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Ventilation System Influence on Hydrogen Explosion Hazards in Industrial Lead-Acid Battery Rooms

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Abstract: When charging most types of industrial lead-acid batteries, hydrogen gas is emitted. A large number of batteries, especially in relatively small areas/enclosures, and in the absence of an adequate ventilation system, may create an explosion hazard. This paper describes full scale tests, which demonstrate conditions that can occur in a battery room in the event of a ventilation system breakdown. Over the course of the tests, full scale hydrogen emission experiments were performed to study emission time and flammable cloud formation according to the assumed emission velocity. On this basis, the characteristics of dispersion of hydrogen in the battery room were obtained. The CFD model Fire Dynamic Simulator created by National Institute of Standards and Technology (NIST) was used for confirmation that the lack of ventilation in a battery room can be the cause of an explosive atmosphere developing, and leading to, a potential huge explosive hazard. It was demonstrated that different ventilation systems provide battery rooms with varying efficiencies of hydrogen removal. The most effective type appeared to be natural ventilation, which proved more effective than mechanical means.

Keywords: hydrogen; battery; ventilation; CFD modelling; explosion

1. Introduction

Storage of energy, especially its electrical form, has been a big challenge for engineers because of its many attendant dangers. Electric batteries are used more and more often for electric vehicles, and an energy storage system used for industrial grids [1–5].

During the charging process of lead-acid batteries, gases are emitted from the cells. This is because of water electrolysis, which produces hydrogen and oxygen. When a cell reaches its fully charged state, water electrolysis occurs in accordance with Faraday's law. When an electrolyte, like metal sulfate, is diluted in water, its molecules split into negative and positive ions. The positive ions move to the electrodes connected to the negative terminal of the battery. This is where the positive ions take electrons, become pure metal atoms, and deposit on the electrode. At the same time, negative ions move to the positive terminal's electrode of the battery, where they give up their extra electrons and become a SO_4 radical. However, SO_4 cannot exist in an electrically neutral state and thus forms a metallic sulfate, which again dissolves in the water [6].

Battery rooms should be ventilated to maintain the hydrogen concentration below its 4% (by volume) Lower Explosive Limit (LEL). Battery rooms can be considered safe areas when the concentration is kept below this limit. The ventilation requirements for stationary batteries are assessed in accordance with the method outlined in BS EN 62485-2014 [7]. The synthesis of the solutions proposed for battery rooms against explosive hazardous in BS EN 62485-2014 [7] is presented in the Table 1. As it is visible on the base of the synthesis, the conventional requirements for battery rooms ventilation are not detailed and allow different technical solutions, which can give their different efficiency.

Table 1. Synthesis of the solutions proposed for battery rooms against explosive hazardous in BS EN 62485-2014 [7].

Required System against Explosive Hazardous	Hydrogen Detection and Natural or Mechanical Ventilation System
The purpose of ventilating	To maintain the hydrogen concentration below the 4% hydrogen threshold.
Technical parameters of ventilation system	The volume flow of ventilation should be designed on the basis of hydrogen emission calculation (based on batteries data) and the battery room volume. The air inlet and outlet shall be located at the best possible location to create best conditions for exchange of the air. The ventilation openings shall be on opposite walls, or the minimum separation distance of 2 m shall be kept between openings on the same wall.

Hydrogen is odourless, colourless, and tasteless, so human senses cannot detect high concentrations of this gas. Hydrogen is also the lightest gas known, with a 0.0695 specific gravity (air = 1.0). When liquefied hydrogen converts to gaseous hydrogen at standard conditions, it expands roughly 850 times and disperses easily into the atmosphere. Hydrogen diffuses through various size openings 2 to 3.8 times faster than air (its diffusion coefficient equals 61.1×10^{-6} m^2/s). Wide flammability ranges in air from 4% and 74% by volume are also a very significant parameter of hydrogen. Minimum ignition energy 0.017 MJ (as compared to 0.28 MJ for methane) means that hydrogen can been ignited even by the static electricity generated by a high velocity leak [8,9]. All these parameters cause the effective ventilation in the battery rooms to become a very significant parameter.

