Numerical simulation of the fire behaviour of façade equipped with aluminium composite material-based claddings—Model validation at intermediate scale

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Summary

Increasing the energy performance of buildings is a crucial sustainable development objective. However, building features, products, mounting, and fixing of façade components have a large impact on fire safety. Authors in previous study performed façade fire propagation tests according to ISO13785-1 on different combinations of ACM claddings and insulants.

In this paper, simulations are performed to reproduce three of these tests. The model is validated with the aforementioned experimental results, including details in terms of thermal conditions in the system. This allows better understanding of the fire propagation on the overall system. Additional information, such as the relative contribution of the cladding and the insulant, are investigated numerically. The fire behaviour of each component of the overall system is thus validated.

Simulations and tests performed show that the ACM cladding is the most important element driving the global fire behaviour of façade types considered. In particular, ACM-PE–based cladding systems show large fire propagation whatever the insulant.

This series of simulations is a part of a larger study including several steps of increasing complexity. Once the model for the fire behaviour of façade system is validated at intermediate scale, larger façade systems will be investigated numerically to evaluate the influence of scaling.

KEYWORDS

façade insulation, fire propagation, ISO 13785-1 intermediate fire test, numerical simulation, ventilated façade

1 | INTRODUCTION

The external thermal insulation (ETI) of residential building façades is exhibiting strong growth in Europe.¹ Many existing buildings are renovated, aiming for better energy efficiency and aesthetic improvements. However, building features and products (on their own or in combination) may have an impact on fire safety, because fire spread through façades can be one of the fastest ways for a fire to spread in buildings. Strong external flames, emerging from a compartment through openings like windows, can impinge on any external façade insulation system. Façade fire spread can be increased by the combustible load of the façade. As the fire safety design of buildings, in general, aims to slow fire spread by deliberate compartmentation, propagation via the façade may lead to quicker fire spread than any compartmentation requirement assumes, leading to difficulties in evacuation and firefighting.
Two types of external façade insulation system are generally encountered: (a) ventilated façades, consisting of an assembly of several layers (such as cladding, air gap and insulation) applied to the wall, and (b) rendered systems or ETICS "external thermal insulation composite systems," comprising insulation fixed to the wall and a finish of thick or semi-thick render, between which are successively inserted a reinforcement and intermediate coats. In the context of fire safety, it should be noticed that for systems such as ETICS or ventilated façades, the materials used (cladding or insulation) may be combustible. Moreover, in ventilated façades, the air gap may be a vector of fire propagation through chimney effect. In recent years, several research studies have investigated the fire performance of ventilated façade systems and shown that flame spread through the air cavity of a ventilated façade can be several times higher than that along the outside the façade. Furthermore, the presence of an air cavity tends to increase the energy released by the façade system. Thus, both the materials taken independently and the whole system (combination of materials and assembly) are potentially a source of propagation of a fire. At present times, the use of fire barriers or compartment systems, as requested by national regulations, can hinder these problems, but they too constitute additional variables in the system.

The fire behaviour of an external façade insulation system is dependent on the overall system's performance, rather than the performance of the individual components. A façade system includes not only the cladding and the insulant's characteristics but also those of cavities, cavity barriers, mounting and fixing, substrate, and any singularities, such as window frames. All these elements interact strongly when involved in a fire; thus, as discussed in Bonner and Rein, the overall flammability of the system more than the individual component combustibility as done in McKenna et al. should be considered. Recent dramatic events (Mermoz Tower in Roubaix, France, 2012; Polat Tower in Istanbul, Turkey, 2012; Lacrosse Tower in Melbourne, Australia, 2014; Torch and Marina Tower in Dubai, United Arab Emirates, 2015; and Grenfell Tower in London, UK, 2017) remind of the importance of addressing fire issues as a whole and clearly highlight the major role played by façade cladding and the associated insulation as fire propagation vectors.

The appropriate scale for fire tests of such façade systems should also be discussed. For a scale to be appropriate, it must make it possible to evaluate the fire performance of the whole façade system by including all of the system's characteristics and fixing methods. Assessment of a specific façade system's fire performance can be undertaken using large-scale testing in accordance with local regulations, and large assembly tests often include the methods described in BS 8414-1 and BS 8414-2, FM 4880-1, or NFPA 285. Many combustible façade systems, incorporating aluminium composite materials (ACMs), have recently been tested using these large-scale test methods. However, these large-scale tests are pass/fail oriented; they give very little quantitative information for further interpretation of the fire behaviour of the tested systems and are expensive and time consuming to prepare.

Recently, a series of façade fire propagation tests have been performed according to the ISO 13785-1 standard, with additional heat release rate and gases analysis using FTIR. The test series comprised nine different combinations of three grades of aluminium composite material (ACM) and three different insulators. This intermediate-scale test method is able to be performed rapidly, on a complete façade system but does not replace large-scale testing. However, it can be correlated with a large-scale reference test to account for small variations (e.g., in geometry or thicknesses of a component) from what is tested at a larger scale. Thus, because this intermediate-scale test method is discriminating enough, different façade system configurations can be tested in a reduced time and accurate quantitative information on the fire behaviour of façade systems can be acquired.

Façade fires have been studied numerically for different test facilities or methods and using different simulation codes. Published results have shown the feasibility of modelling such test methods using large eddy simulation (LES), especially when incombustible claddings were considered. However, great attention must be paid to the numerical model sensitivity, in particular to correctly representing the behaviour of the flames near the façade system and thus the thermal stresses received by the façades. In the case of a combustible façade system, the thermal degradation suffered by the façade materials leads to the release of pyrolysis gases. The unburnt fuel gases are then transported by convection where they react with the ambient air, itself driven in the thermal plume. Moreover, the hot gases are cooled when they ascend as air is naturally convected by the external thermal plume. These aeraulic and combustion phenomena need to be correctly reproduced by the numerical approach.

In this paper, numerical simulations were performed to reproduce these intermediate fire tests. The aim of this study is to validate a numerical model that could predict the behaviour of the whole systems at this scale, for later upscaling scales. Special attention was given to flow and thermal conditions at all locations in the tested system. This allows for additional investigation and understanding of the relative contribution of insulant and ACM cladding. In particular, the relative contribution of each component to the fire behaviour of the system can be numerically assessed.

The numerical simulations as well as the tests performed show that the ACM cladding is the most important element driving the global fire behaviour of the tested façade systems. In particular, ACM-PE-based cladding systems, whatever the insulant used in the system, show very marked fire propagation. Moreover, the integrity of the cavity is affected by the dripping and the destruction of the burning ACM-PE cladding.

