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Combustion Gas Examination of a Battery Housing in Electrically Driven Heavy Goods Vehicle

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Nowadays, electrically propelled vehicles are becoming more and more popular. Due to the propulsion system, the risks derived from the operation have changed, compared to the conventionally driven vehicles. The investigated vehicle has the same, new risk factor originating from the behaviour of rechargeable energy storage system (RESS) during combustion and there is only a minority of available literature dealing with the investigation of the battery housing. According to our assumption the housing is a fire comburent material that hinders the work of first responders. In this research we conducted the laboratory examination of a prismatic $LiFePO_4$ battery cell and battery pack cover used in electrically driven vehicles during burning. Combustion gases were collected and were evaluated with the help of gas chromatography. Our results show that plastic housing and cell covers are not recommended in automotive industrial use, because of their comburent characteristics, also the combustion gases are severely harmful. This paper includes the method of sampling, the experiment itself and the results.

Keywords: *electromobility, electric heavy goods vehicle, operational safety, battery fire, combustion gases*

Introduction

Recently, electromobility gained ground in the field of air pollution reduction. In the European Union, in 2018, for the 29% of the total economic emission of gases causing greenhouse effect, inland and international transport were responsible. Light-duty and commercial vehicles (passenger car, van) in 15%, while heavy-duty vehicles (lorry and bus) in 5% contribute to the European emission rate originated from transportation greenhouse

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gases.[4] Mainly this causes severe air pollution in towns. Because of increasing road freight transport, harmful emission was still rising, in spite of the increasing efficiency of fuel-consumption. The EU 2019/1242[5] norm dealing with the CO_2 emission of heavy-duty vehicles was put into action on 14 August 2019, in which goals were set to decrease the average CO_2 emission of lorries by 2025 and 2030.[6] Nowadays, in this perspective, the goal of any type of vehicle manufacturer is to decrease the CO_2 emission of their product. This process determines the way of vehicle development, thus, propulsion electrification takes place worldwide. This progress in the heavy-duty vehicle sector happens in small steps, the reason behind this can be traced back to batteries, since in case of road freight transport the daily 500–1,000 km distance is not practically achievable with one charging. The size and mass of battery pack create a narrow cross-section, because if the number of batteries is increased, the effective load space and the effective transportable mass is decreased. Therefore, a compromise between the range and effective payload is made. Battery driven lorries can be used in such areas, where the distances are measurable in a few hundreds of kilometres and it is possible to charge in rounds daytime, thus 24 hours service time can be ensured. This can be for instance the transportation between warehouse and premises. During unload, battery can be charged. Currently, the electric lorry visible in Figure 1, transports goods between significant logistic stores in Győr.

Figure 1: Electrically propelled heavy goods vehicle

Source: Picture made by the authors.

It is a very favourable utilisation of electric propulsion, since inside warehouses there are closed spaces, the exhaust emissions of a traditional internal combustion engine with the lack of proper ventilation expose employees to a concentrated air pollution with health damaging effects, also acoustic load of engine noise is ceased.

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4 Buysse–Miller 2021.

5 Regulation (EU) 2019/1242 of the European Parliament and of the Council of 20 June 2019 on the marketing of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003.

6 European Commission 2021.

Hazards of electric propulsion

Unfortunately, electric heavy goods vehicles are not so widespread, moreover their price is multiple of one with internal combustion engine. For a logistic company, it is a convenient solution to convert a vehicle assembled with an internal combustion engine to be electric, rather than buying a new one. Since only the electric drivetrain is changed in a traditional vehicle, the cost of the conversion is part of the purchase price. Whether it is an individually built vehicle or originally electric, this reserves new, yet unknown and not-examined risks from the point of view of operational safety. Focusing on battery fires, first any kind of accident in which collision happens, should be mentioned, because the battery itself can be damaged.