The effect of the low density of hydrogen has been extensively studied in literature. However, a lot of the publications describe the behaviour of light tracer gases of various densities [10], but there are not many real scale tests with hydrogen described. For example, Grimsrud compared different tracer gases to study low air exchange rates in a room, using sulphur hexafluoride (SF_6) from those obtained using nitrous oxide (N_2O), methane (CH_4), or helium (He) [11]. Saw also compared several tracer gases used to measure the general efficiency of the ventilation of a room [12]. In turn, Khan studied the effects of the location of ventilation air intakes and outlets on the dispersion of light gases using the FLUENT 6 CFD computational code [13].

Real scale hydrogen tests, to examine the effect of forced ventilation on the dispersion of hydrogen leaking from a car installation in an underground car park, are described by Tamura [14]. His study found that the safety of rescue activity for a hydrogen-leaking vehicle can be enhanced by applying winds from a blower of an approximately 10 m/s wind velocity and approaching the vehicle leeward from the blower area. However, important previous research does not describe the phenomena relative to the phenomena analyzed in this paper in relation to battery rooms.

CFD simulations can be applied for the most rigorous treatment of the physics of fluid dispersion within the framework of risk assessment [15]. In relation to CFD modelling of the hydrogen dispersion phenomena, several investigations and code validations are described. Most of them describe code validation in relation to helium, because this gas was used during the real scale tests. In 2009, the French Alternative Energies and Atomic Energy Commission has presented experimental work on the accumulation of helium in a garage, describing different accumulation regimes [16,17]. Similar work was presented by The National Institute of Standards and Technology (USA) using the Fire Dynamic Simulator [18]. Air Liquide presented engineering models for vent sizing, highlighting wind influence on hydrogen explosions in vented volumes [19]. On the base of tests and simulations, experts are working with code-developing organizations (e.g., the National Fire Protection Association and the International Organization for Standardization) to incorporate this knowledge into new codes and standards [20].

For simulation, the Fire Dynamic Simulator (FDS) version 6.3.2 of NIST was used. The FDS is a computational fluid dynamics (CFD) model originally created for fire-driven fluid flows modelling.

The software numerically solves a large eddy simulation form of the Navier-Stokes equations appropriate for the thermally-driven flow, with an emphasis on smoke and heat transport from fires. However, it is also used for mechanical ventilation system analyses, sprinklers, nozzles, flows, etc. [21].

2. Battery Rooms Failure Scenarios

During hydrogen emission in a battery room for lead-acid, several scenarios are possible. Figure 1 presents the event tree used for derivation of possible incident scenarios. As the initiating event, the continuous release of hydrogen from batteries in a battery room is taken into account, with ten different outcomes considered. It is clear that an explosion is the worst-case scenario and can be expected in two situations, shown in black lines on the event tree. An important and influential parameter is the ignition source (for example, hot elements in the room). This can occur when a ventilation system does not work, and this can happen when there is a lack of detection and ventilation systems.

