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Modelling intumescent coatings for the fire protection of structural systems: a review

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Abstract

Purpose – Intumescent coatings are nowadays a dominant passive system used to protect structural materials in case of fire. Due to their reactive swelling behaviour, intumescent coatings are particularly complex materials to be modelled and predicted, which can be extremely useful especially for performance-based fire safety designs. In addition, many parameters influence their performance, and this challenges the definition and quantification of their material properties. Several approaches and models of various complexities are proposed in the literature, and they are reviewed and analysed in a critical literature review.

Design/methodology/approach – Analytical, finite-difference and finite-element methods for modelling intumescent coatings are compared, followed by the definition and quantification of the main physical, thermal, and optical properties of intumescent coatings: swelled thickness, thermal conductivity and resistance, density, specific heat capacity, and emissivity/absorptivity.

Findings – The study highlights the scarce consideration of key influencing factors on the material properties, and the tendency to simplify the problem into effective thermo-physical properties, such as effective thermal conductivity. As a conclusion, the literature review underlines the lack of homogenisation of modelling approaches and material properties, as well as the need for a universal modelling method that can generally simulate the performance of intumescent coatings, combine the large amount of published experimental data, and reliably produce fire-safe performance-based designs.

Research limitations/implications – Due to their limited applicability, high complexity and little comparability, the presented literature review does not focus on analysing and comparing different multi-component models, constituted of many model-specific input parameters. On the contrary, the presented literature review compares various approaches, models and thermo-physical properties which primarily focusses on solving the heat transfer problem through swelling intumescent systems.

Originality/value – The presented literature review analyses and discusses the various modelling approaches to describe and predict the behaviour of swelling intumescent coatings as fire protection for structural materials. Due to the vast variety of available commercial products and potential testing conditions, these data are rarely compared and combined to achieve an overall understanding on the response of intumescent coatings as fire protection measure. The study highlights the lack of information and homogenisation of various modelling approaches, and it underlines the research needs about several aspects related to the intumescent coating behaviour modelling, also providing some useful suggestions for future studies.

Keywords Intumescent coatings, Fire protection, Modelling, Fire safety, Structural fire engineering, Performance-based design

Paper type Literature review

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Nomenclature

A	Area [m^2]	$\lambda_{eff,const}$	Effective constant thermal conductivity [W/mK]
V	Volume [m^3]		
A/V	Section factor [m^{-1}]	R	Thermal resistance [m^{2}K/W]
d_c	Coating thickness [m]		
d_s	Substrate/steel thickness [m]	R_{eff}	Effective thermal conductivity [m^{2}K/W]
DFT	Coating dry film thickness [m]	$R_{eff,const}$	Effective constant thermal conductivity [m^{2}K/W]
d_c/DFT	Coating swelling ratio [-]		
$\dot{d}_c$	Coating swelling rate [mm/min]	c_p	Specific heat capacity [J/kgK]
λ	Thermal conductivity [W/mK]	ρ	Density [kg/m^3]
		ε	Emissivity [-]
λ_{eff}	Effective thermal conductivity [W/mK]	α	Absorptivity [-]
		T	Temperature [K]
λ_{app}	Apparent thermal conductivity [W/mK]		

1. Introduction

Several accidental fires occur every year in buildings, causing considerable losses of human life and economic costs. Indeed, for most construction materials, the stability and integrity of structural systems may be compromised during and after a fire due to loss of strength and stiffness, as well as thermally induced forces and displacements (Usmani *et al.*, 2001). To avoid structural failure and substantial damage, structural elements are often equipped with fire protection materials, protecting the load-bearing material and preventing the achievement of high temperatures during fire (Buchanan and Abu, 2017). Especially, fire damages can be important if the affected structure is a steel one. Indeed, due to the high thermal conductivity and the small thickness of steel profiles, in the event of a fire, these structures suffer very high temperatures in a short time, also causing the structural collapse in extreme cases (Wang, 2002).

Fire protection materials can be divided into two categories: passive materials (e.g. incombustible boards, such as gypsum, and or cementitious spray-on systems) and reactive materials (e.g. intumescent coatings). Intumescent coatings are thermally reactive materials, usually composed of a combination of organic and inorganic components bound together in a polymer matrix (typically solvent- or water-based) (Lucherini and Maluk, 2019b). At ambient temperature, intumescent coatings appear as a pigmented thin coating, applied to a dry film thickness (DFT) ranging between 400 and 3000 µm. When exposed to sufficient heat, they swell to form a thick low-density and low-thermal-conductivity porous char that acts as a thermal barrier. Intumescent coatings can swell up to 100 times their initial thickness following typical reaction stages in the so-called intumescent process (Lucherini and Maluk, 2019b). The advantages of this protection system include reduced invasiveness compared to other materials, an easy application (both on- and off-site) and a good surface finishing. These advantages over conventional solutions have fostered their success and extensive use all over the world.

For a commercial use, intumescent coatings have to be tested according to current methods that involve the coating testing on a full-scale structural elements using a standard procedure in a furnace following the standard temperature–time fire curve (EN 1363-1:2012; EN 1363-2:2012; EN 13381-8:2013). This process is highly time-consuming and expensive, and it must be repeated even if the manufacturer has only made a minor modification to the intumescent formulation. Therefore, it seems useful gaining an in-depth understanding on how intumescent coating perform, starting from small-scale tests performed to determine the properties of it, for the development of new product formulations (Dreyer *et al.*, 2021). Moreover, this characterisation can be also useful for the implementation of the protective material in finite element models for the design of a proper intumescent coating thicknesses of protected steel members.

As highlighted by the numerous literature reviews published in the last few years (Lucherini and Maluk, 2019b; Dreyer *et al.*, 2021; Puri and Khanna, 2017; Mariappan, 2016; Weil, 2011; Bourbigot *et al.*, 2004), during the last decades, extensive research and development efforts have been made towards understanding and improving the performance of intumescent coatings in terms of thermal shielding to various substrate materials (primarily steel, but also concrete (Ghiji *et al.*, 2023) and wood (Lucherini *et al.*, 2019a)).

Along with vast experimental and testing campaigns, practitioners and researchers have been continuously developing and suggesting mathematical and/or numerical models of various complexities aimed at predicting and replicating the insulating performance of the thermal barrier provided by swelling intumescent coatings during fire. These engineering models have become more and more relevant and requested due to the push for performance-based solutions, which are becoming more popular and a common trend in many engineering fields, including fire safety and structural fire engineering. The possibility of modelling and predicting the behaviour of intumescent coatings can be extremely useful for selecting performance-based fire safety solutions. These methods usually involve thermal analysis aimed at estimating the temperature evolution of the structural systems and understanding their behaviour in the case of fire. In addition, these processes allow for the optimisation of structural systems and fire protection materials.