Once the model for the fire behaviour of the façade system is validated at intermediate scale, larger façade systems will be investigated numerically to evaluate the influence of scaling.

## 2 | EXPERIMENTAL SET-UP

### 2.1 | Test facility

The set-up of the experimental facility was developed according to ISO 13785-1 specifications. This is an intermediate-scale façade build-up as detailed in Guillaumé et al. It consists of three protective draught screens with dimension $2400 \times 2800$ mm ($l \times h$) made of fire-rated plasterboard and two aluminium frames with calcium silicate.
(CalSil) boards as a support for the tested system and on which the system is installed (Figure 1A).

A 100-kW sand propane burner with dimension 1200 × 100 × 150 mm (l × w × h) is installed with its upper surface placed 250 mm below the lower edge of the sample. The complete system is then placed under a large hood to collect the effluents. The instrumentation used during the test is fully detailed in Guillaume et al.13 (Figure 1B).

2.2 |
Tested systems in the experimental reference13

In the reference paper,13 façade fire tests have been performed on the nine combinations of three different compositions of aluminium composite material (ACM) and three different insulants. In this paper, three of these nine combinations are considered (Table 1). Information regarding these insulants, such as density or thermal conductivity, is available on product datasheets from their respective manufacturers. The different thicknesses of combustible insulants or mineral wool were chosen to achieve similar levels of thermal performance. The ACM-PE panels comprise a 3-mm-thick PE core with 0.5-mm-thick aluminium facings on either side.

Concerning mounting and fixing, the cladding systems were assembled on CalSil boards. The cladding was made of panels of 508 × 508 mm (3 × 2 panels for the back wall and 3 panels for the side wall or test wing). Gaps between cladding panels were 20 mm wide.

Intumescent cavity barriers were installed above the second rank of panels. At the position of the cavity barrier, the thickness of the cavity was reduced to 24 mm.

The vertical frame was made of aluminium profiles, and the lower edge of the test frame was covered by a 2-mm-thick aluminium L profile, with a 20-mm air gap between the bottom ACM panels and the angle.

2.3 |
Main results of the experiments

The façade fire tests described above13 and performed according to ISO 13785-112 allow the evaluation of façade material and system fire behaviour. The main results of the experiments in Guillaume et al.13 show that the tests performed discriminate between solutions. They

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**FIGURE 1** Overview of the fire reaction test facility and of the instrumentation installed according to ISO 13785-113 [Colour figure can be viewed at wileyonlinelibrary.com]

| Tested System Designation | Cladding/Thickness | Air Gap Thickness, mm | Insulant/Thickness |
|---------------------------|--------------------|-----------------------|--------------------|
| 1 [ACM-PE + PIR] Reynobond PE standard cladding with non-fire-retarded polyethylene core | 4 mm | 50 | Celotex RS5000 PIR 50 mm |
| 2 [ACM-PE + MW] Reynobond PE standard cladding with non-fire-retarded polyethylene core | 4 mm | 50 | Rockwool Duoslab 100 mm |
| 3 [ACM-A2 + PIR] Alpolic A2 solid-core limited combustibility (Euroclass A2) | 4 mm | 50 | Celotex RS5000 PIR 50 mm |
highlight that, for tested compositions, the ACM cladding is the most important parameter driving global fire behaviour. ACM-PE-based cladding systems gave very different results from the other solutions tested. This was especially visible in heat release rates, where fire intensity was very high, whatever the insulant used in the system. The contribution of the insulant was only remarkable in these tests during the decay phase. The cavity barrier was largely ineffectual in the three tests with ACM-PE cladding, as the integrity of the cavity was not maintained.

3 | NUMERICAL SET-UP

The objective of the numerical study is to reproduce accurately the thermal loads imposed on the tested system, the thermal behaviour of the system, and the fire propagation through the system, in particular the observations of temperature, heat release rate, smoke, and chemical species (mainly CO and CO₂) released. The thermal characteristics of the system components are integrated in the model.

Once the thermal behaviour of the façade system is validated for the [ACM-PE + PIR] configuration, local phenomena are evaluated with confidence, and specific numerical studies of the flow around the cavity barrier can be detailed. The individual contribution of the cladding and the insulation is addressed through further validation of the numerical model. Simulations of the system including a non-combustible mineral wool insulant and of the system including an inert non-combustible cladding as tested in Guillaume et al[13] allow a deeper analysis of the material contribution to the fire spread in the façade systems.

3.1 | Numerical tools

The numerical simulations are performed with the computational fluid dynamics (CFD) code Fire Dynamics Simulator (FDS) version 6.7.0. FDS is a computational code in fluid dynamics that incorporates a combustion model and a large-scale model (LES) for the description of turbulent flows. This tool allows 3D modelling of the computational domain. It considers heat transfer at walls, ventilation conditions for the removal of hot gases and air intake. The Navier-Stokes equations are solved in the limit of low Mach number, thermally driven flow with an emphasis on smoke and heat transport from fires. The radiative heat transfer is included in the model through the solution of the radiative transport equation for a grey gas. Detailed information is provided in previous work.[23]

The default submodels of FDS were used for the gas phase radiation exchanges even if a sensitivity analysis performed with 100 (default value), 500, and 800 solid angles was addressed. The combustion model with primitive and lumped gas species definition, to solve a transport equation for each species to be tracked, was also investigated, as well as the use of a single step reaction for CO production. This was because of uncertainty in the occurrence of this phenomenon and of well-ventilated conditions for the combustion observed experimentally and numerically. The fuel burnout in each solid numerical cell is accounted for by the specification of the combustible mass and heat of combustion of the object through the bulk density parameter. Thus, when the mass contained in each solid cell is consumed, the solid disappears from the calculation cell by cell. This feature is used to account for the destruction of the cladding, as observed experimentally with ACM-PE experiments. The default Deardorff model is used for the LES subgrid modelling. The default near-wall model with a wall function for smooth wall is used. The heat transfer at walls is simulated with a subsequent heat of vapourisation to account for the energy loss due to the vaporisation of the solid fuel.

3.2 | Description of the numerical model

3.2.1 | Numerical domain

The total dimensions of the numerical domain are 2500 × 2000 × 6000 mm, with open boundary conditions for the pressure at the sides and at the top of the computational domain. The numerical domain is considered large enough to account the test facility and the fire plume resulting from the system combustion. In the numerical model, virtual instrumentation consisting of thermocouples, gauge heat flux detectors, and species detectors are placed at same locations as during the real test (Figure 1).