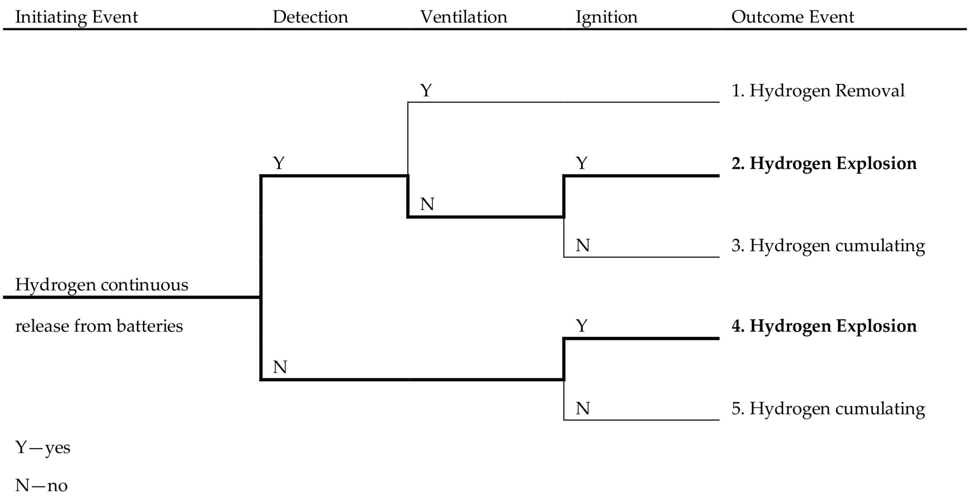


Figure 1. Event tree used for the derivation of possible incident scenarios.

More accurate analyses of the above scenarios can be undertaken through full scale experiments or CFD simulations. The full scale experiments of continuous hydrogen release in a battery room were the next step for the presented work. The results are used for gas dispersion observations and proposals for suggested solutions of battery room ventilation systems. Then, the CFD simulations were used for analysis of ventilation influence on the effectiveness of hydrogen removal from the room. The flow chart in Figure 2 presents subsequent steps of the analyses.

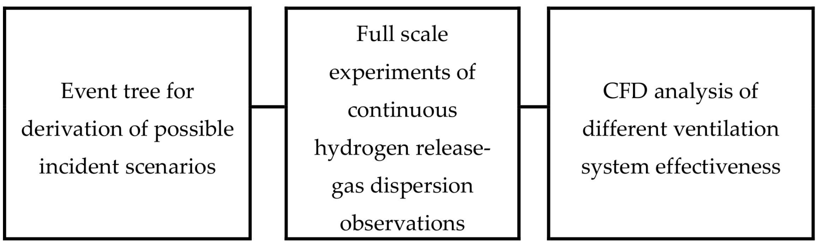


Figure 2. The analysis steps.

3. Conducted Real Scale Experiment

3.1. Experiment Layout

Measurements have been carried out in a small room of 20 m^3 volume. The test stand was designed and manufactured to ensure the correct measurement of the hydrogen propagation in the four points of the measurement, located in different heights of the room. Photograph of the measurement layout is shown in Figure 3. Hydrogen was fed from a cylinder and supplied to the room through the box imitating battery. The hydrogen flow was regulated with the certified Mass Stream Instrument D Series, with calibrated flow range from 1.0×10^{-4} m^3/s to 3.17×10^{-3} m^3/h. The upper surface of the of dimensions 1.0 m $\times$ 0.5 m and had 21 openings of 6 mm diameter each. The box was connected with the cylinder with the 10 m long pipe of 4 mm diameter. Hydrogen concentration was measured by using the hydrogen concentration level meters based on catalytic sensors VQ-21, with sensing range from 0% to 100% of lower explosive limit (LEL). Temperature during measurements was 10 °C.

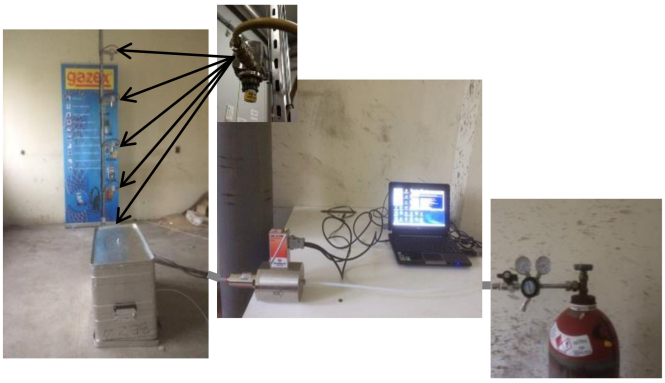


Figure 3. Photo of the measurement layout of hydrogen dispersion.

