Application of Fire Safety Engineering to Rolling Stock

Eric GUILLAUME[1], Anycée CAMILLO, Alain SAINRAT

Summary
The work presented in this document is related to the development, validation and limitations of a Fire Safety Engineering methodology in railways. It is issued from work performed during the European Research program TRANSFEU. As a first step of Fire Safety Engineering methodology, risk analysis has identified the most critical scenarios to be studied, considering actual exploitation conditions and rules in European railway network. The study of one such scenario has been performed to quantify fire safety performance level of a given train using advanced numerical tools and a multi-scale approach. This predictive method shows a good capability to reproduce properly fire growth, heat release rate, temperatures and carbon dioxide concentrations in a real-scale scenario. Nevertheless, this study highlights also a lack of prediction for carbon monoxide and other toxic species.

Keywords: Fire modelling, Fire Safety Engineering, Risk analysis, Fire dynamics

1. Introduction

Fire safety is a main research field in railway transport system. Due to the high number of passengers by unit area in vehicles and delayed evacuation because of operation conditions, it is important that materials and products vehicles have good fire performances. These railway products such as seats, roof or wall panels must follow fire safety requirements according to train operation category and type of vehicle.

In this context, this work highlights some results of the European research project TRANSFEU. The objectives are to predict fire growth of a design fire scenario, considering the limits of the used numerical tool. This work is based on multi-scale investigations on a scenario, selected by a fire risk analysis. The fire behaviour of two products present in vehicle is studied (a seat and a wall panel). These two products have been chosen due to their positions in design fire scenario,

[1] Laboratoire national de métrologie et d’essais, Paris; eric.guillaume@lne.fr.

close to the burner. The seat studied is composed of three different elements: cushion, back and headrest. Each of them is made up of multilayer materials: cover, interliner and foam, framed by polycarbonate shell. The second studied product is an inner wall panel of train vehicle. It is a non-structural composite made of glass fibres and a polyester resin matrix. The composite surface is covered with a polyester gelcoat.

2. Historical and technical background: state-of-the-art of train real-scale tests and modelling

In 1975, the fire research project, named Fire hazard evaluation of the interior of Washington metropolitan area transit authority (Materials cars), conducted a series of fire tests to assess potential fire and smoke hazards represented by various materials incorporated in new metro cars [1]. The full-scale tests results showed that the materials failed to satisfy their end-conditions. In 1978, the National Bureau of Standard (now NIST), conducted a fire hazard evaluation of the Bay Area Rapid Transit (BART) metro system in San Francisco in California [2]. The objective of this study was to check whether any design details of the materials present in the metro car could spread fire. They concluded that the polyamide or the vinyl covering the seats had to be replaced because they represented important hazard. Moreover, they recommended the use of intumescing coating on walls or ceilings to improve fire behaviour and the installation of a fire detection system. Six years later, the National Bureau of Standard conducted fire tests on Amtrak Passenger Rail Vehicle Interiors [32]. The aim was to assess the burning behaviour of the interior of passenger rail vehicles. They established that small scale test results could not be used directly to predict large scale behaviour. Finally, they specified that a small number of full-scale tests should be performed to determine a set of acceptable materials for a given design scenario of the studied vehicle. This could be followed by a set of small scale tests to assess alternative material. Then, materials, which had equal or better fire performance than the material tested in the full-scale test could then be substituted without further full scale tests.

In 1990, SP laboratory in Sweden led a project on fires in buses and trains [16]. Research involved a large-scale experiment to estimate the ignitability and heat release rate of a variety of interior materials from buses and trains.

Between 1995 and 2004, the NIST [29, 30, 31] conducted a project named „Fire Safety of Passengers Trains". They proposed an alternative approach based on heat release rate test methods incorporated with fire modelling and fire hazard analysis. Assessing potential hazards under real fire conditions could provide a more credible and cost effective approach to predict fire performance of passenger trains materials. The project was divided into three phases, including cone calorimeter tests, large- and real- scale tests on railway coaches and fire modelling using zone models. A good match between measured and modelled available time for evacuation was obtained, but White [39] reported that model assumptions and inputs were not explicitly stated and it was not clear whether model inputs were iteratively modified to achieve a good match.

In 2001, the FIRESTARR (Fire Standardisation Research of Railway vehicles, Contract SMT4-CT97-2164) project assisted the work of the CEN, the European Standardisation committee. The objectives of this project were to select suitable tests methods and tests conditions to assess fire performance of materials and propose a classification for railway materials for future European standard. The working group focused on the development of the prescriptive requirements of individual railway interior products based on the small and large scale tests [3, 4].

In 2004, the Commonwealth Scientific and Industrial Research Organization (CSIRO) performed full-scale experiments on a railway passenger car. The project aimed to investigate the fire size of railway products from different ignition sources and to understand passenger rail products fire behaviour and fire spread [38]. The main conclusions were as follows:

- The combination design of the seat and the wall lining are important factors during fire growth.
- Fire safety interest is focused on the use of the heat release rate measurement to assess the material fire performance.
- The measured data from the cone calorimeter test can provide useful data for computer modelling.

In 2005, Chiam [11] objectives were to identify credible fire scenarios, evaluate the materials reaction-to-fire, derive material thermo-physical properties from cone calorimeter tests and predict the heat release rate of this test. Analytical methods were used to predict the heat release rate. However, a computational fluid dynamic (CFD) code (FDS, Version 4) was used to predict the heat release rate on the cone calorimeter scale. Two different methods to simulate the heat release rate were tested proper to FDS. For both FDS methods, the prediction failed: the input data derived from the cone calorimeter tests were not suitable to predict directly heat release rate at lower heat flux. White [8] obtained the same conclusion as Chiam [11].

Hostikka and McGrattan [19] showed that the CFD model failed to predict the heat release rate at low heat flux exposure through a pyrolysis model. They reported that this could be due to the errors in the heat transfer solutions and thermal properties. Furthermore, they added that the absence of some physical phenomena, such as surface reactions and internal mass transfer, may also affect the results.

In 2008, Capote [9] modelled fire development in a passenger train compartment with FDS (Version 4) from the bench and the full scale tests performed during FIRESTARR project. The method involved the use of data from cone calorimeter tests. They concluded that the FDS heat release rate response was influenced by the heat flow, and the ignition temperature from cone calorimeter tests.

In 2012, Hu et alii [20] used a CFD model called SMARTFIRE (Version 4.1) to predict the heat release rate. They also required two ignition parameters criteria: ignition temperature and flame spread rate derived from small scale tests. They achieved a good correlation before the flashover for a small fire compartment. However, they highlighted that the flame spread rate measurement was function of the experimental small scale conditions. They suggested that the flame spread rate could be modelled with more fundamental spread models involving a pyrolysis mechanism.