Mesh size is taken at 20 × 20 × 20 mm for the facility, so that the grid is refined to capture accurately the combustion and turbulence phenomena of the system, and 40 × 40 × 40 mm around the facility. A total of 1.1 million cells are used. In the FDS reference guide[23] and literature,[24] a criterion for the quality of the mesh resolution is given for simulations involving buoyant plumes. It is assessed using the nondimensional $D^+/\Delta x$ ratio, where $\Delta x$ is the size of the grid cells and $D^+$ the characteristic fire diameter. Following this expression, for the total HRR achieves[13] ($Q = 5$ MW), the adequate fine mesh size $\Delta x$ to obtain reliable predictions of the radiative heat flux should be close to 100 mm. To capture the initial 100 kW burner contribution, the fine mesh size should be close to 0.025 m. Thus, the 0.02 m considered grid size is sufficiently fine to capture accurately the combustion and turbulence phenomena of the system from ignition to fully developed fire.

Attention must be paid to the 20 mm gap at the junction between cladding panels. Regarding the mesh size, only one fluid numerical cell is used to represent the gap, with a size adapted to the meshing (ie, 20 mm). No sensitivity analysis was performed regarding the fine mesh size selected and the global fire behaviour mainly lead by the surface propagation of the fire in this application.

This technical choice is made to conserve reasonable calculation costs and regarding the later upscaling application of this numerical model. Compromises were needed to develop a robust numerical model able to be used for this application. The selected cell size is enough to capture the main features of local effects, not in details, but sufficiently to reproduce the fire behaviour in the present application. Furthermore, quickly after the beginning of the test, the fire propagation from the burner to the system leads to its combustion. Thus, the cladding panels, and thereby the gaps between them, disappear in the first minutes of the test.
3.2.2 Numerical model for thermal analysis

The thermal characteristics of the system components are integrated in the numerical model in terms of density, thermal conductivity, heat capacity, emissivity, heat of combustion, ignition temperature, mass loss rate, and species release rates, for every material involved. All thermal and combustion properties considered, for the material making up the systems, are given below.

In this study, the thermal and aeraulic phenomenon involved in the fire development from the initial fire source and in the fire spread through the tested system depends mostly of the fire behaviour of all the materials and of their arrangement in the system. FDS has several approaches for describing the pyrolysis of solids, and the selected approach depends on the availability of material properties and the appropriateness of the underlying pyrolysis model in simulation tools. In FDS, the thermal degradation of materials can be simulated with either a simple pyrolysis model or solid fuels that burn at a specified rate. The second model is used in this study.

The justification of the chosen approach is based on the understanding of the materials in question and mostly on the very bad fire performance of PE. Thus, there is no need to simulate further thermal degradation of PE with a complex pyrolysis model on the large scales considered. This technical choice is justified because the combustion velocity is independent of the environment in this application, and thermal transfer will be only taken into account to reach ignition. For a material with better fire performance (auto extinction, fire retardant, ...), another choice of pyrolysis model would have been considered. Considering this simplified thermal degradation model, the input data required for each material are its bulk thermal properties, its ignition temperature, and its subsequent burning rate as a function of time after ignition. Indeed, the burning rate is kept constant as soon as the ignition temperature is reached locally with a cell by cell calculation.

For the materials considered in this study, a subsequent heat of vaporisation is given to account for the energy loss due to the vaporisation of the solid fuel. This ensures a weak coupling between the burning rate and the solid temperature. In FDS, if the ignition temperature and the heat of vaporisation are used for a given material, the net heat flux at the material surface is reduced by a factor equal to the heat of vaporisation times the instantaneous burning rate.

To compute the thermal transfer inside the solids, the size of the mesh cells on the surface is automatically chosen using a rule that makes the cell size smaller than the square root of the material diffusivity. The solid mesh cells increase towards the middle of the material layer and are smallest on the layer boundaries, with typical size of 1 mm. A 1D thermal transfer is performed for each solid numerical cell, using the given thermal properties of the material and performing boundary exchange with the local gas environment (radiation and convection).

The material heats up until its surface temperature reaches locally the given ignition temperature for every combustible materials. Once the surface of an individual solid cell has ignited locally, the heat transfer into the solid is still calculated, and the fire spread is modelled cell by cell. The appropriate mass loss rate derived from literature review for every combustible material is prescribed when ignition occurs. The fuel burnout in each solid numerical cell is calculated from the combustible mass and the heat of combustion of the object through specification of its bulk density. The bulk density approach used in this study allows taking into account the appropriate heat of combustion of each fuel and is related to the mesh size. Thus, this parameter is calculated for a given cell size and will not be sensitive to the meshing. When the combustible amount of a numerical cell is consumed, the solid disappears from the simulation. This feature is used to account for the local destruction of the cladding, as observed experimentally with ACM-PE experiments. Adjacent cells follow their individual heating and exchanges with ambiance and can ignite or not, leading to the enhancement of the fire spread. The burning rates of the materials are indeed imposed. The burning rate of the façade is however more complex as flame spread occurs. The most challenging point of this approach was to find the suitable parameters, with a physical meaning. These parameters included thermal parameters (so the heat transfer is correctly modelled) and the right combustion properties (ignition temperature and mass loss rate). These complete sets of parameters have to be found for several materials with strong interaction from one to another. Thus, the numerical results achieved will not fit correctly the experimental ones because mass loss rate is prescribed, but because the thermal properties and the fire properties are suitable. Indeed, the materials properties, ignition temperature, and burning rates of the materials are imposed. However, each of those parameters are exactly taken from literature and selected according to proper environmental conditions. None was calibrated for the numerical results achieved to fit correctly the experimental ones.

Fuel properties are linked to the bulk density properties evaluated for each combustible through the heat of combustion. Fuel gas combustion is performed using the mixing-controlled reaction model of FDS. The main reaction stoichiometry is specified in detail with an explicit fuel formula, as well as the definition of each species involved in the combustion reaction. The yields of released species for each material’s combustion (e.g., CO, soot, and HCN) are taken from literature and selected according to appropriate environmental conditions (ventilation, temperature, richness, etc). They are applied for each combustible in association with the individual mass loss rate related to an ignition temperature.

The chemical composition of typical poly-isocyanurate foams (PIR) is given by previous studies.\textsuperscript{25–27} However, the composition given in Marquis et al\textsuperscript{25} and Purser and Purser\textsuperscript{26} is for fire retardant PIR; thus, the composition indicated in\textsuperscript{27} was used.