The three tests series were conducted to investigate the phenomenon of gas outflow from the battery and its dispersion in the room space. During the tests, the volume outflow of hydrogen was changed. The time of gas emission and its volume outflow are presented in Table 2. The smallest outflow in test 3 represents the outflow that can appear in real industrial batteries rooms.

Table 2. Time period and volume of hydrogen outflow.

Test No.	Time Period of the Outflow [s]	Hydrogen Volume Outflow [m^3/s]
Test 1	552	3.17×10^{-3}
Test 2	1140	1.63×10^{-3}
Test 3	4440	3.34×10^{-4}

3.2. Experiment Results

The tests results are presented in the graphs Figures 4–6, which show the hydrogen condensation at different levels, in the time period in which the condensation below the ceiling reached 50% of LEL.

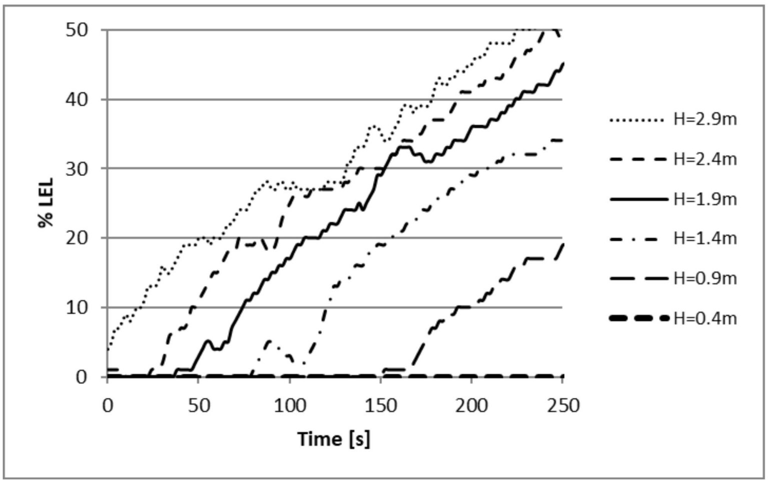


Figure 4. Hydrogen condensation range in the Test 1.

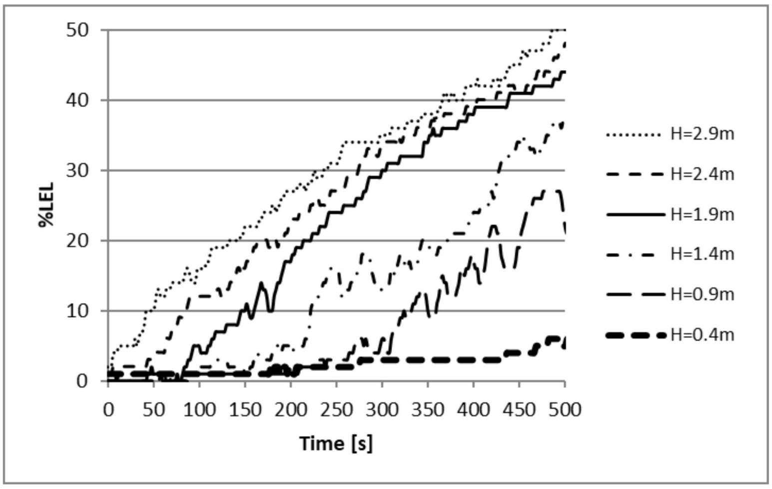


Figure 5. Hydrogen condensation range in the Test 2.