3. TRANSFEU Project

The main goal of TRANSFEU is to develop a holistic approach of fire safety-performance based-design methodology able to support efficiently European surface transport standardisation. In particular, the project will directly contribute to the finalisation of the CEN EN 45545 Part 2 [12, 13] for a dynamic measure of toxicity and to use Fire Safety Engineering (FSE) and simulation as a possible alternative to current way of conformity assessment as stated in Fire safety regulations [15, 36, 37]. It is based on:

- A new, accurate measurement tool for toxic gas fire effluents under dynamic conditions for Public Transport Guided Systems. This new tool will allow a continuous record of toxic gas concentrations versus time to be determined,
- A deeper understanding and measurement of underlying dynamic phenomena governing fire initiation, growth under typical railway vehicle scenarios, which can predict the real scale burning behaviour of products and assemblies,
- The adoption of fire safety engineering methodology that offers the necessary modelling tools for establishing realistic and acceptable economic levels of fire safety without unnecessary constraints in vehicle or vessel design. This will be supported by the development of original simulation tools,
- The application and validation of the tests, methods and tools in public transport guided systems fire safety scenarios and standardization with potential to other surface transports.

4. Methodology

4.1. Context

Fire safety is an essential requirement of European regulations for interoperability, Directive 2008/57/EC [15] and associated Technical Specifications for

Interoperability [36, 37]. The conformity of design and elements to prescriptive rules (as EN 45545-2 for materials), see [12, 13], is a way to prove conformity of the rolling stock, or in better words that the required fire safety level is supposed to be reached at system level.

As this Directive 2008/57/EC is a „New Approach" directive, alternative ways to EN harmonized standards could be used to demonstrate this fire safety level, especially for innovative solutions. Fire Safety Engineering could be a proper tool to assess a given train in terms of absolute or relative fire safety performance. Nevertheless, this approach is not formalized in railways as it is in other domains, such as maritime transportation [34].

Fire Safety Engineering methodology has been recently developed and implemented in ISO 23932 standard [22]. This methodology has not been used in rail transportation, and a large part of TRANSFEU project is dedicated to demonstrate its applicability. This document presents the validation of a given FSE approach to railway rolling stock, and its application to a realistic train situation.

The method used in TRANSFEU program is an ASET/RSET approach, comparing the time required to evacuate with the time available for evacuation [17, 35]. The method is presented as a flowchart in Fig. 1. Calculation of time required for evacuation is not presented in this document, but details are available in reference [26].

4.2. Safety objectives

The first step of a FSE application is the definition of the safety objectives. According to Directive 2008/57/EC, the objective is related to life safety of passenger and staff. The objective is declined on a proper evacuation (depending on Operation Category of the train), with passengers and staff not in compromised tenability during their escape.

4.3. Performance criteria

The associated performance criteria related to safety objectives are related to toxicity of fire effluents, thermal effects (temperature and heat flux) and loss of visibility. All these parameters have to be simulated at system level in order to evaluate its fire safety performance level. Associated criteria could be taken from the literature, especially ISO 13571 standard [21].

4.4. Selection of Design Fire Scenarios

The fire effluents impact on passengers during the running capability of a train might be estimated not only according to the type of products present in the coach

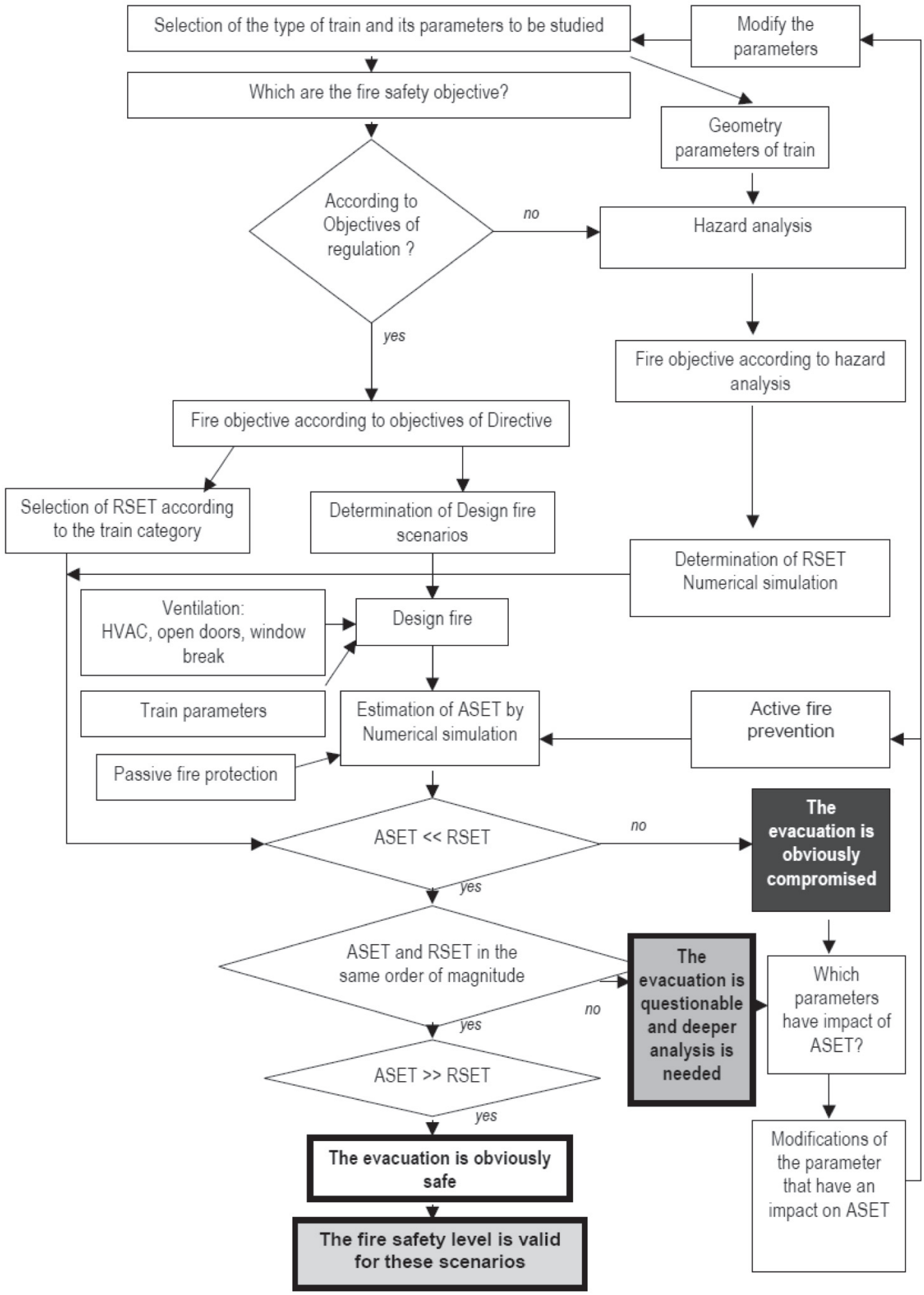


Fig. 1. General FSE methodology developed in TRANSFEU research program

but also to a given Design Fire Scenario (DFS). DFS typically defines the ignition and fire growth process, the fully developed stage and the decay stage, together with the environment and systems that will impact the course of the fire, until the safe evacuation of people. A fire risk analysis has been conducted in order to select some of the most hazardous DFS, in order to study their fire safety performances.

