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Application and Limitations of a Method Based on Pyrolysis Models to Simulate Railway Rolling Stock Fire Scenarios

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Abstract. This article relates the application of pyrolysis models to products used onboard trains, as part of a fire safety engineering design or assessment. It is based on work performed during the European Research program, TRANSFEU. As a first step in the methodology, risk analysis permits identification of the most critical scenarios to be studied, considering actual operational conditions and rules in the European railway network. The study of one such scenario has been performed using advanced numerical tools and a multi-scale approach from raw material to real scale, in order to validate the application of such techniques in fire risk assessment. Simulations have been compared to experimental data at each scale. This predictive method shows a good capability to properly reproduce fire growth, heat release rate, temperatures and carbon dioxide concentrations in a real-scale scenario. On the other hand, this study highlights poor prediction of concentrations of carbon monoxide and other toxic species.

Keywords: Fire modeling, Fire dynamics, Thermal decomposition, Pyrolysis kinetics, Gaseous emissions, Fire safety engineering

1. Introduction and Background

Fire safety is an important area of research for railway transport systems. Due to the large number of passengers per unit area in vehicles and delayed evacuation because of operating conditions, it is important that materials and products in vehicles have good fire performance. 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 1975, a series of fire tests were conducted as part of a project to evaluate fire and smoke hazards in the Washington, DC, USA Metrorail cars [1]. Such hazards are mainly due to the various materials in these subway cars. The full-scale test results showed that the materials failed to satisfy their end-use conditions. In 1978, the National Bureau of Standards (NBS, now NIST), conducted a fire hazard evalu-

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ation of the Bay Area Rapid Transit (BART) metro system in San Francisco, CA, USA [2]. The objective of this study was to check whether any design details of the materials present in the rail car could spread fire. It was concluded that the polyamide or the vinyl covering the seats had to be replaced because these materials represented an important hazard. Moreover, it was recommended that an intumescent coating be used on walls or ceilings to improve fire behavior and that a fire detection system be installed. 6 years later, NBS conducted fire tests on Amtrak Passenger Rail Vehicle Interiors [3]. The aim was to assess the burning behavior of the interior of passenger rail vehicles. It was established in this study that small scale test results could not be used directly to predict large scale behavior. Finally, the study specified that a small number of full-scale tests should be performed to determine a set of acceptable materials for a given vehicle design scenario. This could be followed by a set of small scale tests to assess alternative materials. Alternative materials that 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 in Sweden led a project on fires in buses and trains [4]. 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 USA National Institute of Standards and Technology (NIST) [5–7] conducted a project named ‘‘Fire Safety of Passenger Trains’’. This project resulted in an alternative approach based on heat release rate test methods combined with fire modeling 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 train materials. The project was divided into three phases, including cone calorimeter tests, large- and real- scale tests on railway coaches and fire modeling using zone fire models. A good match between measured and modeled available safe egress time (ASET) was obtained, but White [8] 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) project assisted the work of CEN, the European Standardization committee. The objectives of this project were to select suitable test methods and test conditions to assess fire performance of materials and propose a classification for railway materials for future European standards. The working group focused on the development of the prescriptive requirements of individual railway interior products based on small and large scale tests [9, 10].

In 2004, the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia performed full-scale experiments on a railway passenger car. The project aimed at investigating the fire size of railway products from different ignition sources and to understand fire behavior and fire spread for passenger rail products [11]. The main conclusions were as follows:

- The combined design of the seat and the wall lining are important factors during fire growth.
- Fire safety is focused on the use of heat release rate measurements to assess material fire performance.

- Measured data from the cone calorimeter test can provide useful data for computer modeling.

In a 2005 thesis by Chiam [12], the objectives were to identify credible fire scenarios, evaluate material reaction-to-fire, derive material thermo-physical properties from cone calorimeter tests and predict heat release rate, using analytical methods. Fire Dynamics Simulator (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 within FDS. For both FDS methods, the prediction failed: the input data derived from the cone calorimeter tests were not suitable to predict heat release rate directly at lower heat flux levels. White [8] obtained the same conclusion as Chiam [12].

Hostikka and McGrattan [13] showed that the FDS model failed to predict heat release rate at low heat flux exposure using 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 et al. [14] modeled fire development in a passenger train compartment with FDS (Version 4) from bench and full scale tests performed during the FIRESTARR project. The method involved the use of data from cone calorimeter tests. It was concluded that the FDS heat release rate response was influenced by the heat flow and the ignition temperature from cone calorimeter tests.

In 2009, Coles et al. [15] used FDS (version 5) to predict fire growth on the interior of rail vehicles, in order to predict design fires for ventilation of tunnels and stations. Their study included a deterministic methodology and an alternative probabilistic assessment. The study related to fires that grow to cause problems for infrastructure. It didn't focus on the safety of people inside vehicles in the initial fire development and didn't consider materials and products with increased reaction-to-fire characteristics as installed now in European trains.

In 2012, Hu et al. [16] used a CFD model called SMARTFIRE (Version 4.1) to predict the heat release rate. They also required two ignition criteria: ignition temperature and flame spread rate derived from small scale tests. A good correlation was achieved before the flashover for a small fire compartment. However, it was emphasized that the flame spread rate measurement was a function of the experimental small scale conditions but it was suggested that the flame spread rate could be modeled with more fundamental spread models involving a pyrolysis mechanism.

Train fire safety was mainly designed since the 1970s on the basis of prescriptive rules and codes. These codes focused on reaction-to-fire, smoke and toxicity requirements for materials. Such requirements have been defined according to feedback from accidents. However, construction and operation conditions of trains in Europe have greatly evolved the last few years and new challenges such as introduction of composite materials are possible future developments. Regulation in Europe allows Fire Safety Engineering as an alternative way to demonstrate conformity, but there are neither case studies nor methodologies developed to accomplish this. Moreover, the intrinsically good fire behavior of train materials and products requires an innovative approach to catch fire growth phenomena onboard trains. A classic approach based on prescribed fire curves is not relevant in many cases because of improved reaction-to-fire behavior of train components.

The cited past studies provide a first step to a risk-based approach in fire safety analysis and fire modeling of train scenarios. These case studies demonstrate the capabilities and limitation of various modeling tools applied to trains. More recent studies [12, 13, 16] prove especially the difficulty in modeling fire spread on train materials. To correct this lack of knowledge, a research program named TRANSFEU has been performed between 2008 and 2012. The present study summarizes the application of pyrolysis models in the TRANSFEU research program. The main goal of the TRANSFEU project is to develop a holistic approach to fire-safe performance based design able to support efficiently European surface transport standardization. In particular, the project directly contributes to standardization [17, 18] for a dynamic measure of toxicity and to the use of engineering simulations as a possible alternative to current conformity assessment methods, as stated in regulations [19–21].

The objectives of the current study are to predict fire growth for a complete design fire scenario (DFS), considering the limits of the numerical tools that are used. The methodology is a multi-scale investigation for a scenario selected on the basis of a fire risk analysis. The fire behavior of two products (a seat and a wall panel) present in a vehicle is studied in detail using pyrolysis models. These two products have been chosen due to their position in the DFS, close to the burner used as the ignition source. 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 a polycarbonate shell. The second studied product is an inner wall panel of the train vehicle. It is a non-structural composite made of glass fibers and a polyester resin matrix. The composite surface is covered with a polyester gel-coat.

This article first summarizes the selection of a DFS from a risk analysis. Next, the experimental and the numerical characterization and modeling of the thermal decomposition of each product involved in the selected fire scenario is described. Analysis of the fire behavior of these products is then performed from a material scale to a real scale configuration.

2. Methodology

2.1. Context

Fire safety is an essential requirement of European regulations for interoperability [19] and associated Technical Specifications for Interoperability [20, 21]. The conformity of design and elements to prescriptive rules [17, 18] is one way to prove conformity of the rolling stock to required fire safety at a system level.

As the 2008/57/EC is a ‘‘New Approach’’ directive, alternative ways to EN harmonized standards could be used to demonstrate that the requested fire safety level is reached, 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 [22].

An outline of the FSE methodology has been recently developed and implemented in the ISO 23932 standard [23]. This methodology has not been formerly applied to rail transportation so a large part of the TRANSFEU project is dedicated to demonstrate its applicability. This article presents the validation of a given FSE approach to railway rolling stock and its application to a realistic train situation.

The method used in the TRANSFEU program is an ASET/RSET approach, comparing the required safe evacuation time (RSET) with the time available for evacuation [24, 25]. Application of this method requires a proper determination of ASET, the time before compromised tenability conditions are reached in the train passenger area. Calculation of RSET, time required for evacuation, is not presented here, but details are available in [26].

2.2. 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 specified as a proper evacuation (depending on Operation Category of the train), with passengers and staff not in compromised tenability during their escape.

2.3. 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 the level of fire safety performance. Associated criteria can be taken from the literature, especially ISO 13571 [27]. The criteria chosen for the study could be based on FED/FEC models proposed in [27] for toxicity or thermal impact on people. For example, a criteria of FED = 0.3 corresponds to 11.4 % of the population in compromised tenability according to the standard.

