodpile, with 10 thermo-couples each, placed at 25 cm intervals, starting from 50 cm from the floor (therefore the highest thermocouple is located 2.75 m from the floor). The experimental evidence included two tests:

TEST01: ignition of the woodpile with all ventilation openings closed, up to 64°C near the upper openings, then simultaneous opening of both the upper and lower windows, with continuation of the test until complete ignition of the entire woodpile, waiting for a suitable interval of time and finally switching off with fire extinguishers (the test simulates the operating conditions of the system);

TEST02: ignition of the woodpile with all ventilation openings closed and maintenance of this condition until the flames are extinguished with consequent hatching fire scenario, then opening only of the upper windows with fire development up to possible flashover and finally extinguishing with fire extinguishers (the test simulates the operation of a smoke evacuation system similar to the system under test, but without the lower ventilation openings).

From the literature values, a wood stack like the one we are talking about can be considered characterized by $t_g$ = 200 s (growth time, necessary for the thermal power released to reach the value of 1000 kW) and from this data it is possible to deduce the value of the growth rate α [1]:

$$\alpha = 1000/t_g^2 = 1000/200^2 = 25 \cdot 10^{-3}\ kJ/s^3$$

The development of an evolving fire within a confined environment depends on the value assumed by the ventilation factor O (Opening factor), since it affects the maximum combustion speed (kg/s) that can be achieved and allows to determine if the fire is controlled by fuel or ventilation. The opening factor can be calculated with the following equation, expressed in $m^{0.5}$:

$$O = (A_v \cdot h_{eq}^{0,5})/A_t$$

where $A_t$ is the total area of the compartment, $A_v$ is the surface of the ventilation openings obtained on the walls and $h_{eq}$ is the equivalent height, given by the weighted average (based on the surfaces) of the heights hi of all the ventilation openings present in the walls. For the two tests, the values of the quantities shown in Table 1 are obtained.

**Table 1. Main quantities calculated for the two tests**

| | TEST01 | TEST02 |
|---|---|---|
| $A_t$ | 69.12 $m^2$ | 69.12 $m^2$ |
| $A_v$ | 3.61 $m^2$ | 1.09 $m^2$ |
| $h_{eq}$ | 0.69 m | 0.36 m |
| O | 0.043 $m^{0.5}$ | 0.009 $m^{0.5}$ |

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Since O < 0.06 ÷ 0.07, the development of the fire is controlled by ventilation in both tests [1]. Flashover is only possible if the fire releases a minimum $RHR_F$ value, which can be calculated (in kW) from the Walton-Thomas relationship contained in the NFPA 555 standard [3]:

$$RHR_F = 7{,}8 \cdot A_T + 378 \cdot A_{Vequiv} \cdot \sqrt{h_{Vequiv}}$$

where $h_{Vequiv}$ is the difference between the highest and lowest point among all the ventilation openings present (3 m in our case), $A_{Vequiv} = W_{Vequiv} \cdot h_{Vequiv}$, where $W_{Vequiv}$ is the width of an equivalent opening for the purpose of flashover and $A_T$ is the difference between the total area of the $A_t$ compartment and the $A_{Vequiv}$ area. The total energy in the compartment is worth:

$E_{tot} = g_{tot} \cdot H = 85$ kg · 17.5 MJ/kg = 1487.5 MJ

where $g_{tot}$ is the mass of fuel and H its lower calorific value. If $E_{tot} >> RHR_F$ is found, the flashover could be theoretically reached and, in this case, the fire would release the maximum and constant value of the thermal power $RHR_{max}$. This theoretical condition is verified for TEST01 and TEST02, but during the experimental tests, it was found that the flashover conditions occurred only during TEST02. In fact, the temperatures measured in the area close to the ceiling in TEST01 reached 550°C only near the fire, remaining largely lower near the windows, while the same temperatures in TEST02 exceeded 850°C near the fire and 650°C near the windows. This experimental evidence confirmed:

- the proper functioning of the device under test, which in real operating conditions, i.e. those of TEST01, kept the room free of combustion products and averted the occurrence of flashover;
- the fact that a similar device, which however cannot guarantee the opening of fixtures in the area near the floor, to allow the entry of air from the outside, is not able to offer adequate protection from the consequences of fire, which actually reaches full development conditions.

