

Hydrogen explosion hazards limitation in battery rooms with different ventilation systems

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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 in confined space, 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 (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

During the charging process of lead-acid batteries, gases are emitted from the cells. This is as a result 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 [1].

Battery rooms should be ventilated to maintain the hydrogen concentration below its 4% (by volume) Lower Flammability Limit (LFL). Battery rooms can be considered as 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 [2]

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 (diffusion coefficient equals $61.1 \cdot 10^{-6} \text{ m}^2/\text{s}$). Wide flammability ranges in air from 4% and 74% by volume is 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 be ignited even by the static electricity generated from a high velocity leak [3, 4]. All that parameters conclude that effective ventilation in the battery rooms becomes 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 [5], but there are not many full 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) [6]. Saw also compared several tracer gases used to measure the general efficiency of ventilation of a room [7]. In turn, Khan studied the effects of the location of ventilation air intakes and outlets on the dispersion of light gases using FLUENT 6 CFD computational code [8].

CFD simulations can be applied for the most rigorous treatment of the physics of fluid dispersion within the framework of risk assessment. 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 full 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 [9-12]. Similar work was presented by The National Institute of Standards and Technology (USA) using the Fire Dynamic Simulator [13]. Air Liquide presented engineering models for vent sizing, highlighting wind influence on hydrogen vented explosions [14]. 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 [15].

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. [16].

During hydrogen emission in a battery room for lead-acid, several scenarios are possible. The full scale experiments of continuous hydrogen release in a battery room were realised and are presented in this paper. The experimental results were used for gas dispersion observations and verification of different battery room ventilation systems. Then, the CFD simulations were used

for analysis of ventilation influence on the effectiveness of hydrogen removal from the room.

2. Conducted full scale experiment

2.1 Experiment layout

Measurements have been carried out in a confined space of a small room of 20 m³ volume (2.4mx2.8mx3m). The room had been closed and all the openings were sealed against hydrogen dispersion outside. 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 Fig. 1. 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 m³/s to 3.17 10⁻³ m³/h. The box imitating battery was 0.5 m high with the upper surface of dimensions 1.0 m x 0.5 m with 21 openings of 6 mm diameter each. The openings allowed distribution of hydrogen outflow, what represented the hydrogen emission from batteries. 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 Flammability Limit (LFL). Temperature during measurements was 10°C.