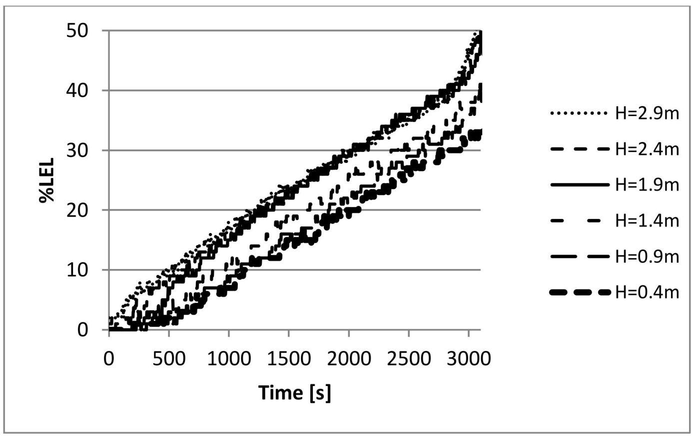


Figure 6. Hydrogen condensation range in the Test 3.

The tests results show that hydrogen dispersion in the room varies, and depends on the volume outflow of the gas. In the case when the gas outflow is fast (Test 1), big differences in the gas condensation at the several heights are observed. It becomes lower when the gas outflow goes down, up to almost an even increase in the concentration over the entire height of the room in the case of the very slow gas outflow. This means that in the case of real battery rooms, in which the hydrogen generation and outflow are similar to the outflow from the Test 3, the gas would fill the entire room space evenly, and the concentration under the ceiling and in the lower parts of the room increased almost at the same time. Presented results evidently show that hydrogen would not cumulate below the ceiling of the battery room. This means that the lower explosive limit would be reached in one moment in the whole room, resulting in a very high explosive hazard caused by relatively huge mass of hydrogen cumulated. The solution against the explosive hazard is the proper ventilation system. The next steps of research were focused on different ventilation systems in the batteries rooms and were realized on the base of CFD simulations.

4. CFD Analysis of Different Ventilation Systems Effectiveness

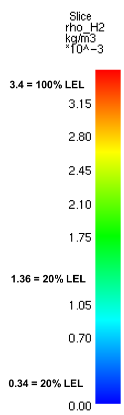
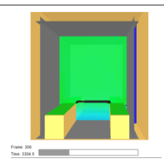
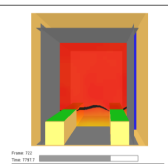
4.1. Explosive Hazards in Battery Rooms without Ventilation

Through the use of simulations, it has become possible to see the influence of ventilation on hydrogen dispersion in a battery room. Analysis was carried out using, as an example, an actual case battery room. As a model for analysis, a battery room with a total volume of 20 m^3 was assumed, in which 20 open lead batteries with a capacity of 2100 Ah each were powered. The calculations were based on the requirements outlined in the standard; BS EN 62485-2014 [2].

As a first step of calculation, hydrogen emission from the batteries was estimated as 9.7×10^{-5} m^3/s [2]. This gives the possibility of calculating the theoretical time, when, without a ventilation system, the entire battery room hydrogen concentration should exceed the threshold points taken as 10% and 40% of LEL, and last the explosive concentration (100% of LEL). That theoretical time and its comparison with simulation results is presented in Table 3. The red colour on the scale means the concentration of hydrogen is 100% LEL, which is equal to 3.4×10^{-3} kg/m^3.

The simulation results presented in Table 3 confirm that in the battery room, the increase of hydrogen concentration occurs uniformly over the entire space/volume of the room. Moreover, the period of increasing hydrogen concentration in the room without ventilation is a little slower than calculated theoretically. The reason for this is that the lower part of the enclosure stays free of hydrogen. This is a very important observation, which allows one to draw the conclusion that in a situation where the battery room is reaching hydrogen concentrations exceeding LEL, its volume of explosive cloud may be already close to the volume of the entire room and become the cause of a very potent explosion.

Table 3. Increase in the hydrogen concentration in the room without ventilation.