2.4. Selection of DFSs

European trains have to maintain their running capability with a fire onboard, e.g. to pass a tunnel and allow the safe evacuation of passengers on a platform. The impact of fire effluents on passengers during this period might be estimated not only according to the type of products present in the coach but also according to a given DFS. The DFS concept typically is a chronological chain of events (see Fig. 1) that define 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 occupants are safely evacuated. A fire risk analysis has been conducted in order to select some of the most hazardous DFS, in order to study fire safety performance.

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 ana-

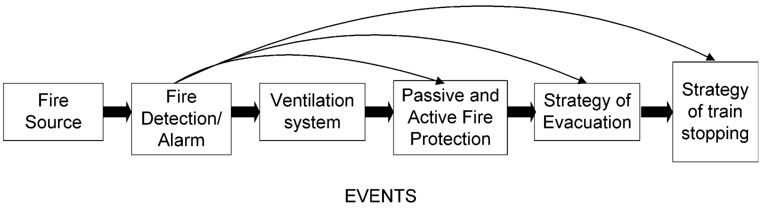


Figure 1. Events constituting the DFS.

lysis 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 method chosen to identify this succession of events is to use risk analysis tools, such as event trees. In support of risk analysis and requirements of risk analysis techniques, fire safety experts from train manufacturers, train operators and regulators constitute an expert team that predefines two design scenarios and helps to define probabilities and severities for the risk analysis. Relative fire risk analysis results are a matrix of relative occurrence probabilities versus relative severities of each DFS. The risk level positions of these two pre-selected DFS are compared with others in the global matrix.

Each event in the DFS (see Fig. 1) must be well documented and described according to the future European fire standard for train fire safety design [28]. Each event is conditioned by the pre-existing situation and events that already happened. The chronology of events that 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 [28].
- Passive and Active fire protection: the passive and/or active fire protection systems are methods to mitigate fire spread or to bring the fire under control, according to [29]. It includes fire alarms, portable and fixed extinguishment systems.
- Train movement strategy: After detection is activated, the driver or the control center has 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 localized, 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 relatively safe places, such as adjacent vehicles: these allow passengers to be temporarily safe from fire effects before they reach an ultimate place of safety. The evacuation strategy in trains could occur in two steps.

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 fire risk analysis methodology developed for this problem consists of:

- 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 performed has identified more than 170,000 DFSs. Detailed results are available in [30–32] and summarized in Figs. 2 and 3. 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 (but not extreme) 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 in the European railways transport network.

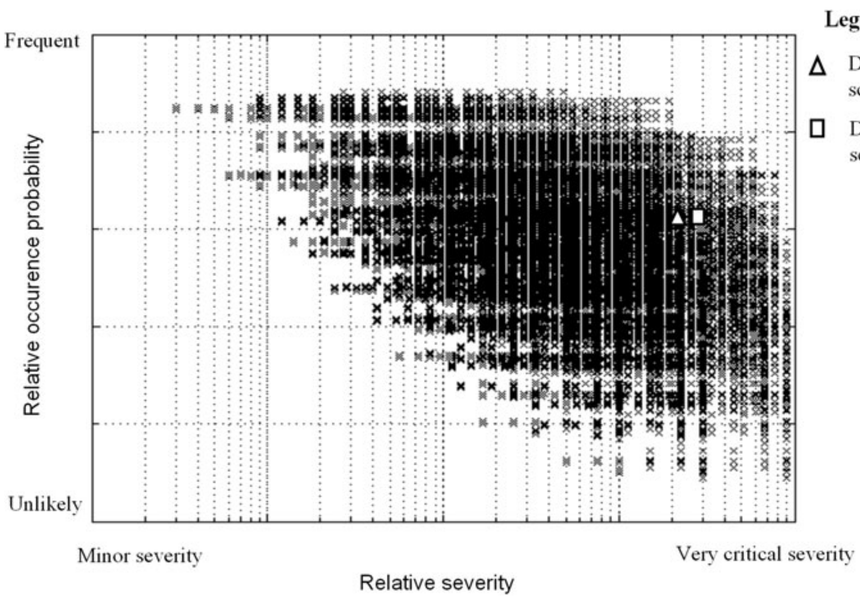


Figure 2. Risk matrix. Each point represents a given DFS.

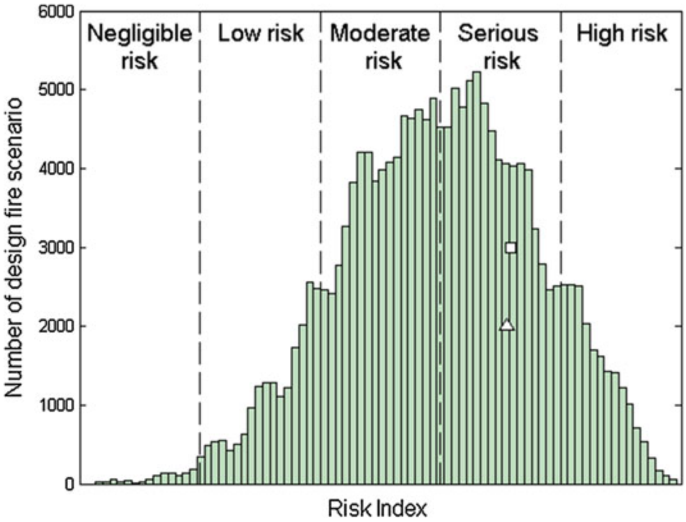


Figure 3. Risk index classification.

2.5. Quantitative Approach and Modeling Tool Used

The selected approach involves modeling flame spread on materials and products used onboard trains. This type of modeling is a challenge, as it requires advanced knowledge on materials and products thermo-chemical behavior to establish a pyrolysis model. It is not used in other fields such as building fire safety, where building contents are not regulated or not well known in terms of fire performance. However, train materials are advanced products with good fire performance resulting from decades of strict prescriptive selection rules for fire behavior.

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

Physical fire phenomena are very complex and often inter-dependent. The phenomena most often encountered are flow turbulence, heat transfer (radiative, convective and conductive), combustion and pyrolysis processes. The modeling and the simulation of these phenomena are a great challenge because of the limitations in understanding the physics and in the calculation power available [33]. Despite these limitations, it is now possible to simulate a fire using several models adapted to different purposes. The modeling tool used in the present work is FDS, v5.5.3 [34]. 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.

The steps chosen for the study have been validated during previous research [35] for other types of materials. Nevertheless, the authors have not investigated upholstered furniture and highly flame-retarded products previously. The specific approach used here is presented in Fig. 4. The first step is to determine a decomposition chemical path and associated kinetic constants at TGA scale for each specific material. The numerical tool used at this step is homemade software already used in previous work [35]. The second step consists in modeling material behavior in the cone calorimeter, using FDS software. At this step, additional parameters such as thermal transfer data are needed. These parameters have been measured when possible, or extracted from literature. This step helps in understanding the additional phenomena that occur when materials are combined onto a multilayer assembly, as the behavior of the product is not only the contribution of individual materials. Interactions and additional physical phenomena that can occur during thermal stress of the assembly are essential to understanding how the product behaves. However, the second step doesn't provide any information on flame-spread modeling, as heat exposure in the cone is constant and uniformly applied to the whole sample surface. A third step is then needed to chose the best conditions such as mesh size or heat transfer coefficients that represent the flame spread over studied products. The last step is the validation case, where products are combined together in a real-scale realistic configuration. Parameters like mesh size or LES subgrid model have been already selected at the previous scale.

3. Application: Validation of the Method

3.1. Detailed Experimental and Numerical Fire Scenario to be Reproduced

The scenario selected for the validation case is scenario 1A issued from the risk analysis. It consists of an arson fire source in a train coach. The studied vehicle type is a standard single coach (French MS 61 train) refurbished with materials and products compliant with the requirements in [18]. This vehicle has four doors on each side. There is no possible evacuation through another vehicle. The number of passengers is 75. The air conditioning openings are located at the ceiling. Either passive or active fire protection is used during the fire mitigation in this scenario. The fire source is a square propane sand diffusion burner. The burner is applied for 10 min according to the following sequence: 75 kW during the first 2 min and then 150 kW for the next 8 min. This square burner has the following dimensions: length 0.305 m × width 0.305 m × height 0.30 m as proposed in ISO 9705 [36]. The burner is located where luggage can be placed under normal operating conditions, on the floor close to the seats and the side wall, at an extremity of the coach. The DFS is composed of seats, wall panel, strips, ceiling, floor and partition. Figure 5 shows an overview of the vehicle and products onboard.