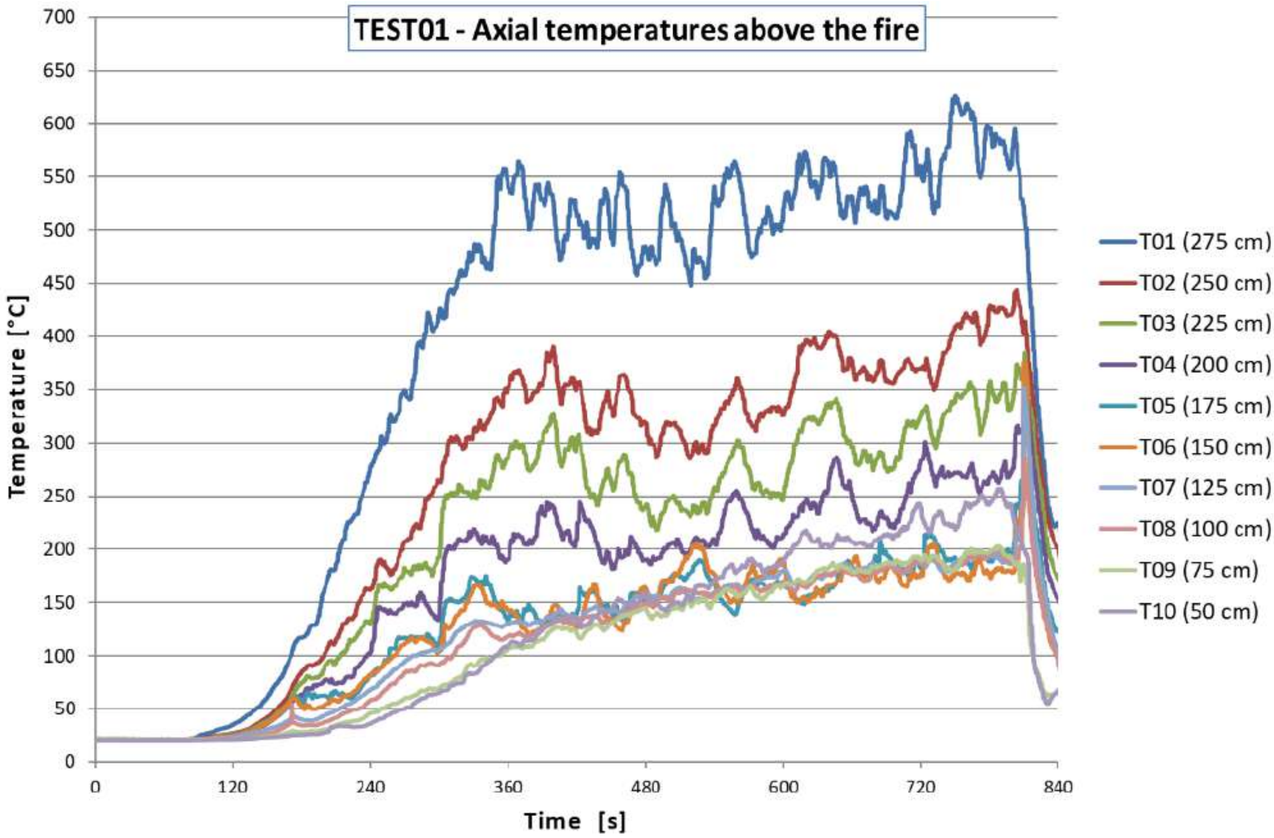


**Figure 3: TEST01, temperatures along the vertical axis near the test fire site**

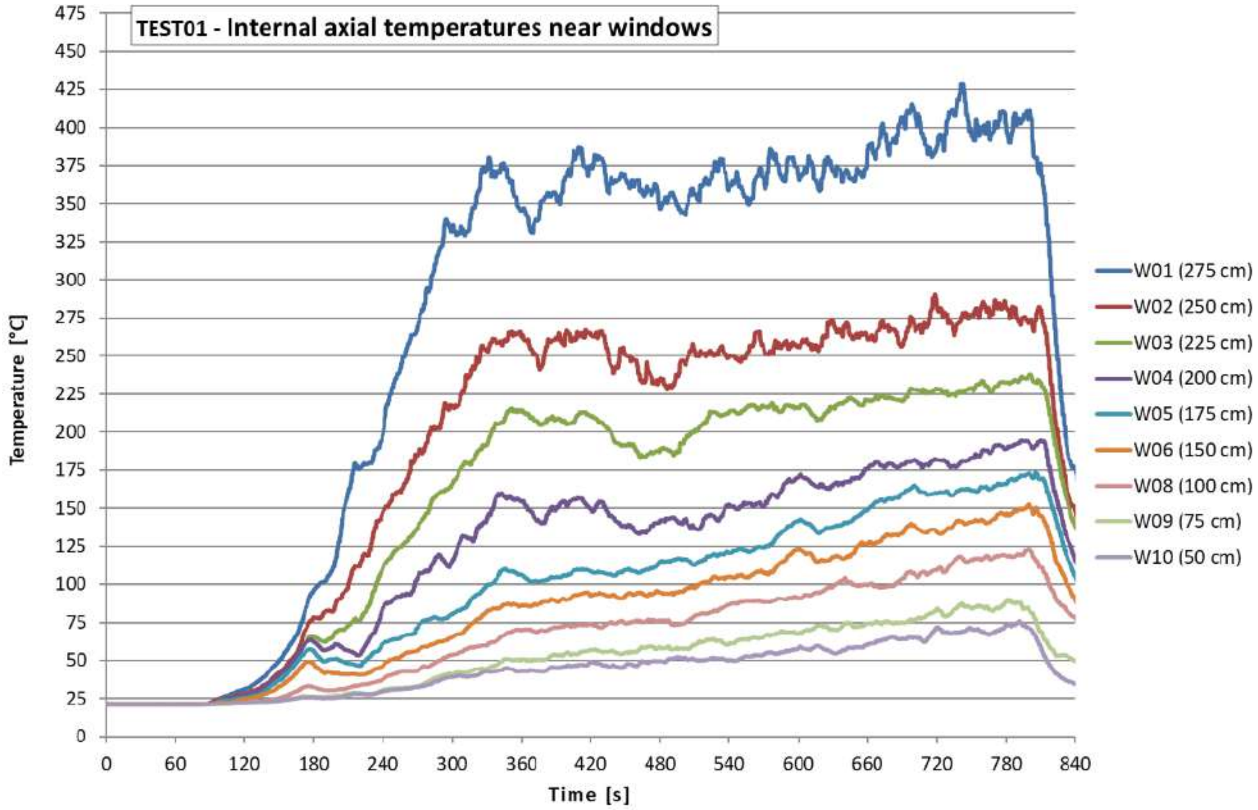


**Figure 4: TEST01, temperatures along the vertical axis near the upper window.**

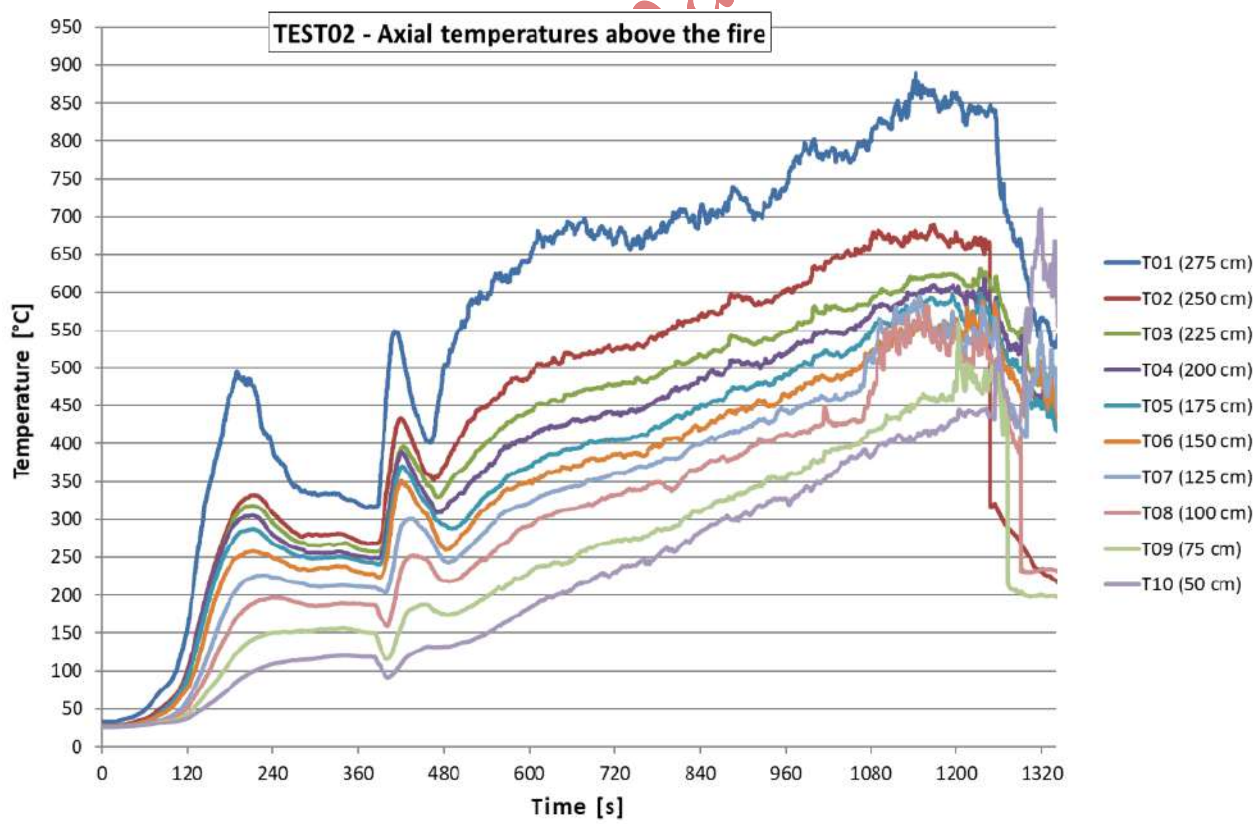