The aim of this fire risk analysis is to compare a few selected DFS with the overall possible scenarios, hence the name: Relative Fire Risk Analysis. This analysis consists in finding all possible fire sequences, from fire outbreak through fire spread in the railway transport network (limited to fire outbreak in passenger areas). The chosen way to identify this succession of events is to use risk analysis tools, such as events trees. In support of this risk analysis and in harmony with requirements of risk analysis techniques, fire safety experts of train manufacturers, train operators and fire safety regulator constituted an expert team. In parallel to this risk analysis, TRANSFEU railway fire safety experts, based on their relevance and feedback experience, have identified two DFS. Relative fire risk analysis results are a matrix of relative occurrence probabilities versus relative severities of each DFS. The risk level position of these two pre-selected DFS is compared with the others in the global matrix.

This relative fire risk analysis is based on the design fire scenario concept. A design fire scenario represents a chronological chain of events from fire ignition to completion of the train evacuation for this case (see Fig. 2). Each event must be well identified and described according to the future European fire standard, used for train fire safety design (CEN/TS 45545-1 (2009). Each event is conditioned by the pre-existing situation and events that already happened. The chronology of events, which affects fire dynamics, is:

- Fire ignition source: it represents all possible fire sources inside a vehicle.
- Fire detection: when a fire occurs on a train, the automatic or manual detection / alarm is activated. In this study, the event of fire detection/alarm becomes always true, but time to detection depends on a set of possible events.
- Ventilation system: the ventilation system could be stopped when detection is activated in the European railway transport network, depending on train operation category according to CEN/TS 45545-1 (2009).
- Passive and Active fire protection: the passive and/or active fire protection are methods to mitigate fire spread or to bring the fire under control, according to CEN/TS 45545-6 (2009).
- Train stopping strategy: After detection is activated, the driver or the control center have to decide where the train has to be stopped in order to evacuate people safely. If this is an outdoor fire, the train could stop immediately, whereas in a tunnel, the train may have to continue running to bring passengers to a proper evacuation place, such as a station.

- Evacuation strategy: Once detection is activated and the fire localised, passengers make important decisions with the help of the train staff, in order to save their lives, depending on the train design. Some trains have relative safety places, such as adjacent vehicles: these allow passengers to be temporarily safe from fire effects before they reach an ultimate place of safety.

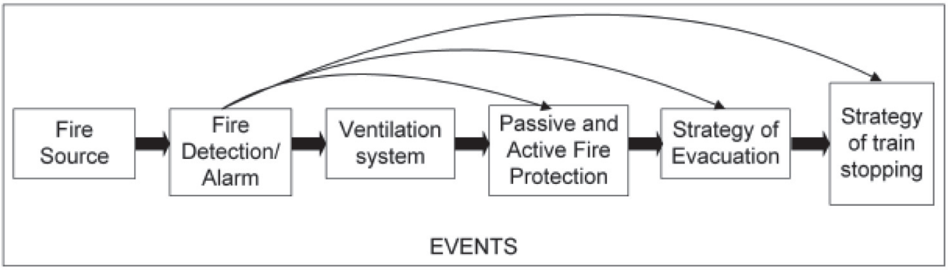


Fig. 2. Events constituting the Design Fire Scenario

Risk analysis is one of the first parts of the fire safety engineering methodology – ISO 23932 (2009). Its objective is to select the most hazardous scenarios in order to study their fire safety performances. A design fire scenario goes from fire outbreak to the completion of people evacuation. The developed methodology of a fire risk analysis used different tools such as event trees or probability distribution. This methodology consists in:

- Describing the railway transport network, the ignition source and the events that may affect the propagation of fire.
- Estimating the input parameters: the relative probability and the relative severity scale. For each event, the occurrence probability and severity are assumed to be independent from each other.
- Building the matrix of relative occurrence probability / relative severity for each type of train.

The analysis identified more than 170 000 Design Fire Secnarios. Detailed results are available in refs [5, 7] and summarized in Fig. 3 and Fig. 4. On the basis of the risk matrix for a standard train, both pre-selected scenarios (1A and 1B), defined by railway fire safety experts, have a high relative occurrence probability as well as a high relative severity compared with the other DFS. The sensitivity analysis is essential because the probability and severity data used are very difficult to obtain due to the rarity of these kinds of events, nowadays, in the railways European transport network.

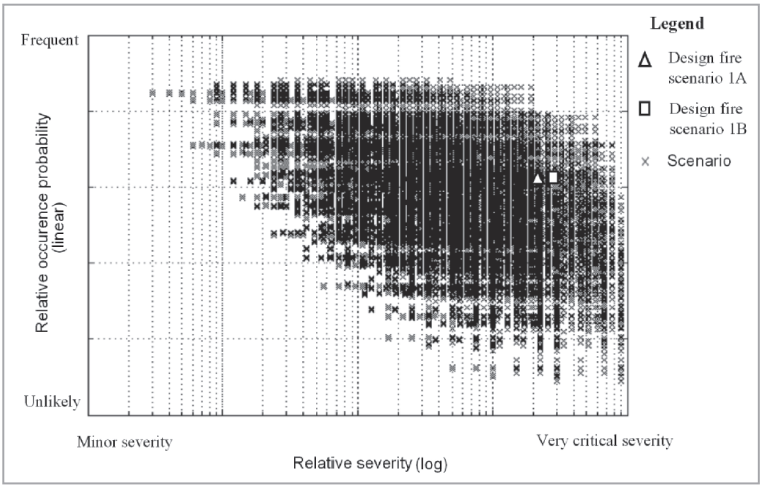


Fig. 3. Risk matrix. Each point represents a given DFS

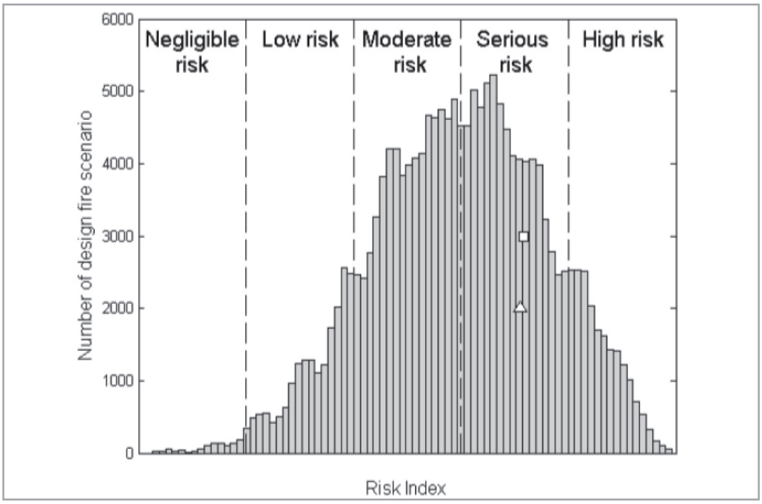


Fig. 4. Risk index classification

4.5. Quantitative approach and modelling tool used

The approach selected concerns modelling flame spread on materials and products used onboard trains. This way of modelling is quite a challenge, as it requires advanced knowledge on materials and interactions to perform a pyrolysis model. It is not used in other fields such as building fire safety, where building contents are not regulated of not well known in terms of fire performance. However, train materials are advanced materials with a good fire performance issued from decades of strict prescriptive selection rules for fire behaviour.

