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Comparison of the Fire Consequences of an Electric Vehicle and an Internal Combustion Engine Vehicle.

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ABSTRACT

Since energy storage systems represent key new technologies in the development of electric vehicles (EV), risks pertaining to them have to be examined closely. Lithium-ion (Li-ion) batteries powering EV contain highly energetic active materials and flammable organic electrolytes, which raise safety questions, different to conventional cars. In case of EV fire, concerns remain about batteries fire behavior, about their impact on the fire growth, about their fire-induced potential toxicity, especially in confined spaces and underground car parks and about their reaction with water in case of firemen intervention. Fire tests were therefore achieved for two French car manufacturers on two battery units, on a full battery pack, on an EV and on an analogous internal combustion engine (ICE) vehicle. Thermal and toxic threat parameters governing the fire risk were quantified. For this purpose, the heat release rate and the effective heat of combustion were determined to qualify the thermal impact whereas the main emitted gases governing the toxic potency of the fire effluents were measured. Fire consequences of an EV and the corresponding ICE vehicle were compared. This paper aims at presenting the main results of these fire tests.

KEYWORDS: electric vehicles, battery, fire, safety, experimental measurements.

INTRODUCTION

In 2005, the transport sector was responsible for approximately 15% of global greenhouse gas emissions, to which road transport contributes as high as 73% [1]. As part of emissions reduction policy, research devoted to alternative and decarbonated energy sources in substitution of fossil fuels in the transportation sector is crucial. In this field, making use of electric energy provided by a powerful battery is an innovative way. The high energy Li-ion battery is indeed one of the emerging new systems of electric storage [2][3][4] proposed in industries for innovative applications, in particular in the automotive sector (e.g. for Battery EV & plug-in EV), thanks to its high energy density.

Due to the reactivity of the materials and the high energy density involved, the Li-ion system may be subject to failures like thermal runaway leading to leakage, gas venting, fire and, in the worst case, explosion [5]. For this reason, more but still affordable safety precautions are needed: safety vent on each cell, fuses, battery and cell electrical management capable of single-cell supervision and control, etc. In general, most of the inherent hazards trigger accidental scenario when batteries are misused or facing abnormal environmental conditions. When operating out of the stability domain of the system (in terms of temperature or voltage), a series of undesirable reactions (varying according to the type of electrochemistry involved) may occur [6]. These side reactions can lead to the release of heat and gases, and then subsequently cause thermal runaway [7] that entails significant threats including fire phenomena or even explosion as a result of the combustion of the electrolyte and other combustible components after rupture of battery confinement.

External fire of Li-ion batteries and more globally of Li-ion powered EV represents a scenario likely to occur during battery or vehicle life. Indeed, in France, 60 832 ICE vehicle fires required assistance from the rescue services in 2011 [8].

To ensure the safe development of EV, French public authorities conducted different working groups with regard to EV safety management. To compensate a lack of technical knowledge on real EV fire behavior, the decision to proceed to EV full scale fire testing was taken with the aim of adjusting, as needed, some regulations, more particularly the ones regarding recharge station for EV in underground car parks or petrol stations. Public authorities led a group of experts, car manufacturers and emergency services to define an experimental procedure able to assess, in a suitable manner, the effects of EV fires and their consequences in confined spaces. The main objectives of this procedure were to characterize the general behavior of batteries and vehicles in case of external heat stress, to characterize batteries behavior in contact with water in case of firemen intervention, to identify and quantify emitted gases and energies and to compare fire growth. The defined protocol included five different tests on: two battery units (with and without fire fighting operation), one full battery pack, one EV and one analogous ICE vehicle.

INERIS was commissioned to conduct these fire tests for two French car manufacturers in its fire gallery where many parameters were measured throughout the tests.

This paper presents the main results and comparisons of the tests between an EV and the corresponding ICE car. A special attention was paid to the analysis of emitted gases, specifically toxic gases as HF and CO.

EXPERIMENTAL

Test procedure specifications

Full scale tests were achieved in the INERIS fire gallery, according to fire test procedure specifications developed by the EV safety group, which was mentioned above.

The procedure included five different tests:

- A fire test on a battery unit, a modular assembly of some elemental cells, which was a representative element of the full EV battery. (A battery unit represented at least ten percent of the full battery mass or its energy was at least 1.5 kWh.)
- A fire test on a battery unit, with fire fighting operation.
- A fire test on a full battery pack (which mass was around 250-300kg), with late fire fighting attempt.
- A fire test on an EV with a fully charged battery.
- A fire test on an analogous Diesel vehicle with a full gas tank.