**Figure 4: TEST02, temperatures along the vertical axis near the test fire site**

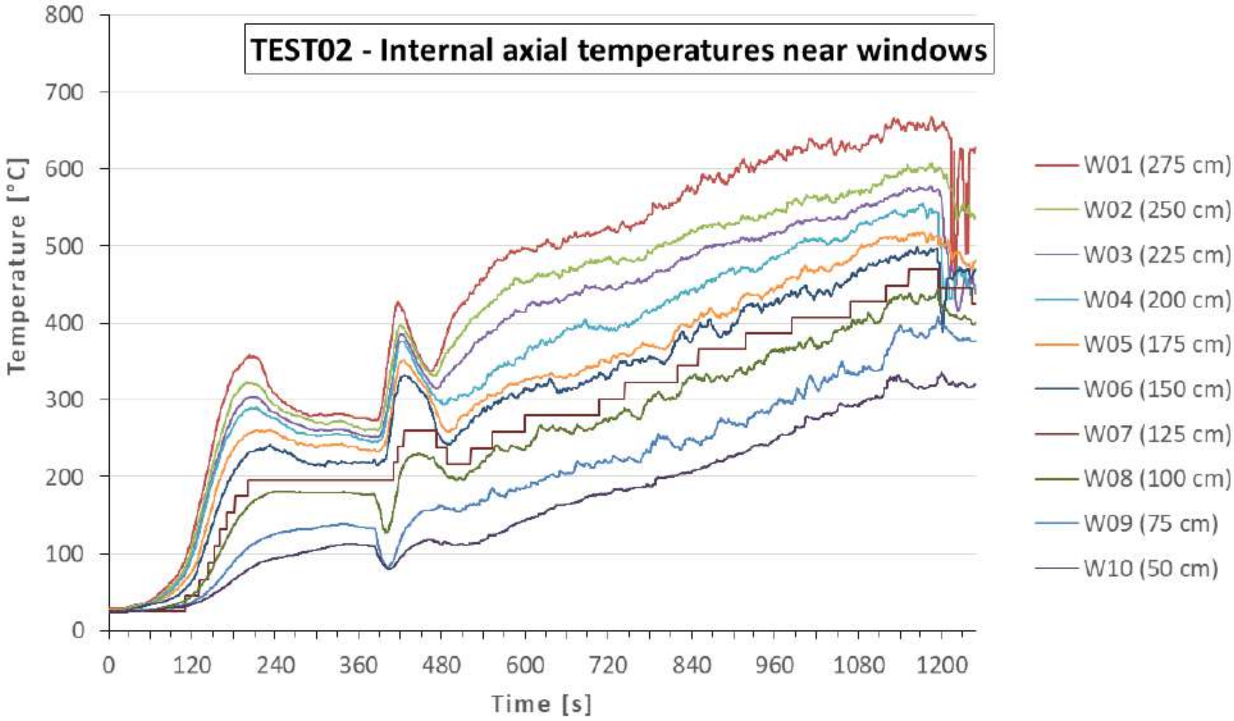


**Figure 4: TEST02, temperatures along the vertical axis near the window**

Instead, using the expression contained in European standard EN 1991 1-2:

$$RHR_{max} = 0.1 \cdot m \cdot H \cdot A_v \cdot \sqrt{h_{eq}}$$

and by imposing a combustion participation factor m of 0.8, the theoretically released maximum thermal power is calculated, equal to 4.19 MW for TEST01 and 0.92 MW for TEST02.