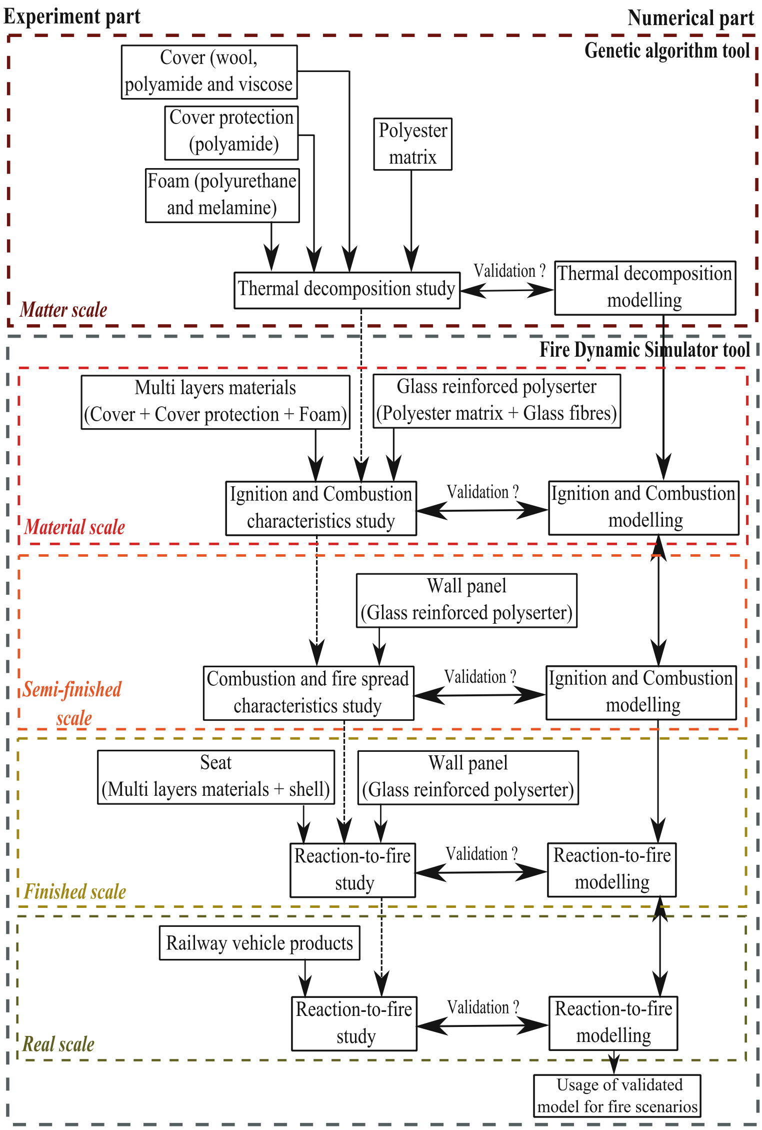


Figure 4. Presentation of the multiscale experimental–numerical approach used.

At t_0 ($t = 0$ s), all doors are closed and the burner ignites and reaches a heat release rate of 75 kW. After 40 s ($t = 40$ 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-extinguished (less than two min after the burner stops). The seat and wall panel are the two products most likely to participate in the fire due to their positions with regard to the burner. These two products are studied in detail.

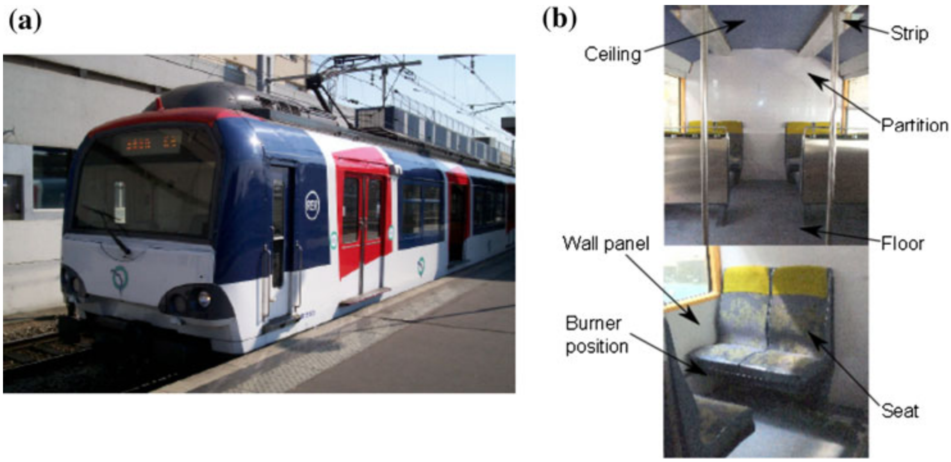


Figure 5. Case-study: French MS61 train and view of products for scenario 1A. (a) General view and (b) Products for scenario 1A.

3.2. Seat

The seat is a classical train seat for urban applications. It is made of a flame-retarded polycarbonate frame enclosing the seat back and cushion. These two elements are made of a textile, a fire protecting inter-liner and a foam.

3.2.1. Raw Material Scale. The aim of the raw material scale is to understand the decomposition of each single material that constitutes the seat (cover, inter-liner and foam) and to estimate pyrolysis parameters (kinetic parameters and residual mass fraction) corresponding to each decomposition reaction for each material. Figure 6 presents TGA results of mass loss rate of the seat cover, inter-liner and foam under air and nitrogen atmospheres and for two heating rates (5 K/min and 10 K/min).

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 comprehensive multi-step reaction mechanism with thermo-pyrolysis and oxidation reactions. This reaction mechanism has 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 material scale is to estimate kinetic parameters of each reaction for each seat element according to a pyrolysis model. This model corresponds to the one used to model the temperature dependence of fuel production at upper scales. Furthermore, this model has to be independent of heating rate. Some hypotheses are needed before calculation of kinetic parameters:

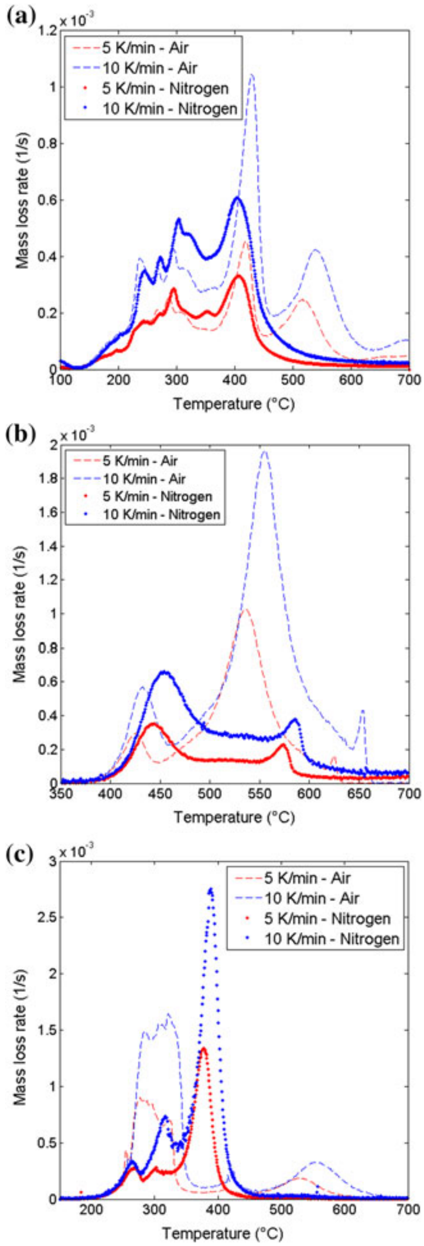


Figure 6. Thermal decomposition of the multilayer seat material under two types of atmosphere (air and nitrogen) and for two different heating rates (5 and 10 K/min). (a) Cover, (b) Interliner, and (c) Foam.

– For the cover, a significant mass loss rate is observed below 300°C in experimental data. Nevertheless, at upper scales, no ignition was observed for surface temperature below 300°C. It seems that these first steps observed from 150 to 300°C are associated with the release of non-combustible fractions. These reactions have been excluded for the model.
– In the FDS model used at larger scales, oxygen diffusion to the surface is not calculated. A choice for the diffusion mechanism used at larger scales is then needed. The choice was made by using the relative position of materials and diffusion of oxygen at the larger scale (and presented further):

  - At the beginning of the cone calorimeter tests, it is assumed that the oxidative regime is predominant, and that oxygen can diffuse to the surface of the cover. So, the model for the cover has been established on the basis of TGA results in air.
  - Ignition of the inter-liner is observed just after ignition of the cover in the cone calorimeter. Its place just below and in contact with the cover (and its char) lead to an estimate of the absence of oxygen diffusion at the time when inter-liner is involved in combustion.
  - For the foam, as it burns later than the cover and inter-liner, it is assumed that oxygen has time to diffuse again and into foam cells. The mechanism with air has been selected.

If the fire develops so that oxygen could not diffuse properly, this set of hypotheses could become less relevant at real scale.

The estimation of kinetic parameters is done with a homemade code by solving an inverse problem. The method is based on a robust optimization technique that uses the genetic algorithms (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 [37, 38]. The best optimization of the cover (starting at 300°C), the inter-liner and the foam are respectively presented in Fig. 7. The optimization only concerns kinetic parameters and intends to reproduce a best fit with experimental data from several heating rates simultaneously. The Hilbert hybrid method is used to fit simultaneously values and curvatures [39, 40].