<table>
<tr><th>The Threshold</th><th>Theoretical Time for Reaching the Threshold</th><th>Simulation Results</th><th>Scale</th></tr>
<tr><td>10% LEL
($0.4\%_{vol}$)</td><td>840 s</td><td></td><td rowspan="3">
</td></tr>
<tr><td>40% LEL
($1.6\%_{vol}$)</td><td>4260 s</td><td></td></tr>
<tr><td>100% LEL
($4\%_{vol}$)</td><td>8520 s</td><td></td></tr>
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4.2. Ventilation Systems in Battery Rooms

In order to avoid the occurrence of an explosive atmosphere, a ventilation system should be designed for a battery room in which both mechanical and natural ventilation systems are applied, so that their required parameters for the analysed battery room are taken into account and calculated. Based on standard BS EN 62485-2014 requirements of [2], the volume of mechanical air extraction was received as 42.3 m^3/h and area of opening for natural ventilation of 0.12 m^2. Because the standard does not give accurate design recommendations, different ventilation systems were compared on the base of CFD simulations results. The mechanical extraction system with extraction point in the ceiling of the room was analyzed as the second option, with extraction points in the hoods localized directly above the batteries (with two optional length of hoods). The natural ventilation system efficiency was also compared in two options—with extract point in the ceiling and in the wall. In both cases, the supply of fresh air was provided to the room by an opening localized in the wall, close to the floor.

Table 4. Scenarios of the battery room ventilation system.

Scenario Number	Description	Figure
Scenario 1	Mechanical ventilation with extraction point in the ceiling of the room	7
Scenario 2	Natural ventilation with extraction point in the ceiling of the room	8
Scenario 3	Natural ventilation with extraction point in the wall of the room	8
Scenario 4	Mechanical ventilation with extraction point in short hoods	9
Scenario 5	Mechanical ventilation with extraction point in long hoods	9

As a result, five scenarios of ventilation of a battery room were taken into account; these are described in Table 4 and presented in the Figures 7–9.

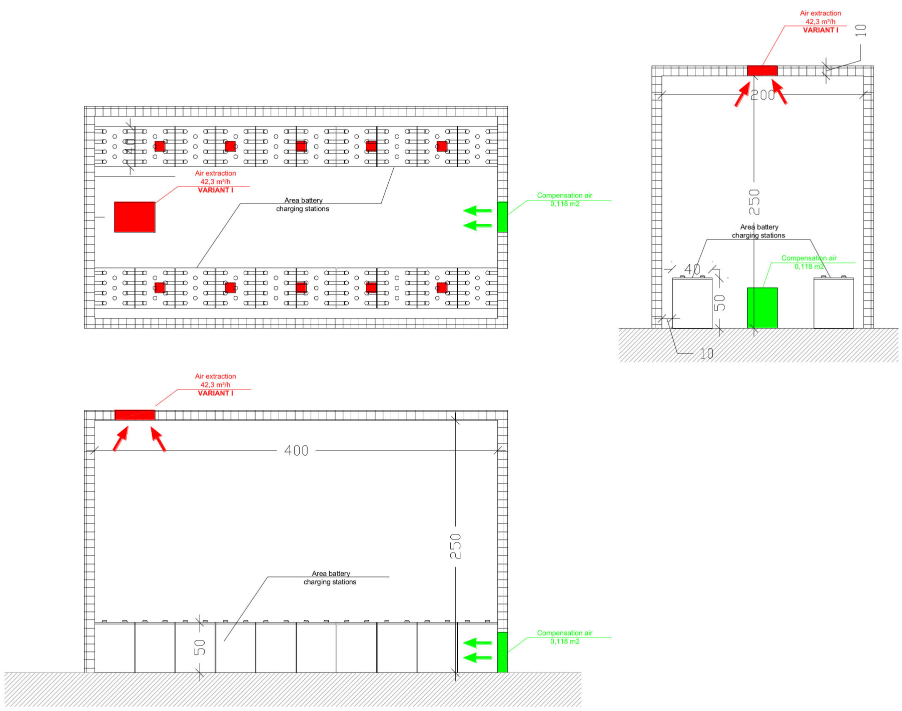


Figure 7. The mechanical ventilation system scheme with exhaust point in the ceiling and supply point near the floor.

