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A PILOT STUDY ON HYPOXIC AIR PERFORMANCE AT THE INTERFACE OF FIRE PREVENTION AND FIRE SUPPRESSION

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ABSTRACT

Even fire suppression is not acceptable in applications where a fire, although suppressed quickly, would cause unacceptable damages. In these cases fire can be prevented rather than suppressed by using hypoxic air. Due to limited research on fire prevention techniques, pilot studies are made to establish the facts, available test methods and performance of present options as well as identifying the less researched areas. Hypoxic air technology for fire prevention is based on a continuous reduction of the oxygen in the protected enclosures in order to limit the oxygen availability to the combustion process: typically a small amount of the oxygen in the air is replaced with nitrogen. The effect of low oxygen concentrations on the combustion process is investigated by a literature survey of the existing pertinent sources. An overview of ignition property test methods is made and a recent test method to assess the performance of a hypoxic air fire prevention system is discussed. The borderline performance of hypoxic air systems is explored by means of a test series which include reference tests of known ignitable specimens as well as new materials, configurations and applications.

INTRODUCTION

Hypoxic Air Technology (HAT) is an innovative and simple fire preventive technology based on a permanent reduction of the oxygen concentration in the protected rooms. Unlike traditional systems, HA prevents and does not suppress fire: this feature makes HAT unique in the panorama of firefighting systems. In a room protected by hypoxic air (HA), a normobaric hypoxic atmosphere is continuously retained: hypoxic means that the partial pressure of the oxygen is lower than at the sea level, normobaric means that the barometric pressure is equal to the barometric pressure at the sea level. Usually a certain amount of oxygen molecules contained in the air is replaced by the same amount nitrogen molecules to obtain this normobaric hypoxic atmosphere: as a consequence an air mixture containing usually 14 -15 vol% of O_2 and 85-84 vol% of N_2 is created. In a normobaric hypoxic environment, common materials like plastic or wood cannot ignite or burn. Thus, considering the well-know fire triangle a fire cannot occur because of the lack of oxygen. HA can also be used for fire suppression, like traditional inert gas systems, but in this case oxygen concentration shall be consistent with the values applicable to inert gas extinguishing systems.

PREVIOUS RESEARCH

Effects of low oxygen concentration on ignition and combustion

It is well known that every material has its own minimum oxygen concentration, MOC, above which combustion is not possible, independent of fuel concentration. The MOC values

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depend on the diluent used: if the diluent is N_2, and this is the case of HA, then the MOC can be predicted by the formula:

$$MOC = LFL \cdot \frac{1}{4.77} \cdot \left(\frac{100}{C_{st}} - 1 \right)$$

where LFL is the lower flammable limit [%vol] and C_{st} is the stoichiometric oxygen/fuel concentration [%vol]. A similar relation can be found when calculating the MOC of dust clouds: in this case the LFL is measured in [$g \cdot m^{-3}$] and the elemental composition of the fuel is normally reported as mass-fractions. Lowering the oxygen level below the MOC of a certain substance prevents combustion and explosion of that substance.

Oxygen concentration, m_{oxygen} affects the ignition time. A theory by Mc Alevy et al. (1960) says that the ignition time, t_{ign}, depends on the oxygen mass fraction as $t_{ign} \propto m_{oxygen}^{-2/3}$. Kumar and Hermance (1972) did a theoretical study of propellant ignition and their results show that ignition time and oxygen concentration are related as $t_{ign} \propto m_{oxygen}^{-n}$, where $1 \leq n \leq 2$ for $m_{oxygen} \geq 0.2$ and $n \rightarrow 0$ for $m_{oxygen} \leq 0.2$. Mikkola (1993) tested six different materials at 21% and 15% oxygen level with a heat flux of 50 kW/m^2: PVC showed an average of 300% increased ignition time in 15 vol% O_2 compared to 21 vol% O_2 whereas PMMA an average of 24% increased ignition time. Hirsch (1998) observed for an intumescent FR PUR foam and a PVC/acrylic copolymer that once oxygen concentration approaches their MOC, ignition times increase drastically. Similar results were reported for silicone elastomers by Hshieh (1997). Like in many other studies about ignition, it was not investigated what happened after ignition, i.e. if materials continued burning or self-extinguished