In the European Union, electric vehicles participating in public transportation that are equipped with lithium-ion battery have to withstand the criteria of the UN UNECE 100 Regulation,[7] such as vibration test or mechanical impact. Due to physical damage, the cover and housing of the battery may get some injuries, causing fire in the cells. Electrolyte leakage, shortcut and electric failures can lead to certain electrochemical reactions causing a so-called thermal runaway, thus starting a fire inside the battery.[8] Secondly, operation conditions are severe for batteries used in electric vehicles, further mentioned as EV. Frequent accelerations and deceleration in traffic again mean higher probability of thermal runaway and ignition. In addition, extreme cold and extreme hot weather can influence the power and lifespan of the battery. High temperatures can result in overheated cells and chemical reactions inside the cells. Cold temperatures lead to internal resistance increase, promoting metallic dendrites increasing the chance for battery fire.[9] Moreover, charging is another potential risk from the point of view of EV fire. In certain cases, it was concluded that the cause of the fire while charging was faulty plug for the charging socket, resulting in significant resistance to current flow. This ended in high temperatures and spontaneous combustion. Short circuits also contribute to charging fires. The negligent usage of dedicated factory charger with the higher current parameters can lead to battery fire as well. Last, improperly performed maintenance is a problem resulting in EV fire. Because these systems are equipped with real-time monitoring battery management system, frequent service, upgrades and refreshment is compulsory.[10] If the battery catches fire from an external ignition source, the first part that accelerates and builds the fire is the housing and cover. Even if the fire is caused by internal thermal runaway, the combustible materials composing the housing and cover can keep the fire alive. Furthermore, the inner electrode separators are composites that are also combustible.[11] The EV batteries are tested because their compact size and high energy density suppose fire hazards. Very strict safety instructions are required in case of battery manufacturing. These tests are designated to

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7 Regulation No 100 of the Economic Commission for Europe of the United Nations (UNECE) – Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train (2015/505).

8 Larsson et al. 2014: 33–44.

9 Sun et al. 2020: 1361–1410.

10 Dorsz–Lewandowski 2022.

11 Aydemir et al. 2017: 25–28; Egelhaaf et al. 2014: 221–230.

verify the battery to manufacturing failures, leakage, heat and pressure resistance, those that may occur during operation. According to the IEC 62133[12] standard, fire resistance is also measured. In this fire resistance test, different temperature limits are determined, and the reaction of the battery is monitored. Manufacturers tend to test their products and to fulfil the requirements of different national standards, but it is not compulsory, since these standards are industry standards.

When describing an incident in connection with electric vehicle battery, it is always unpredictable what kind of impacts act on the battery – thus further investigation of a housing part and cell cover can serve with information about the consequences of battery fires. With the help of the test results and proper consequences, first responders may receive better understanding about $LiFePO_4$ battery fires.

Short description of the vehicle transformation

The vehicle represented in the figure above was converted in Hungary. As a first step, the conventional internal combustion engine, the gearbox and tank of the vehicle were dismounted. In the next step, the elements of the electric drivetrain were assembled into the chassis, electric motor, battery packs and control unit, which contains the necessary power electronics. During this type of conversion, it must be taken into account that the axle load remains almost equal to the original one. Beneath the compartment, the battery was mounted in the place of the tank. From the point of view of operational safety, batteries possess high risk. In this vehicle, the safest batteries with $LiFePO_4$ cathode material, exactly 6 packs, were placed. The battery containing module has two parts, a lower holder and an upper wrapping part, this is represented in Figure 2. Their joint sponge is used as a sealing. The box cover is secured by M8 type screws. The battery has no function as frame stiffener, as the material of the box is composite. Battery packs are provided with safety functions such as fuses and ventilation holes to ensure safe operational circumstances.

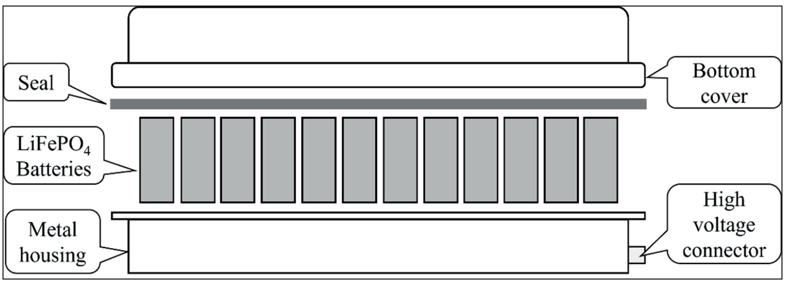

Figure 2: Exploded view of battery module

Source: Compiled by the authors.

[12] IEC 62133: Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications.