Due to the complicated swelling process of intumescent coatings, which involves a complex combination of different material phases, mixtures and reactions, many researchers tended to develop multi-component mathematical and numerical models (Zhu *et al.*, 2022; Swann and Stoliarov, 2021; Kang *et al.*, 2019; Hsu, 2018; Ogrin *et al.*, 2018; Kang *et al.*, 2017; Cirpici *et al.*, 2016b; Zhang *et al.*, 2012a, b; Zhang *et al.*, 2012, ; Staggs *et al.*, 2012; Staggs, 2010; Griffin, 2010; Gillet *et al.*, 2007; Omrane *et al.*, 2007; Griffin *et al.*, 2005; Di Blasi and Branca, 2001; Bourbigot *et al.*, 1995; Anderson *et al.*, 1985, 1988; Henderson, 1985; Cagliostro *et al.*, 1975). These models aim at predicting the insulating capability of intumescent coatings by resolving many aspects of the intumescent process (e.g. mixtures, phases, species, mass factions, porosity, viscosity, pyrolysis, etc.). However, they often end up in research-focused models with limited applicability due to the many case-specific input parameters (e.g. activation temperature, thermal degradation kinetics, viscosity, pores diameter, thermo-mechanical properties of multi-phase material, heat transfer coefficient of inner re-radiation), usually largely empirical and very hard to define/measure/quantify.

Due to their limited applicability, high complexity and little comparability, the presented literature review does not focus on analysing and comparing different multi-component models, constituted of many model-specific input parameters. On the contrary, the presented literature review compares various approaches, models and thermo-physical properties which primarily focusses on solving the heat transfer problem through swelling intumescent systems. Indeed, performance-based design methods for fire safety and structural fire engineering typically involve thermal analysis aimed at estimating the temperature evolution of the coated substrate material, and the intumescent coatings are usually considered as one entity/material with specific thermo-physical properties. The presented literature review highlights the lack of information and homogenisation of various modelling approaches, and it underlines the research needs about several aspects related to the intumescent coating behaviour characterisation, also providing some useful suggestions for future studies.

2. Modelling approaches

2.1 Analytical methods

Many analytical expressions to solve simplified (conduction) heat transfer problems are available in the literature (Incropera *et al.*, 2006). For the case of intumescent coatings, in particular for applications on steel substrates, the transient one-dimensional heat conduction equation can be simplified through a lumped capacitance approximation (Lucherini and Maluk, 2019b; EN 13381-8:2013; EN 1993-1-2:2005). According to this method, a low-density insulation material, such as the swelling intumescent coating, is approximated as a thermal mass included between the fire gas temperature and the protected substrate temperature. The complex thermo-physical behaviour of swelling intumescent coatings is simplified in an effective parameter (usually thermal conductivity or thermal resistance), its swelling and change in thickness are ignored, and the thermal capacitance of the coating is neglected compared to the one of the protected substrate. This is usually an appropriate assumption for steel substrates, due to the much higher thermal inertia of the steel substrate compared to the thin (low-density) coating. Thanks to this method, analytical solutions of the heat transfer problem can be obtained. This is the case of Eurocode 3, where the intumescent coating's insulating ability is assessed through this lumped capacitance method (Annex E of EN 13381-8 (EN 13381-8:2013), see Figure 1a). Since the thermal capacitance of the intumescent coating is neglected, the only coating properties to be defined are related to its conduction properties, namely its thickness and its thermal conductivity or, together, its thermal resistance. These properties define an equivalent thermal barrier provided by the intumescent coating to the protected substrate and they are usually estimated in terms of an effective thermal conductivity λ_{eff} [W/mK], calculated based on the initial coating dry film thickness (DFT), or an effective thermal resistance R_{eff} (d_c/λ_{eff}) [m^{2}K/W]. The definition of these material properties and typical values are reported and discussed in Section 3.

2.2 Finite-difference methods

The one-dimensional heat transfer problem for substrates protected with intumescent coatings is often solved through finite-difference methods. Following this approach, the differential equation describing the transient heat conduction problem can be solved by using various explicit or implicit finite-difference schemes of various complexities (Incropera *et al.*, 2006). An example of explicit schemes is the numerical method developed by Emmons and Dusinberre with numerical stability requirements (Emmons, 1943; Dusinberre, 1961) and the Crank-Nicolson method represents an example of numerically stable implicit scheme (Incropera *et al.*, 2006; Lucherini, 2020). Following the main direction of the heat flow (fire-exposed intumescent coating surface towards the protected substrate), the transient conduction problem is solved through energy-balance equations, where the space is discretised in finite nodes and differential quantities are substituted with finite differences, assuming a small time increment and therefore small temperature increments between consecutive iterations (refer to Figure 1b).

The analytical solutions like the previously described lumped capacitance method are usually restricted to simple geometries and boundary conditions, while finite-difference methods can solve a larger extension of transient conduction problems, for instance allowing for more detailed definition of the materials properties, geometry, and thermal boundary conditions. In addition, these modelling approaches enable a more precise control on thermal problem, since the heat transfer problem is solved node by node (typically surface, interface and internal nodes). For instance, they enable the assessment of the thermal profile within swelling intumescent coatings during the thermal exposure: exemplar research studies compared experimentally measured in-depth temperature profiles with the ones predicted using a heat transfer model (Lucherini *et al.*, 2023; Bozzoli *et al.*, 2018; Kang *et al.*, 2018).

Various researchers have followed this approach to model the heat transfer through swelling intumescent coatings. Apart from defining temperature-dependent thermo-physical properties, the coating swelling can be implemented in numerous manners. For instance, modelling the coating swelling by adding nodes at the coating-substrate interphase, by using an adaptive mesh and a swelling rate, or by controlling nodes properties and mass factions/