Oxygen concentration affects autoignition as well: a theoretical analysis done by Kashiwagi (1974) shows there to be a limiting value of m_{oxygen} needed for successful autoignition: this value depends strongly on the problem, but is commonly around 0.15. For m_{oxygen} just slightly higher than this minimum value, there is a very narrow area where autoignition time goes from infinite to a very low value, as m_{oxygen} is raised slightly. For further increases in m_{oxygen}, the autoignition time (AIT) is little affected by m_{oxygen}, dropping about 15% as m_{oxygen} goes from 0.23 to 1.00. Alvares (1970) found a similar behavior in experimental studies on thin cellulose sheets. His results show that for an oxygen partial pressure, P_{oxygen}, greater than about 0.18 atm there is a slight effect going as $t_{ign} \propto P_{oxygen}^{-0.25}$. If the oxygen partial pressure is decreased below 0.18 atm, ignition times become drastically prolonged and ignition becomes impossible once the partial pressure drops below around 0.16 atm. Experiments on AIT for gases show that decreasing the oxygen concentration generally raises the AIT and this effect can be explained by the formula:

$$AIT \propto \frac{e^{E/RT}}{[O_2]^n}$$

where $[O_2]$ is the oxygen concentration in [vol%], R is the universal gas constant, T is the temperature in [K], E is the activation energy in [kJ/mol] and n is a constant whose value goes from 0.25 to 2.

Increasing oxygen concentration lowers the minimum ignition energy (MIE). Experiments on gases show that the MIE is proportional to the Oxygen Index, OI as $MIE \propto OI^{-n}$, where $OI = O_2/(O_2 + N_2)$. Chin (1983) proposed n=4, whereas Lewis and Von Elbe (1949) proposed $n = 2.5$ for propane.

The mass loss rate, MLR, is affected by oxygen concentration: Tewarson (1975 and 1983) and Santo (1979) observed that the mass loss rate decreases significantly with decreasing ambient oxygen concentration. For some materials Babrauskas (1992) reported that it was found a linear relationship between m_{oxygen} and the mass loss rate per unit surface area, MLR" = $a \cdot m_{oxygen} - b$, where a and b are constant. This relationship remains linear down to the lowest oxygen mass fraction value at which combustion is sustained. For other materials, especially charring ones, however, this linear relationship levels off at higher m_{oxygen} values.

Babrauskas (1992) reported that the flame spread velocity, V, is related to m_{oxygen} in a power law relationship: $V \propto m_{oxygen}{}^2$. This relationship is valid only for large m_{oxygen} values; for lower values the dependence of the flame spread velocity becomes progressively greater, approaching an infinite-slope asymptote at the m_{oxygen} value at which extinction occurs. Other studies, however, support the belief that this relationship would be more precise replacing the second power of m_{oxygen} with the first power.

Mulholland (1991) studied the heat release rate of some materials, decreasing from ambient 20.9% oxygen concentration to the lowest concentration at which sustained combustion could be achieved in an enclosed Cone Calorimeter. For thermoplastic materials the heat peak decreases a lot if the oxygen mole concentration is lowered and this effect is progressively greater at lower oxygen concentrations. For the one charring material tested, Douglas fir, the dependence is very slight, with a linear proportionality.

Experiments on flammability of combustible materials in a reduced oxygen environment have also been performed by Xin and Khan (2007). Their article describes a method to find the LOC for suppression and re-ignition. The method fits well to the scenario that occurs when HA is used not to prevent fire, but to suppress it. The oxygen concentration is lowered once the ignition source has been applied, the external radiant flux (0 – 65 kW/m^2) and the constant artificial air flow (100 l/min) represents well the conditions of a flaming fire. The article provides LOC values for fire extinction of some materials: these values are relevant to those used while designing inert gas extinguishing systems, but substantially lower than those applicable for fire prevention. For example the LOC for extinction of PMMA and corrugated paper are respectively 10.48 Vol. % and 12.94 Vol. %, whereas, according to VdS 3527:2007, the values applicable to prevent ignition of such materials are respectively 14.90 vol% and 14.00 vol%. The article demonstrates a substantial difference between the LOC values for extinction with horizontal configurations and vertical configurations as well a theoretical method to assess the change of LOCs at low temperatures.