EV batteries, such that were built in the described heavy goods vehicle, can have different material-made housings to ensure proper protection for the battery cells. These housings are commonly made from aluminum, steel or plastic. The chosen material depends on the environmental conditions, also on different safety level requirements and of course, weight reduction and cost are crucial aspects. Aluminum and steel-made housings have better heat ventilation, so the battery can be cooled more effectively, which contributes to longer lifespan. They are more stiff and more resistant to intrusion. Plastic housings are lighter and cheaper, but these cannot resist to external effects to the same extent (as collision or corrosion).[13]

Regarding the fire safety of batteries, choosing the right design and material plays an important role. The battery under investigation has plastic housing. The purpose of this research is to unveil harmful gases emitted from the combustion process of battery housings and cell covers and the potential risks they may cause.

Sampling

As earlier mentioned, it is becoming more and more crucial to investigate the emission gases of the batteries placed in electrically driven vehicles. Practical experiences show that the emitted gases during combustion are more severe and dangerous than fire itself.[14]

In this study we focused on the harmful gases emitted from the housing of the battery during fire. The first sample can be found in heavy goods vehicles and go-carts as well. This is a yellow-coloured cover of a battery cell represented in Figure 3; it was dismounted for the experiment and a proper-sized sample was cut from the cell cover.

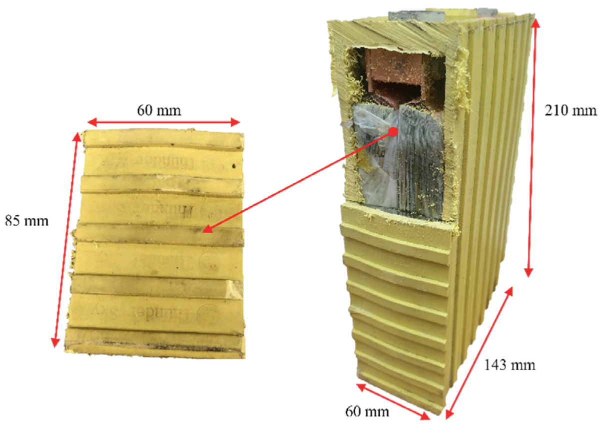

Figure 3: Dimension of Thundersky 90Ah $LiFePO_4$ battery cell

Source: Compiled by the authors.

[13] SCHMERLER et al. 2017: 26–31.

[14] DÜSER–SCHRAMM 2019: 36–39; LARSSON et al. 2017: 1–14.

The second sample is the outer part of the battery pack, which holds the housing on the chassis. This sample was cut from the housing with useful dimensions to prepare the laboratory experiment. The original sample can be observed on the next figure.

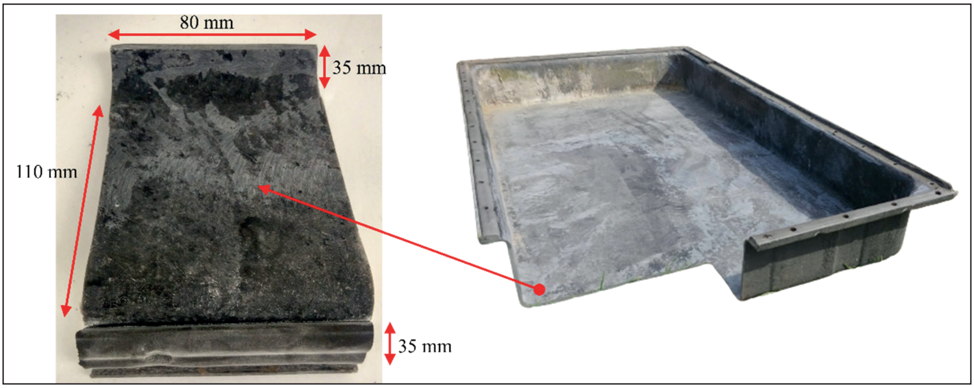

Figure 4: Sample with dimensions

Source: Compiled by the authors.

To determine the components of investigated samples, gas chromatography is used. The aim of the analytical chromatography is to detect and determine the relative ratio of the different compounds found in the gas mixture released during combustion. The burning experiment of the cell cover and the housing were conducted in the Fire Protection Laboratory of Széchenyi István University. The measurement method is represented in Figure 5, it was conducted in fume hood.