In order to quantify emitted gases and energies, the tests had to be performed in a confined space which could be operated like a large-scale fire calorimeter.

The ventilation had to be slightly forced and monitored to fully extract combustion gases in the exhaust system and to carry out measurements.

The calibrated ignition source had to ensure a self-sustained fire of the tested elements. It was important to be able to stop the ignition source once the fire was self-sustained, in order to quantify the energy produced by the fire of the tested element without any external contribution of energy. The impact of the transitional ignition phase had to be minimised to get as accurate measurements as possible and not to interfere with emission of gases from the tested element.

Therefore a 6 kW propane burner was used to set fire to the vehicles.

Testing facilities and equipments

These fire tests were achieved in the INERIS fire gallery. This gallery, schematized on Figure 1, is 50m long, 3.5m high (on the top of the vaulted ceiling), 3m wide (10 m^2 cross section), with a tower were the main sensors and samplers are set up. The tower is 2m long, 3m wide and 10m high.

This gallery has a monitored ventilation system and a gas scrubber system which enables to canalize and clean up combustion smoke before rejection in the atmosphere.

Controlled conditions are generated in the fire gallery with the opportunity to analyze standard decomposition and combustion gases and therefore to quantify thermal and toxic parameters.
The online gas analysis instrumentation, including a Fourier-Transform Infra-Red (FTIR) equipment, conjugated to flow rates measurements enable to determine the nature and yields of toxic combustion or decomposition products.

Procedure dedicated to fire tests on vehicles

For each car manufacturer, after preliminary tests on battery units and pack, a fire test was carried out on an EV and another test was carried out on an analogous ICE vehicle. In total, 4 large scale car fire tests were achieved with an identical experimental procedure.

The flow rate in the gallery was approximately 25 000m^3/h and it was measured throughout the fire tests. The ventilation system is an extraction one, which means that the fresh air gets in the gallery through the section under the door (section of 3m by 30cm) and it is extracted in the tower. For each test, the vehicle was set up in the tunnel of the fire gallery (Figure 1).

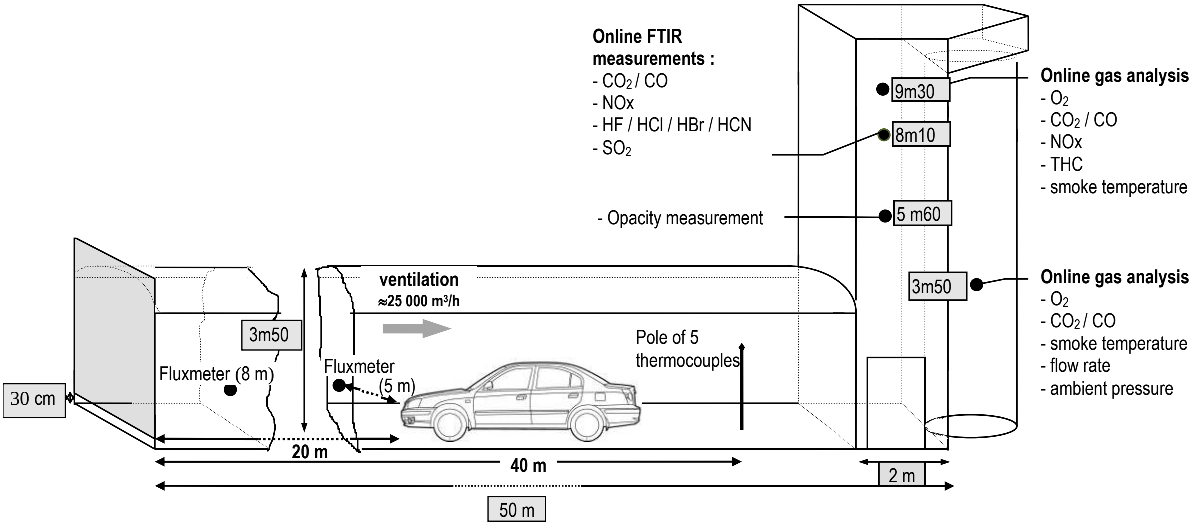

Figure 1 Experimental set-up for the fire tests on a vehicle.