Discussion

Based on these results, it can be inferred that HA, after a careful assessment of the exact oxygen concentration required in the protected volumes, can have several benefits with regard to the ignition and combustion processes: longer ignition time, higher MIE, lower flame spread velocity and reduced MLR. But, if HA were used as a fire suppression system, the oxygen concentration should be consistent with the values used to design inert gas extinguishing systems.

TEST METHOD TO ASSESS HYPOXIC AIR PERFORMANCE

Test enclosure

Experiments were conducted in an enclosure with a volume of 10.35 m^3 and a height of 2.3 m. The enclosure was provided with an adjoining air lock vestibule in front of the entrance to limit air infiltration (see figure 1). The air lock vestibule had the same height of the test enclosure, a width of 2.5 m and a length of 1 m. The test enclosure was fitted with a smoke extractor fan and with a door and two observation windows to allow observation of the fire tests (see figure 2). Door and windows were sealed with smoke sealant to limit air infiltrations. The test enclosure is located at SINTEF NBL, Trondheim, Norway.

Figure 1: The test enclosure and the air lock vestibule.

Figure 2: The test enclosure. The door and the observation windows allow observation of fire tests from three different sides.

Instrumentation

The oxygen concentration inside the test enclosure was lowered and kept constant by means of three nitrogen generators providing hypoxic air with residual oxygen content varying from 5 vol% to 11 vol%. Hypoxic air inlet was spaced 1.0 m away from the test specimen. The enclosure was equipped with three oxygen sensors located at three different height of the enclosure (0.2 m, 1.0 m and 2.2 m) to ensure that the oxygen concentration remained homogeneous at any height of the room. The oxygen sensors were disposed in a vertical array, 1 m away from the test sample on the opposite side to the torch. Oxygen sensors had a sensitivity of 0.01 vol%. An oxyacetylene premixed pilot flame (approximately 0.3 m long) was spaced 0.2 m away from the specimen and approximately 0.025 m inwards from the edge of the specimen to ignite. A calibrated scale measured the loss mass of the specimen throughout the test. The sensitivity of the scale was 0.00001 kg. A heavy-gauge steel wire mesh frame was installed inside the room to support vertical test samples and a heavy-gauge metal-frame table with wire mesh to support horizontal samples. Video-recording equipment was set to record each test for a review after the test completion. Figure 3 shows the experimental set-up.