To be able to catch fire behaviour of such materials, a multi-scale approach is used from small-scale to real scale. Each scale gives additional information on the fire behaviour: the smallest scales inform on material fire behaviour and heat transfer, where larger ones include assemblies, mounting and fixing aspects.

Physical fire phenomena are very complex and often dependent on each other. The most encountered phenomena are the study of flow, the turbulence, the heat transfer (radiative, convective and conductive), the combustion and the pyrolysis processes. The modelling and the simulation of these phenomena are a great challenge because of the limitations due to the physics understanding and the power calculation available [18]. Despite these limitations, it is now possible to simulate a fire according to several models adapted to different hypothesis. The modelling tool used in this work is Fire Dynamics Simulator, v5.5.3 [28]. FDS solves an approximation of the Navier-Stokes equations appropriate for low-mach number, thermally-driven flows. The numerical algorithm employed is an explicit predictor/corrector scheme, second order accurate both in space and time, using a direct Poisson solver. Turbulence is treated using Large Eddy Simulation (LES), *via* the classical Smagorinsky subgrid scale model. A mixture fraction combustion model assuming a unique, infinitely fast global chemical reaction is used to estimate the heat release and smoke distributions in the computational domain. The radiation transport is treated using a finite volume solver in which grey gas absorption coefficient for soot and gas species is linked to the mixture fraction.

5. Application: validation of the method

5.1. Detailed experimental and numerical fire scenario to be reproduced

The scenario selected for this work is scenario 1A issued from the risk analysis. It consists in an arson fire source in a train coach. The studied vehicle type is a standard single coach (French MS 61 train). It has four doors on each side. There is no possible evacuation through an other vehicle. The number of passengers is 75. The air conditioning is continuously injected by the ceiling. Either passive or active fire protection are used during the fire mitigation in this scenario. The fire source is a propane sand diffusion burner. The burner is applied during 10 minutes: 75 kW during 2 minutes and then 150 kW during 8 minutes.

This square burner has the following dimensions: length 0,305 m x width 0,305 m x height 0,30 m as proposed in ISO 9705 [25]. The burner is located where a luggage can be placed under normal operation conditions, on the floor close to the seats and the wall deep down of the coach. The design fire scenario is composed of seats, wall panel, strips, ceiling, floor and partition.

At t_0 (t = 0 s), the burner starts to ignite until 75 kW and all doors are closed. After 40 seconds (t = 40 s), three doors open on the same side as the burner. At t_{120}, the second phase of the burner (150 kW) begins until t_{600}. The scenario stops when products have self-extinguish (less than two minutes after the burner stop). The seat and wall panel are potentially the two products, which are going to participate to the fire due to their positions with the burner. These two materials are studied in details.

5.2. Seat

Raw matter scale

The aim of the raw matter scale is to understand the decomposition of each material, which constitutes the seat (cover, inerliner and foam) and to estimate pyrolysis parameters (kinetic parameters and residual mass fraction) corresponding to each decomposition reaction for each material. The Fig. 5 presents TGA results of mass loss rate of the seat cover, interliner and foam under air and nitrogen atmospheres and for two heating rates (5 and 10 $K.min_{-1}$).

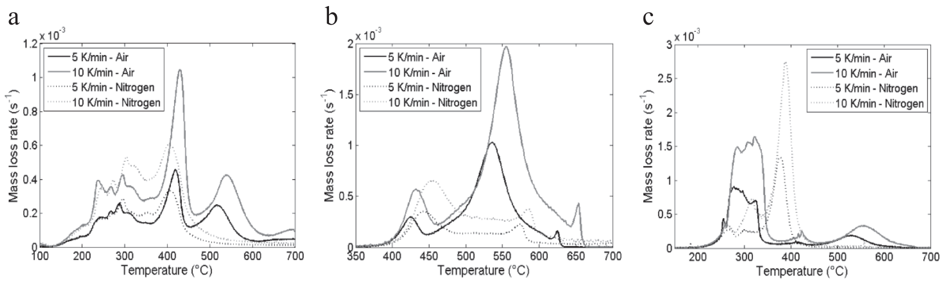


Fig. 5. Thermal decomposition of the multilayer seat material under two atmosphere (air and nitrogen) and for two different heating rates (5 and 10 K/min): a) Cover, b) Interliner, c) Foam

The thermal decomposition analysis of the elements is complex because many peaks and shoulders are identified under air and nitrogen atmospheres. The thermal decomposition of each element was defined in the form of a comprehensible multi-step reaction mechanism with thermolysis and oxidation reactions. These mechanisms have been generated based on the hypothesis that each peak of the mass loss rate graph from TGA represents a solid reacting species. When the global reaction mechanism for each seat element is assessed, the next objective at the raw matter scale is to estimate pyrolysis parameters of each reaction for each seat element according to a pyrolysis model. This model corresponds to the one used to model the fuel production at upper scales, i.e. the FDS pyrolysis model. Furthermore, this model is independent on heating rate. The estimation of kinetic parameter is done by solving an inverse problem. The method is based on a robust optimization technique that uses a genetic algorithm (GA), a research tool that uses the principle of Darwinian evolution to seek an optimal solution to a problem having a large number of adjustable parameters [27, 33]. The best optimization of the cover (starting at 300°C), the interliner and the foam are respectively presented in the Fig. 6.

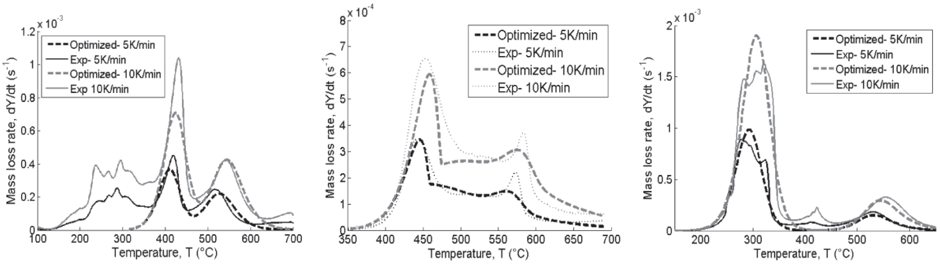


Fig. 6. Experimental and optimized comparison of thermal decomposition of the cover (left side), the interliner (center) and the foam (right side) at 5 and 10 K/min for the estimation of the pyrolysis parameters corresponding to the simplified reaction mechanism

Material scale

The aim of the simulation at material scale is to predict the fire behaviour of the multilayer seat material, and not on separate elements. Another important challenge is to estimate the materials properties through fire tests or by literature, such as thermo-physical and radiative properties, which are used as input data for this simulation. When, the fire behaviour of seat material is validated at this scale, the input data are used at upper scales.