A gas burner of approximately 6 kW was used to set fire to the vehicle.
To ensure a sustained fire of the vehicle, the left front seat had been lacerated and the car windows had been opened before the test. The gas burner was activated during 1 minute, orientated to the left front seat, inside the passenger cell.

Online gas analysis was performed by several methods:

- classical analytical methods using non-dispersive infra-red spectroscopy (NDIR) for CO_2 and CO, paramagnetic measurement for O_2, chemiluminescence for nitrogen oxides (NO_x) and flame ionization detector (FID) for total hydrocarbons (THC);
- a method based on an online Nicolet 6700 FTIR spectrometer, using a 2m gas cell of a volume of 200mL for further analysis of gases and vapors including HF, HCl, HBr, HCN, SO_2, CO, CO_2 and NO_x. The sampling probe and installation was set up to be compatible with the HF specificities, in the above mentioned operational conditions.

The gas analysis methods followed the principles of ISO 19701 [9] and ISO 19702 [10] standards.

The other online measured parameters were:

- thermal flux with two fluxmeters located 5m and 8m upstream the vehicle,

- temperature inside and on the surface of the vehicle,
- smoke temperature,
- flow rate (smoke exhaust rate),
- video and thermal IR camera,
- online gas analysis (CO, CO_2, O_2, THC, NO_x, HF, HCl, HBr, HCN, SO_2, etc.).

Off-line measurements and analysis were also carried out, including soot analysis and mass loss measurement.

The total effective heat of combustion and the fire growth were determined using the method of O_2 consumption.

TEST RESULTS AND COMPARISON

Fire behavior and heat release rate (HRR)

Fire development was found similar for all vehicles; the fire spread inside the passenger cell before propagating to the rear of the vehicle and then to the front of the vehicle. It's worth noting however that fire propagation can be influenced by the ventilation imposed during the test and by the ignition method which is used.

The general behavior in case of an external fire initiating event was globally found similar for both types of vehicles. No explosion or projection related to the battery was observed during EV fire tests in our test conditions.

The measured mass loss was close for EV and ICE vehicles. For both car manufacturers, the measured mass loss was around 20% of the initial mass.

The maximal HRR and the overall dissipated effective heat of combustion (integration of HRR profile) were close for both analogous vehicles. The comparison of the evolution of HRR versus time for EV and ICE vehicle for the car manufacturer 1 and for the car manufacturer 2 are respectively represented in Figure 2 and Figure 3. In the present case, HRR computation is based on O_2 consumption corrected for CO and soot production. For the car manufacturer 1, the maximal HRR was 4.2 MW for the EV and 4.8 MW for ICE vehicle. Peaks attributed to the combustion of the battery pack appear at approximately 35 minutes after ignition. For the car manufacturer 2, the maximal HRR was 4.7 MW for the EV and 6.1 MW for ICE vehicle. Data of the literature mentioned that the HRR for a single passenger automobile (ICE vehicle) varies from 1.5 to 8 MW [11] [12] according to its size, but the majority of the tests reported in the literature show HRR values less than 5 MW [13] for medium size cars. Then, measured HRR values during our tests are consistent with data from literature.

The overall dissipated effective heat of combustion was computed at 6300 MJ for EV and 6900 MJ for ICE vehicle for the car manufacturer 1 (Figure 4) and at 8500 MJ for EV and 10000 MJ for ICE vehicle for the car manufacturer 2 (Figure 5). From these values, the effective heat of combustion expressed as heat of combustion (in MJ) per kg of combusted material was evaluated. The effective heat of combustion was around 36-36.5 MJ/kg for ICE vehicles of both manufacturers. This value is consistent with the plastic heats of combustion and with the effective heat of combustion of 35 MJ/kg reported in [13]. The effective heat of combustion was around 30-31 MJ/kg for electric vehicles of both car manufacturers.