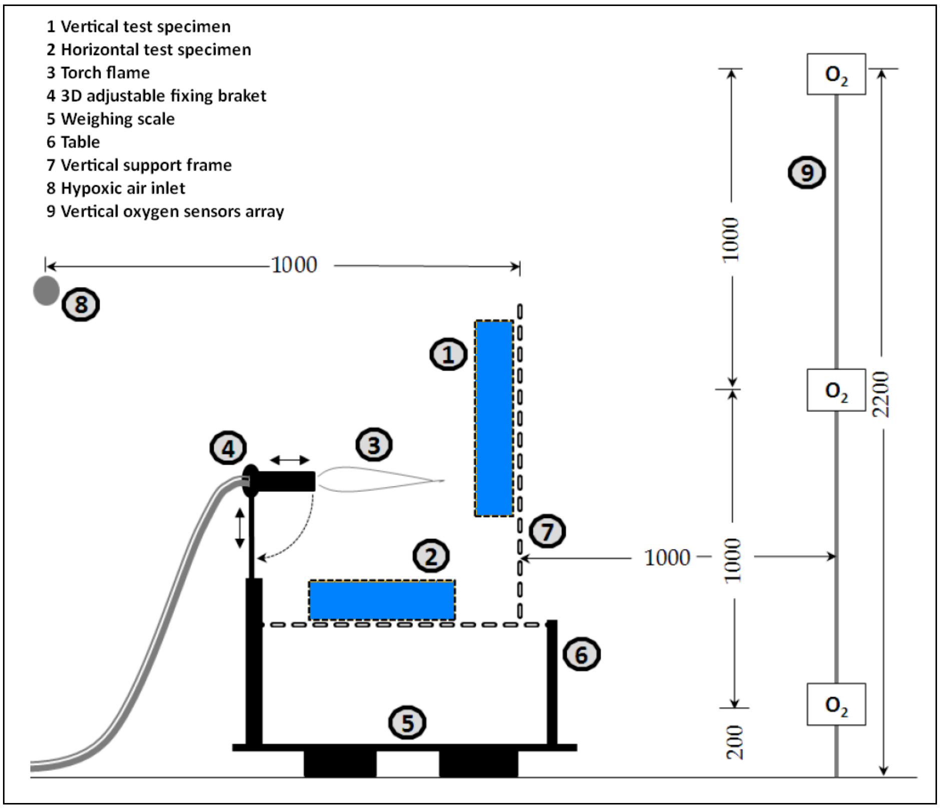

Figure 3: Experimental set-up for ignition test, horizontal and vertical configurations.

Experimental procedure

Three different test methods were carried out: ignition test with horizontal configuration, ignition test with vertical configuration and flame spread test. The test method aimed to create the conditions that represent real applications protected by HA system. This means that the test enclosure was filled up with hypoxic air before the pilot flame was applied, the oxygen concentration remained constant throughout the test, no significant air draft was reported inside the enclosure, common specimens that usually are present in real applications were used, the room temperature was around 20 ºC, there was not pressure difference to the outside and the specimens were not exposed to any external heat flux.

In the ignition test with horizontal configuration, the specimen was placed on the metal-frame table and fixed in a horizontal position. Then the unobstructed length of the oxyacetylene flame was set to 0.3 m and hit a lateral side of the test specimen for 180 s (flame exposure time, FET). Visual observations were made during the FET to see whether self-sustained burning or spread of fire were observed on the sample beyond the area directly hit by the torch flame. The specimen was observed for a further period, at least 60 s (post exposure time, PET), to see whether it continued to produce flames independently of the pilot flame (self-sustained burning or spread of fire). The mass of the test specimen was recorded throughout the test (FET and PET) with the calibrated scale.

In the ignition test with vertical configuration, the specimen was fixed in the vertical position on the metal-frame. Then the unobstructed length of the oxyacetylene flame was set to 0.3 m and hit a lowermost corner of the vertical specimen for 180 s (FET). Visual observations were made during the FET to see whether self-sustained burning or spread of fire were observed on the sample beyond the area directly hit by the torch flame. The specimen was observed for a further period, at least 60 s (PET), to see whether it continued to produce flames independently of the pilot flame. The mass of the test specimen was recorded throughout the test (FET and PET) with the calibrated scale.

The ignition test method is consistent to those ones described in BSI PAS 95:2011 and VdS 3527:2007: these are acknowledge methods to assess the ignition-limiting oxygen threshold for solid materials contained in rooms to protect with HA.

The flame spread test aimed to represent the situation that occurs when an item ignites and flames spread to adjacent items: this is a scenario that is likely to happen in storage rooms or in server racks. In the flame spread test a vertical array of three test specimens was arranged; the space between two specimens was 10 cm. Then an oxyacetylene pilot flame was set so that the unobstructed length was 0.3 m and hit a lowermost corner of the bottom specimen for 180 s. Visual observations were made to investigate whether the flames spread to the other two specimens arranged above the specimen directly hit by the pilot flame (see figure 4). The mass of all specimens was recorded before and after the test.

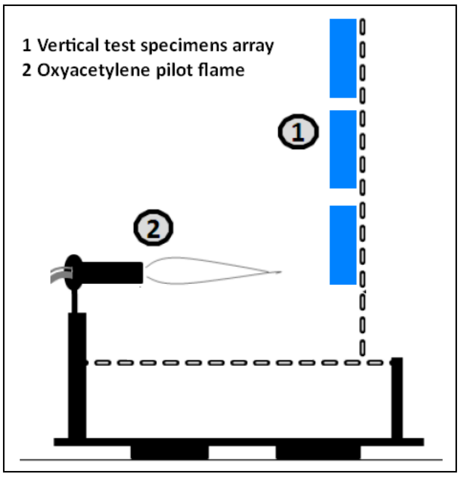

Figure 4: Experimental set-up for fire spread test.