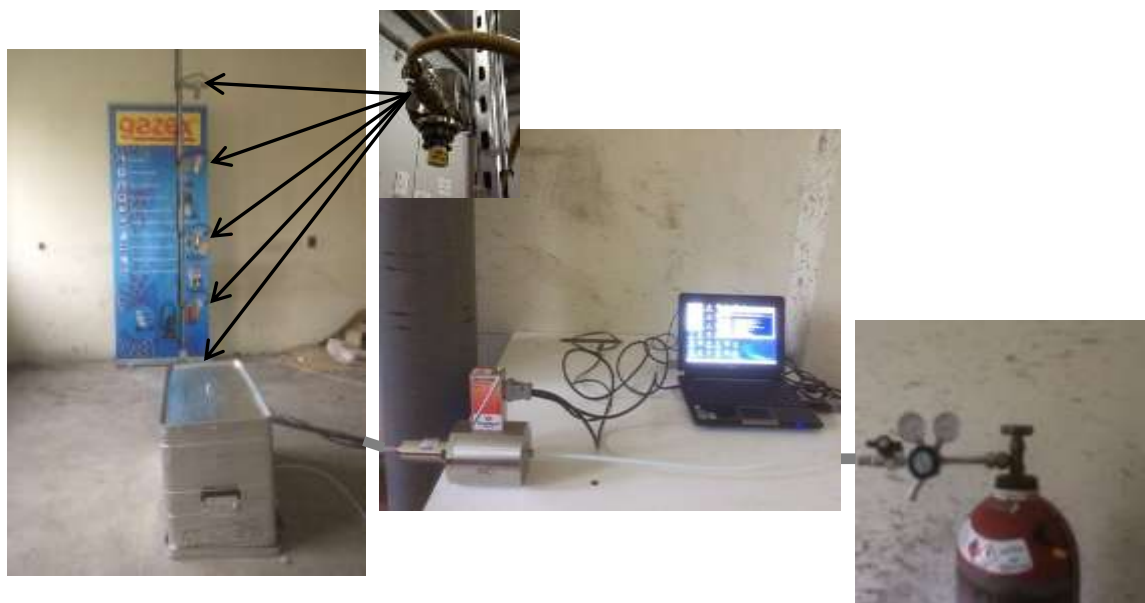


Fig. 1. Photo of the measurement layout of hydrogen dispersion [17].

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 1. The smallest outflow in test 3 represents the outflow which can appear in real industrial batteries rooms.

Table 1. Time period and volume of hydrogen outflow [17].

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

2.2. Experiment results

The tests results are presented in the graphs Figures 2-4, which show the hydrogen condensation on the different levels, in the time period in which the condensation below the ceiling reached 50 % of LFL.

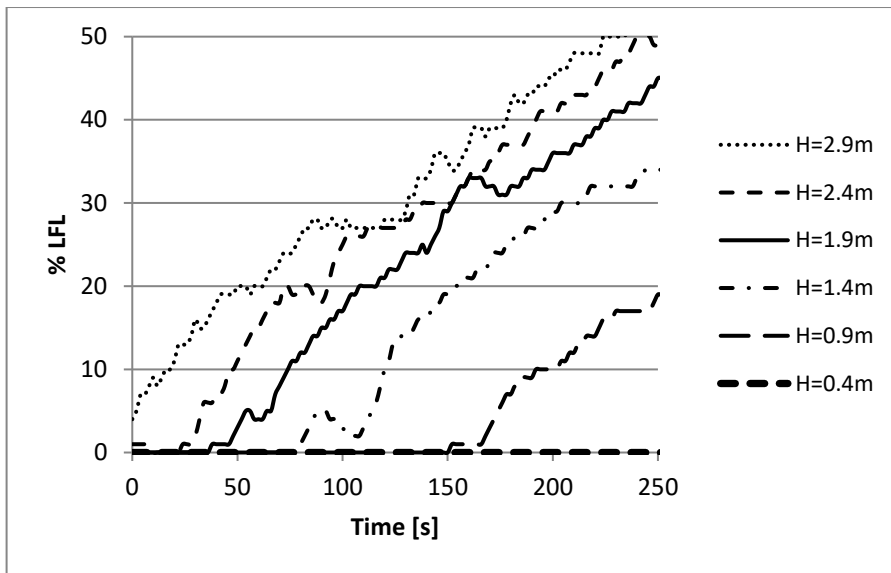


Fig. 2. Hydrogen condensation range in the Test 1.