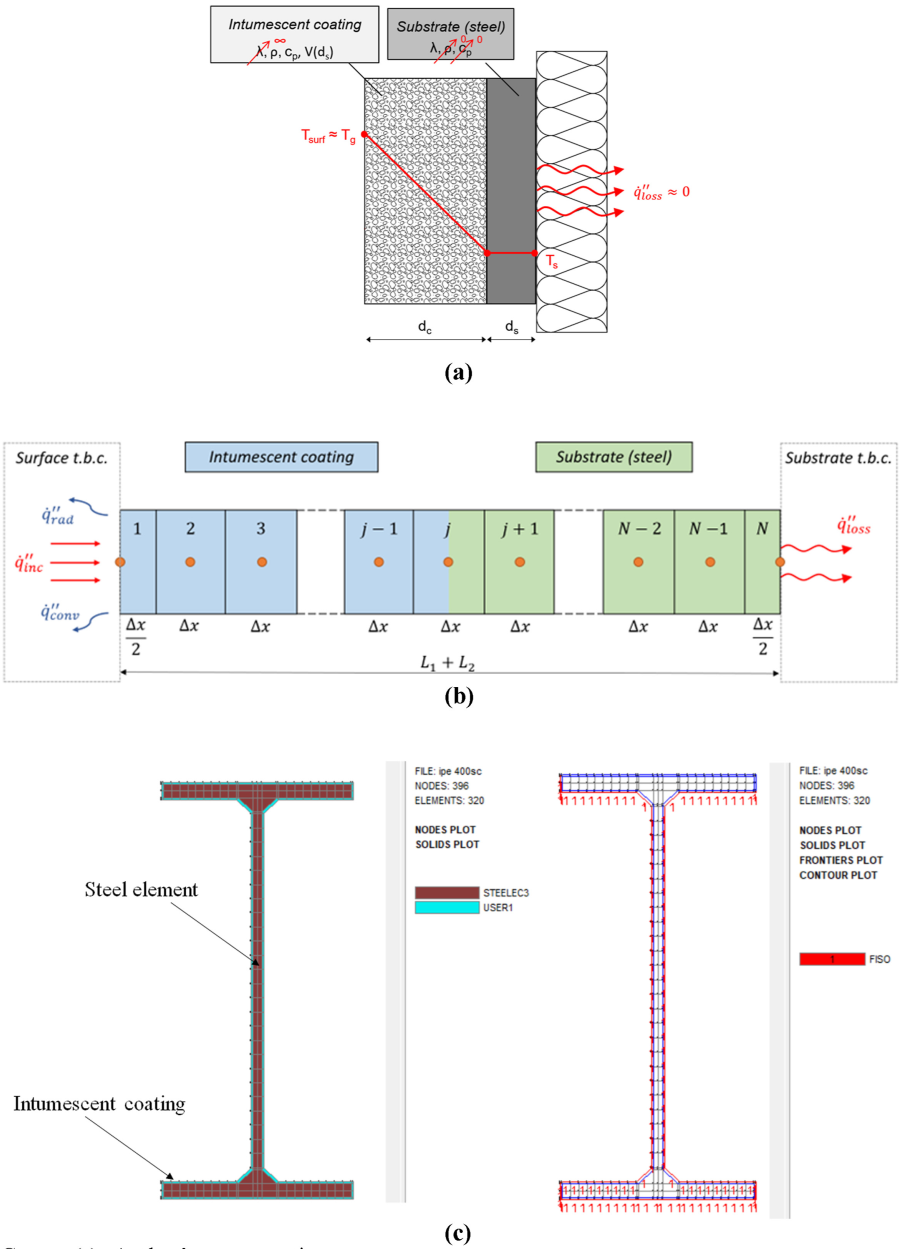

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Figure 1.
Exemplar illustrations for the three main modelling approaches for intumescent coatings: (a) analytical model (lumped capacitance method); (b) finite-difference model (intumescent coating and substrate) with exemplar surface and substrate thermal boundary conditions (t.b.c.); (c) typical FEM analysis using SAFIR

multi-phase mixtures (Zhu *et al.*, 2022; Kang *et al.*, 2019; Hsu, 2018; Ogrin *et al.*, 2018; Kang *et al.*, 2017; Zhang *et al.*, 2012a, b; Zhang *et al.*, 2012; Staggs *et al.*, 2012; Lucherini *et al.*, 2023; Lucherini and Maluk, 2019a; Wang *et al.*, 2012; Bartholmai and Schartel, 2007).

2.3 Computational models (finite-element methods – FEM)

Many researchers also use different finite-element methods (FEM) software to model the protecting performance of intumescent coatings. These software typically solve simplified transient heat conduction problems, starting from defined materials properties and thermal boundary conditions (see Figure 1c). Through these software, thermal analyses are often combined with mechanical analyses, for instance for the assessment of the behaviour of fire-exposed steel structures protected with intumescent coatings. These analyses can be carried out at the level of the single load-bearing element (e.g. beam or column) or the overall structural system (e.g. moment-resisting frame).

Many commercial software have been adopted by engineers, practitioners, and researchers for the thermo-mechanical analysis of structural systems protected with intumescent coatings. ABAQUS and ANSYS are the most common FEM software adopted in different studies aimed at simulating the temperature evolutions and/or failure modes of various protected structural elements exposed to fire. Examples of these applications are concrete filled steel tubular (CFST) columns (Cirpici and Aydin, 2023; Jafarian *et al.*, 2022; Dai and Lam, 2014), thin-walled steel members under localised fires (Xu *et al.*, 2021), partially protected steel members (Šejna *et al.*, 2023), steel beams and columns of various profiles (Ma *et al.*, 2020; Weisheim *et al.*, 2019; Shaumann *et al.*, 2016; Kolsek and Cesarek, 2015) and composite structural members (Dzolev *et al.*, 2021; Cirpici *et al.*, 2019). SAFIR (Franssen and Gernay, 2017) is also largely adopted in commercial and research applications for structural fire engineering, and steel and composite steel-concrete structures protected with intumescent coatings represent interesting application examples (de Silva *et al.*, 2020; Bilotta *et al.*, 2016b). Other FEM software like TNO-Diana (Nadjai *et al.*, 2016), LS-DYNA (Barber *et al.*, 2021) and Opensees (Usmani *et al.*, 2017) have been also used for structural fire engineering applications, like unprotected and intumescent-protected cellular beams and steel–timber hybrid connections in fire conditions.

However, due to the complexity of the swelling process of intumescent coatings, these software must rely on several assumptions. Common simplifications to solve the thermo-mechanical problems are modelling the intumescent coating as an inert fire protection material, characterised by a constant geometry (thickness, therefore mesh) and effective temperature-dependent thermo-physical properties (i.e. thermal conductivity, density, and specific heat capacity). In contrast, other simplified approaches involve changes in the coating geometry due to swelling. An interesting method suggests modelling the swelling of intumescent coatings by defining a (linear) thermal expansion coefficient, along with semi-realistic material properties (Kang *et al.*, 2017; Ma *et al.*, 2020; Weisheim *et al.*, 2019; Shaumann *et al.*, 2016; Cirpici *et al.*, 2019).

3. Thermo-physical properties of intumescent coatings

The adoption of numerous modelling approaches based on various assumptions and simplifications has led to a lack of harmonisation and generalisation in the definition and evaluation of the physical and thermal properties of intumescent coatings, fundamental parameters for the resolution of any heat transfer problem. This situation produced a large variety and formulations of material properties aimed at reproducing the response of intumescent coatings when exposed to fire. These properties have never been universally specified, and models often define and rely on various assumptions and characteristic parameters, which are hard to generalise, and they may differ case by case, model by model, and product by product.