Results and discussion

The first material tested was polypropylene (PP). The oxygen ignition threshold of PP is set to 16.0 vol% according to VdS 3527:2007. The test specimen was a box with a length of 37 cm, a width of 25, and a height of 12 cm. The first test was an ignition test with horizontal configuration and it was carried out with an oxygen concentration inside the test room of 16.0 vol%. Then it was decided to perform a second test with the same configuration, but with an oxygen concentration of 17.9 vol%. A third reference test was performed in normal air, i.e. with an oxygen concentration of 20.9 vol%. Results from visual observations of this first set of tests are resumed in table 1. The graph that charts the mass loss throughout the tests is shown in figure 5.

	Ignition during FET	***Self-sustained burning/flame spread during PET***
O_2 = 16.0 vol%	NO	NO
O_2 = 17.9 vol%	YES	Small flames, self-extinguishing after 20 s
O_2 = 20.9 vol%	YES	YES

Table 1: Results from visual observations of ignition test of PP (horizontal configuration).

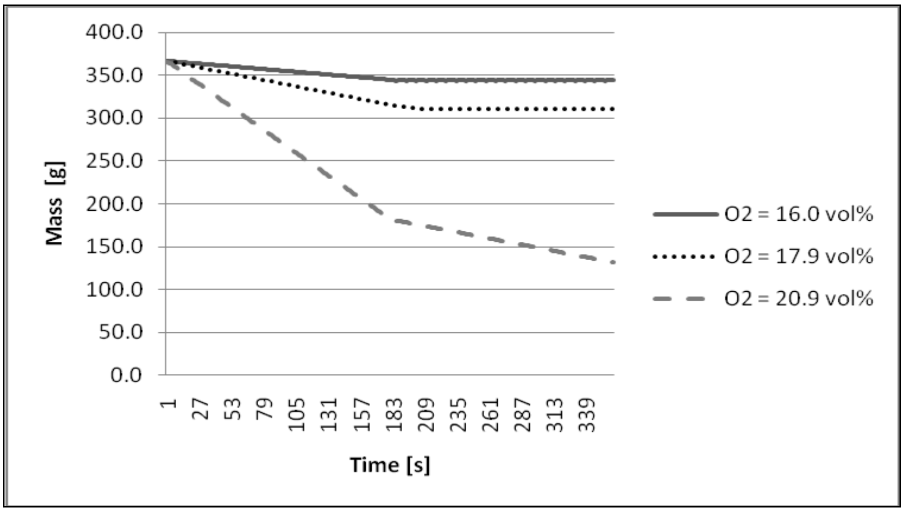

Figure 5: Test specimen mass throughout the ignition test of PP (horizontal configuration).

It was decided to perform another set of 3 ignition tests for PP, but this time with vertical configuration. The test specimen was a lid for box with a length of 39 cm and a width of 28 cm. The first test was carried out with an oxygen concentration inside the test room of 14.9 vol%, the second one with 17 vol% and the third one (reference test) in normal air. Results from visual observations of this second set of tests for PP are resumed in table 2. The graph that charts the mass loss throughout the tests is shown in figure 5.

	Ignition during FET	***Self-sustained burning/flame spread during PET***
O_2 = 14.9 vol%	NO	NO
O_2 = 17.0 vol%	YES	NO
O_2 = 20.9 vol%	YES	YES

Table 2: Results from visual observations of ignition test of PP (vertical configuration).