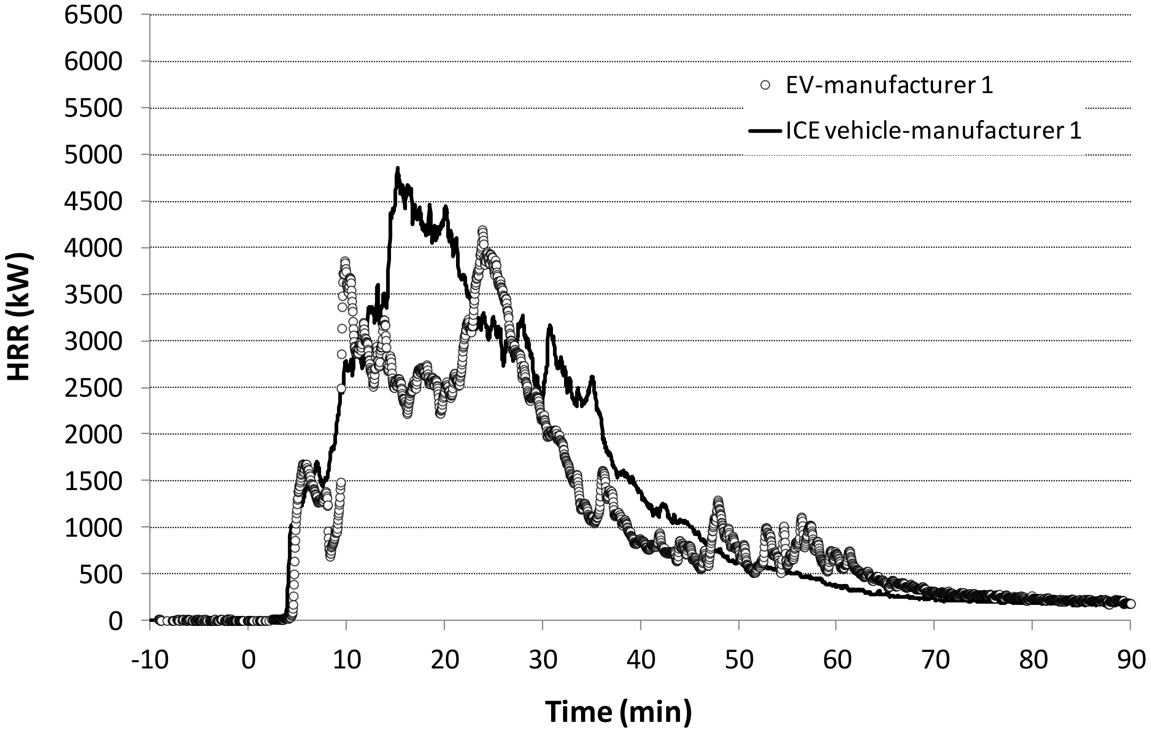

Figure 2 Comparison of the heat release rate vs. time for EV and analogous ICE vehicle tests for the car manufacturer 1.