In this regard, a three dimensional model of the cone calorimeter test geometry was created according to the dimensions of the test bench ISO 5660-1 [24]. The choice of the mesh size for a given domain of study is not obvious and depends on the domain size as well as the physical used models. The ideal mesh size for a given study is issued from Froude Number of fire established by the reference [28]. Like the material scale fire simulation, the criteria is satisfied for a mesh size of 1,25 cm and almost satisfied for 2,5 cm. All surfaces of the domain are considered open, i.e. the initial velocities in the three directions are null and the initial pressure corresponds to the atmospheric pressure (101 325 Pa).

The great challenge is to use the simplified reactions mechanism as well as the pyrolysis parameters (validated at raw matter scale) for the three components of the seat, as an input data for the FDS pyrolysis models at material scale. Concerning the condensed phase, the thermal properties and the density of each species are assessed according to literature or supplier. As the thermal and radiative properties (emissivity, conductivity and specific heat) of intermediate species (Char, intermediate species or Residue) are unknown, thermal properties of original materials are applied. The effective heat of combustion of each reaction associated to each intermediate species are estimated from the cone calorimeter results at an external radiation of 50 kW/m^2. The heat of reaction for each reaction is one of the most difficult input data to estimate due to the thermal decomposition phenomena. Consequently, this data is fitted according to the experimental data but always in the order of magnitude of a heat of reaction found in literature. Various trials have been performed, and one of the main issue found was the dependence of the results to an air gap between interliner and the foam before ignition. This air gap is crucial for fire modelling, and is due to foam shrinkage during its heating. A fictive layer of a predefined thickness numerically reproduces it. Results obtained at Cone calorimeter scale are detailed in Fig. 7 and Fig. 8.

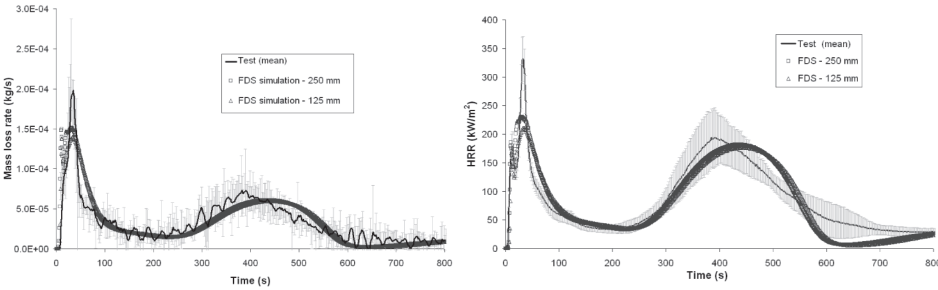


Fig. 7. Comparison of the MLR and HRR of the seat material under an incident heat flux of 50 kW/m^2

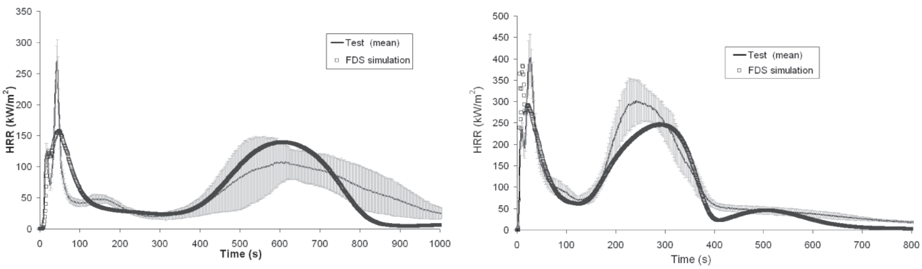


Fig. 8. Comparison of the HRR of seat material from an incident heat flux of 35 kW/m^2 (left side) and 75 kW/m^2 (right side)

Taking into account the decomposition effect, such as the shrinking of a foam part, by the formation of an equivalent multilayer materials, the new input data depend on the incident heat flux received at the surface of the material, whereas the aim of a pyrolysis model is to be independent on the external radiation heat flux. The FDS code has some weaknesses in simulating the pyrolysis and the reaction-to-fire at low heat flux, but these results are validated for next scale.

Finished product scale

The finished product scale simulation objective is to predict seat fire behaviour taking into account the effect of mounting and fixing configuration (impact of the ceiling and the corner) and then confirms numerical constants, numerical geometry and the mesh size in the simulation. This scale allows comparing the total experimental and numerical generation of released gases from the propane burner and from the product itself. In this regard, a three dimensional model of the open calorimetry test geometry was created according to the dimensions of the test bench ISO 24473 [23]. The ignition source corresponds to a propane diffusion flame 75 kW during 2 minutes and then 150 kW during 8 minutes. Details on this test and related modelling are available in reference [8]. The thickness of the fictive layer, used to reproduce gas gap during decomposition is set at 5,4 mm, equivalent to the one obtained with a 35 kW/m^2 incident heat flux. The Fig. 9 presents the comparison between the experimental and numerical heat release rate with a mesh size of 2,5 cm.

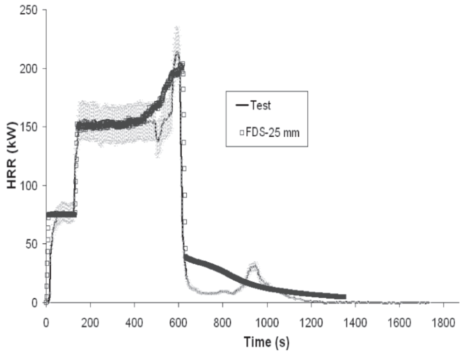


Fig. 9. Numerical and experimental HRR comparison at finished product scale

The experimental observations have shown that around 270 s after the ignition of the burner, the right corner of the seat cushion (close to the burner) starts to ignite. 240 s later, the whole cover ignites. After 600 s, the burner stops and the seat continues to burn. It is possible then that the fire has modified the geometry of the seat back: the top of the seat back is not connected anymore to the bottom of the headset. The foam is not protected by the covers and then burns. The second HRR peak observed at the time t = 950 s may be due to the combustion of the foam located on the seat back. The comparison between results shows that the intensity of the numerical prediction matches the experimental ones taking into account uncertainties. However, the kinetic of the numerical HRR is almost partially reproduced: experimentally the seat back combustion happens in two phases while numerically the combustion of seat materials is continuous. Indeed, experimentally, once the cover ignites, the seat partially begins to deconstruct at shell level and between the headrest and the back. This structural change cannot be simulated with the numerical tool. This result highlights the difficulty of FDS code to simulate the seat fire behaviour due to the use of numerical invariant solid phase in FDS pyrolysis model.