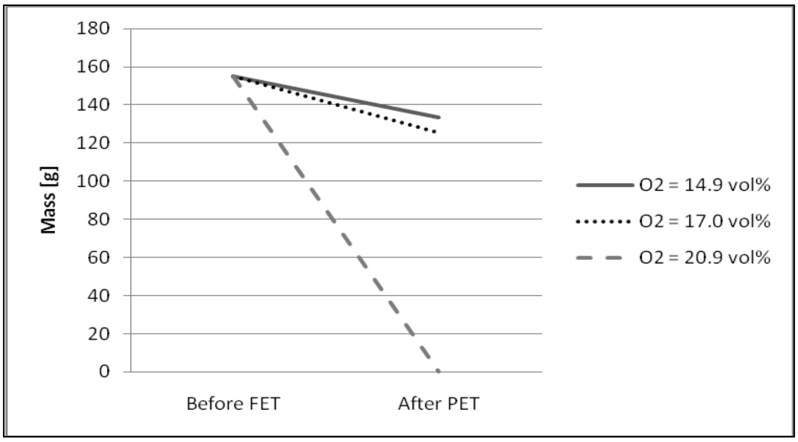

Figure 6: Test specimen mass (before FET and after PET) of the ignition test of PP (vertical configuration).

The second material tested was paper. The oxygen ignition threshold of paper (single sheet) is set to 14.1 vol% according to VdS 3527:2007. The test specimen was a rolled newspaper. The first test was an ignition test with horizontal configuration and it was carried out with an oxygen concentration inside the test room of 14.9 vol%. In fact it was assumed that the ignition threshold of a rolled newspaper was somewhat higher than the ignition threshold of a single sheet of paper. It was then decided to perform two additional tests with the same configuration, but with an oxygen concentration of 17.0 vol% and 18.0 vol% respectively. Finally a reference test was performed in normal air. Results from visual observations of this set of tests are resumed in table 3. The graph that charts the mass loss throughout the tests is shown in figure 7.

	Ignition during FET	***Self-sustained burning/flame spread during PET***
O_2 = 14.9 vol%	NO	NO
O_2 = 17.0 vol%	YES	Pyrolizing fire
O_2 = 18.0 vol%	YES	YES
O_2 = 20.9 vol%	YES	YES

Table 3: Results from visual observations of ignition test of paper (horizontal configuration).

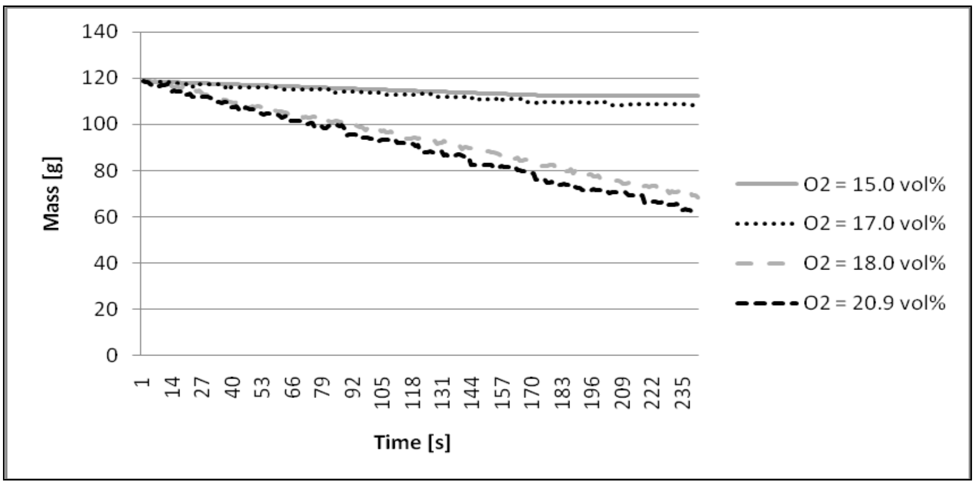

Figure 7: Test specimen mass throughout the ignition test of paper (horizontal configuration).

The third material tested was ISO wood. The oxygen ignition threshold of wood (pallet wood, untreated) is set to 17.0 vol% according to VdS 3527:2007. The test specimen was a wood crib, mini crib type (10 x 12 x 65 mm), 5 layers each crib, 2 members each layer: the total wood volume was therefore 78 cm^3. The wood crib was moistened with pure alcohol to make ignition easier. The test set was performed according to the ignition test with horizontal configuration. Seven different oxygen concentrations were investigated: 14.9 vol%, 16.0 vol%, 17.0 vol%, 18.0 vol%, 19.0 vol%, 20.0 vol% and 20.9 vol% (reference test). Results from visual observations of this set of tests are resumed in table 4. Data regarding the mass loss during the tests are resumed in table 5. Figure 8 shows a picture of test specimens before and after the ignition tests.