To offer an extended overview of the main thermo-physical properties of intumescent coatings, Table 1 reports the estimation and quantification of all the major material properties found in the available literature though a systematic review. The literature review analysed

Table 1. Systematic literature review of the material properties of intumescent coatings, arranged in reserve chronological order

Source	Study/Data type	d_c/DFT [-] $\dot{d}_c$ [mm/min]	λ [W/mK] R [m^{2}K/W]	ρ [kg/m^3]	c_p [J/kgK]	ε [-] α [-]
Lucherini *et al.* (2023)	Mod.	23–35 (d_c/DFT) 0.3–1.8 ($\dot{d}_c$)	0.16 (λ)	50	1,550	0.90
Šejna *et al.* (2023)	Exp. + Mod.	–	0.079–0.5 (λ_{eff})	440	924–1,320	–
Cirpici and Aydin (2023)	Mod.	–	0.01–0.15 (λ_{eff})	100	1,000	–
Baena *et al.* (2023)	Exp.	10–50 (d_c/DFT)	–	–	–	–
Wang *et al.* (2023)	Exp. + Mod.		0.01–0.07 (λ_{eff})	100	1,000	0.92
Li *et al.* (2023)	Exp.	10–17 (d_c/DFT) 0.8–2.8 ($\dot{d}_c$)	–	–	–	–
Jafarian *et al.* (2022)	Exp. + Mod.	–	0.01–0.70 (λ_{eff})	100	1,000	0.92
Zhu *et al.* (2022)	Mod.	–	0.10–0.42 (λ)	1,139–1,223 (coating) 31–51 (char)	1,200–2,600	0.70 (coating) 0.85 (char)
Lucherini *et al.* (2022) Lucherini *et al.* (2021) Lucherini (2020) Lucherini *et al.* (2019a) Lucherini *et al.* (2019)	Exp. + Mod.	0–35 (d_c/DFT) 0.3–1.8 ($\dot{d}_c$)	0.50 (λ,virgin) 0.05 (λ,char)	1,500 (virgin) 50 (char)	1,300 (virgin) 1,550 (char)	0.86–0.93
Xu *et al.* (2021)	Exp. + Mod.	–	$\lambda_{eff,const}$	–	–	–
Dzolev *et al.* (2021)	Mod.	–	λ_{eff}	200	1,200	0.95
Swann and Stoliarov (2021)	Exp. + Mod.	–	–	1,790 (virgin)	179–2,100	0.70–0.94
de Silva *et al.* (2020)	Mod.	9–33 (d_c/DFT)	0.01–0.04 (λ_{eff})	200	1,200	0.95
Xu *et al.* (2020)	Exp.	0–40 (d_c/DFT)	0.01–0.11 (λ_{eff})	–	–	–
Ma *et al.* (2020)	Mod.	–	0.45 (λ,virgin) 0.20–1.20 (λ) 0.01–0.45 (λ_{eff})	1,600 (virgin) 50 (char)	1,300 (virgin)	0.80
Wang *et al.* (2020)	Exp.	14–52 (d_c/DFT)	0.013–0.030 ($\lambda_{eff,const}$)	–	–	–
Morys *et al.* (2020) Morys *et al.* (2017a) Morys *et al.* (2017b) Morys *et al.* (2017c)	Exp.	18–73 (d_c/DFT)	0.05–60 (λ_{eff}/d_c)	–	–	–

(*continued*)

Table 1.

Source	Study/Data type	d_c/DFT [-] $\dot{d}_c$ [mm/min]	λ [W/mK] R [m^{2}K/W]	ρ [kg/m^3]	c_p [J/kgK]	ε [-] α [-]
Inerhunwa *et al.* (2019)	Exp. + Mod.	–	0.01–0.20 (λ_{eff})	–	–	–
Cirpici *et al.* (2019)	Mod.	–	0.01–0.15 (λ_{eff})	100	1,000	0.92
Kang *et al.* (2019)	Exp. + Mod.	–	1.56 (λ,virgin) 0.08–0.45 (λ_{eff})	2077 (virgin)	1780 (virgin)	0.77
Han *et al.* (2019)	Exp.	7–22 (d_c/DFT)	0.001–0.014 (λ_{eff}) $\lambda_{eff,const}$ (3 stages) - melting: 0.003–0.023 - expanding: 0.001–0.005 - full expansion: 0.002–0.007	–	–	–
Lucherini and Maluk (2019)	Exp. + Mod.	–	0.30–0.50 (λ, virgin)	1,500 (virgin)	1,293–1,860 (virgin)	0.92 (virgin)
Weisheim *et al.* (2019)	Exp. + Mod.	28–44 (d_c/DFT)	0.11–1.40 (λ)	50–1,400	–	0.80
de Silva *et al.* (2019)	Exp. + Mod.	18–32 (d_c/DFT)	0.01–0.05 (λ_{eff})	200	1,200	0.95
Wang *et al.* (2019)	Exp.	9–32 (d_c/DFT)	0.01–0.10 (λ_{eff})	–	–	–
Gillet *et al.* (2019)	Mod.	–	0.12 (λ, virgin) 0.08 (λ, char)	1,000 (virgin) 50 (char)	1,884 (virgin) 1,005 (char)	0.90
Hsu (2018)	Mod.		λ_{eff}	1,500	2000	0.70
Luangtriratana *et al.* (2018)	Exp.	2–26 (d_c/DFT)	0.09–0.53 (λ)	–	–	–
Kang *et al.* (2018)	Exp. + Mod.	5–23 (d_c/DFT) 0.0–0.2 ($\dot{d}_c$)	0.05–0.40 (λ_{app})	–	–	–
Bozzoli *et al.* (2018)	Exp. + Mod.	–	0.25–0.45 (λ_{app})	–	–	–
Lucherini *et al.* (2018)	Exp. + Mod.	10–83 (d_c/DFT)	0.03–0.50 (R_{eff})	1,300	–	0.92
Xu *et al.* (2018)	Exp. + Mod.	10–49 (d_c/DFT)	0.009–0.034 ($\lambda_{eff,const}$)	–	–	–
Kang *et al.* (2017)	Exp. + Mod.	9–11 (d_c/DFT)	0.10–1.60 (λ_{eff})	–	500–7,000	0.77
Tranchard *et al.* (2017)	Mod.	–	0.60–0.80 (λ_{eff}, virgin) 0.10–1.00 (λ_{eff}, char)	1,575 (virgin) 1,165 (char)	700–1,200 (virgin) 900–1700 (char)	–
Li *et al.* (2017)	Exp.	–	0.004–0.051 ($\lambda_{eff,const}$)	–	–	–
Cirpici *et al.* (2016a)	Exp.	10–40 (d_c/DFT)	0.10–1.20 (λ_{app}) 0.01–0.50 (λ_{eff})	–	–	–
Cirpici *et al.* (2016b)	Mod.	16–80 (d_c/DFT)	–	–	–	–

(*continued*)