The density of PIR foam is taken at 36 kg/m\textsuperscript{3} as presented in the product datasheet.\textsuperscript{28} As no indication about the emissivity of PIR foam materials can be found in the literature, a value of 1 is assumed. This is justified by the surface charring of the foam. The heat capacity of PIR is around 1.10 J/g/K at ambient temperature.\textsuperscript{25} Its thermal conductivity is around 0.021 W/m/K at ambient temperature\textsuperscript{15,28,29} and can go up to 0.0531 at 90°C\textsuperscript{25}. A temperature-independent value of 0.048 W/m/K is taken in this study. According to the literature, the
heat of combustion of PIR can be taken at 26.3 MJ/kg with a CO and HCN yields of 0.038 and 0.01 g/g respectively.\textsuperscript{26,27,30,31} The soot yield is 0.1 g/g.\textsuperscript{27} The ignition temperature of PIR can be found around 370°C\textsuperscript{26} and the maximum HRR is around 160 kW/m\textsuperscript{2}.\textsuperscript{25,29} The heat of decomposition of PIR is taken at 1750 J/g.\textsuperscript{30} In Marquis et al\textsuperscript{25,32} and Purser and Purser,\textsuperscript{26} the effect of oxygen concentration depletion on the mass loss rate and on the residual mass fraction of PIR foam at 50 kW/m\textsuperscript{2} is studied. The maximal value of mass loss rate of 0.006 kg/m\textsuperscript{2}/s used in this study is then representative of the maximum value achieved in well ventilated conditions and high thermal solicitations. Thus, this value is always secure in the numerical models. In Marquis et al\textsuperscript{25} Lyon and Janssens\textsuperscript{30} and Purser,\textsuperscript{32} the CO yield released by PIR foam is indicated as a function of the equivalence ratio Φ accounting for the recovery fraction due to ventilation conditions. The average value of 0.038 g/g used in this study is thus representative of well-ventilated regimes\textsuperscript{30,33} to well-ventilated regimes with medium thermal loads (20% O\textsubscript{2}, 15 kW/m\textsuperscript{2}).\textsuperscript{25}

The thermal properties of PE used in this study are indicated in Trouvé\textsuperscript{34} and Hietaniemi and Mikkola.\textsuperscript{35} According to material datasheet, PE has a density of 1360 kg/m\textsuperscript{3}. Its heat of decomposition is taken at 2300 J/g.\textsuperscript{30,34} The ignition temperature of PE can be estimated around 380°C.\textsuperscript{35} PE has a heat of combustion ranging between 40.3 and 46.3 MJ/kg.\textsuperscript{27,30} The CO yield is of 0.024 g/g.\textsuperscript{27,30} and the soot yield is 0.056 g/g.\textsuperscript{27} The char yield is close to 0%.\textsuperscript{27,30} and the asymptotic mass loss rate is 0.04 kg/m\textsuperscript{2}/s.\textsuperscript{27,30,35}

In previous works,\textsuperscript{27,36} the CO yield released by rigid PE is indicated in function of the equivalence ratio Φ accounting for the recovery fraction due to ventilation conditions. The average value of 0.024 g/g used in this study is thus representative of well-ventilated regimes. The cladding being the external part of the façade system, this ventilation regime is coherent. Stolarov et al\textsuperscript{37} studied PE of different thickness under 25, 50, and 75 kW/m\textsuperscript{2} exposure in cone calorimeter as well as under nitrogen. Assuming a heat of combustion of 43.5 MJ/kg, the average MLR value for PE under cone can be taken at 0.031 ± 0.015 kg/m\textsuperscript{2}/s. Moreover the average MLR under nitrogen (for a 7 mm-thick PE under 50 kW/m\textsuperscript{2} irradiance) is around 0.04 kg/m\textsuperscript{2}/s. The MLR value (0.04 kg/m\textsuperscript{2}/s) selected in this study is accordance with these literature values and is representative of the combustion of PE.

In the numerical model, the aluminium frame and cavity barriers are implemented at same locations as during the tests. The expansion of the intumescent part of the cavity barrier is assumed to occur at 260°C. The intumescence is modelled as the appearance of an additional thickness of the solid obstacle representative of the cavity barrier when the local temperature criterion is reached.

The thermal properties for aluminium are extracted from Eurocode 9.\textsuperscript{36,38} Namely, a density of 2700 kg/m\textsuperscript{3} is used in this study. The emissivity of aluminium ranges between 0.3 and 0.7.\textsuperscript{26} In order to be conservative, a value of 0.7 was chosen.

The cavity barriers include an intumescent coating. Their thermal properties are extracted from laboratory databases and supplier datasheet. It has a density of 360 kg/m\textsuperscript{3} and a specific heat of 1.0 J/g/K. The emissivity of the cavity barrier is taken at 1.

The thermal properties of the calcium silicate supports are extracted from laboratory database and supplier datasheet. It has a density of 285 kg/m\textsuperscript{3} and a specific heat of 1.05 J/g/K. The emissivity is taken at 0.8.

4 | NUMERICAL FIRE REACTION TEST: RESULTS AND VALIDATION

The comparison between numerical and experimental results for temperatures, heat flux, species concentrations, and heat release rate is analysed. Experimental data and numerical results are smoothed using a rolling average over 30-seconds periods as proposed in ISO 13785-1.

The overall uncertainty of a numerical prediction is the combination of the uncertainties of both the numerical model and of the input parameters.\textsuperscript{39} The numerical uncertainties are evaluated following\textsuperscript{40,41} and are indicated in Table 2. Numerical parameter uncertainty is an important consideration to assess the reliability of the results and the impact of the input parameters of a model. In this study, the input parameters are taken from the literature and used to fit the experimental results. Thus, no input uncertainties are evaluated. However, a sensibility analysis was performed for the ignition temperatures of the cladding and the insulant.

In addition, the method described in ISO 16730-1:2015\textsuperscript{42} is used to further validate the numerical model against the experimental results by evaluating the variance of the numerical prediction to experimental measurements. This standard focuses on the predictive accuracy of calculation methods using a mathematical technique known as functional analysis. Problems are described in vector

### Table 2  Numerical and experimental uncertainties

| Quantity               | Experiment Relative Uncertainty\textsuperscript{13} % | Numerical Relative Uncertainty\textsuperscript{40} % | Relative Uncertainty\textsuperscript{42} % | Cosine\textsuperscript{42} |
|------------------------|------------------------------------------------------|-----------------------------------------------------|-------------------------------------------|-----------------------------|
| Surface temperature    | 5                                                    | 8                                                   | 22                                        | 0.86                        |
| Gas temperature        | 5                                                    | 8                                                   | 40                                        | 0.75                        |
| Heat flux              | 7                                                    | 15                                                  | 2                                         | 0.89                        |
| Heat release rate      | 10                                                   | 17                                                  | 9                                         | 0.98                        |
| CO concentration       | 10                                                   | 11                                                  | 57                                        | 0.72                        |
| CO\textsubscript{2} concentration | 5                                                   | 7                                                   | 2                                         | 0.95                        |
notation, and appropriate operations on these vectors are defined to allow quantitative analysis of the properties of the underlying physical system. The relative difference achieved with the hybrid method and the cosine associated with each quantity to be validated are evaluated to highlight numerical uncertainties.