Specifically, during the TEST01, with the disposal system in the fully open position, it was found that all smoke produced was evacuated. The time interval analyzed ranges from the ignition of the woodpile (the instant in which the first flames appear on it) at the start of the extinguishing operations, therefore it does not include the time required for the ignition of the woodpile (assessed at the time test in about 2 minutes), nor the time taken to extinguish the fire. After about 91 s from the trigger, the highest thermocouple near the fixtures measured the temperature of 64°C and the upper and lower fixtures were opened. The temperature detected near the window, at a height of 1.75 m from the ground provides a valid indication of the air temperature inspired by an occupant of the building during the fire. The temperature of 60°C, which is the maximum for breathable air in order not to cause serious damage to the respiratory tract, based on the data collected, is reached and exceeded in about 167 seconds, near the window. Therefore, based on the aforementioned parameter, the maximum time for evacuation is 167 seconds from the appearance of the flames (also counting the ignition time, at least two more minutes would be available). Concerning the height of the smoke layer, at the theoretical level, the following equations were used [1]:

$$m_g(t) = 0{,}124 \cdot RHR^{0{,}242}(t) \cdot Y^{1{,}895}(t)\,[kg/s]$$

$$Y(t_i) = h - V_g(t_{i-1})/A\,[m]$$

$$\rho_g = \rho_a \cdot T_a / T_g\,[kg/m^3].$$

The second of these three equations, valid for rooms without openings, in the presence of openings becomes [1]:

$$Y(t_i) = h - [V_g(t_{i-1}) - V_u(t_{i-1})]/A\,[m]$$

where t is the time, $m_g$ is the mass flow rate of smoke and gas produced by combustion, h the height of the room, A its surface in plan, Y the height from the ground of the smoke layer, $\rho_g$ and $T_g$ are the average density and temperature of the smoke layer, while $\rho_a$ and $T_a$ those of the ambient air. From the previous equations, applied iteratively, between successive instants, it appears that the environment being tested is saturated with smoke in 90 s, and – in case of subsequent opening of the fixtures – the layer of smoke moves upwards, but not enough to ensure occupant safety. Both of the above phenomena actually occurred during TEST02, however, during TEST01, after the opening of the upper and lower fixtures, the layer of smoke was observed to rise rapidly from ground level, at which it was after 90 seconds from the start of the test, to stabilize at a height of more than 2 meters. Another parameter taken into consideration is the concentration of carbon monoxide present in the room. Considering the achievement of a 30% concentration of carboxyhemoglobin in the blood, a respiratory activity of 23 l/min, a mass yield (in kg of CO per kg of burnt fuel) equal to 0.004 and a constant concentration of CO in the room and equal to the maximum reached in the first 100 seconds of the test, around 500 ppm [3], a very wide margin of time is obtained for both TEST01 and TEST02, before it is reached the aforementioned threshold. This result, although positive, in terms of time for the evacuation of the occupants, does not necessarily entail their safety, because it does not take into account neither the hyperventilating effect, due to the presence of carbon dioxide produced by the fire, nor the presence of particles suspended in smoke, which reduce visibility and irritate the eyes and the respiratory tract.

Finally, the irradiation caused by the flames present on the woodpile in the early stages of the fire was assessed. This parameter is important, because the radiation generated by the layer of smoke and hot gases assumes important values only in the advanced stages of the fire, while that due to the flames can be dangerous for the occupants already in the early stages, especially at close range, as in the case under consideration. For the estimate of the radiation due to the flames, this known equation can be used [5]:

$$q = \phi \cdot \varepsilon \cdot \sigma \cdot (T_e^4 - T_r^4).$$

In this equation, q is the heat flux in W/m$^2$, affecting the receiving surface, Φ is the configuration factor, which assumes a value ranging from 0 to 1 in relation to the geometry and mutual position of the two emitting and receiving surfaces, ε is the resulting emissivity, between 0 and 1 and depending on both the efficiency of the emitting surface and the emissivity of the receiving surface, σ is the Stefan-Boltzmann constant, equal to 5,67 · 10$^{-8}$ W/(m$^2$·°K$^4$) and $T_e$ and $T_r$ are respectively the temperatures in °K of the emitting and receiving surfaces.