3.2.2. Material Scale. The aim of the simulation at material scale is to predict the fire behavior of the multilayer seat material, and not of separate elements. The behavior of the assembly depends on single materials that constitute it, but also on interactions between them and various physical phenomena that could occur during thermal transfer. Another important challenge is to estimate the material properties through fire tests or from literature, such as thermo-physical and radiative properties, which are used as input data for this simulation. These properties have been measured when possible, or extracted from the literature. When the fire behavior of seat material is validated at this scale, the input data may be used at larger scales.

In this regard, a three dimensional model of the cone calorimeter test geometry has been created with FDS according to the dimensions of the bench test, ISO 5660-1 [41]. The choice of the mesh size for a given domain of study is not obvi-

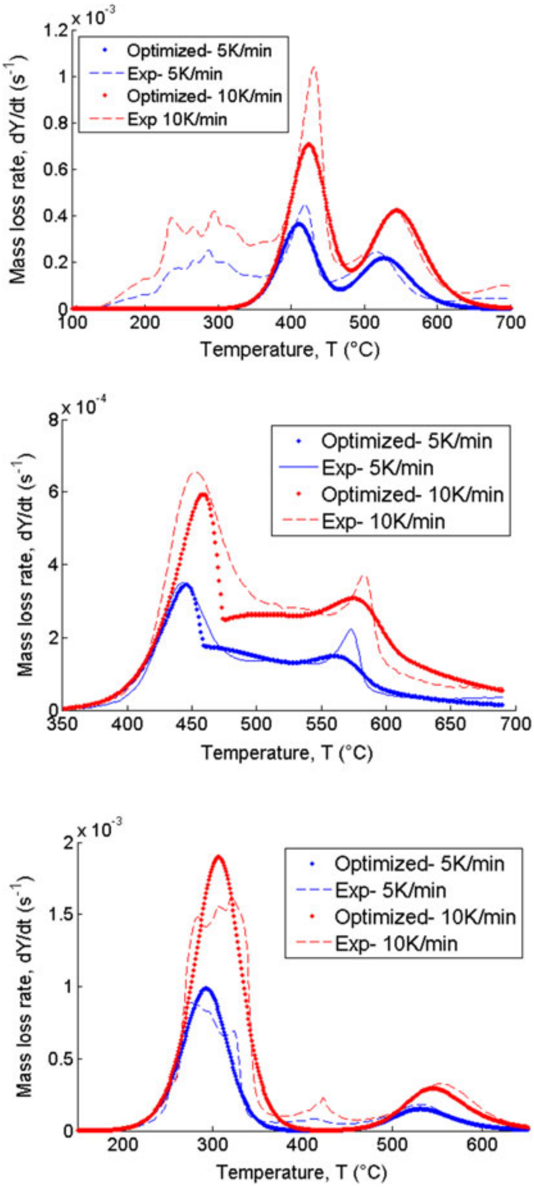


Figure 7. Experimental and optimized comparison of thermal decomposition of the cover (*top*), the interliner (*middle*) and the foam (*bottom*) at 5 K/min and 10 K/min for the estimation of the pyrolysis parameters corresponding to the simplified reaction mechanism.

ous and depends on the domain size as well as the physical models to be used. The ideal mesh size for a given study is determined from the Froude Number of the fire, as established in [34]. Like the material scale fire simulation, the criterion

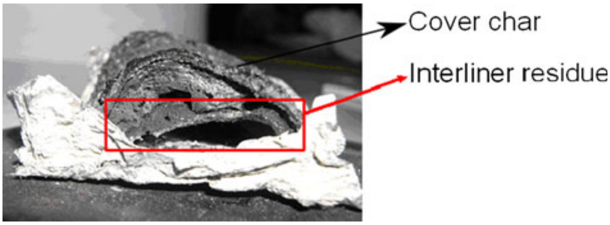


Figure 8. Observations of the seat composition after cone calorimeter experiments. The chars recover a cavity formed in place of the foam.

is satisfied for a mesh size of 12.5 mm and almost satisfied for 25 mm. All boundaries 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 (101325 Pa).

A great challenge is to use the simplified reaction mechanism as well as the pyrolysis parameters (validated at raw material scale) for the three components of the seat, as input data for the FDS pyrolysis models at cone calorimeter scale. Concerning the condensed phase, the thermal properties and the density of each species are selected 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 the original materials are applied when no data are available. The effective heat of combustion of each reaction associated with each intermediate species is estimated from the cone calorimeter results at an external irradiance of 50 kW/m^2. The heat of reaction for each reaction is one of the most difficult input parameters to estimate due to the thermal decomposition phenomena. Consequently, this parameter is obtained from a fit of the experimental data but always in the same order of magnitude as heats of reaction found in the literature for similar products.

Various trials have been performed, and one of the main issues found was the dependence of the results on an air gap between the inter-liner and the foam before ignition (see Fig. 8). This air gap is crucial for fire modeling and is due to foam shrinkage during its heating. A fictitious air layer of a predefined thickness numerically reproduces this phenomenon, as proposed in the flowchart of Fig. 9. The thickness of this air gap has been found to depend on the heating scenario, as it corresponds to the rate of shrinkage of the foam under the cover and inter-liner, and their respective chars. A relation between incident heat flux and gap thickness used has been established (see Fig. 10).

Final results obtained at cone calorimeter scale are detailed in Figs. 11 and 12. Taking into account the decomposition effect, such as the shrinkage of the foam, by the formation of this equivalent multilayer material including an air gap, means that the new input data depend on the incident heat flux received at the surface of the material. A choice of the thickness of the air gap is then needed at a larger scale. The aim of the pyrolysis model, however, is to be independent of the external radiation heat flux and the method partially fails on this point.

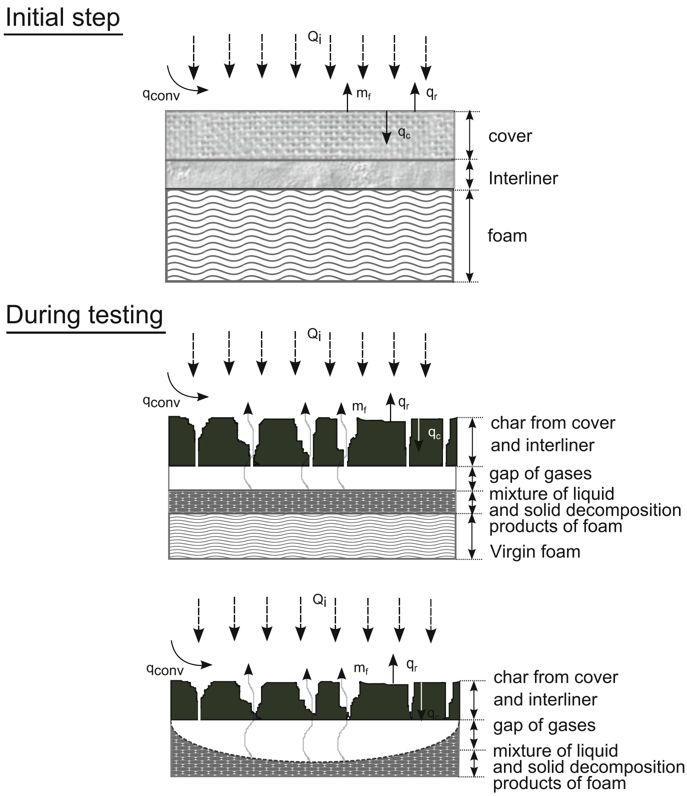


Figure 9. Mechanism proposed to explain observations at cone-calorimeter scale. This proposal involves the introduction of an air gap for modeling.

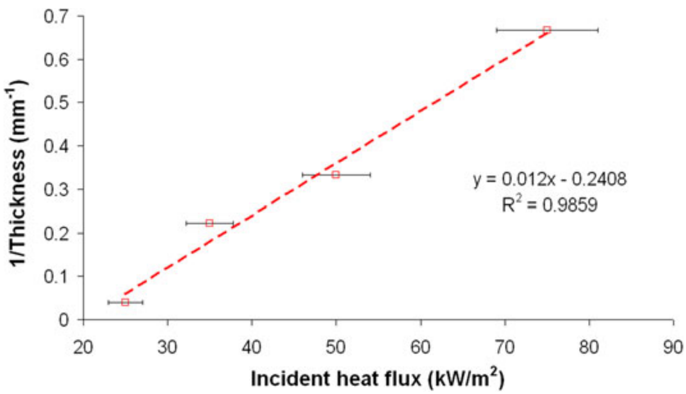


Figure 10. Relation between thickness of air gap and incident heat flux.