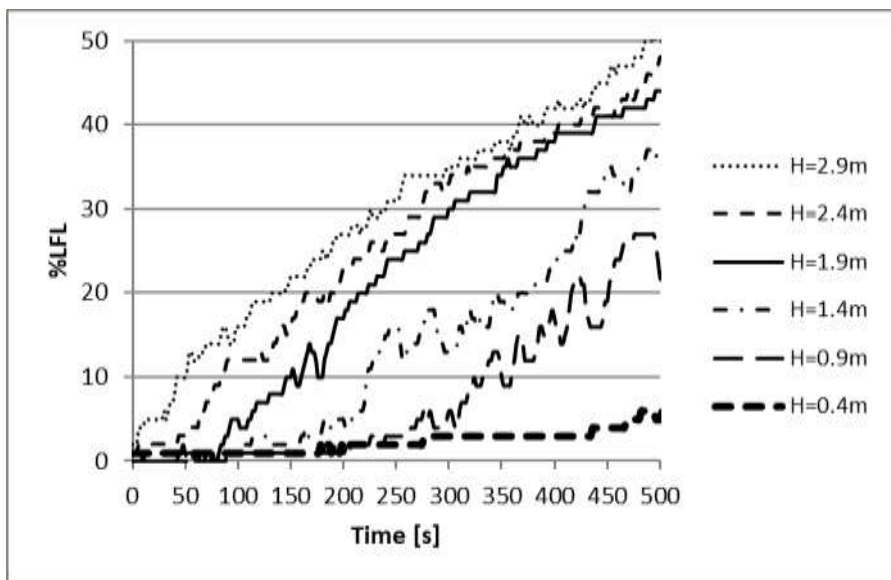


Fig. 3. Hydrogen condensation range in the Test 2.

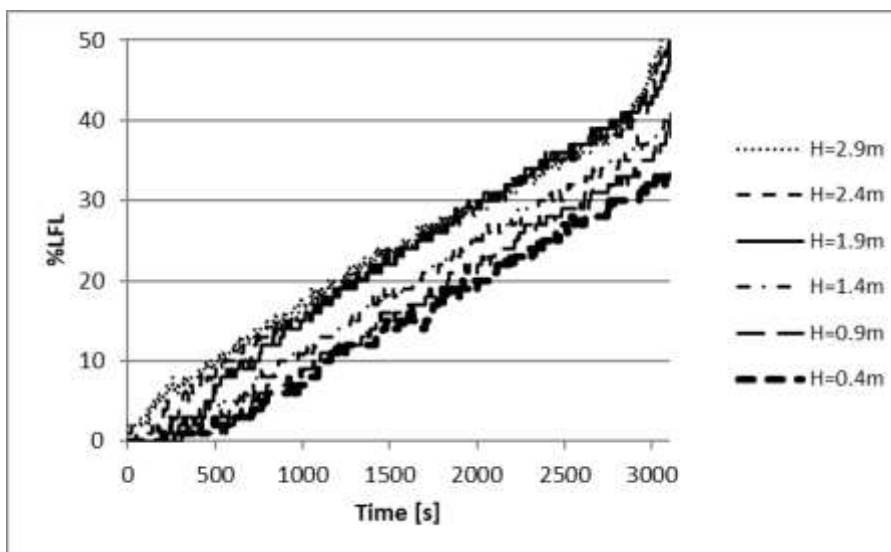


Fig. 4. Hydrogen condensation range in the Test 3.

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 of 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. It means, that in the case of real battery rooms, where 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 was increasing almost in the same time. Presented results evidently show that hydrogen wouldn't cumulate below the ceiling of the battery room! That means that the lower flammability limit would be reached in one moment in the whole room causing 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.

3. CFD analysis of different ventilation systems effectiveness


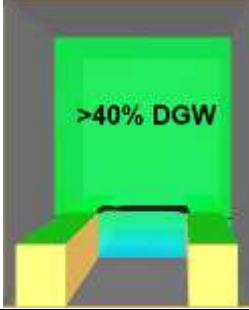
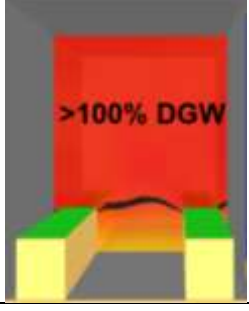
3.1. Explosive hazards in battery rooms without ventilation

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, of total volume 20 m³ 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 calculations, hydrogen emission from the batteries was estimated as 9.7 10⁻⁵ m³/s [2]. This gave a 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 LFL, and last the explosive concentration (100% of LFL). That theoretical time and its comparison with simulation results is presented in Table 2. The red colour on the scale means the concentration of hydrogen is 100% LFL, which is equal to 3,4x10⁻³ kg/m³.