Further comparisons were performed on the two main gases detected during the experiments: carbon dioxide (CO2), carbon monoxide (CO), as seen on Fig. 10. The experimental kinetic of CO_2 is closed to those of the HRR. Considering the experimental uncertainties, the CO_2 experimental mass flow result is in compliance with the numerical one. While, experimentally the generation of the CO_2 comes from different fuel (seat and propane), numerically the CO_2 generation is only linked to the stoechiometry of the propane combustion reaction. Despite this important combustion model difference, the CO_2 mass flow comparison is quite good.

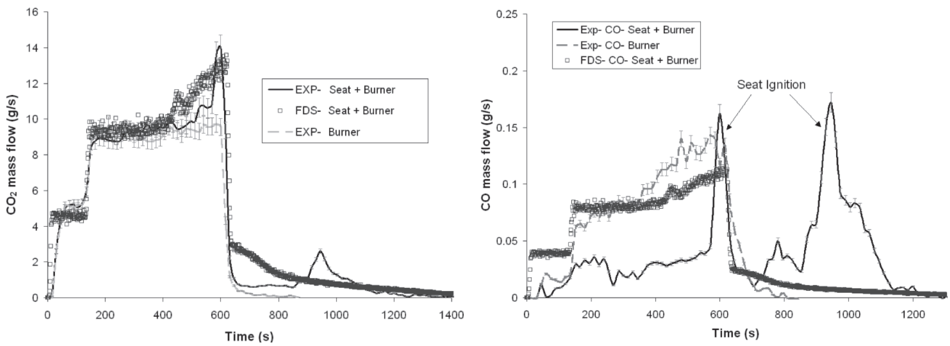


Fig. 10. Experimental and numerical comparison of the CO_2 (left side) and CO (right side) mass flow during the finished seat test

For CO, two major peaks are observed. The first one is due to the ignition of the seat back cover blend and seat cushion. The second one may be due to the foam combustion of the seat. Moreover, before the seat ignition (around 500 s), there is a difference between the experimental burner alone and experimental finished seat test. The numerical CO production is based on the mixture fraction combustion model, this implies that the same quantity of CO is released by each flame mesh surface and based on the propane combustion stoechiometry.

This required quantity comes from the burner experimental test alone and represents the total quantity of CO released (in kg divided by the total mass loss of the product in kg). The numerical CO generation is closer to the propane test alone one. Indeed, in FDS the CO generation is linked to the quantity of fuel and the combustion reaction. While, experimentally the CO generation depends on the type of fuel, the flame temperature and its residence time and oxygen diffusion into the flame. For the finished product seat test, the comparison between experimental and numerical CO released has failed. This divergence highlights the FDS combustion model (mixture fraction model and a global combustion reaction of a unique fuel) limits.

5.3. Wall panel

The same procedure has been applied to the wall panel. This GRP composite is composed of two parts: a polyester gelcoat and a hand-laminated glass fibres / polyester / mineral fillers composite. This wall panel is flame-retarded. The same procedure as for seat has been applied.

Results obtained at raw matter scale are presented on Fig. 11 for TGA data and on Fig. 12 for numerical results. For the model, reaction of ATH (used as flame retardant) is separated from reaction of the polyester resin. The material is then considered as an assembly of these two reactive parts, plus inert fillers (fibres, mineral fillers). Results are validated for material scale.

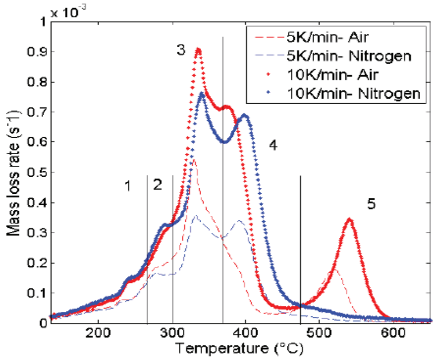


Fig. 11. Experimental results at raw matter scale for the wall panel

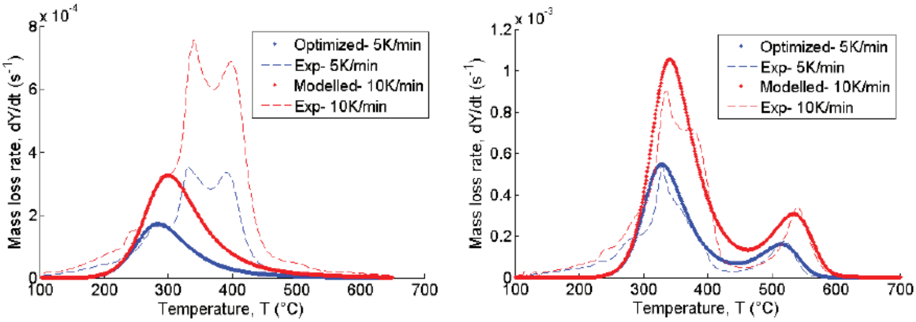
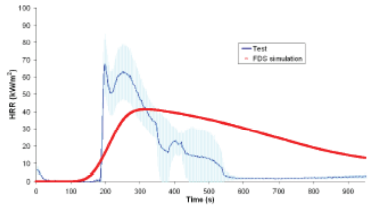
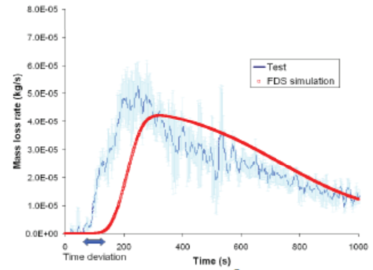


Fig. 12: Experimental and numerical results at raw matter scale for ATH (left) and Polyester (Right)

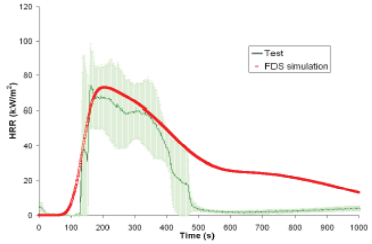
At material scale, this GRP has been tested and simulated on cone calorimeter ISO 5660-1 [24], with the same conditions as previously. Experimental and numerical results are presented on Fig. 13. Except for the numerical results obtained from 20 kW/m¸, the numerical MLR and HRR have the same kinetic and order of



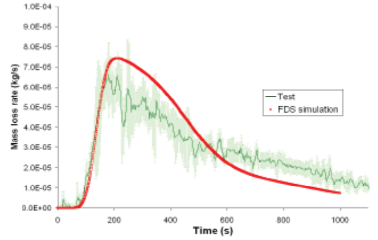
a/ Experimental HRR, 20 $kW.m^{-2}$.



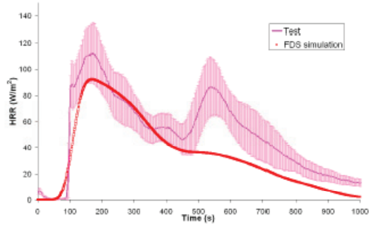
b/ Experimental MLR, 20 $kW.m^{-2}$.