4.1 Fire behaviour observations

A comparison of the experimental fire behaviour of the system with numerical observations is presented in Figure 2 at different elapsed times. It can be seen that there is a close correlation between the numerical modelling results and observations from the experimental tests involving [ACM-PE + PIR].

At 1 minute, the fire from the burner ignites the insulation system at its lower part. The fire propagates quickly to the cladding and is driven inside the cavity at 2 minutes. Flames are visible after 3 minutes and pass from the cavity to the exterior through the gap between the cladding panels. The fire is fully developed to the whole visible external cladding at 5 minutes. A hole appears at the lower central part of the back wall cladding after 6 minutes. The fire intensity tends to decrease after this time. After 8 minutes, only residual flames remain.

4.2 Comparison between experimental and numerical values

4.3 Comparison with experimentally measured values

The simulated temperatures at the back and side wall surfaces are comparable in magnitude and evolution with the experimental temperatures (Figure 3) over time and at each thermocouple location. The

| 1 min | 2 min | 3 min |
|-------|-------|-------|
| Numerical | Experimental | Numerical | Experimental | Numerical | Experimental |
| ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) | ![Image](image4.png) | ![Image](image5.png) | ![Image](image6.png) |
| 4 min | 5 min | 6 min |
| Numerical | Experimental | Numerical | Experimental | Numerical | Experimental |
| ![Image](image7.png) | ![Image](image8.png) | ![Image](image9.png) | ![Image](image10.png) | ![Image](image11.png) | ![Image](image12.png) |
| 7 min | 8 min | 9 min |
| Numerical | Experimental | Numerical | Experimental | Numerical | Experimental |
| ![Image](image13.png) | ![Image](image14.png) | ![Image](image15.png) | ![Image](image16.png) | ![Image](image17.png) | ![Image](image18.png) |

FIGURE 2 Numerical and experimental comparison of the fire behaviour of the system during the ISO 13785-1 test of the [ACM-PE + PIR] system [Colour figure can be viewed at wileyonlinelibrary.com]
The global thermal behaviour of the system is captured using simulation, and the thermal properties used are suitable. The good agreement between experimental and numerical results for surface temperatures validates the material thermal properties used in the study.

Similar conclusions can be made for gas temperatures in the back and side air cavities (Figure 4), meaning that thermal, dynamic, and aeraulic phenomena are properly represented by the numerical model. The main differences observed can be attributed to the fact that thermocouples can slightly move in the cavity, due to local turbulence during the test. Furthermore, only one experiment was conducted.

Measurements of gas temperature in the air cavity are used to understand the phenomenon involved during the test. Hot gases enter the system cavity around 1 minute after the beginning of the test, mainly through the horizontal gap between the panels. Then the insulant ignites around 2 minutes 45 seconds, followed by the unexposed face of the cladding around 3 minutes 30 seconds near the corner area. The lower aluminium frame at the bottom of the panels is lost around 4 minutes 10 seconds. The loss of the lower aluminium frame is consistent with experimental observation, where a time close to 5 minutes is predicted on temperature profiles.

The numerical evaluation of the temperature at the cavity barrier location in the back and side walls shows the full development of the cavity barriers at 4 minutes 20 seconds for the back wall and 4 minutes 35 seconds for the side wall. The expansion of the intumescent part of the cavity barrier is assumed to occur at 260°C. The propagation seems limited by the cavity barrier, and the upper panel away from the corner seems intact: The hot gases are trapped by the cavity barrier. Regarding both numerical and experimental results for
temperature at the side wall and in the air cavity, a “double maximum” is observed between 4 and 7 minutes (Figure 4). This double peak behaviour appears on the cavity temperature measurement before those of the side wall, with a delay in the range 30 seconds to 1 minute, due to the thermal inertia of the insulant and cladding materials. The first peak is due to the insulant ignition, with a maximum mass loss rate observed around 4 minutes. Then, at side wall, the horizontal cavity barrier intumesces around 4 minutes 30 seconds. The second peak can be explained by the cladding ignition. The model shows a maximum mass loss rate due to combustion of the ACM cladding at around 4 minutes 50 seconds. Then the upper part of the panel away from the corner starts to burn. After this time, the performances of the cavity barriers are decreased since the cavities do not exist anymore at several location. All parts of the ACM cladding are burning after 7 minutes 30 seconds. Fresh air enters in the system’s cavity due to holes appearing in the ACM cladding after 8 minutes, mainly at the lower part of the panel near the corner.

There is an excellent agreement between the numerical prediction and experimental data for the heat release rate during the test without the burner contribution (100 kW) (Figure 5). The maximum values are close: 5.0 ± 0.5 MW during test (10% uncertainty) and 5.3 ± 0.9 MW in simulation (17% uncertainty) and reached at 5.5 minutes of test. This is correlated with the observations of the fire development (Figure 2) inside the system. The numerical model does not reproduce the small contribution early in the test (between 1 and 4 min) and predicts a longer contribution after the mean peak (between 6.5 and 9 min).

Regarding the energy released (THR), there is a good match between experimental and numerical results. The maximum values are close to (683 ± 68) MJ during the test and (710 ± 120) MJ in the simulation, corresponding to a difference of only 4%.

Moreover, the numerical approach allows the evaluation of the contribution of each part of the system (ACM-PE cladding or PIR insulant) during the test. The HRR evaluated for the cladding and for the insulant is presented in Figure 6. The insulant has a much lower contribution to the global HRR of the system than the ACM-PE cladding. Moreover, for the [ACM-PE + PIR] configuration, the insulant shows a maximum heat release rate of 0.46 MW, while it is around 5 MW for the cladding. Additionally, the peak of HRR for the insulant happens
earlier (1 min before) than the peak of HRR for the cladding contribution. The contribution of the insulant represents 5% of the cladding heat release rate measured during the test.

The comparison of the experimental and numerical total heat fluxes at the upper part of the back wall addressed in Figure 7 shows that the heat flux profile is well predicted for the duration of the experiment. The overall fire dynamics of the intermediate-scale fire test is correctly reproduced by the model and by the combustion and fuel properties of the materials, thus validating the model. Experimental data and numerical results are smoothed using a rolling average over 30-seconds periods as proposed in ISO 13785-1.