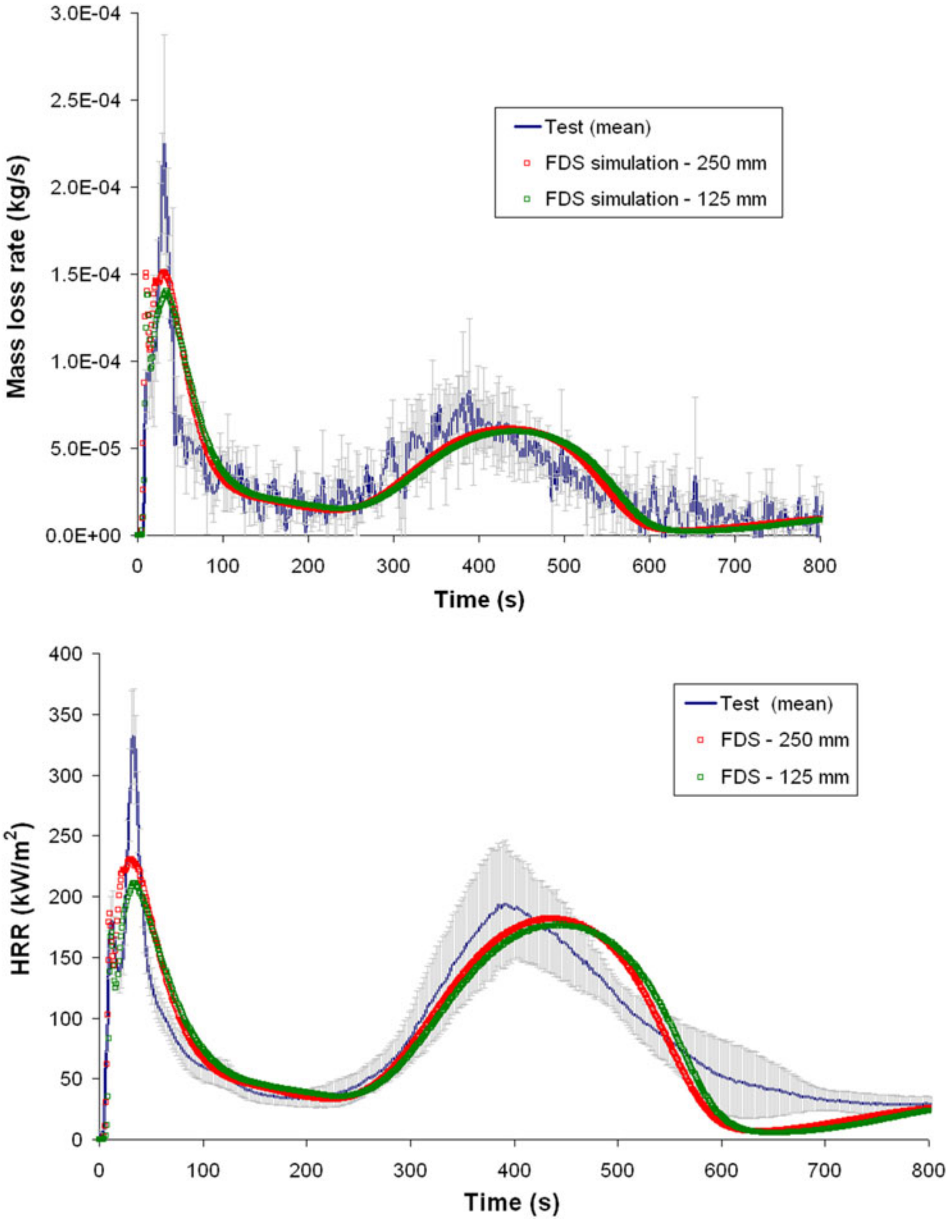


Figure 11. Comparison of the MLR and HRR of the seat material for an incident heat flux of 50 kW/m^2.

The FDS code has some weaknesses in simulating the pyrolysis and the reaction-to-fire at low heat flux as discussed previously in the literature, but the precision of the results is sufficiently good so that the model and parameters are

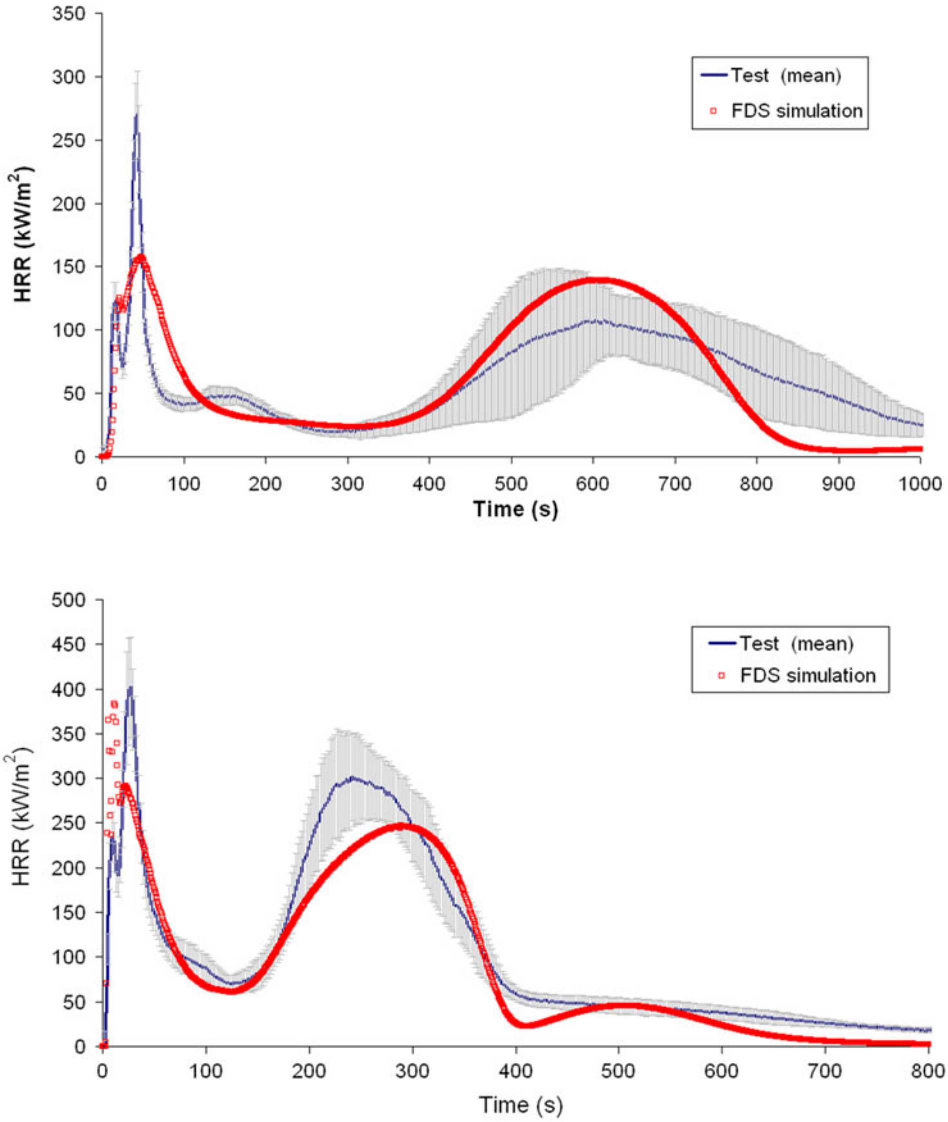


Figure 12. Comparison of the HRR of seat material for an incident heat flux of 35 kW/m^2 (*top*) and 75 kW/m^2 (*bottom*).

confirmed for their application at a larger scale, for which the thickness of air gap will be selected.

3.2.3. Finished Product Scale. The finished product scale simulation objective is to predict seat fire behavior taking into account the effects of mounting and adjacent configuration (impact of the ceiling and the corner) and to confirm numerical constants, numerical geometry and the mesh size in the simulation for final applica-

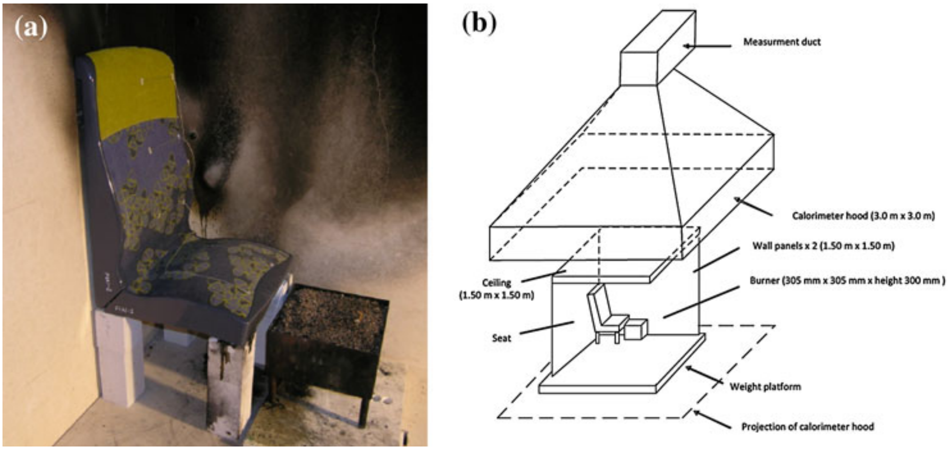


Figure 13. Finished product scale test for seat. (a) General view and (b) Details of test rig.

tion (Fig. 13). 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, tests have been performed on train seat using an open calorimeter according to ISO 24473 [42]. This test has been modeled also using FDS. The ignition source corresponds to a propane diffusion flame of 75 kW during the first 2 min and then 150 kW during the next 8 min. Details of this test and related modeling are available in [43].