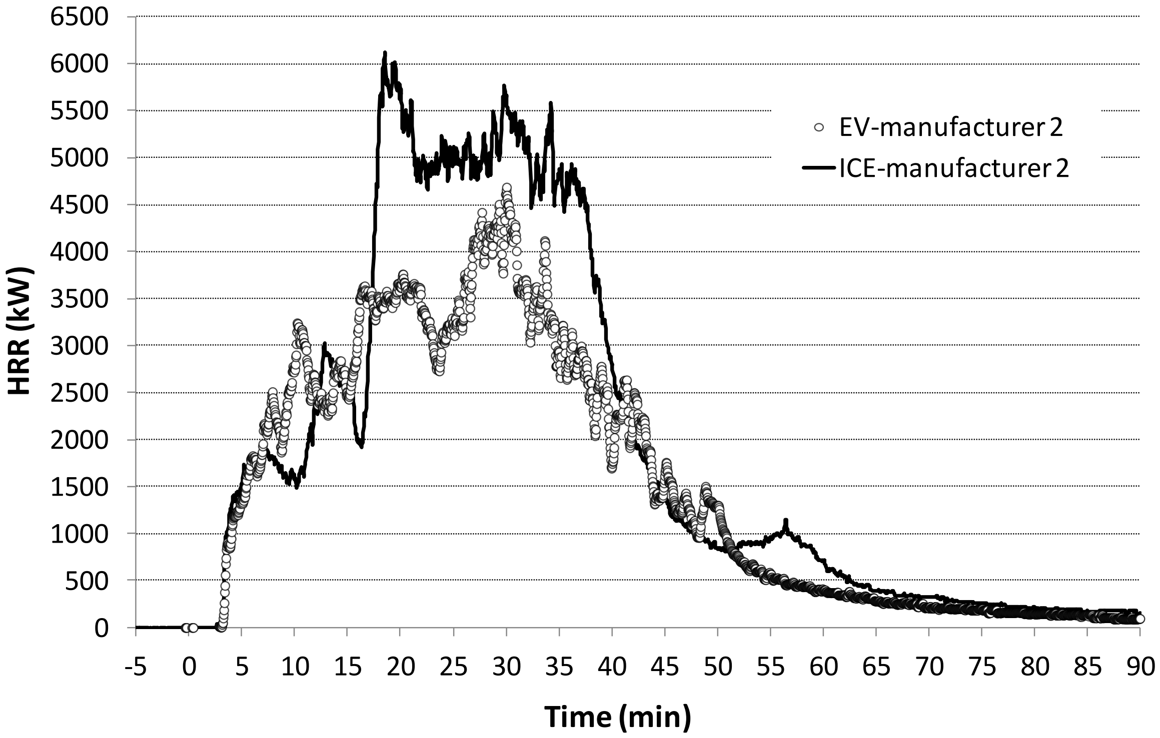

Figure 3 Comparison of the heat release rate vs. time for EV and analogous ICE vehicle tests for the car manufacturer 2.

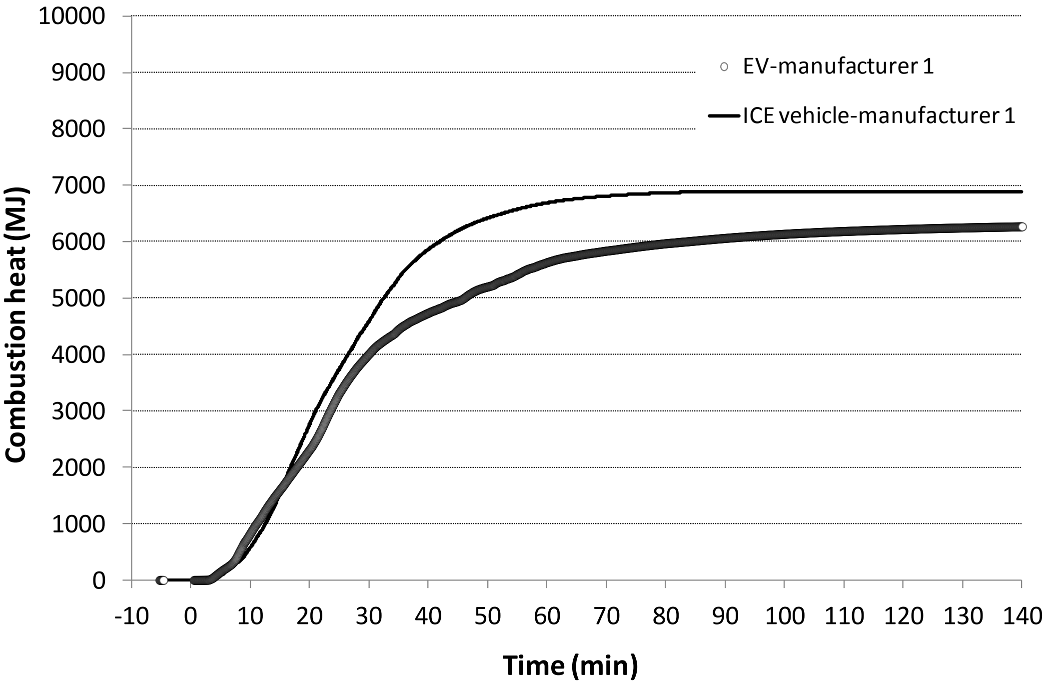

Figure 4 Comparison of the effective heat of combustion released vs. time for EV and analogous ICE vehicle tests for the car manufacturer 1