A simple method to calculate Φ, which we used in this work, is to use the area of the emitting surface, approximated to a rectangle having a base and a height equal to the thickness and height of the flame, divided by the product between π and the square of the distance between target and source.

For the resulting emissivity ε, the following equation can be used [5]:

$$\varepsilon = 1 - e^{-K \cdot D_f}$$

where $D_f$ is the thickness of the flame and K a parameter dependent on the type of fuel, which is 0.8 for wood. During the test, the temperature was measured near the flame, but not exactly above the flame, where it will be necessary to estimate the temperature in an approximate way. During TEST01, at the instant of opening of the windows (t = 91 s), the flame reached a thickness of about one meter and a height of about 90 cm. At the instant of window opening, considering $T_r$ equal to 21°C, the temperature $T_e$ of the flame (estimated at half its height, in the intermittent region of the plume) equal to at least 750°C (McCaffrey B.J., 1979) [5] and inserting the values obtained in the above mentioned expression of q, we obtain for it:

- 1.6 kW/m$^2$ for an occupant who is in a corner of the manufactured object being tested;
- 2.6 kW/m$^2$ for an occupant who is adjacent to a wall halfway along its length.

The first of the two values obtained is close to the threshold value for a person without protection, equal to 2.5 kW/m$^2$, while the second is even higher than the threshold. In general, given the dependence on the thermal power released, which grows over time with a quadratic trend, in the moments following the window opening, the conditions will actually become rapidly critical for any occupants, due to the progress of the fire [4].

## 4. POSSIBLE IMPROVEMENTS OF THE SYSTEM

It is possible, however, to identify improvement measures, which are simple to implement, to ensure the safety of the occupants, for a short period, in any case sufficient to ensure the exodus. A solution in this regard may consist in enslaving the opening of the fixtures to a temperature sensor with a lower threshold than that established for the test and located not near the window, but on the ceiling in the center of the room, or to a detector of smoke, installed in the same position. The result that would be obtained by adopting the aforementioned solution consists in an early opening of the fixtures belonging to the NSHES, compared to what occurred in the first experimental test (TEST01), with a consequent improvement in the conditions for the occupants starting from the instant of opening of the fixtures. The improvement consists in a decrease in the growth of temperatures measurable at different heights, more accentuated in the lower area of the room and due both to the evacuation of smoke and hot gases, and to the flow of fresh air from outside. To get an idea of the exodus times, let us assume the door located on the opposite wall to that of the windows and the presence of an occupant, who is inside the room, in the corner farthest from the exit. The occupant should walk $3.6 \cdot 2 = 7.2$ m to get to the exit and, considering a speed of 1.2 m/s (normal value, for uncrowded venues), it would take 6 s, plus the time to open the door, estimated in about 4 s, counted from the moment of the activation of an alarm and the simultaneous opening of the windows.

## 5. CONCLUSION

The system covered by this article, while already providing unquestionable positive results for the structures on which it is installed in the event of a fire, it can be easily improved, in terms of occupant safety, also due to its simplicity, modularity and cost-effectiveness. It is still in the testing phase and will be subject to future development, carrying out further experimental tests, if necessary. The system described in this work is covered by an international patent.

## 6. ACKNOWLEDGMENTS

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## 7. REFERENCES

[1]. A. La Malfa, S. La Malfa, Approccio ingegneristico alla sicurezza antincendio. Roma (IT): Legislazione Tecnica, 2014, ISBN 978-8862191814.

[2]. P.G. Smith, P.H. Thomas, The rate of burning of cribs of wood, in Fire Research Notes n.728, Borehamwood (UK): Fire Research Station, 1968.

[3]. SFPE Handbook of Fire Protection Engineering, 3rd ed. Quincy, MA, National Fire Protection Association, 2002, ISBN 978-0877654513.

[4]. Drysdale D., An introduction to Fire Dynamics. Hoboken, NJ: John Wiley & Sons, 2011, ISBN 978-0470319031.

[5]. B. Karlsson, J. G. Quintiere, Enclosure Fire Dynamics, 2nd ed.. Boca Raton, FL: CRC Press, 2020, ISBN 978-1-138-05866-8.