	Ignition during FET	***Self-sustained burning/flame spread during PET***
O_2 = 14.9 vol%	YES	Small flames, self-extinguishing after 10 seconds.
O_2 = 16.0 vol%	YES	Small flames, self-extinguishing after 120 seconds.
O_2 = 17.0 vol%	YES	Flames, self-extinguishing after 180 seconds.
O_2 = 18.0 vol%	YES	YES
O_2 = 19.0 vol%	YES	YES
O_2 = 20.0 vol%	YES	YES
O_2 = 20.9 vol%	YES	YES

Table 4: Results from visual observations of ignition test of ISO wood (horizontal configuration).

	Initial mass	***Mass lost during FET***	***Mass lost during PET***	***Mass loss during FET+PET***	***Final mass***
O_2 = 14.9 vol%	16.9 g	13.61 %	2.37 %	15.98 %	14.2 g
O_2 = 16.0 vol%	16.9 g	14.20 %	27.81 %	42.01 %	9.8 g
O_2 = 17.0 vol%	16.9 g	16.57 %	55.03 %	71.60 %	4.8 g
O_2 = 18.0 vol%	16.9 g	14.20 %	77.51 %	91.71 %	1.4 g
O_2 = 19.0 vol%	16.7 g	--------	--------	96.41 %	0.6 g
O_2 = 20.0 vol%	16.8 g	--------	--------	97.62 %	0.4 g
O_2 = 20.9 vol%	16.6 g	--------	--------	100 %	0.0 g

Table 5: Test specimens mass of ISO wood measured during FET and PET.

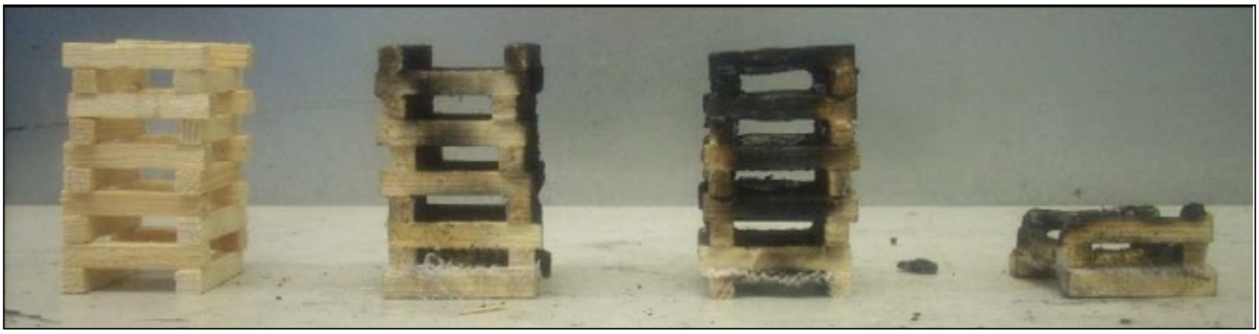

Figure 8: From left to right: wood crib before the test, wood crib after the test at 14.9 vol%, wood crib after the test at 16.0 vol%, wood crib after the test at 17.0 vol%.

Once the ignition preventing benefits of HA are confirmed, the question becomes what effect HA has on flame spread. This can be answered by means of a test which investigates whether HA can prevent, or at least mitigate, flame spread. It is well known that fires propagate faster on vertical than on horizontal surfaces so it was decided to carry out a flame spread test with vertical configuration. Two square wicker boards (20 x 20 cm) and a newspaper (40 x 28 cm) were arranged in a vertical array (see figure 4). The first test was performed with an oxygen concentration of 15.9 vol%. The oxyacetylene pilot flame hit a lowermost corner of the bottom wicker board for 180 s. Visual observations were made to see whether the flames spread to the other wicker board and the newspaper. Then a reference test was mad in normal air. Results from visual observation and mass loss of all the specimens are resumed in table 6. Figure 9 shows the pictures taken to the test specimens before the test and after the tests at 15.9 vol% and 20.9 vol% respectively.