The simulation results presented in Table 2, confirm that in the battery room, the increase of hydrogen concentration occurs uniformly over the entire space/volume of the room, above the emission source (top of the batteries). 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 LFL, 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 2. Increase the hydrogen concentration in the room without ventilation [17].

the threshold	Theoretical time for reaching the threshold	Simulation results	Scale
10% LFL (0,4% vol)	840 s		<p>3.4 = 100% LFL</p> <p>3.15</p> <p>2.80</p> <p>2.45</p> <p>2.10</p> <p>1.75</p> <p>1.36 = 20% LFL</p> <p>1.05</p> <p>0.70</p> <p>0.34 = 20% LFL</p> <p>0.00</p>
40% LFL (1,6% vol)	4260 s		
100% LFL (4% vol)	8520 s		

3.2. 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 where 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 calculated volume of mechanical air extraction was received as 42.3 m³/h and area of opening for natural ventilation of 0,12 m². 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 analysed and 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 all cases the supply of fresh air was provided into the room by an opening localized in the wall, close to the floor.

Table 3. Scenarios of the battery room ventilation system [17].

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 3 and presented in the Figs. 5-7 [17].

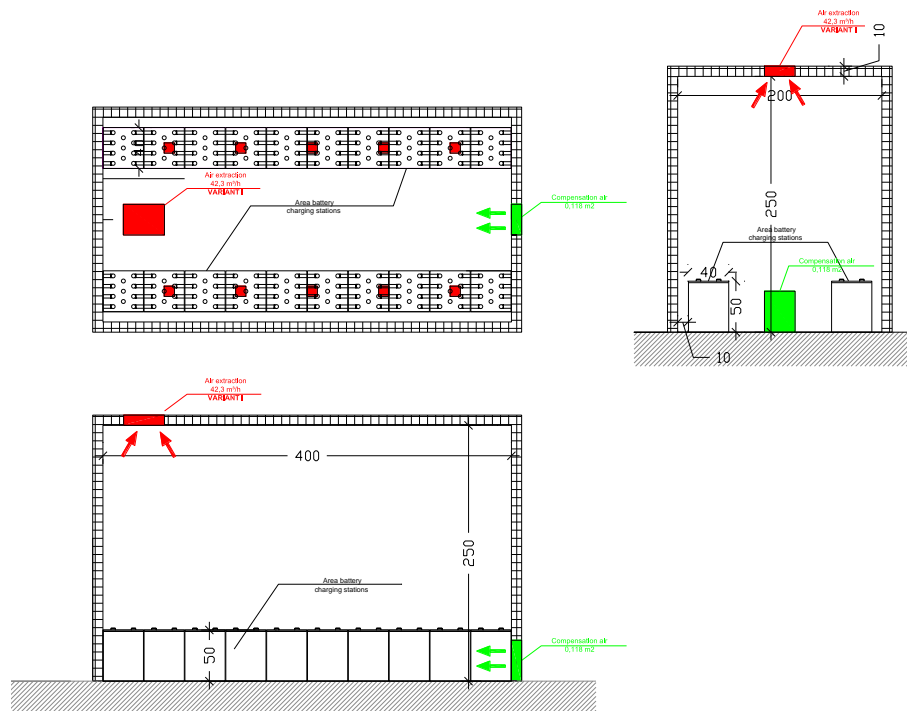


Fig. 5. The mechanical ventilation system scheme with exhaust point in the ceiling and supply point near the floor.