Preliminary calculations yield a large surface area of seat cushion impacted at an average incident heat flux of 35 kW/m^2 from the burner. The thickness of the fictitious air layer between inter-liner and foam, used to reproduce the air gap during decomposition, is taken to be 5.4 mm, as determined during the previous step for this level of irradiance.

Figure 14 presents the comparison between the experimental and numerical heat release rate with a mesh size of 25 mm. 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. About 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 no longer connected to the bottom of the headset. The foam is not protected by the cover 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 one taking into account uncertainties. However, the kinetics of the numerical HRR are only 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.

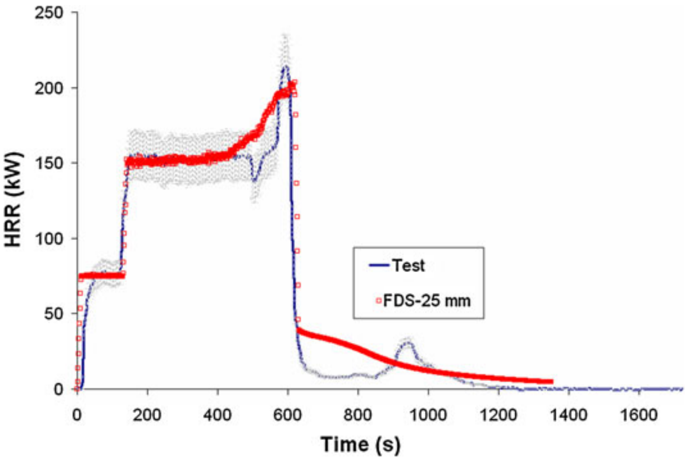


Figure 14. Numerical and experimental HRR comparison at finished product scale.

Such results highlight the difficulty of using the FDS code to simulate seat fire behavior, due to the invariant solid phase in the FDS pyrolysis model.

Further comparisons were performed on the two main gases detected during the experiments: carbon dioxide (CO_2) and carbon monoxide (CO), as seen on Fig. 15. The experimental kinetics of CO_2 is close to those of the HRR. Considering the experimental uncertainties, the CO_2 experimental mass flow result is in agreement 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 stoichiometry of the propane combustion reaction. Despite this important combustion model difference, the CO_2 mass flow comparison is quite good.

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 and occurs after the extinction of the burner. For this second peak, it is assumed that a locally under-ventilated combustion of the foam occurs under the char formed by the inter-liner and the cover. It could explain the low production of CO_2 compared to CO in the period between 800 s and 1200 s. Before the ignition of the seat (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 based on the propane combustion stoichiometry. The CO yield needed as input data comes from a "blank" burner test performed on the same geometrical conditions, where combustible items were removed. CO experimental results are slightly modified by the presence of the combustible seat: when the seat is not burning, CO released is lower than during a "blank" burner test. The contribution of the seat to CO generation appears experimentally after 500 s, when the seat ignites. The numerical

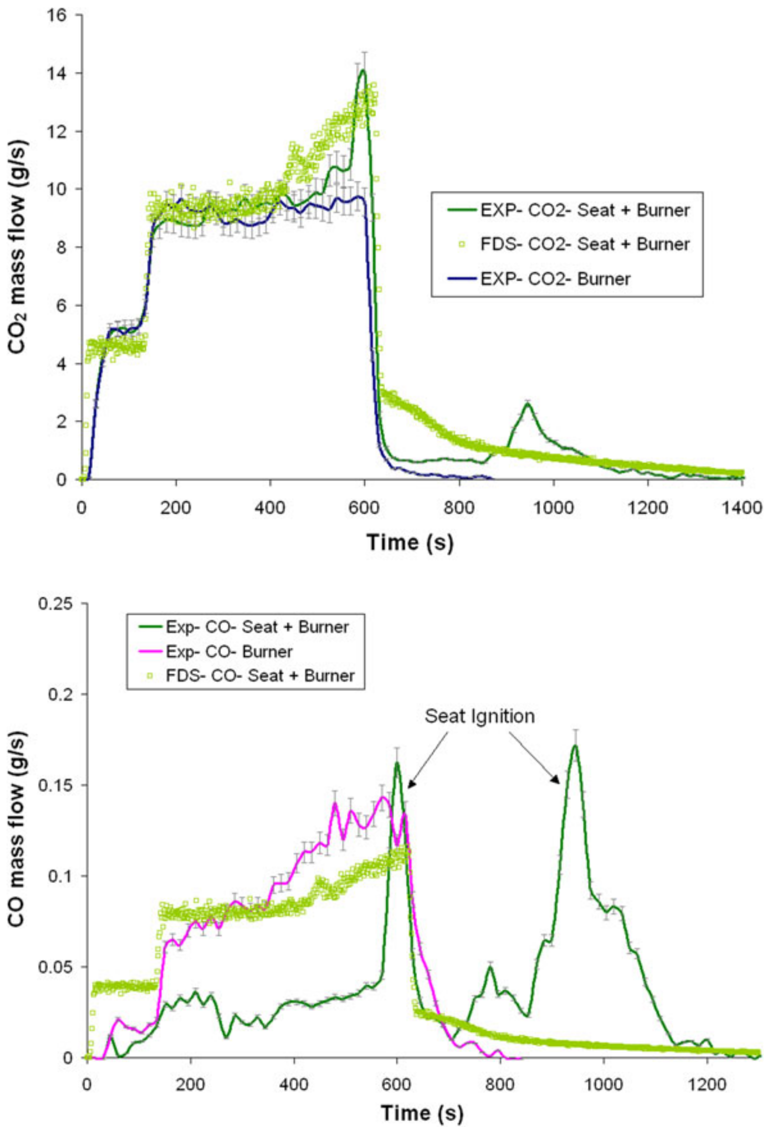


Figure 15. Experimental and numerical comparison of the CO_2 (*top*) and CO (*bottom*) mass flow during the finished seat test.

CO generation obtained is closer to the experimental result obtained for the ‘‘blank’’ burner test, as expected when using the output data of this test as input data for the calculation. In FDS, the CO generation is linked to the quantity of fuel and also to the combustion reaction. However, experimentally the CO generation depends on the type of fuel, the flame temperature, fuel residence time and oxygen diffusion into the flame. A unique reaction has to be selected for the FDS combustion model. When ‘‘propane’’ is chosen, the burner is well reproduced.

Reproducing a different CO production rate simultaneously from the burner and from the seat is not possible in FDS version 5. For the finished product seat test, the comparison between experimental and numerical CO release has failed. This divergence highlights the limits of the FDS combustion model (mixture fraction model and a global combustion reaction of a unique fuel).

3.3. Wall Panel

The same procedure has been applied to the train side wall panel made of glass reinforced polyester (GRP). This material is flame-retarded using a large quantity of aluminium trihydrate (ATH). This GRP composite is composed of two parts: a polyester gelcoat and a hand-laminated glass fiber/polyester/mineral fillers composite. The same procedure as for the seat has been applied.

Results obtained at raw material scale are presented in Fig. 16 for TGA data and in Fig. 17 for numerical results. For the model, the 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 (fibers, mineral fillers). Results are validated for the material scale.

At material scale, this GRP has been tested and simulated in the cone calorimeter ISO 5660-1 [41], with the same conditions as previously. Phenomena are presented conceptually in Fig. 18. Experimental and numerical results are presented in Fig. 19. Except for the numerical results obtained from 20 kW/m^2, the numerical MLR and HRR have the same kinetics and order of magnitude as the experimental ones until the second sudden HRR peak occurs, taking into account

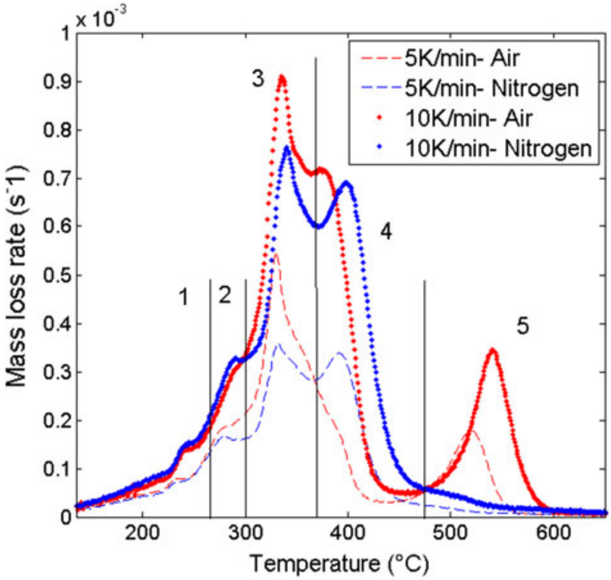


Figure 16. Experimental results at raw material scale for the wall panel.