Source	Study/Data type	d_c/DFT [-] $\dot{d}_c$ [mm/min]	λ [W/mK] R [m^{2}K/W]	ρ [kg/m^3]	c_p [J/kgK]	ε [-] α [-]
Shaumann *et al.* (2016)	Mod.	–	0.45 (λ, virgin) 0.18–1.00 (λ_{eff})	–	100–1,100	0.80
Li *et al.* (2016)	Exp.	–	0.006–0.044 ($\lambda_{eff,const}$)	–	–	0.92
Nadjai *et al.* (2016)	Exp. + Mod.	–	0.01–0.50 (λ_{eff})	1,300	1,000	–
Bilotta *et al.* (2016a)	Exp. + Mod.	–	53.3 (λ, virgin)	200	1,200	0.95
Bilotta *et al.* (2016b)			0.01–0.04 (λ_{eff})			
Kolsek and Cesarek (2015)	Exp. + Mod.	–	λ_{eff}	100	1,000	–
Wang *et al.* (2015)	Exp.	10–24 (d_c/DFT)	0.01–0.12 (λ_{eff})	–	–	–
Elliott *et al.* (2014)	Exp.	19–48 (d_c/DFT)	0.05–0.35 (λ_{eff})	–	–	–
Rush *et al.* (2014)	Exp.	–	0.01–0.15 (λ_{eff})	–	–	–
Dai and Lam (2014)	Exp. + Mod.	–	0.01–0.15 (λ_{eff})	1,300	1,000	–
Dai *et al.* (2010)						
EN 13381-8:2013	–	–	λ_{eff}	100	1,000	–
Gardelle *et al.* (2013)	Exp.	10–34 (d_c/DFT)	0.22–0.50 (λ)	–	–	–
Muller *et al.* (2013)	Exp.	–	0.05–0.45 (λ)	–	–	–
Wang *et al.* (2013)	Exp.	10–46 (d_c/DFT)	0.01–0.20 (λ_{eff})	–	–	–
Gardelle *et al.* (2012)	Exp.	–	0.13–0.35 (λ)	–	–	0.92
Zhang *et al.* (2012a)	Mod.	15–50 (d_c/DFT)	–	1,400	1,884	–
Zhang *et al.* (2012b)						
Li *et al.* (2012)	Exp. + Mod.	–	0.03–0.60 ($R_{eff,const}$)	–	–	0.92
Wang *et al.* (2012)	Exp. + Mod.	10–46 (d_c/DFT)	0.01–0.15 (λ_{eff})	–	–	–
Staggs *et al.* (2012)	Exp. + Mod.	10–12 (d_c/DFT)	0.36 (λ, char) 0.026 (λ, gas) 0.009 (λ, rad)	1,200 (virgin) 1 (gas) 1,186 (char)	1,498 (virgin) 2,170 (gas) 663 (char)	–
Staggs (2010)	Mod.	–	0.10–0.50 (λ_{eff})	–	–	–
Griffin (2010)	Exp. + Mod.	10–60 (d_c/DFT)	0.20–0.24 (λ, virgin) λ (gas)	1,100–1,270 (virgin)	1,500 (virgin)	0.92
Opstad (2010)	Exp. + Mod.	–	0.02–0.08 (λ)	1,600	840	–
Yuan (2009)	Exp. + Mod.	10–60 (d_c/DFT)	0.05–0.50 (λ_{eff})	1,340–1,400	1,884	1.00

(*continued*)

Table 1.

Table 1.

Source	Study/Data type	d_c/DFT [-] $\dot{d}_c$ [mm/min]	λ [W/mK] R [m^{2}K/W]	ρ [kg/m^3]	c_p [J/kgK]	ε [-] α [-]
Gillet *et al.* (2007)	Exp. + Mod.	–	0.12 (λ, coating) 0.024 (λ, gas)	1,000 (coating) 1.5 (gas)	1884 (coating) 1,005 (gas)	1.00
Bartholmai and Schartel (2007) Bartholmai *et al.* (2003)	Exp. + Mod.	–	0.01–0.30 (R_{eff})	1	1	0.95
Omrane *et al.* (2007)	Exp. + Mod.	30–70 (d_c/DFT)	–	1,000	1,000	0.92
Griffin *et al.* (2005)	Exp. + Mod.	5–25 (d_c/DFT)	2–65 (R_{eff}/d)	–	–	–
Wang *et al.* (2005)	Mod.	–	0.01–0.10 (λ_{eff})	1,000	1,000	0.92
Bourbigot *et al.* (1999)	Exp. + Mod.	–	0.60–1.00 (λ)	–	2,800–5,300	–
Anderson *et al.* (1988) Anderson *et al.* (1985)	Exp. + Mod.	2–10 (d_c/DFT)	2.31 (λ, virgin) 0.83 (λ, char)	1,490	840	–
Henderson (1985)	Exp. + Mod.	–	0.70–1.00 (λ, virgin) 0.70–2.00 (λ, char)	1,810 (virgin) 880–1,440 (char)	1,000–1,900 (virgin) 850–1,600 (char) 963 (gas)	0.90

Note(s): Exp. (experimental study), Mod. (modelling study), Exp. + Mod. (experimental and modelling study)
Source(s): Author's own creation

the most relevant and recent scientific publications which involved experimental and theoretical research with significant modelling efforts and/or important results for modelling purposes. In the following sections, the various material properties are singularly analysed and discussed.

3.1 Coating thickness

Intumescent coatings as fire safety measure are specifically characterised by their ability to swell upon sufficient heating and develop a thick high-insulating porous char, able to create a thermal barrier to protect the substrate from temperature-driven consequences. Recent research has highlighted how their performance is primarily governed by their ability to swell and create swelled porous char (Lucherini and Maluk, 2019b). Accordingly, any heat transfer model aimed at simulating the thermo-physical response of fire-exposed intumescent coatings is principally dependent on a correct prediction of the evolution of the swelled coating thickness.

However, the available literature rarely offers research studies in which the evolution of the swelled coating thickness is explicitly predicted and implemented in heat transfer models. The main reason for this is related to the fact that measuring the swelled coating thickness is experimentally challenging and, as a consequence, experimental data are often missing for comparisons between experiments and numerical models. Therefore, research studies often assess the effectiveness of intumescent coatings in an implicit manner, typically by investigating the temperature evolution of coated structural elements. In addition, especially for experiments carried out in closed environments (e.g. furnaces and ovens), researchers often report the final residual coating thickness (e.g. final swelling ratio) (Zhang *et al.*, 2012a, b; Zhang *et al.*, 2012, ; Staggs *et al.*, 2012; Omrane *et al.*, 2007; Wang *et al.*, 2012, 2013, 2015, 2019, 2020; de Silva *et al.*, 2020; Xu *et al.*, 2018, 2020; Han *et al.*, 2019; Lucherini *et al.*, 2018). Nevertheless, this information provides very little understanding on the temporal evolution of the coating thickness.

In absence of any explicit quantification of the transient coating thickness, the main relevant parameter is often used is the initial coating dry film thickness (DFT). This is the case for the Eurocode lumped capacitance method (Annex E of EN 13381-8) that defines an effective value of the coating thermal conductivity based on the initial DFT (EN 13381-8:2013). This method and similar ones are discussed in detail in the following section.