Carbon monoxide (CO) and carbon dioxide (CO₂) concentrations show a good agreement between numerical and experimental values (Figure 8). The CO concentration is slightly overestimated in the numerical model, but the prediction is on the safe side and experimental data are close to the limit of measurement and, because of dilution, highly uncertain. This difference can be partially explained by the one-step mixture fraction combustion model used, with no second reaction for the CO consumption, because of uncertainty in the occurrence of this phenomena. Regarding the low measured values, the difference can also be explained by the resolution of the gas analyser in the range of these concentration levels. The CO/CO₂ ratio is lower than 0.1 indicating that the combustion occurs in well-ventilated conditions. The strong combustion of the polyethylene leads to the consumption of the material quickly after its ignition. The external cladding burns in well-ventilated conditions because of its external location. Moreover, as the cladding disappears in the early stages of the fire, it reduces the cavity performance. The insulant will then be exposed to the fire contribution of the cladding and the flames in the cavity. During the fire test, the insulant can then burn in well-ventilated conditions because it is quickly exposed to the external environment once the cladding has disappeared. This effect is well reproduced by the model, thus indicating that the fuels stoichiometry and the fuel mass released are correctly considered in the simulation.

4.3.1 Evaluation of the PIR charring depths

Temperature profiles at different depths inside the PIR insulant and different locations on the back wall were evaluated numerically. The 360°C (selected ignition temperature of PIR) isotherm inside the PIR is an estimation of the charring depth of the PIR. The burning rate value reached at the insulant indicates the charring area observed during the test. It was numerically predicted that an average thickness of 10 to 25 mm of PIR would be charred during ISO test, depending on the panel location. This is consistent with the experimentally evaluated charring depth, close to 10 mm. The backside of the insulant stays cold (less than 70°C) during the test, and so, no thermal feedback happens. The predicted maximum charring depth of the insulant for the back and side walls of the system is synthetized in Table 3.

4.3.2 Sensibility analysis of the PIR ignition temperature

According to the literature, PIR ignition temperature can commonly range between 350 and 420°C. Critical heat flux measurements have been performed by cone calorimeter tests on Celotex RS5000 with an incident heat flux of 10 to 50 kW/m². These tests have shown an ignition temperature close to 350°C when the insulant had no aluminium facing or when the aluminium facing has disappear (safer condition) and 600°C with the product’s reflective aluminium facing in place (less critical condition). The influence of PIR ignition temperature
on the ISO 13785-1 simulation was thus investigated using three different values:

- An easily flammable PIR with an ignition temperature of 350°C,
- A PIR with a moderate flammability associated with an ignition of 370°C,
- A PIR with a low flammability associated with an ignition temperature of 420°C.

The comparison between experimental data and the numerical prediction for the different values of peak HRR attributed to the PIR insulant to the ACM cladding and to the system is synthesized in Table 4. A relative deviation of 9% is found comparing with experimental measure.

It can be concluded that the ignition temperature of PIR does not play a significant role in the overall behaviour of the system as the predicted maximum HRR value for the PIR insulant is always in the margin of incertitude of the measurements of 10% (Table 2). However, ignition temperatures ranging between 370°C and 420°C decrease the difference between experimental and numerical data for the HRR of the whole system. Furthermore, using values of between 350°C and 420°C is conservative with respect to the incertitude of measurement.

### 4.3.3 Variance of the numerical model for the [ACM-PE + PIR] system

The method described in ISO 16730-1:2015 is used to further validate the numerical model against the experimental results. The relative difference (hybrid method) and the cosine associated with each quantity to be validated are presented in Table 5. The minimum cosine value evaluated, close to 0.72, is associated with the maximum relative difference value close to 57% and concerns the CO concentration. However, this low cosine value and high relative difference value are explained by the CO concentration that is slightly overestimated in the numerical model. As justified previously, this difference can be related to the one-step mixture fraction combustion model used, but especially, regarding the low measured values, by the resolution of the gas analyser in the range of these concentration levels. The HRR and THR representative of the mass loss and the energy balance show cosine values close to 1 and low relative difference (under 10%). This relative difference is in the range of the numerical and experimental uncertainties. Same conclusions are drawn for surface temperatures in the back and side walls, as well as air cavity temperatures. Cosines are in all case higher than 0.75, and relative differences lower than 22% for the surface temperatures, and 40% for the air cavity temperatures. The values for the relative differences are also in the range of both numerical and experimental uncertainties. As a preliminary conclusion, the numerical model addressed for the [ACM-PE + PIR] tested configuration is valid and can be used for further investigations.

### 5 FURTHER VALIDATION OF THE NUMERICAL MODEL

Further validation of the numerical model is addressed to evaluate the combustion behaviour of each component of the system. These additional investigations allow the verification of the robustness of the numerical model and the investigation of the effect of the use of non-combustible cladding or insulation instead of combustible cladding or insulation.
ACM-PE or PIR. The numerical approach addressed is then useful to further understand the role played by the individual components of the system and to provide a deeper evaluation of façade systems in case of fire.

Thus, a simulation is performed with the same ACM cladding [ACM-PE] but with an inert insulant (mineral wool) [MW], designated as [ACM-PE + MW]. Then a second calculation was performed using the original insulant [PIR], but with an inert non-combustible cladding [ACM-A2 like], designated as [ACM-A2 like + PIR].

Only the thermal and fire properties of the cladding or insulant were changes in the model. The numerical model of the test rig remained the same. The numerical model for the [ACM-A2 like] cladding assumed the same thermal properties as for the [ACM-PE] cladding but no combustible content. Thus, in this configuration, the ACM cladding will have no contribution to the heat released. Furthermore, no fire retardants were considered in the cladding properties. The experimental results for these systems can be found elsewhere.13

The simulated temperatures at back and side wall surfaces are comparable in magnitude and evolution with the experimental ones for the [ACM-PE + MW] configuration (Figure 9), at each thermocouple location and during the full duration of the fire test. The same conclusion are drawn for the [ACM-A2 like + PIR] configuration (Figure 10). However, at higher thermocouple locations (L4, L5, S4, and S5), the numerical model predicts a local increase in temperature. This can be related to a small contribution from the PIR insulant in the upper part of the system and local surface charring. This is observed on the numerically modelled HRR (Figure 15). Thus, the global experimental thermal behaviour of the system is well captured by the model, thus validating the assumed thermal properties of the materials for both configurations. The fire behaviour of the insulant is correctly simulated.

The same conclusions are drawn for the temperature in the back and side air cavities for both system configurations, meaning that the thermal, dynamic, and aeraulic phenomena are properly represented by the numerical model. For the [ACM-PE + MW] configuration (Figure 9), the main differences observed can be related to the thermocouple moving in the cavity due to local turbulence during the test. The good agreement between experimental and numerical results for the surface and air cavity temperatures thus validates the thermal properties for each material used in the study and in particular for the cladding.