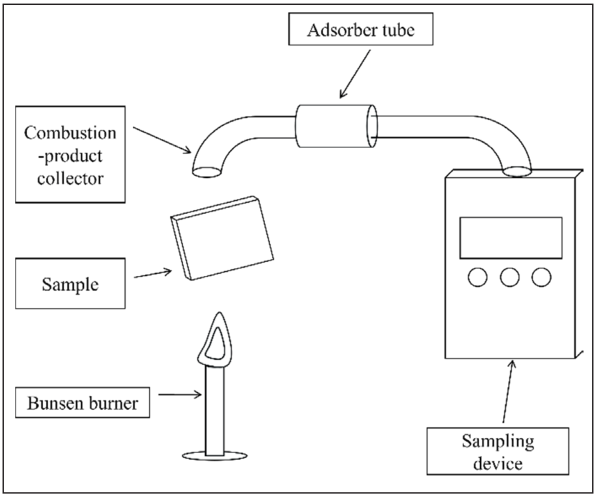

Figure 5: Measurement principle

Source: Compiled by the authors.

Before the gas chromatography examination, emission sampling must be executed on the site where the emissions of harmful compounds are released in a closed space. Since sampling is from air, atmospheric pressure, temperature and humidity must be considered in the calculations and those values are true for the day of the experiment.

Table 1: Value of influencing factors

β	1013 hPa
T_0	273 K
P	1011.38 hPa
T	292 K

Source: Compiled by the authors.

A portable gas exhauster pumps in the different gases originating from the combustion process through a short pipeline. This pipeline contains a special sample holder SKC Anasorb CSC type glass tube. The glass tube is built in the pipeline before the portable gas exhauster, thus all compounds of the smoke formed during combustion is stored. This device is transferred to a laboratory, in which, gas chromatography is conducted after preparation. Table 2 contains data about the investigated samples.

Table 2: Investigated samples

No. of sample	**Name**	**Size**	**Burning time (min.)**	**Mass (g)**
1.	$LiFePO_4$ battery housing cover	60 × 85 × 5	5:20	63.75
2.	Battery box cover	110 × 80 × 35	3:00	70.24

Source: Compiled by the authors.

Examination of battery cell cover

The mass of the battery is 2,900 g, according to its surface (1).

$$A_{cell} = 2 \times (143\text{ mm} \times 60\text{ mm} + 210\text{ mm} \times 143\text{ mm} + 210\text{ mm} \times 60\text{ mm}) = 102\,420\ mm^2 \tag{1}$$

The mass of the examined sample is 63.75 g, according to its area of the greatest surface (2).

$$T_{sample} = 60\text{ mm} \times 85\text{ mm} = 5100\text{ mm}^2 \tag{2}$$

Ratio of the two surfaces

$$\frac{102\,420\ mm^2}{5100\ mm^2} \approx 20 \tag{3}$$

According to (1) and (2) the mass of the whole battery housing is

$$m_{housing}{=}20 \times 63.75\ g = 1275\ g \tag{4}$$

216 pieces of this type can be found in a heavy goods truck and their summarised mass is

$$m_{sum} = 1275\ g \times 216 = 275.4\ kg \tag{5}$$

There was no exact information about the material of the battery housing, thus it is not recorded. The cut sample was ignited with open flame ignition source (Bunsen burner). After 5 seconds, the ignition source came to a stop, the sample was capable of self-sufficient burning with great flame. Dripping was also observed, which means that liquefied plastic droplets were released during burning. After falling, they merged and continued burning. The investigated sample flowed from the sample holder, so that it was put out. Samples from flue gases were taken for 3 minutes, since after the burning process along with flame, it released gases. The burning sample and the residuals of it can be observed in the next figure.