In contrast, a few researchers have developed different experimental methodologies to explicitly measure the temporal evolution of the swelling coating thickness during heating (Lucherini, 2020; Kang *et al.*, 2018; Weisheim *et al.*, 2019; Baena *et al.*, 2023; Li *et al.*, 2023; Lucherini *et al.*, 2019, 2021, 2022, Lucherini and Maluk, 2019a; Morys *et al.*, 2017a, b, c; de Silva *et al.*, 2019; Elliott *et al.*, 2014; Gardelle *et al.*, 2013). These experimental results can support the implementation of heat transfer models in which the coating swelling is explicitly considered. Using finite-difference or finite-element approaches, researchers have attempted to change the coating geometry and/or spatial discretisation by adding nodes (for instance, at the coating-substrate interphase) or by using an adaptive mesh (increasing mesh size, having a fixes number of nodes/elements) (Zhu *et al.*, 2022; Kang *et al.*, 2019; Hsu, 2018; Ogrin *et al.*, 2018; Kang *et al.*, 2017; Cirpici *et al.*, 2016b; Zhang *et al.*, 2012a, b; Staggs *et al.*, 2012; Griffin, 2010; Lucherini *et al.*, 2023; Lucherini and Maluk, 2019a; Wang *et al.*, 2012; Bartholmai and Schartel, 2007). In these models, the coating swelling is usually controlled by defining a final and/or maximum *swelling ratio* (d_c/DFT [-]) or by defining a *swelling rate* ($\dot{d}_c$ [mm/min]), which are usually obtained empirically (Lucherini *et al.*, 2023; Li *et al.*, 2023). This exercise is typically challenging because, as well-known within the research community focused on intumescence, the coating swelling is dependent on many factors (e.g. coating temperature, applied heat flux, initial coating thickness, substrate conditions) (Lucherini and Maluk, 2019b). Indeed, as evident from Table 1, these values can largely vary depending on the testing conditions: in the literature, researchers reported extreme cases, from no swelling to swelling ratios up to 100 times the initial coating dry film thickness (DFT) (Lucherini and Maluk, 2019b).

On the contrary, commercial FEM software do not generally offer the possibility to implement a changing geometry/mesh representing the swelling coating. Thus, approaches that employ a constant geometry (e.g. initial DFT) and effective properties are usually preferred. Moreover, finite-element models often analyse the fire behaviour of whole structure systems or significant parts of it and inserting also the coating thickness as variable could excessively complicate the FEM model. However, in a few cases, researchers have attempted to model swelling intumescent coatings by assigning a temperature-dependent (linear) thermal expansion coefficient to the intumescent coating, along with semi-realistic material properties (Kang *et al.*, 2017; Ma *et al.*, 2020; Weisheim *et al.*, 2019; Shaumann *et al.*, 2016; Cirpici *et al.*, 2019).

3.2 Thermal conductivity and thermal resistance

The main performance criteria for estimating and modelling the insulating capacity of an intumescent coating are usually represented by the quantification of its thermal conductivity. However, since the complex intumescent process simultaneously affects the physical (i.e. thickness and density) and thermal (i.e. thermal conductivity) coating characteristics, it is very challenging to universally define a value of thermal conductivity for swelling intumescent coatings. Consequently, many researchers attempted to evaluate this specific parameter in many different ways and making numerous assumptions and simplifications.

As shown in Table 1, the *effective thermal conductivity* (λ_{eff} [W/mK]) in accordance with the European assessment method (Annex E of EN 13381-8) is the most common way to evaluate the thermal conductivity of intumescent coatings (EN 13381-8:2013; Kang *et al.*, 2019; Hsu, 2018; Kang *et al.*, 2017; Staggs, 2010; Wang *et al.*, 2012; Cirpici and Aydin, 2023; Jafarian *et al.*, 2022; Dai and Lam, 2014; Shaumann *et al.*, 2016; Kolsek and Cesarek, 2015; Dzolev *et al.*, 2021; Cirpici *et al.*, 2019; de Silva *et al.*, 2020; Bilotta *et al.*, 2016a, b; Nadjai *et al.*, 2016; Wang *et al.*, 2023; Xu *et al.*, 2020; Inerhunwa *et al.*, 2019; Han *et al.*, 2019; de Silva *et al.*, 2019; Wang *et al.*, 2019; Cirpici *et al.*, 2016a; Wang *et al.*, 2015; Elliott *et al.*, 2014; Rush *et al.*, 2014; Dai *et al.*, 2010; Wang *et al.*, 2013; Yuan, 2009; Wang *et al.*, 2005). Using this analytical method based on the lumped capacitance approximation of the transient one-dimensional heat conduction problem, the insulating capacity of intumescent coatings is simplified in an effective parameter, which incorporates the coating swelling and any other phenomena that undergo during the intumescent process, such as endo- and exothermic reactions (i.e. melting, pyrolysis, swelling). The methodology is highly simplified, but it enables to accurately reproduce the temperature evolution of the protected samples (i.e. inverse approach from experimental measurements).

Following a similar approach, other researchers proposed the concept of *effective constant thermal conductivity* ($\lambda_{eff,const}$ [W/mK]). They observed that the insulating performance of intumescent coatings for steel structures, expressed in terms of effective thermal conductivity, could be simplified in a temperature-averaged constant value, calculated within the temperature range of interest for the fire-safe design of steel structures (400–600 °C) (Wang *et al.*, 2020; Xu *et al.*, 2018; Li *et al.*, 2016, 2017) As for the effective thermal conductivity, using this constant highly simplifies the design process, but it does not represent any fundamental physical property of the coating. In addition, researchers recommended that, to ensure a safe design using $\lambda_{eff,const}$, a 20% safety factor should be adopted (Li *et al.*, 2017).

In addition, the concept of the effective thermal conductivity underwent further developments based on multi-stage approaches. A first example is represented by the variable function for the effective thermal conductivity based on three stages: before activation phase (below 120 °C), a swelling phase (until when the minimum value of λ_{eff} is reached) and a fully developed char phase (de Silva *et al.*, 2020). Similarly, the effective constant thermal conductivity was defined for one stage (Xu *et al.*, 2018; Li *et al.*, 2016, 2017), or three stages (solid state and melting stage <300 °C, expanding stage 300–400 °C, and full expansion stage >400 °C) (Xu *et al.*, 2020, 2021; Han *et al.*, 2019).

As it is evident from the literature review presented in Table 1, the success of the concept of the effective thermal conductivity produced a large amount of data for the quantification of the effective (constant) thermal conductivity of intumescent coatings. However, its strong simplified approach is reflected by the high variance of the values estimated by various researchers testing different products and using various experimental techniques. Values typically range from 0.50 W/mK to below 0.01 W/mK, even reporting values lower than thermal conductivity of air, questioning the correctness of this approach. Nevertheless, the large amount of experimental data also enabled the possibility to combine experimental results through various regression analyses to define the coating effective thermal conductivity as a function of its temperature and/or other governing parameters (e.g. fire heating rate, initial DFT, section factor) (Staggs, 2010; Kolsek and Cesarek, 2015; de Silva *et al.*, 2020; Li *et al.*, 2017; Cirpici *et al.*, 2016a).