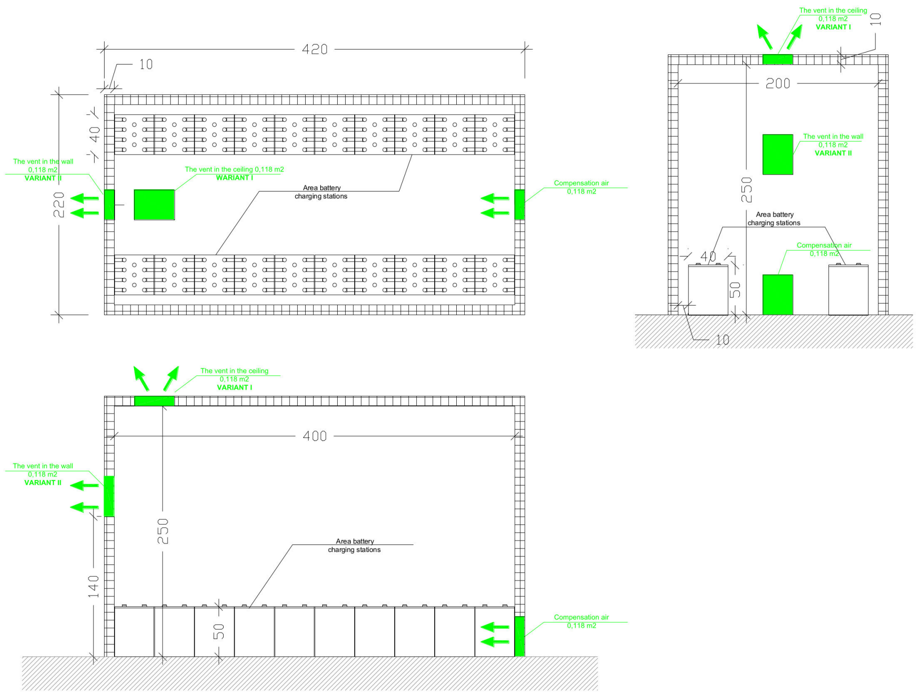


Figure 8. The natural ventilation system scheme with alternative exhaust point in the ceiling and supply point near the floor.

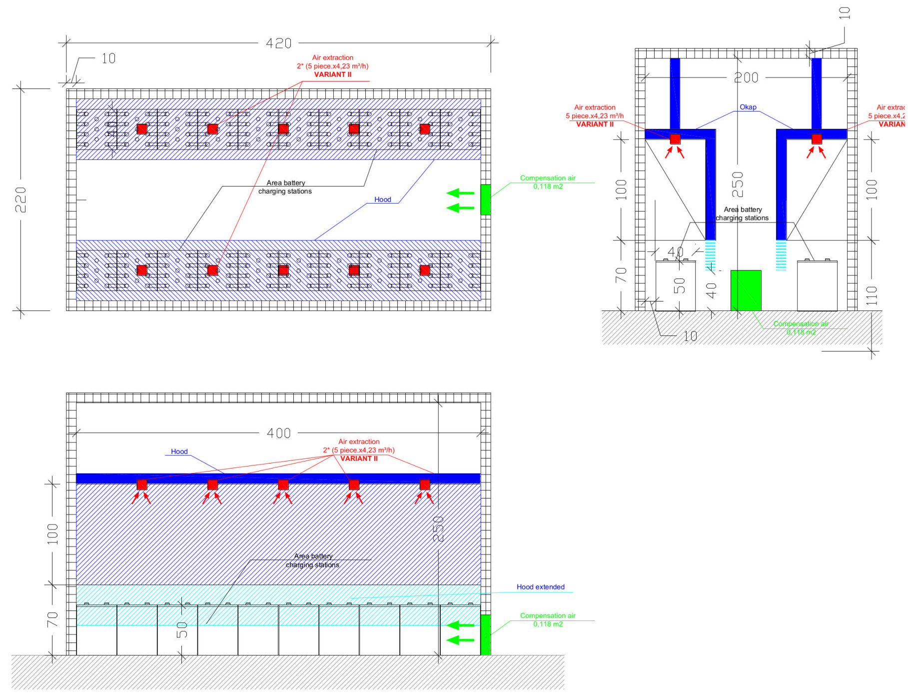
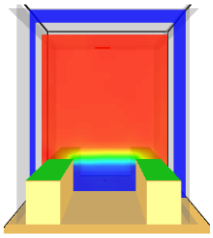
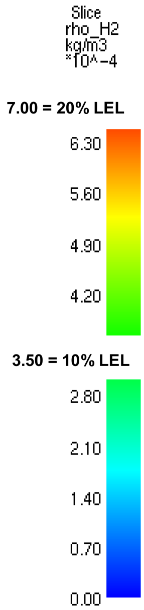
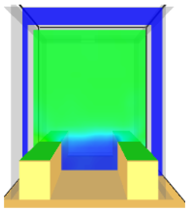
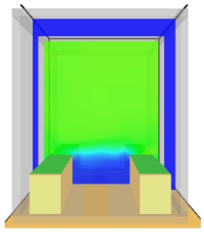
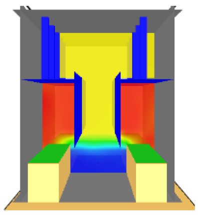
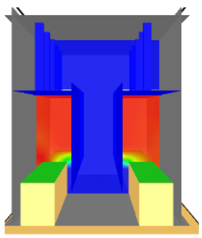