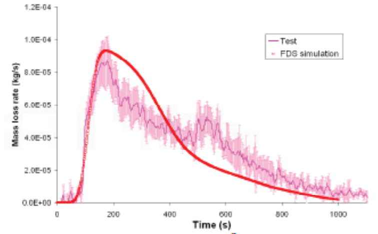
c/ Experimental HRR, 25 $kW.m^{-2}$.



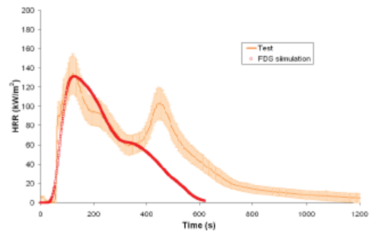
d/ Experimental MLR, 25 $kW.m^{-2}$.



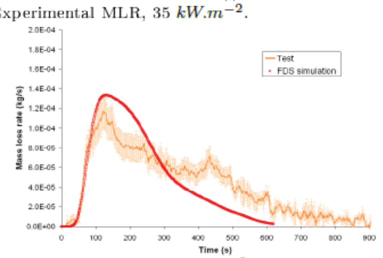
e/ Experimental HRR, 35 $kW.m^{-2}$.



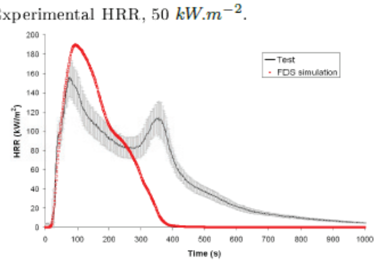
f/ Experimental MLR, 35 $kW.m^{-2}$.



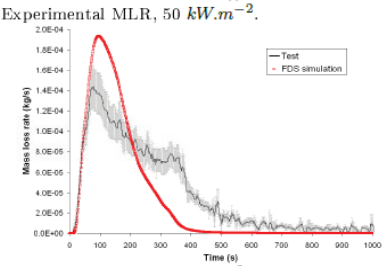
g/ Experimental HRR, 50 $kW.m^{-2}$.



h/ Experimental MLR, 50 $kW.m^{-2}$.



i/ Experimental HRR, 75 $kW.m^{-2}$.



j/ Experimental MLR, 75 $kW.m^{-2}$.

Fig. 13. Experimental and numerical results at material scale for GRP composite wall panel

magnitude as the experimental ones until the second sudden HRR peak occurs, taking into account the uncertainties. At 20 kW/m^2, time-related aspects are not well represented, as the FDS model is not adapted for low heat fluxes, mainly because of its 1D heat transfer equation.

At product scale, ISO 24473 [23] large-scale experiments have been performed to validate geometrical and assemblies aspects. A corner of two panels was tested. The ignition source corresponds to a propane diffusion flame 75 kW during 2 minutes and then 150 kW during 8 minutes. Details on this test and related modelling are available in reference [8]. Fig. 14 represents the HRR numerical and experimental comparison at two different mesh sizes: 2,5 and 5 cm of the finished wall panel test. For both mesh sizes, the numerical result has the same kinetic and intensity compared to the experimental one. Based on the HRR results, the mesh size has no important influence in this range and for this configuration. The experimental and numerical gases released are compared in Fig. 15. As the HRR comparison, for the 5 cm mesh, the experimental and numerical carbon dioxide

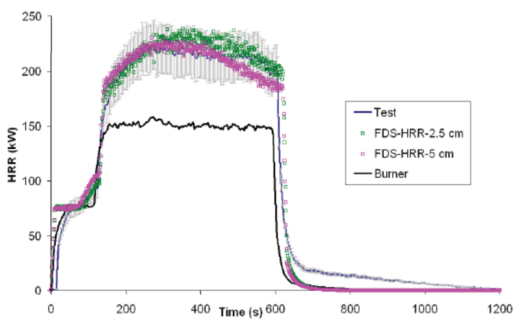
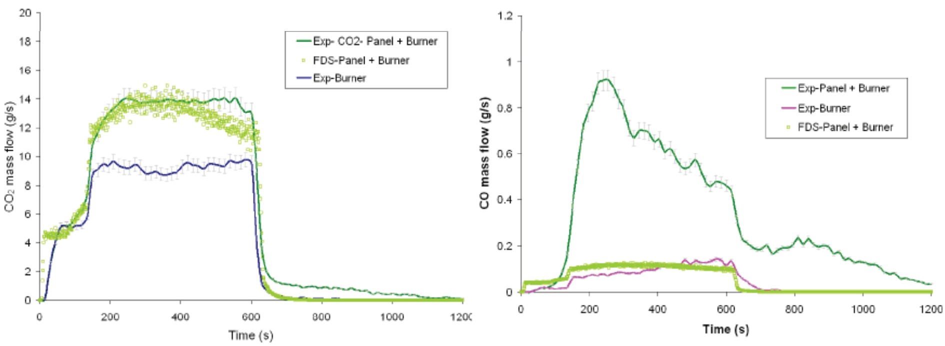


Fig. 14. Experimental and numerical HRR results at large-scale for GRP composite wall panel



a/ Experimental and numerical CO_2 comparison of the finished panel test.

b/ Experimental and numerical CO comparison of the finished panel test.

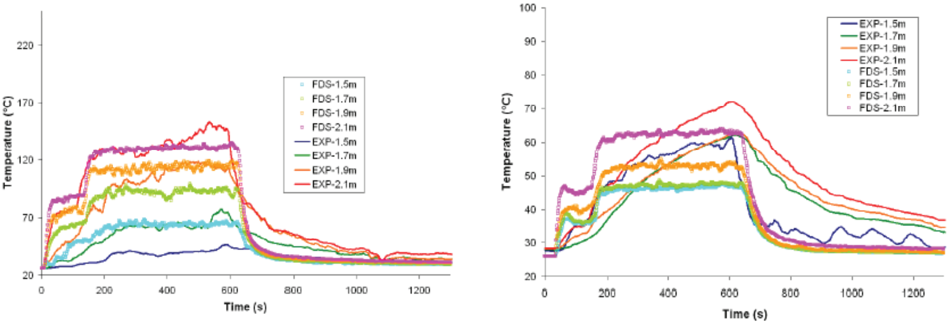
Fig. 15. Experimental and numerical CO/CO_2 results at large-scale for GRP composite wall panel

mass flows have the same kinetic and the same intensity. For carbon monoxide released, the numerical response is close to the experimental burner. In fact, when a quantity of fuel is released from the numerical wall panel, the fuel (the propane) is oxidized in the FDS gas phase according to propane stoichiometry reaction. Thus, the comparison on the released carbon monoxide failed due to the FDS mixture fraction combustion model.

5.4. Real-scale configuration

A MS61 French suburban coach refurbished with the materials previously studied has been tested according to scenario 1A from risk analysis. Tests results have been compared to simulation results using the data validated as previously for seat and wall panel. Details on this test and related modelling are available in reference [8].