	Flame spread	***Mass loss***	***Visual observations***
O_2 = 15.9 vol%	NO	3.89 %	Only the bottom wicker board (the one directly hit by the pilot flame) ignited.
O_2 = 20.9 vol%	YES	82.39 %	The fire spread almost immediately to all the three specimens.

Table 6: Results from visual observations and mass loss recordings of flame spread test.

Figure 9: From left to right: test specimens before the test, test specimens after the test at 15.9 vol%, test specimens after the test at 20.9 vol%.

Most specimens did not ignite during the test performed at the lowest oxygen concentrations: PP (horizontal configuration) at 16.0 vol%, PP (vertical configuration) at 14.9 vol%, paper at 14.9 vol%. However wood crib ignited, although with difficulties, during the test performed at 14.9 vol%: this may be due to the pure alcohol which the crib was damped with and the fact that the pilot flame was an extremely severe heat source (oxyacetylene flames can reach a temperature up to 3600 K) and markedly bigger than the wood crib. It was observed that specimen ignition was very difficult during the tests performed with an oxygen concentration between 16.0 vol% and 17.0 vol%: PP (vertical configuration) at 17.0 vol%, paper at 17.0 vol%, wood at 16.0 vol% and 17.0 vol%. Flames and burning self-extinguished anyway during the PET, the mass loss of the specimen was reduced. Except for PP in horizontal configuration, all the tests carried out with an oxygen concentration higher than 17 vol% showed a quick ignition during FET, self-sustained burning, flame spread during PET and strong mass loss. The ignition test of PP in horizontal configuration at 18 vol% did not show a quick ignition of the specimen, self sustained burning or flame spread: this may be due to the horizontal configuration. This confirms that material configuration really affects ignitability and flame spread of materials. For most material (PP, paper) it was observed a sort of response threshold in term of ignitibility and self-sustaining burning inside the oxygen concentration range 17 – 18 vol%: it is evident that the results of ignition tests performed with an oxygen concentration of 17vol% were more similar to those ones of the tests at lower oxygen levels (14.9 – 16.0 vol%), whereas the results of the ignition tests performed with an oxygen concentration of 18 vol% were more similar to those ones of the tests performed in normal air. This was also confirmed by the measurement of mass loss throughout ignition tests. Flame spread turned out to be impossible in the test performed at 15.9 vol%, although the specimen was exposed to a very intense ignition source for 180 s.

It can be inferred, therefore, that HA for fire prevention, by keeping down continuously the oxygen concentration in the protected rooms, is able to limit ignition and to prevent flame spread. Based on the test results, an oxygen concentration between 14.5 vol% and 15.0 vol% is sufficient to guarantee that HA will limit ignition and prevent flame in most HA ordinary applications. An oxygen concentration between 16.0 vol% and 17.0 vol%, although not able to prevent ignition and flame spread, is, however, able to lessen damages and losses in case of fire. In every case it is strongly recommended that the exact oxygen level to retain in the protected rooms is determined after a careful and accurate assessment of materials, configurations and hazards.

CONCLUSIONS

Hypoxic Air is a relatively new technology and, as any new technology, needs research and scientific evidence in order to evolve and progress. This work aimed to be a simple pilot study on HA and definitively more research in this field would help to exploit further Hypoxic Air Technology. However some results and observations drawn in this paper can be interesting and worth to explore:

- An oxygen concentration between 14.5 vol% and 15.0 vol% is able to limit ignition and prevent flame spread for most solid materials.
- An oxygen concentration between 16.0 vol% and 17.0 vol%, although it is not able to prevent ignition, is however able to lessen fire damages.
- An accurate assessment of materials, configurations and hazards is necessary to determine the correct oxygen concentration to keep in the protected rooms.
- For the materials investigated a sort of response threshold of fire spread is observed in the oxygen concentration range 17.0 – 18.0 vol%.

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