Figure 9. The mechanical ventilation system scheme with exhaust points in the hoods and supply point near the floor.

The simulation results are shown in Table 5. It can be noticed that, although all analysed ventilation systems fulfil requirements of standard BS EN 62485-2014 [2], their effectiveness is markedly different.

Table 5. The simulation results for analysed scenarios.

Scenario Number	Simulation Results	Scale
Scenario 1		
Scenario 2		
Scenario 3		
Scenario 4		
Scenario 5		

The simulations results presented in Table 5 show that each ventilation system gives a different hydrogen removal effectiveness. However, all of them provide a sufficient safety level, which keeps the hydrogen concentration below 20% of LEL. The most effective solution turned out to be the natural ventilation system, with an exhaust opening in the ceiling of the battery room. Very good results were also obtained with the hood system, but in this solution a sufficient length of hood is required. Too short a hood can cause leakage of hydrogen into a non-ventilated enclosure, which can cause hazardous concentrations inside. What is very interesting is that the mechanical exhaust system appeared to be less effective than the natural one.

5. Conclusions

The full-scale experiments of hydrogen dispersion in the battery room were completed on the basis of event tree analysis, in which the possible incident scenarios and the worst-case scenarios were estimated. It was confirmed that detection and ventilation systems are the key to eliminating fire or explosive risk. Experimental results also confirmed the expectation that reducing the hydrogen flow rate in the room changes the distribution of the concentration of the gas at different heights in the room. It was found that when the hydrogen emission rate is lower, its distribution becomes more uniform in the entire room. This situation represents the typical conditions in the battery rooms and shows that hydrogen would not cumulate below the ceiling. The lower explosive limit would be reached in the whole room, leading to a very high explosive hazard caused by a huge mass of hydrogen. As indicated by the British standard BS EN 62485-2014, the solution against the explosive hazard would be the use of the proper ventilation system. Different ventilation solutions were verified on the base of CFD simulations. The CFD analyses confirmed that, in non-ventilated battery rooms, a high explosive hazard could be expected, and each ventilation system can give a different level of efficiency in hydrogen removal. However, all of them kept the hydrogen concentration below 20% of lower explosive limit (LEL). The most effective solution appeared to be the natural ventilation system with an exhaust opening in the ceiling of the battery room. The observations could be taken into account during preparation of a new version of British standard BS EN 62485-2014.

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Conflicts of Interest: The authors declare no conflict of interest.

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