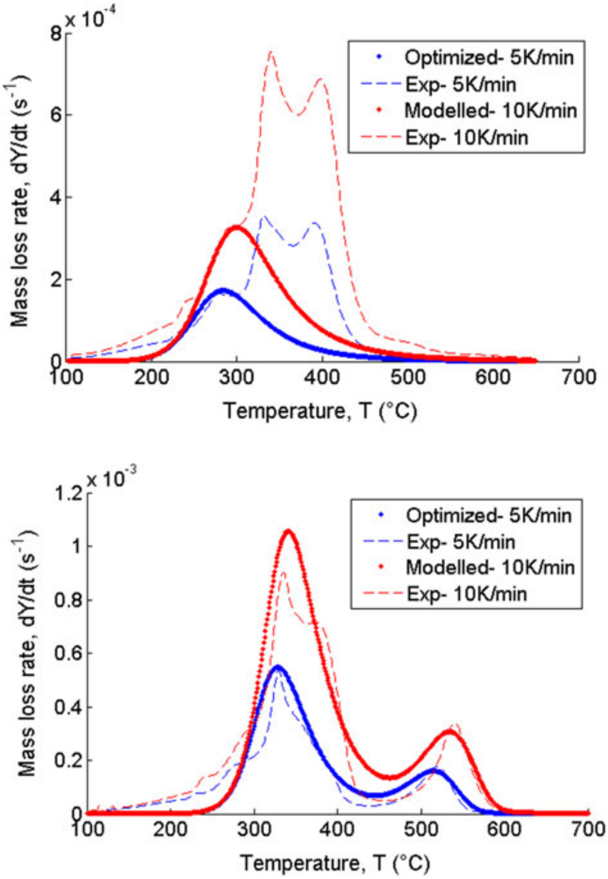


Figure 17. Experimental and numerical results at raw material scale for ATH (*top*) and Polyester (*bottom*).

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 [42] large-scale experiments have been performed to validate geometrical and assembly aspects. A corner of two panels was tested. The ignition source corresponds to a propane diffusion flame of 75 kW during the first 2 min and then 150 kW during the next 8 min. Details of this test and related modeling are available in [43]. Figure 20 represents the HRR numerical and experimental comparison at two different mesh sizes: 25 mm and 50 mm of the finished wall panel test. For both mesh sizes, the numerical result has the same kinetics 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. 21. As for the HRR comparison, for the 50 mm mesh, the experimental and numeri-

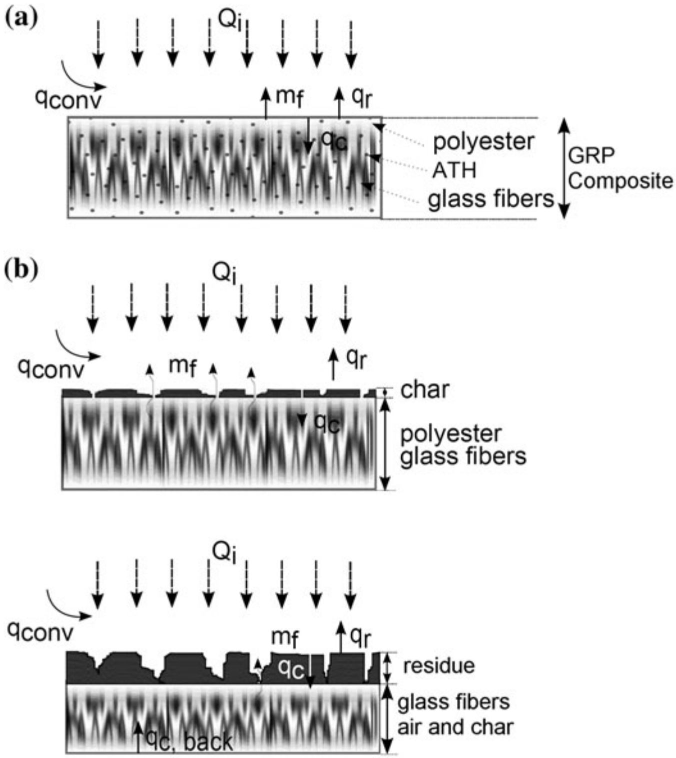


Figure 18. Fire behavior of the GRP panel. (a) Initial stage and (b) During test.

cal carbon dioxide mass flows have the same kinetics 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. Thus, the comparison for the released carbon monoxide fails due to the FDS mixture fraction combustion model.

3.4. Real-Scale Configuration

A MS61 French suburban coach refurbished with these products has been tested according to scenario 1A from the risk analysis. Test results have been compared to simulation results using the data validated previously for seat and wall panel. The ignition scenario is applied at an extremity of the coach, between two seats and against the side wall. Two series of measurements are especially detailed hereafter, both placed on the median axis of the train corridor. The first point, close to the fire, is at the level of the first door, ~4.5 m from the coach end. The second one is placed at the level of the last door, in the opposite part of the train, ~17.5 m from the extremity where the fire occurs. Gas concentrations are mea-

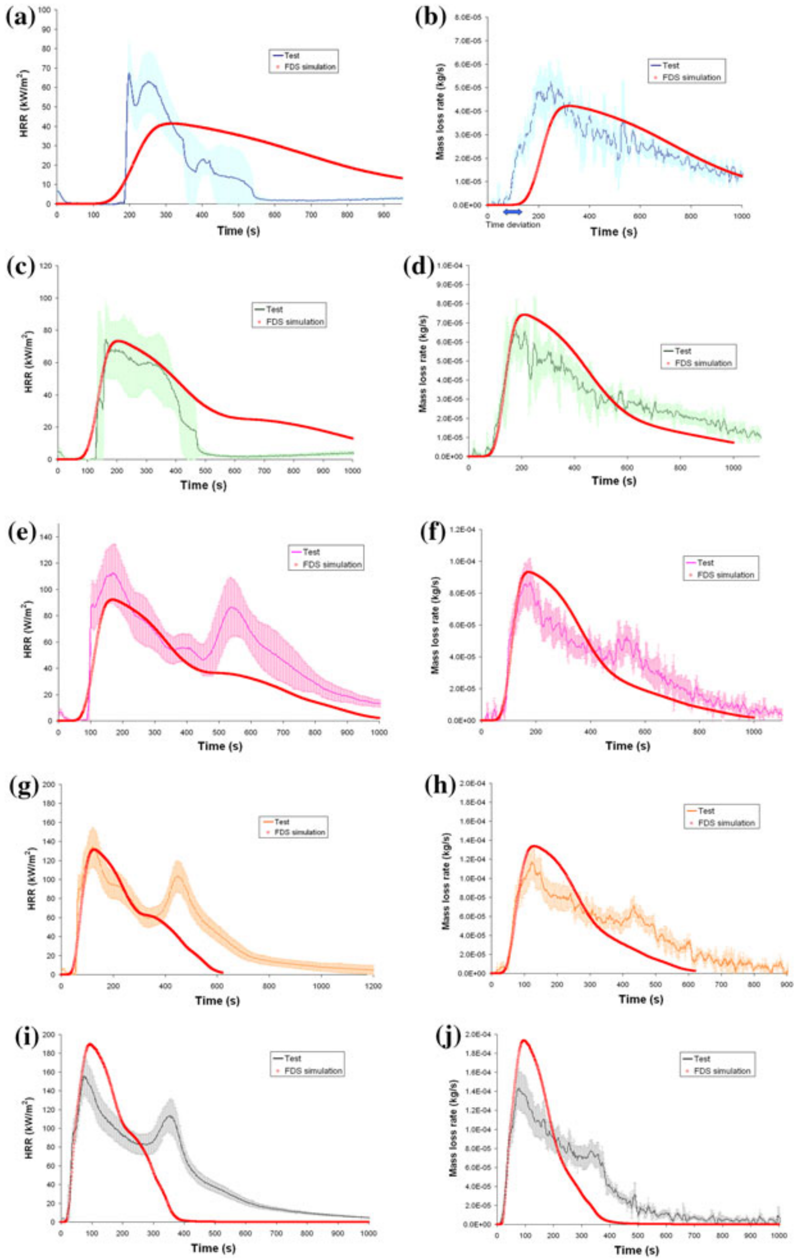


Figure 19. Experimental and numerical results at material scale for GRP composite wall panel. (a) HRR, 20 kW/m^2, (b) MLR, 20 kW/m^2, (c) HRR, 25 kW/m^2, (d) MLR, 25 kW/m^2, (e) HRR, 35 kW/m^2, (f) MLR, 35 kW/m^2, (g) HRR, 50 kW/m^2, (h) MLR, 50 kW/m^2, (i) HRR, 75 kW/m^2, and (j) MLR, 75 kW/m^2.