Rupture of the ACM-PE cladding is observed in the experimental tests at around 7 minutes in case of the [ACM-PE + MW] system (8 min for [ACM-PE + PIR]13). Similar observations are made with the numerical model.

For the [ACM-A2 like + PIR] configuration (Figure 10), the main differences observed can be related to the thermocouple moving in the cavity due to local turbulence during the test and to a small contribution from the PIR insulant in the upper part of the system. The good agreement between experimental and numerical results for the surface and air cavity temperatures thus validates the thermal properties for each materials used in the study, and in particular for the insulant.

A numerical evaluation of the temperature at the cavity barrier location in the back and side walls shows that for the [ACM-PE + MW] configuration, the barriers develop at around 4 minutes 15 seconds for both the back and side walls. Thus, the cavity barrier intumesces at a

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**FIGURE 9** Comparison of numerical and experimental temperature at the back (L2 and L3 locations) and side (S1 and S4 locations) walls of the system during the ISO 13785-1 test of the [ACM-PE + MW] configuration [Colour figure can be viewed at wileyonlinelibrary.com]
FIGURE 10  Comparison of numerical and experimental temperature at the back (L3 and L4 locations) and side (S1 and S3 locations) walls of the system during the ISO 13785-1 test of the [ACM-A2 like + PIR] configuration [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 11  Comparison of numerical and experimental temperature in the air cavity of the back (LC2) and side (SC2) walls of the system during the ISO 13785-1 test of the [ACM-PE + MW] configuration [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 12  Comparison of numerical and experimental temperature in the air cavity of the back (LC1) and side (SC1) walls of the system during the ISO 13785-1 test of the [ACM-A2 like + PIR] configuration [Colour figure can be viewed at wileyonlinelibrary.com]
similar time as for the configuration with the PIR insulant, where the cavity barrier intumesced at around 4 minutes 20 seconds. For the [ACM-A2 like + PIR] configuration, this temperature is reached at around 5 minutes for both the back and side walls. Thus, the cavity barrier intumesces latter than with the ACM-PE cladding.

For the [ACM-PE + MW] configuration, a comparison between the experimental and numerical heat flux at the upper part of the back wall is presented in Figure 13. It can be seen that the model predicts the experimental heat flux profile well, for the duration of the experiment, validating the dynamics of the fire during the test with MW used as insulant. The overall fire dynamics of the fire at the ISO 13785-1 scale is correctly reproduced by the model using the assumed combustion and fuel properties of the materials. When compared with the heat flux measured above the system during the test of the [ACM-PE + PIR] configuration, we observe higher heat fluxes when PIR is used rather than MW. This is not related to the PIR combustion, but to the insulating properties of this material. The PIR shows better insulating performance than MW, and the heat is thus kept away from the insulant. This energy is then available for the cladding combustion. In the case of the MW, the heat is absorbed by the insulant and can be released later. No experimental measurement of the heat flux was available for the [ACM-A2 + PIR] configuration.

For the [ACM-PE + MW] configuration, there is quite good agreement between numerical and experimental values for CO$_2$ concentrations and also for CO ones regarding the low values achieved (Figure 14). For the [ACM-A2 like + PIR] configuration, the numerical model underestimates the CO and CO$_2$ concentrations. That can be related to limited thermal degradation of the ACM cladding, which is not taken into account in the numerical model, and because the measured experimental values are so low compared with the resolution of the gas analyser in the range of these concentration levels. However, for both system configurations, the CO/CO$_2$ ratio is lower than 0.1 indicating that the combustion occurs in well-ventilated conditions. This effect is well reproduced by the model and indicates that the fuels stoichiometry and the fuel mass released are correctly taken into account in the simulation. For the [ACM-PE + MW] configuration, the CO$_2$ release is five times higher than for the inert cladding configuration, but comparable with the concentration evaluated for the [ACM-PE + PIR] system. Thus, the high CO$_2$ release seems mainly due to the PE cladding combustion.
The HRR evaluated for the [ACM-PE + MW] and [ACM-A2 like + MW] configurations without the propane burner contribution allows to evaluate the impact of the material constituting the system. In Figure 15, the HRR evaluated for the [ACM-PE + PIR] configuration is also shown for comparison purposes. For the [ACM-PE + MW] configuration, there is excellent agreement between the numerical model and experimental data. The maximum values are similar, with an experimental peak HRR of 4.6 ± 0.5 MW (10% uncertainty) and 4.9 ± 0.5 MW in simulation (17% uncertainty). A comparison of the experimental HRR and that from the numerical models for the [ACM-PE + MW] and [ACM-PE + PIR] configurations shows that when PIR is used, a higher peak of HRR (of around 0.4 MW) is observed, but delayed of around 1 minute compared with that for the configuration with MW. This higher value is due to the small contribution of the PIR to the heat released. The delay is because ACM combustion begins more slowly for the configuration with PIR. This is due to the energy absorbed by the PIR for charring, thermal cracking and pyrolysis, leading to a competition between thermal and thermochemical effects.

For the [ACM-A2 like + PIR] configuration, the results show an overall good agreement between the numerical prediction and the experimental data. However, the numerical model predicts a local increase in the HRR at 6 minutes 30 seconds (peak) into the test, for 2 minutes. It relates to limited combustion of the PIR insulant and to pyrolysis gases released by the PIR burning out of the system. There are two reasons for this discrepancy. Firstly, in the numerical model, the PIR insulant surface burns quickly, until the fuel mass is consumed in the numerical cell. During the experiments, this burning at the PIR surface is more progressive and cannot be accurately reproduced with the mixture fraction model used (the use of finite rate pyrolysis model should help). Secondly, this contribution from the insulant, not observed during the test, can be due to the limited thermal degradation of the cladding that is not taken into account numerically. In the model, all of the heat is kept in the air cavity without participating to the cladding degradation. This leads to extra combustion of the insulant. However, the PIR contribution is low, and same orders of magnitude of hundreds of kW are reached. Without this local increase, the numerical and experimental HRRs are comparable. Maximum values are close to 0.20 MW during the test (10% uncertainty) and 0.55 MW in the simulation (17% uncertainty). Thus, the numerical model can evaluate the contribution of the insulant during the test.

The energy released (THR) is addressed in Figure 16 for the [ACM-PE + MW] and the [ACM-A2 + PIR] configurations. A good fit was observed between experimental (solid lines) and numerical (dashed lines) results. The small differences can be explained by the fact that the mineral wool binder was not taken into account in the numerical model for the [ACM-PE + MW] configuration and by the local increase in the HRR of the PIR insulant that was not observed during the test for the [ACM-A2 like + PIR] configuration.