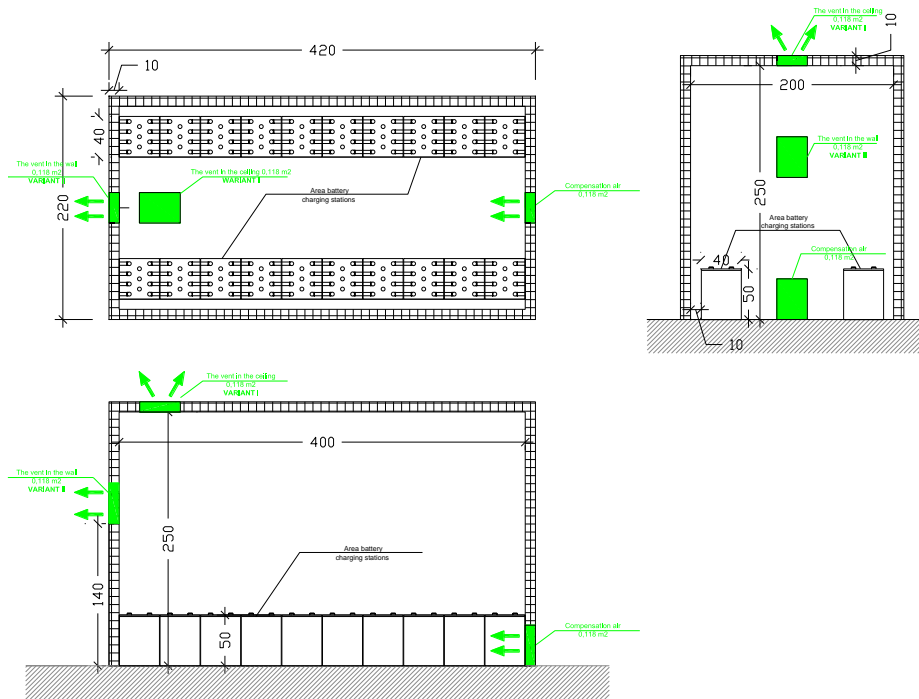


Fig. 6. The natural ventilation system scheme with alternative exhaust point in the ceiling or in the ceiling and supply point near the floor.

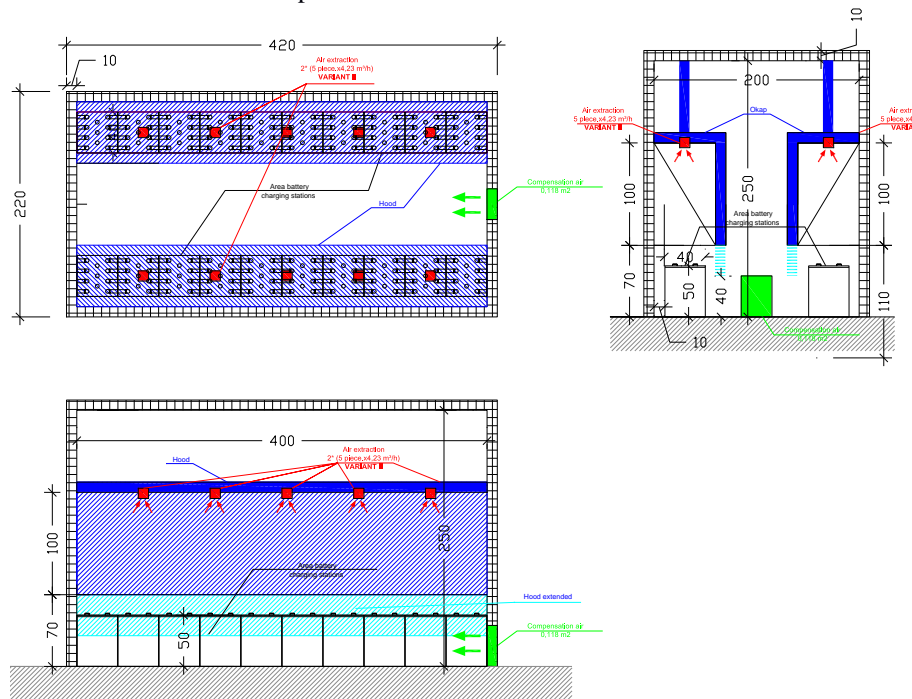
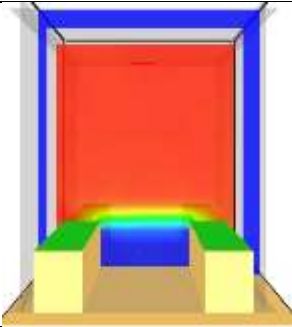
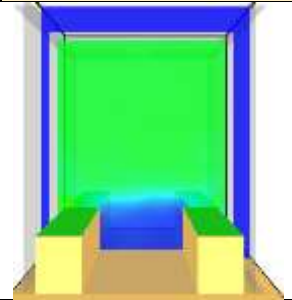