In line with the concept of effective thermal conductivity, other researchers preferred to quantify the effectiveness of intumescent coatings by estimating their *effective thermal resistance* (R_{eff} [m^{2}K/W]), expressed as the ratio between the coating thickness and its thermal conductivity (Bartholmai and Schartel, 2007; Lucherini *et al.*, 2018; Bartholmai *et al.*, 2003). In this way, the combined effect of the coating transformation in thickness (therefore density) and thermal conductivity is lumped in one parameter, and the overall coating performance can be assessed in a unique term. Furthermore, analogously to the effective thermal conductivity, the concept for the *effective constant thermal resistance* ($R_{eff,const}$ [m^{2}K/W]) was also developed (Li *et al.*, 2012). Just in a few cases, the inverse of the thermal resistance or the effective thermal conductivity per thickness ($1/R_{eff} = \lambda_{eff}/d_c$ [W/m^{2}K]) was introduced (Morys *et al.*, 2020).

Contrarily to effective values, other research studies evaluated the *apparent thermal conductivity* (λ_{app} [W/mK]) of intumescent coatings by using an inverse model that considers the actual swelled coating thickness and these calculations are sometimes verified by analysing the in-depth temperatures within the swelled coating (Bozzoli *et al.*, 2018; Kang *et al.*, 2018; Cirpici *et al.*, 2016a). This methodology has been adopted in only a few research studies because of the experimental difficulties in gauging accurate measurements of the in-depth temperature profiles without disturbing the swelling process. In a few cases, the actual *thermal conductivity* (λ [W/mK]) of intumescent coatings (as unique system) was estimated (Zhu *et al.*, 2022; Griffin, 2010; Lucherini *et al.*, 2023; Lucherini and Maluk, 2019a; Luangtriratana *et al.*, 2018; Muller *et al.*, 2013; Gardelle *et al.*, 2012; Opstad, 2010; Bourbigot *et al.*, 1999). Approaches that consider swelling intumescent coatings as multi-material composite are more common in the published literature. In these multi-component models, the intumescent coating is modelled as a porous media composed of a combination of various materials with different properties: these often are the virgin coating or the coating solid skeleton, gas (air) bubbles/cavities and coating char (Staggs *et al.*, 2012; Anderson *et al.*, 1985, 1988; Henderson, 1985; Gillet *et al.*, 2019; Tranchard *et al.*, 2017). For instance, a few researchers adopted a method that estimates the thermal conductivity of intumescent coatings based on an approximated coating porosity (Hsu, 2018; Ma *et al.*, 2020; Weisheim *et al.*, 2019).

It is important to highlight that, differently from effective parameters, using values of apparent thermal conductivity or actual thermal conductivity enables the explicit calculation of the transient temperature gradients within swelled intumescent coatings using simple heat transfer finite-element models.

Finally, only a few research studies supported modelling efforts with experiments primarily focused on quantifying the thermal transport properties of solid materials (e.g. thermal conductivity). In these experiments, the steady-state thermal conductivity of intumescent coatings at various temperature ranges (and corresponding swelling levels) was measured using standard equipment like the transient plate source (TPS) equipment (Lucherini, 2020; Lucherini and Maluk, 2019a; Muller *et al.*, 2013; ISO 22007-2:2015; Gustafsson, 1991) and the Laser Flash Analysis (LFA) equipment (Zhu *et al.*, 2022; Lucherini, 2020; ISO 22007-4:2008; Parker *et al.*, 1961). As show in Table 1, experimental results highlight how the thermal conductivity of virgin intumescent coatings (order of 0.50 W/mK) drastically reduce for swelled coating chars (order of 0.05 W/mK) due to the intumescent process, which significantly affect the volume, therefore density, of the protection material.

3.3 Density

In many of the mentioned heat transfer models and formulations (e.g. effective thermal conductivity), the thermal capacitance of the intumescent coating is typically neglected in comparison with the thermal capacitance of the protected substrate. Since these methods were first developed for metallic structures (e.g. steel), this assumption is usually appropriate, given the high thermal mass of the protected substrate, the limited coating physical thickness (dry film thickness in the order of few millimetres) and low density of swelled intumescent coatings. Consequently, modelling studies rarely explicitly investigate the density and the specific heat capacity of intumescent coatings due to their marginal importance.

As reported in Table 1, the density (ρ [kg/m^3]) of intumescent coating is typically set as a fixed value (e.g. 100 kg/m^3), not based on any physical consideration, since all thermal parameters are assumed as "effective": the thermal conductivity or resistance are the governing parameter, and they are actually varied. This is the case for most analytical methods (e.g. European effective thermal conductivity method) and FEM commercial software.

Rarely, the available literature reports explicit quantification and measurements on the density of intumescent coatings, both on virgin and swelled coatings. This is usually done by simple mass/volume measurements (Lucherini, 2020) or analysing thermo-gravimetric analysis (TGA) experiments (Coats and Refern, 1963; Wagner, 2009). Many researchers, especially in the field of research and development for new intumescent formulations, report and discuss TGA curves, which provide a unique relationship between the coating mass and temperature (Puri and Khanna, 2017; Bourbigot *et al.*, 2004; Zhu *et al.*, 2022; Kang *et al.*, 2017; Griffin, 2010; Griffin *et al.*, 2005; Lucherini, 2020; Weisheim *et al.*, 2019; Shaumann *et al.*, 2016; Baena *et al.*, 2023; Lucherini *et al.*, 2021; Wang *et al.*, 2006, 2020; Morys *et al.*, 2017b; Tranchard *et al.*, 2017). However, to quantify the density, the coating volume remains the challenging aspect, as discussed in Section 3.1.

In general, the literature review suggests that the density of intumescent coatings drastically decreases due to swelling, and it is highly dependent on the coating chemical composition. From values in the range of 1,300–1,500 kg/m^3 for virgin coatings, swelled chars reach values around 30–50 kg/m^3, about 3–4% its initial value considering the significant mass loss due to the thermal decomposition (only about 30–40% inorganic content (Wang *et al.*, 2006)) and the fact that intumescent coatings can swell up to 100 times their initial applied DFT (Lucherini and Maluk, 2019b).

3.4 Specific heat capacity

As discussed for the coating density, the same concept applies to the *specific heat capacity* (c_p [J/kgK]). Due to the marginal importance of the coating thermal capacitance and the challenges related to explicitly quantifying the change in enthalpy of the intumescent coating, fixed values in the range of 1,000 J/kgK are usually defined in most analytical methods (e.g. European effective thermal conductivity method) and FEM commercial software. Again, these values are not based on any physical consideration, and they just act as effective values, only with the purpose of solving simplified heat transfer models.