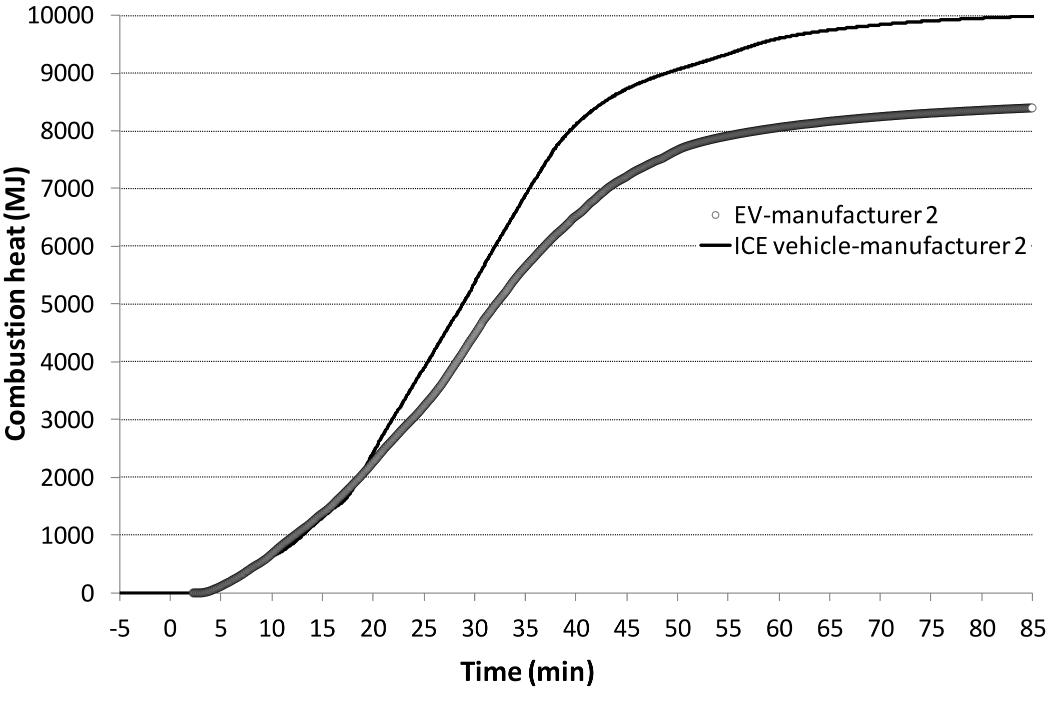

Figure 5 Comparison of the effective heat of combustion released vs. time for EV and analogous ICE vehicle tests for the car manufacturer 2

Gas analysis

According to actual measurements, HF was emitted in significant quantities during both electric and ICE vehicles fire tests. This is shown in the graphs hereinafter, Figure 6 and Figure 7, representing mass flow of HF production as a function of time for both car manufacturers. It's worth noting that a significant emission of HF was also measured during ICE vehicle tests. A similar peak of HF emission at 14 min was observed for EV and ICE fire experiments. It may come from fluorinated materials contained in the vehicle (e.g. from a fluorinated refrigerant contained in the air conditioning system; this hypothesis wasn't confirmed).

In the case of EV, additional HF emission peaks corresponding to the combustion of the lithium-ion battery pack were observed around 25-30 minutes after triggering vehicle fire, Figure 6 and Figure 7. This is consistent with known existing potential sources of fluorine in a Li-ion battery like the electrolyte (most often $LiPF_6$ in current technologies) and the binder material of the electrodes (often PVDF). This is also coherent with preliminary tests achieved on battery units and full battery pack. Consequently, HF cumulative mass was measured in higher quantities in the case of EV due to the combustion of Li-ion battery pack.