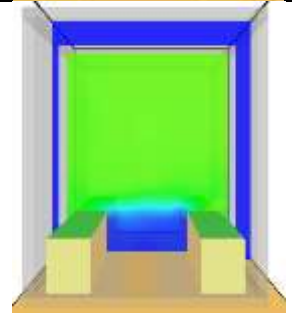
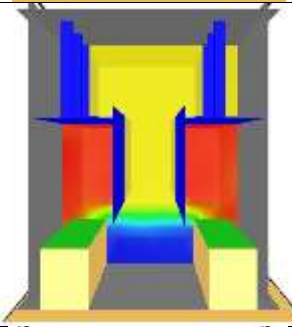
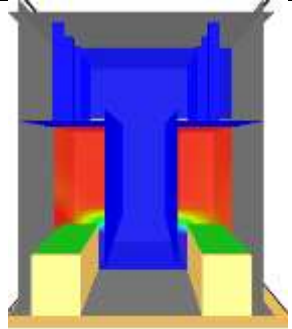


Fig. 7. The mechanical ventilation system scheme with exhaust points in the hoods and supply point near the floor.

The simulation results are shown in Table 4 [17]. 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 4. The simulation results for analysed scenarios.

Scenario number	Simulation results	Scale
Scenario 1		
Scenario 2		<p data-bbox="1241 633 1318 719">Slice rho_H2 kg/m3 *10^-4</p> <p data-bbox="1102 748 1259 770">7.00 = 20% LFL</p> <p data-bbox="1246 801 1289 824">6.30</p> <p data-bbox="1246 869 1289 891">5.60</p> <p data-bbox="1246 936 1289 958">4.90</p> <p data-bbox="1246 1003 1289 1025">4.20</p> <p data-bbox="1110 1077 1267 1099">3.50 = 10% LFL</p> <p data-bbox="1246 1131 1289 1153">2.80</p> <p data-bbox="1246 1198 1289 1220">2.10</p> <p data-bbox="1246 1265 1289 1288">1.40</p> <p data-bbox="1246 1332 1289 1355">0.70</p> <p data-bbox="1246 1400 1289 1422">0.00</p> 
Scenario 3		
Scenario 4		
Scenario 5		

The simulation results presented in Table 5 show that each ventilation system gives a differing effectiveness of hydrogen removal. However, all of them provide a sufficient enough safety level which keeps the hydrogen concentration below 20% of LFL. 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 enough 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.

Conclusions

Full-scale experiments of hydrogen dispersion in a battery room were carried out to assess the explosion hazard in such a room, and to evaluate the impact of various ventilation systems on reducing this hazard. It was found that detection and ventilation systems are the key aspect to eliminating fire or explosive risk in a battery room. Furthermore, different technical solutions would provide varying levels of effectiveness. Experimental results have confirmed also that variation in hydrogen emission area and intensity, changes the distribution of the gas concentration and its stratification in the room. The lower emission rate and/or the larger emission area result more uniform hydrogen distribution over the entire room. This situation represents typical conditions in the battery rooms. In turn, when hydrogen is emitted intensively, it cumulates below the ceiling. Assuming that an explosive hazard in the room can occur in each case, when the Lower Flammability Limit (LFL) is reached, the situation when hydrogen condensation grows uniformly in the whole room becomes more dangerous, and leads to a higher explosive hazard than the situation when the gas is cumulated below the ceiling. As it was mentioned earlier, the solution against the explosive hazard would be the use of proper ventilation systems, which was verified on the basis of CFD simulations. The most effective solution of ventilation appeared to be a natural system, with an exhaust vent in the ceiling of the battery room, and an air supply point near the floor. However, mechanical ventilation systems were also able to keep the hydrogen concentration below 20% of LFL.

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