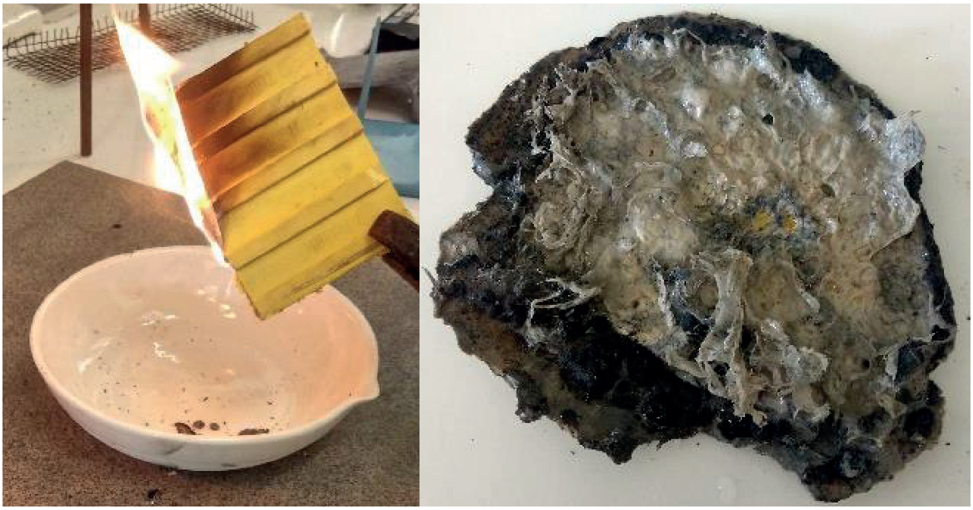

Figure 6: Behaviour of sample during the burning process and burning residual

Source: Compiled by the authors.

Examination of battery holder cover

The mass of the battery pack cover is 7.2 kg, the 6 pieces altogether are 43.3 kg. The examination process is represented in Figure 7.

Figure 7: Investigated sample placed to ignition source

Source: Compiled by the authors.

The first part of the ignition took 5 seconds, while the sample did not catch fire. Consequently, a 15 second ignition time was required, after that it burnt with small flame, self-sufficient and soot was released. After 5 seconds, the intensity of burning increased along with grey smoke generation, without any material loss. After eliminating the heat source, before the 3 minute investigation time, burning with flames stopped; however, a glowing phenomenon and smoke generation were observed, thus 3 minutes long sampling was conducted during this experiment.

Evaluation of results

The evaluation of collected samples was conducted in Agilent Technologies 6890N Network GC system. Exploration time is 20 minutes, the solvent was carbon disulfide. The following chromatograms resulted.

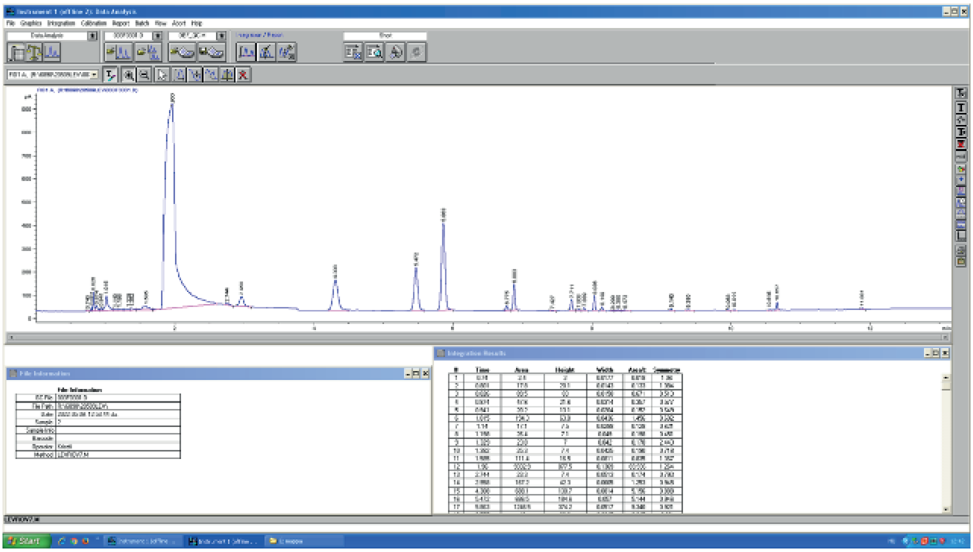

Figure 8: Chromatogram of compounds derived from the battery housing

Source: Compiled by the authors.