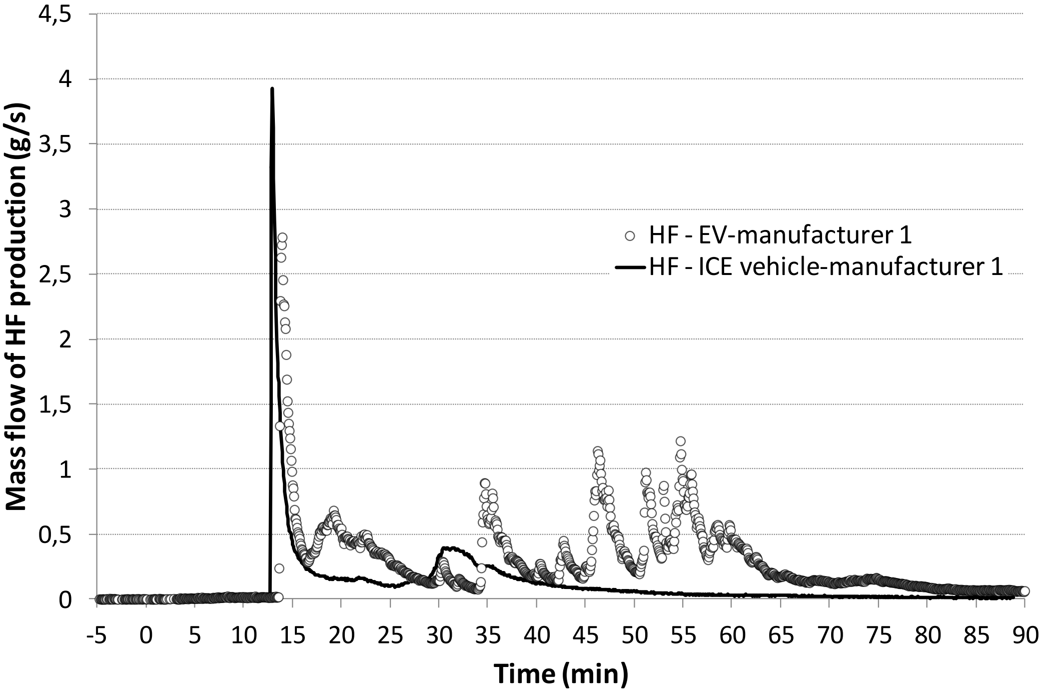

Figure 6 Comparison of HF production vs. time for EV and analogous ICE vehicle tests for the car manufacturer 1

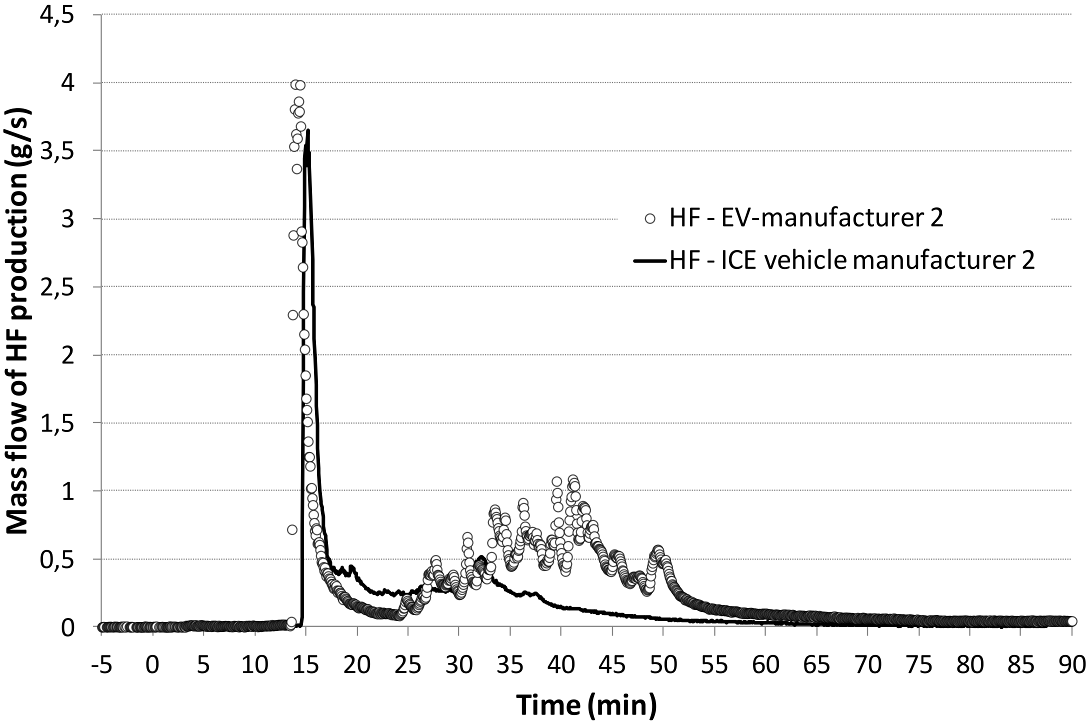

Figure 7 Comparison of HF production vs. time for EV and analogous ICE vehicle tests for the car manufacturer 2

As regards the other emitted gases, fire experiments showed the production of similar cumulative masses of CO_2, CO, THC, NO_x, HCl and HCN for both types of vehicles. No HBr was detected for these 4 tests.

The total quantity of emitted gases (limited to measured gas and vapors) is reported in Table 1, in bold. This table doesn’t take into account the kinetic of gas emission, which is an important parameter.

The measured quantity of the main emitted gases (CO_2, CO, THC, etc.) and the thermal effects (HRR, heat of combustion) were higher for the manufacturer 2 due to the presence of a bigger amount of combustible material in its cars which are bigger models.