6 | SYNTHESIS

This study aimed to understand and to model the fire behaviour of different insulated ventilated façade systems at the intermediate scale of ISO 13785-1. Systems comprising [ACM-PE + PIR], [ACM-A2

FIGURE 15 Numerical (dashed lines) and experimental (solid lines) heat release rates (HRR) during the ISO 13785-1 tests of the [ACM-PE + PIR], [ACM-PE + MW], and [ACM-A2 like + PIR] configurations [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 16 Numerical (dashed lines) and experimental (solid lines) combustion energy (THR) during the ISO 13785-1 tests of the [ACM-PE + MW] and [ACM-A2 like + PIR] configurations [Colour figure can be viewed at wileyonlinelibrary.com]
like + PIR) and [ACM-PE + MW] were modelled numerically following previous fire tests.\textsuperscript{13}

Based on the thermal and combustion properties of each material component of these insulated façade systems, it was possible to simulate the experimental fire tests with an excellent agreement. The global fire behaviour of the systems was captured using simulation based on comparison with experimental data. More precisely, the heat release rate behaviour, the gas temperature inside the cavities, and the surface temperature of the insulant were predicted with very good agreement with the experimental data.

This allows a better understanding of how the fire propagates on the insulation and cladding, of which the cladding system comprises, and on the overall system. The numerical model can thus predict the behaviour of the whole systems at this scale, for later upscaling studies. Special attention was given to flow and thermal conditions at all locations in the tested system.

Simulations of gas temperature in the air cavity were used to understand the phenomenon involved during the test. In particular, the global fire behaviour was deeply analysed in terms of delay for hot gases to enter the system cavity, for the insulant to ignite, followed by the unexposed face of the cladding, and of behaviour of the lower aluminium frame at the bottom of the panels, or of the intumesence of the cavity barriers. The numerical evaluation of the temperature at the cavity barrier location in the back and side walls shows the full development of the barriers. The fire propagation seems limited by the cavity barrier. However, all parts of the ACM-PE cladding are burning in few minutes of the tests, and fresh air enters in the system’s cavity due to holes appearing in the cladding.

Additional information, such as the relative contribution of each part of the system (ACM-PE cladding or PIR insulant) during the test, which cannot be measured experimentally, was investigated with this numerical approach. The fire behaviour of each component of the overall system was thus validated numerically. The HRR evaluated for the cladding and for the insulant shows that the insulant has a much lower contribution to the global HRR of the system than the ACM-PE cladding. Additionally, the peak of HRR for the insulant happens earlier than the peak of HRR for the cladding contribution. Thus, the numerical modelling approach can help to understand the relative contribution of one material versus another in complex system. Hence, the ACM-PE represents more than 90% of the value of the peak of HRR and of the total energy released.

An additional sensitivity analysis was performed to evaluate the influence of the ignition temperature considered for the PIR insulant for the [ACM-PE + PIR] configuration. It can be concluded that the ignition temperature of PIR does not play a significant role in the overall behaviour of the system as the predicted maximum HRR value is always in the margin of incertitude of the measurements (10%).

Temperature profiles at different depths inside the PIR insulant and different location on the back wall were evaluated numerically for the [ACM-PE + PIR] configuration. The model predicted that an average thickness of 10 to 25 mm of PIR would achieve ignition temperature, depending on location. This is consistent with the experimentally observed char depth, of close to 10 mm.\textsuperscript{13}

Further validation of the numerical model was addressed through simulations of the system including a non-combustible mineral wool insulant and of the system including an inert non-combustible cladding. This allows a deeper analysis of the material contribution to the fire spread in the façade systems and is then useful to further understand the role played by the individual components of the system, and to provide a reliable evaluation of façade systems in case of fire.

When compared with the heat flux measured above the system during the test of the [ACM-PE + PIR] configuration, higher heat fluxes are evaluated when PIR is used rather than MW. This is not related to the PIR combustion, but to the insulating properties of this material.

In all the simulated configurations and experimental results, the CO/CO\textsubscript{2} ratio is lower than 0.1 indicating that the combustion occurred in well-ventilated conditions. The strong combustion of the polyethylene in the ACM-PE leads to the consumption of the material quickly after its ignition. The external cladding burns in well-ventilated conditions because of its external location, and it burns away at early stage of the fire. The insulant is exposed to the fire contribution of the cladding and resulting flames in the cavity, even if the cladding has disappeared. During the fire test, the insulant can then burn in well-ventilated conditions because it is quickly exposed to the external environment once the cladding has disappeared. This effect is well reproduced by the model, thus indicating that the fuels’ stoichiometry and the fuel mass released are correctly taken into account in the simulation. For the [ACM-PE + MW] configuration, the CO\textsubscript{2} release is five times higher than for the inert cladding configuration, but comparable with the concentration evaluated for the [ACM-PE + PIR] system. Thus, the high CO\textsubscript{2} release seems mainly due to the PE cladding combustion.

A comparison of the experimental HRR and that from the numerical models for the [ACM-PE + MW] and [ACM-PE + PIR] configurations shows that when PIR is used, a higher peak of HRR (of around 0.4 MW) is observed, but delayed of around 1 minute compared with that for the configuration with MW. This higher value is due to the small contribution of the PIR to the heat released. The delay is because ACM-PE combustion begins more slowly for the configuration with PIR. This is due to the energy absorbed by the PIR for charring, thermal cracking, and pyrolysis, leading to a competition between thermal and thermochemical effects.

For the [ACM-A2 like + PIR] system, maximum HRR values are close to 0.20 MW during the test and 0.55 MW in the simulation and thus 10 to 25 times lower than for ACM-PE claddings configurations.

Finally, the numerical simulations as well as the tests performed show that the ACM cladding is the most important element driving the global fire behaviour of the tested façade systems. In particular, ACM-PE-based cladding systems, whatever the insulant used in the system, show very marked fire propagation. Moreover, the integrity of the cavity is affected by the dripping and the destruction of the burning ACM-PE cladding.

This series of simulations is a part of a larger study including several steps of increasing in complexity. Now this model for the fire
behaviour of façade systems has been validated at intermediate scale, larger façade systems will be investigated numerically to evaluate the influence of scaling. The change in the ignition temperature or other thermal parameter will be investigated while changing the mesh resolution. The approaches for the use of ignition temperature model accompanied by area adjust for coarse mesh fire spread simulations following the work of Janardhan and Hostikka will be investigated.

Additionally, further researches could address extended investigation in terms of numerical modelling with finest grid in cavities to observe the impact of more resolved mesh, or 3D thermal transfer for solid materials. Experimental developments could also be needed to evaluate the velocity in the cavity.

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