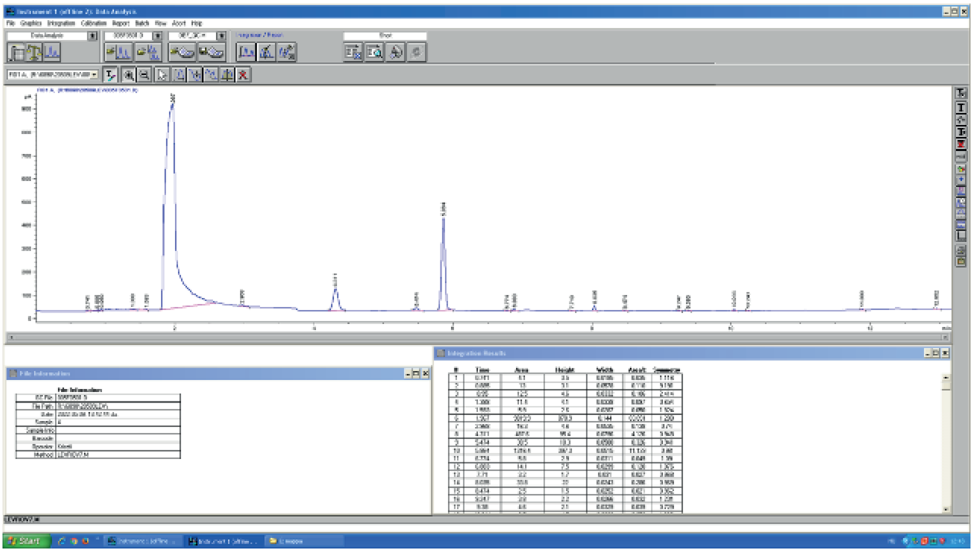

Figure 9: Chromatogram of compounds derived from the battery box cover

Source: Compiled by the authors.

To determine the different polluting compounds and their mass flow, the chromatogram of the sample is needed. Figures 8 and 9 represent the signal belonging to the searched compound, so its presence corresponding to time. This is the so-called retention time.

Concentration of compounds found in air are determined according to (6) MSZ EN 13649:2002 standard.[15]

$$c_i = \frac{m_i}{V_{cor}} \times 1000 \quad (6)$$

In the standard c_i is the concentration of the compound in gas sample (mg/m3), m_i is the mass of the compound in gas sample (mg); V_{cor} means the volume of the sample at normal state (273 K and 1013 hPa) for dry gas. To determine the concentration of normal state sample is conducted according to (7)

$$v_{cor} = V \times \frac{p_0}{p} \times \frac{T}{T_0} \quad (7)$$

in which V is the measured volume of dry gas sample, p is the pressure of sample air (hPa), p_0 = 1013 hPa, T is the real temperature of waste gas (K), T_0 = 273 K.

Table 3: Data of present compounds to determine the mass flow of housing and cover

Sample	Cell cover	Housing cover
Measured volume of dry gas sample (l)	2 l	2 l
Pressure of sample air (hPa)	1011.38	
p_0 (hPa)	1013	
T_0 (K)	273	
Real temperature of waste gas (K)	292	
$m_{benzole}$ (mg)	0.036	0.002
$m_{toluene}$ (mg)	0.042	0.003
$m_{ethylbenzene}$ (mg)	0.002	–
$m_{xylenes}$ (mg)	0.022	0.006
m_{cumene} (mg)	0.002	–
$m_{propylbenzene}$ (mg)	0.001	–
$m_{1,2,3\text{-trimethylebenzene}}$ (mg)	0.001	–
$m_{ethanol}$ (mg)	0.025	–
$m_{isopropanol}$ (mg)	0.074	–
$m_{acetone}$ (mg)	0.008	0.004
$m_{ethyl\text{-}acetate}$ (mg)	0.088	–
$m_{isobutyl\text{-}acetate}$ (mg)	0.079	–

Source: Compiled by the authors.