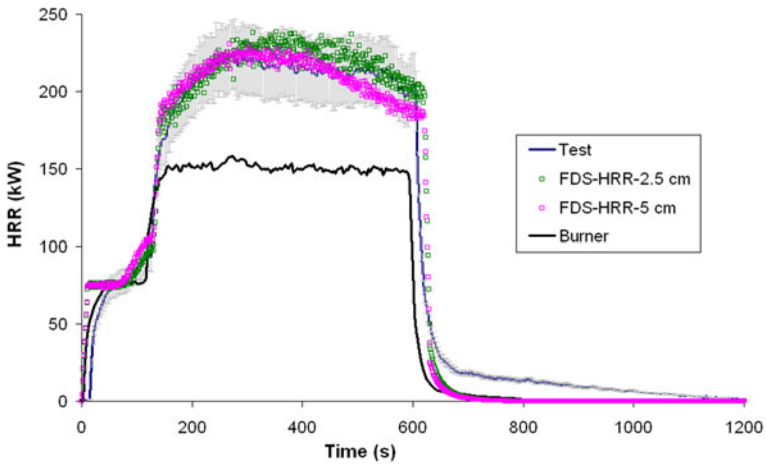
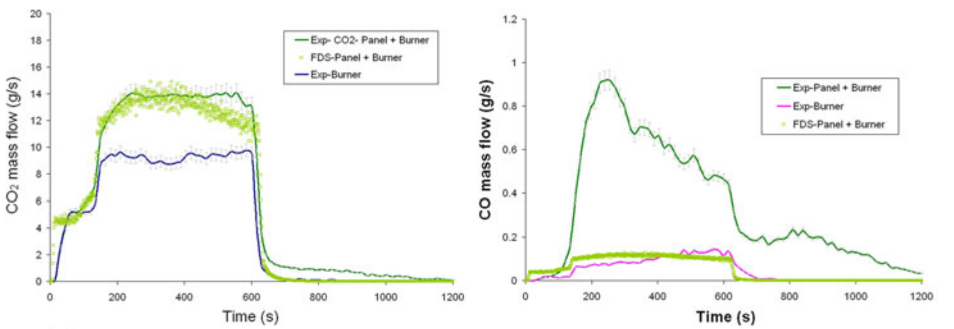


Figure 20. Experimental and numerical HRR results at large-scale for GRP composite wall panel.



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

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

Figure 21. Experimental and numerical CO/CO_2 results at large-scale for GRP composite wall panel. (a) CO2 comparison and (b) CO comparison.

sured at an elevation of 1.7 m from the floor. Details of this test and related modeling are available in [43]. Fig. 22 shows pictures of damage after the test. An ASET calculation according to ISO 13571 [27] using experimental results indicates that the value of FEC/FED >0.3 is not reached in 20 min. An RSET calculation has been performed to estimate evacuation time in this scenario, and gives a maximum of 101 s when very crowded.

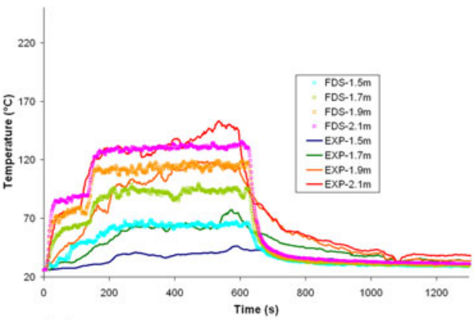
For temperature measurements (see Fig. 23) at all positions, the numerical trends follow the kinetics of the burner heat release rate (75 kW for 2 min and then 150 kW for 8 min) and have the same order of magnitude. Concerning thermocouple response located far from the fire, the numerical and experimental temperature kinetics are slightly different. Indeed, two numerical temperature levels

(a) view of the burner and seats after test

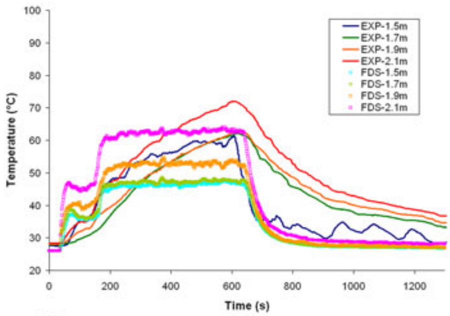
(b) view of seat and wall. The falling object is a polycarbonate light diffuser softened during test

(c) view of the window and wall panel

Figure 22. View of burnt areas after the real-scale test according to scenario 1A. (a) view of the burner and seats after test, (b) view of seat and wall. The falling object is a polycarbonate light diffuser softened during test, and (c) view of the window and wall panel.

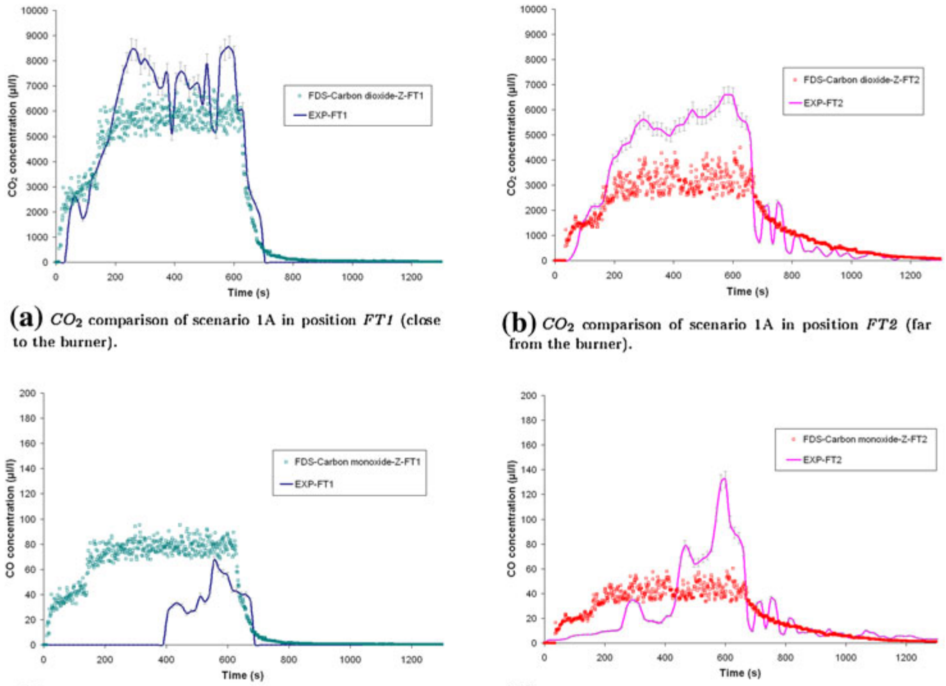


(a) Thermocouples tree 1.5 to 2.1 m from the fire.



(b) Thermocouples tree 1.5 to 2.1 m far from the fire.

Figure 23. Experimental and numerical temperature results at real-scale. (a) Thermocouples tree 1.5 to 2.1 m, in position close to the fire and (b) Thermocouples tree 1.5 to 2.1 m, in position far from the fire.



(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).

Figure 24. Experimental and numerical CO/CO_2 results at real-scale. (a) CO_2 in position close to the fire, (b) CO_2 in position far from the fire, (c) CO in position close to the fire, and (d) CO in position far from the fire.

are observed while the experimental temperatures continuously increase. This difference may be due to the mesh size used to model the fire into the coach.

The experimental and numerical gases released are compared in Fig. 24. The experimental and numerical carbon dioxide and carbon monoxide concentrations have the same kinetics as the burner (two stages are observed). Concerning carbon dioxide results at the first position, the numerical response has the same level of magnitude as 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.

The results show that carbon monoxide levels are not well reproduced. The concentrations observed are low, with a maximum around 100 µL/L. The measurement shows the absence of CO at the point closest to the fire during the first 400 s. During this same period, the calculation accounts for the presence of carbon monoxide. The mesh size and the sub-grid turbulence model associated with LES in the simulation makes it difficult to represent a sampling point. One possible explanation is that the sampling point is in an area of strong gradients. A finer vertical mesh size could improve this prediction, but at the expense of computing time. In addition, the simplicity of the model for CO generation in FDS software probably leads to an insufficiently accurate source term.

For the sampling point far from the fire, plumes of smoke and the proximity of the sampling point with the interface between air and smoke can explain strong temporal variations observed in the experimental values. The numerical data show an inadequate dispersion calculation, although the mean level is of the same order of magnitude. The two reasons mentioned above are valid for this point too, i.e. the error in CO generation and the inaccuracy of dispersion caused by LES parameters and the proximity of the mixing zone.

4. Conclusions

The work presented here is related to the modeling of actual train materials up to end-use conditions, for application in a fire safety engineering approach. The study of one such scenario defined according to a risk analysis has been performed to quantify the fire safety performance level of a given train using advanced numerical tools and a multi-scale approach.

The predictive method has shown a good capability to reproduce fire growth, heat release rate and temperatures in the real-scale scenario presented. Main species such as carbon dioxide have been reproduced properly too. Nevertheless, this study highlights a lack of prediction for carbon monoxide. If CO is not reproduced properly, calculation of other toxic species may fail and the method would not be accurate to predict tenability conditions with an acceptable level of confidence. Further work has to be performed on combustion models in order to improve the capability for such goals. At the present time, the authors recommend the assessment of tenability of occupants in train fire scenarios be limited to thermal-related effects and to track with CO_2 if they are exposed to smoke. A finer analysis of the smoke toxicity impact on occupants is not sufficiently validated.

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