Tested element	*EV manufacturer 1*	*ICE vehicle manufacturer 1*	*EV manufacturer 2*	*ICE vehicle manufacturer 2*
Test	***Fire***	***Fire***	***Fire***	***Fire***
Nominal Voltage (V)	330 V [a]	-	355 V [a]	-
Capacity (Ah)	50 Ah [a]	-	66,6 Ah [a]	-
Energy (kWh)	16,5 kWh [a]	-	23,5 kWh [a]	-
Mass (kg)	1 122 kg	1 128 kg	1 501 kg	1 404 kg
Lost mass (kg)	212 kg	192 kg	278,5 kg	275 kg
Lost mass (%)	19%	17%	18,6%	19,6%
Online gas analysis – total quantity of emitted gases (FTIR and online analyzers)				
CO_2 (g)	**460 400**	**508 000**	**618 490**	**722 640**
CO_2 (mg/lost g)	*2 172*	*2 646*	*2 220,8*	*2 627,8*
CO (g)	**10 400**	**12 040**	**11 700**	**15 730**
CO (mg/lost g)	*49*	*63*	*42*	*57,2*
THC (g)	**2 430**	**2 380**	**2 860**	**2 730**
THC (mg/lost g)	*11,5*	*12,4*	*10,3*	*9,9*
NO (g)	**500**	**679**	**770**	**740**
NO (mg/lost g)	*2,4*	*3,5*	*2,8*	*2,7*
NO_2 (g)	**198**	**307**	**349**	**410**
NO_2 (mg/lost g)	*0,9*	*1,6*	*1,3*	*1,5*
HF (g)	**1 540**	**621**	**1 470**	**813**
HF (mg/lost g)	*7,3*	*3,2*	*5,3*	*3*
HCl (g)	**2 060**	**1 990**	**1 930**	**2 140**
HCl (mg/lost g)	*10*	*10,4*	*6,9*	*7,8*
HCN (g)	**113**	**167**	**148**	**178**
HCN (mg/lost g)	*0,5*	*0,9*	*0,5*	*0,6*
Thermal effects				
***Maximal HRR** (MW)*	4,2 MW	4,8 MW	4,7 MW	6,1 MW
***Heat of combustion** (MJ)*	6 314 MJ	6 890 MJ	8 540 MJ	10 000 MJ
***Heat of combustion/unit mass loss** (MJ/ kg)*	29,8 MJ/kg	35,9 MJ/kg	30,7 MJ/kg	36,4 MJ/kg

[a] *Characteristics of the battery pack of the EV.*

Table 1 Results synthesis

CONLUSION

Four large scale fire tests were recently achieved, with an identical experimental procedure, for two French car manufacturers. For each of them, the fire testing program involved a) two battery units, b) a full battery pack, c) an EV and d) an analogous ICE vehicle. The present paper focused on the main results of the fire tests conducted on EV and corresponding ICE vehicles

Our tests show that the general behavior of EV and ICE vehicles exposed to the same external heat stress was similar. The maximal heat release rate (HRR), the overall dissipated heat of combustion and the effective heat of combustion were close for both types of vehicles.

The analysis of the combustion gases from car fires highlighted that the cumulative masses of CO_2, CO, total hydrocarbons, NO, NO_2, HCl and HCN were similar for both types of vehicles.
A significant quantity of HF was measured during EV and ICE vehicle fire tests. To our knowledge, HF emissions from conventional ICE vehicles have not been reported into the literature so far, may be due to recent introduction of fluorine sources in modern cars. The cumulative mass of HF was higher for EV due to the combustion of the Li-ion battery pack.
In addition to HF, a significant quantity of toxic gases including CO and HCl, in relation with the presence of chlorinated polymers, was produced during the fire tests on both types of vehicles.
All toxic compounds have to be examined to assess the global toxicity of combustion smokes during EV and ICE vehicle fires. These tests provided source terms, which can be used in modeling work to predict toxic gas dispersion and thermal effects in confined spaces, such as tunnels, underground car parks or other underground facilities.

The results of these tests are only valid for the four tested vehicles of two car manufacturers. Indeed, numerous parameters such as the fire scenario initiating event, the battery technology, its packaging, its design and its position within the vehicle are liable to play a significant role on the overall behavior of an EV exposed to an external fire. Thus, these results cannot be extrapolated to other vehicles, to other car manufacturers, to other potential fire scenarios or to other battery technologies.

These tests only studied the vehicle behavior in the case of a fire outbreak in passenger cell. In the case of a fire outbreak generated in the battery by an internal short circuit or an overcharge, the kinetics of observed phenomena would certainly be different.

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