For temperature measurements (see Fig. 16), at all positions, the numerical trends follow the kinetic of the burner heat release rate (75 kW for 2 min. and then 150 kW for 8 min.) and have the same order of magnitude. Concerning thermocouples responses located far from the fire, the numerical and experimental temperatures kinetic are slightly different. Indeed, two numerical temperature levels are observed while the experimental temperatures continuously increase. This difference may be due to the mesh size of the coach.

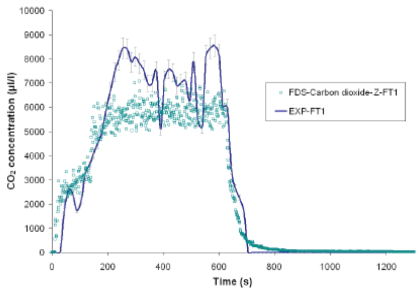


a/ Thermocouples tree 1.5 to 2.1 *m* from the fire. *b/* Thermocouples tree 1.5 to 2.1 *m* far from the fire.

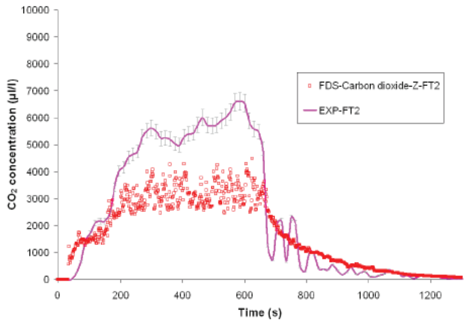
Fig. 16. Experimental and numerical temperature results at real-scale

The experimental and numerical gases released are compared in Fig. 17. The experimental and numerical carbon dioxide and carbon monoxide concentrations have the same kinetic as the burner (two stages are observed). Concerning carbon dioxide results at first position, the numerical response has the same level of magnitude than the experimental one: around 2,500 μL/L and 6,000 μL/L for each plateau. For the second position, the numerical concentration is about two times lower than the experimental one.

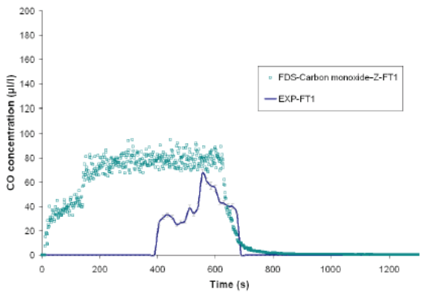
ASET calculation indicates that the value of FEC/FED > 0,3 according to ISO 13571 is not reached in 20 minutes. RSET calculation has been performed to estimate evacuation time in this scenario, and gives a maximum of 101 seconds when very crowded.



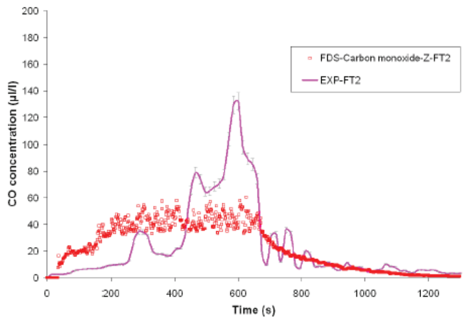
a/ CO_2 comparison of scenario 1A in position FT1 (close to the burner).



b/ CO_2 comparison of scenario 1A in position FT2 (far from the burner).



c/ CO comparison of scenario 1A in position FT1 (close to the burner).



d/ CO comparison of scenario 1A in the position FT2 (far from the burner).

Fig. 17. Experimental and numerical CO/CO_2 results at real-scale

6. Conclusions

The work presented in this document is related to the modelling of actual train materials up to end-use conditions, for application in a fire safety engineering approach. The fire safety engineering approach has been applied to trains. Risk analysis has identified the most critical scenarios to be studied, considering actual exploitation conditions and rules in European railway network. The study of one such scenario has been performed to quantify fire safety performance level of a given train using advanced numerical tools and a multi-scale approach.

This predictive method has shown good capability to reproduce properly fire growth, heat release rate and temperatures in a real-scale scenario. Main species such as carbon dioxide have been reproduced properly too. Nevertheless, this study highlights also a lack of prediction for carbon monoxide and other toxic species. Further work has to be performed too in order to analyze visibility data, which has not been studied at present time.

At present time, authors recommend to limit assessment of tenability of people to thermal-related effects and to track with CO_2 if they are exposed to smoke. A fine analysis of smoke toxicity impact on passengers, and loss of visibility, are not sufficiently validated and need further technical developments to be reproduced properly.

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Streszczenie

W artykule omówiono zakres i wyniki finansowanego w ramach 7 Ramowego Programu UE (FP7-SST-2008-RTD-1 dla Transportu Powierzchniowego) projektu TRANSFEU (*Transport Fire Safety Engineering in the European Union*) „Inżynieria ochrony przeciwpożarowej w transporcie UE". W projekcie wykorzystano holistyczne podejście do bezpieczeństwa pożarowego taboru pasażerskiego. Po analizie ryzyka i wytypowaniu najbardziej krytycznych scenariuszy, przeprowadzono wiele badań, od skali laboratoryjnej do naturalnej, których wyniki na każdym etapie walidowano symulacjami numerycznymi. Uzyskano dużą przewidywalność rozwoju pożaru w skali naturalnej na podstawie symulacji FSE w zakresie szybkości wydzielania ciepła, temperatury i stężenia dwutlenku węgla. Natomiast dla emisji tlenku węgla oraz innych gazów toksycznych wystąpiły duże rozbieżności. Powyższe potwierdziło, że pożar w wagonie jest zjawiskiem bardzo skomplikowanym, na którego przebieg ma wpływ wiele czynników.

Słowa kluczowe: TRANSFEU, bezpieczeństwo pożarowe, tabor pasażerski, przewidywalność rozwoju pożaru, symulacja FSE

Вклад противопожарной техники в ценку уровня пожарной безопасности в европейских поездах и ограничения при её проведении

Резюме

Автор обсуждает объём и результаты проекта TRANSFEU (Transport Fire Safety Engineering in the European Union) «Противопожарная техника в транспорте ЕС», финансированного в рамках седьмой Общей программы ЕС (FP7-SST-2008-RTD-1 для сухопутного транспорта). Применяя холистический подход к пожарной безопасности пассажирского подвижного состава, после анализа рынка и определения самых критических сценариев, в рамках проекта проведён ряд испытаний, как в лабораторных, так и в естественных условиях, которых результаты были подтверждены на каждом этапе численными моделированиями. Достигнута высокая степень предвидения распространения пожара в естественных условиях на основе моделирования FSE по скорости тепловыделения, температуры и концентрации двуокиси углерода. Однако, по эмиссии окиси углерода и других токсических газов появились большие расхождения. Вышеуказанное подтверждает, что пожар в вагоне это очень сложное явление, на ход которого влияют многие факторы.

Ключевые слова: TRANSFEU, пожарная безопасность, пассажирский подвижной состав, предвидение распространения пожара, моделирование FSE