The volume of sample (V_{cor}) is in unit litre, at normal state p_0 = 1013 hPa and T_0 = 273 K for dry gas is according to (8) and (9)

$$V_{cor} = V \times \frac{p_0}{p} \times \frac{T}{T_0} = 5.3 \times 2 \times \frac{1013\ hPa}{1011.38\ hPa} \times \frac{292K}{273K} = 11.35\ l \quad (8)$$

15 EN 13649:2002 Stationary source emissions – Determination of the mass concentration of individual gaseous organic compounds – Activated carbon and solvent desorption method.

$$V_{cor} = V \times \frac{p_0}{p} \times \frac{T}{T_0} = 3 \times 2 \times \frac{1013}{1011.38} \times \frac{292}{273} = 7.08\ l \tag{9}$$

Concentrations of compounds found in the air sample are represented in mg/m^3 in Table 4 and 5.

The concentration of the compounds found in the sample are calculated from the following equation with the values respected to all found compounds.

$$c_{compound} = \frac{m_i}{V_{cor}} \times 1000 \tag{10}$$

Table 4: Concentration of compounds in air sample in mg/m^3, in case of battery cell cover

Compound	**Concentration** $\left[\frac{mg}{m^3}\right]$
Benzol	3.172
Toluene	3.7
Ethylbenzene	0.176
Xylenes	1.938
Cumene	0.176
Propyl benzene	0.088
1,2,3-trimethylebenzene	0.088
Ethanol	2.202
Isopropanol	6.519
Acetone	0.704
Ethyl-acetate	7.753
Isobutyl-acetate	6.96
Isoamyl-methyl-ketone	2.555

Source: Compiled by the authors.

Table 5: Concentration of compounds in air sample in mg/m^3, in case of battery housing

Compound	**Concentration** $\left[\frac{mg}{m^3}\right]$
Benzol	0.282
Toluene	0.423
Xylenes	0.847
Acetone	0.565

Source: Compiled by the authors.

Compounds found in Table 5 were calculated with 10th equations with the unique value of the battery housing part.

It is important to remark, that in Table 4 and 5 concentrations are the values of compounds released during the combustion of samples described in Table 1. Their normal exposure limit values are determined by the World Health Organization, in the EU it is 1272/2008/EK (CLP) decree. If the whole battery system is considered, concentrations can be calculated in case the whole battery system is on fire (Table 6).

Table 6: Calculated concentration in case of 216 pcs of cells and 6 pcs of housing

Sample	**1 cover**	**216 covers**	**1 housing**	**6 housings**
Mass (kg)	1.275	275.4	7.227	43.3
Benzol	63.44	13,703	18.110	108.66
Toluene	74	15,984	27.165	162.99
Ethylbenzene	3.52	760.32	–	–
Xylenes	7.26	1,568	54.331	325.986
Cumene	3.52	760.32	–	–
Propyl benzene	1.76	380.16	–	–
1,2,3-trimethylebenzene	1.76	380.16	–	–
Ethanol	40.4	8,726.4	–	–
Isopropanol	130.38	2,8162	–	–
Acetone	14.08	3,041.28	36.220	217.32
Ethyl-acetate	155.06	33,492	–	–
Isobutyl-acetate	139.2	30,067	–	–
Isoamyl-methyl-ketone	51.1	11,037	–	–

Note: Compounds in air sample are represented in the unit of mg/m^3.

Source: Compiled by the authors.

Data represented in the table above exceed the boundary limits determined in the belonging law[16] to a great extent. All the identified gases are toxic, strongly harm human health and environment as well.

Summary

In our research work, the change of plastic cover of batteries used in an electrified heavy goods truck was investigated in laboratory burning tests. Furthermore, samples were taken from released burning gases, which were analysed, especially their compounds with gas chromatography. Sampling of the released fumes and their analysis were conducted according to MSZ standards. Sample preparation was conducted with desorption, the analysis was done with GC-FID method. During the evaluation, it was concluded that during the burning process several severe gases are released that can be harmful to the environment and to human health as well. Values presented in Table 6 exceed boundary limits determined in law. Due to the increase in electric car park, the number of accidents happening in public roads is increasing, thus the number of involved people is also increasing, as a reason of this, it is important to note that the effective and quick fire extinguishing in these cases can mean the decrease in the harmful effect of released fumes. Electrolytes of the batteries were not investigated in our examinations; these are planned to be investigated in our further research work.

16 Government Decree 4/2011 (I.14.) on the limit values of air pollution levels and emission limit values of stationary air pollutants; EN 13649:2002 Stationary source emissions – Determination of the mass concentration of individual gaseous organic compounds – Activated carbon and solvent desorption method.

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