Following a similar approach as TGA for the coating density, a few researchers attempted to estimate the specific heat capacity of intumescent coatings analysing differential scanning calorimetry (DSC) experiments (Wagner, 2009; O'Neill, 1966). From the heat flow measured by the equipment sensor with respect to a reference sample, the coating specific heat capacity and reaction enthalpies can be quantified, and temperature-dependent functions obtained (Zhu *et al.*, 2022; Swann and Stoliarov, 2021; Kang *et al.*, 2017; Weisheim *et al.*, 2019; Shaumann *et al.*, 2016; Wang *et al.*, 2020; Tranchard *et al.*, 2017). As for the case of TGA, many DSC curves can be found in the available literature, in particular in research and development studies that investigate the thermal stability of novel intumescent formulations.

Similarly to the steady-state thermal conductivity, the literature reports that standard equipment for the quantification of the thermal transport properties of solid materials (e.g. TPS and LFA) can be used also for estimating the (volumetric) specific heat capacity of intumescent coatings (Lucherini, 2020).

In general, as show in Table 1, the literature review suggests that the specific heat capacity of intumescent coatings lays between typical values for solid materials (1,000–1,500 J/kgK) and, most importantly, the enthalpies for the main thermal decomposition reactions occurring in the coating (i.e. melting, swelling and oxidation) have a limited impact (Lucherini and Maluk, 2019b).

3.5 Emissivity and absorptivity

Finally, the optical properties of materials, namely *emissivity* (ε [-]) and *absorptivity* (α [-]), have a key role in thermal radiation and heat transfer, as they govern the radiative heat transfer and heat losses between emitting surfaces, therefore the thermal boundary conditions at the fire-exposed surfaces. Indeed, given the elevated temperatures typical of compartment fires, radiative heat transfer is often the governing mode, and the optical properties have direct consequences on the energy gain and temperatures experienced by construction materials. Especially, this is the case if fire experiments involve pure thermal irradiation (e.g. radiant panels and cone calorimeter), but also radiation-driven heat fluxes are also typical in ovens and furnaces.

For the case of intumescent coatings, analytical models (e.g. European effective thermal conductivity method (EN 13381-8:2013)) usually disregard these parameters because the swelling coating is assumed as thermally thick material, therefore its surface temperature is frequently approximated with the fire gas phase temperature. On the other hand, the optical properties are often required to define the thermal boundary conditions in finite-difference models and commercial FEM software. The absorptivity and emissivity of intumescent coatings are normally considered as interchangeable parameters, following the assumption of grey body (Incropera *et al.*, 2006). They are often assumed as a constant value, defined *a priori* or implicitly obtained through the calibration of numerical models (Kang *et al.*, 2019; Hsu, 2018; Kang *et al.*, 2017; Griffin, 2010; Gillet *et al.*, 2007, 2019; Omrane *et al.*, 2007; Lucherini *et al.*, 2023; Lucherini and Maluk, 2019a; Bartholmai and Schartel, 2007; Jafarian *et al.*, 2022; Weisheim *et al.*, 2019; Shaumann *et al.*, 2016; Dzolev *et al.*, 2021; Cirpici *et al.*, 2019; de Silva *et al.*, 2019, 2020; Bilotta *et al.*, 2016b; Wang *et al.*, 2023; Li *et al.*, 2012, 2016; Gardelle *et al.*, 2012; Bartholmai *et al.*, 2003; Wang *et al.*, 2005; Bourbigot *et al.*, 1999). As shown in Table 1, the absorptivity and the emissivity of intumescent coatings are in the range of typical opaque construction materials, between 0.85 and 0.95, where values in the range 0.90–0.92 are common. Rarely, they decrease to lower values, down to 0.70–0.80 (Swann and Stoliarov, 2021; Kang *et al.*, 2019; Hsu, 2018; Kang *et al.*, 2017; Ma *et al.*, 2020; Shaumann *et al.*, 2016), or they are defined differently for the virgin and charred coating (Zhu *et al.*, 2022; Lucherini, 2020; Lucherini and Maluk, 2019a).

As in the case for all other properties of intumescent coatings, optical properties are rarely experimentally measured using techniques for diffuse reflection and diffuse transmission, for instance by using integrating sphere system. Even more, measuring the reflectivity and absorptivity of solid materials at elevated temperatures is technically very challenging and only a few research studies have been published regarding this topic (Acem *et al.*, 2017; Boulet *et al.*, 2015; Seifer *et al.*, 2011).

A research study attempted to measure the optical properties of virgin and degraded thin intumescent coatings using an integrating sphere system (Lucherini, 2020; Lucherini and Maluk, 2019a). The experiments were carried out in the range of wavelengths for near-infrared and mid-infrared radiations, range that covers most of the total thermal radiation emitted by a typical building fire, usually characterised by high soot content (ISO 20473:2007; SFPE, 2016). The coating reflectivity was estimated in the range 0.07–0.14 and, following the assumptions for opaque materials that act as grey bodies, absorptivity/emissivity in the range 0.86–0.93 (Lucherini, 2020; Lucherini and Maluk, 2019a). All optical properties were assumed independent on the wavelength and averaged over the tested range, and all measurements were conducted on the coating samples at ambient temperature on virgin/degraded coatings. As a consequence, the influence of different degradation levels at the coating surface was investigated and the obtained properties were considered as “residual,” affected by the thermal exposure, but not the actual one at elevated temperatures.

4. Discussion

The presented literature review highlighted how many modelling approaches have been developed to describe and predict the complex thermo-physical behaviour of swelling intumescent coatings for the fire protection of various substrate materials. Along with this, a wide of thermal, physical, and optical properties have been defined and estimated to quantify various material properties necessary to study heat transfer problems within intumescent coatings. Apart from the many formulations and large variability ranges for many parameters, it was underlined how the coating properties are defined as constant or temperature-dependent: this assumes that the thermo-physical response of intumescent coatings is only affected by temperature, and it is independent of all other factors. However, despite the well-known important influence of other factors on the intumescent coatings’ performance, other affecting parameters in the definition of the material properties are rarely considered. For example, in many of the discussed cases, the coating insulating properties are estimated only considering standard testing conditions (Wang *et al.*, 2012, 2013, 2020; Jafarian *et al.*, 2022; Dai and Lam, 2014; Šejna *et al.*, 2023; Shaumann *et al.*, 2016; Kolsek and Cesarek, 2015; Nadjai *et al.*, 2016; Wang *et al.*, 2023; Inerhunwa *et al.*, 2019; Li *et al.*, 2016; Bilotta *et al.*, 2016b; Rush *et al.*, 2014; Dai *et al.*, 2010). In contrast, only a few modelling studies explicitly take into account the effect of various conditions (e.g. substrate, initial thickness, fire conditions) on the effectiveness of intumescent coatings, for instance in the quantification of the temperature-dependent effective thermal conductivity (Staggs, 2010; Kolsek and Cesarek, 2015; de Silva *et al.*, 2020; Li *et al.*, 2017; Cirpici *et al.*, 2016a).

The research and fire safety engineering communities are in need of a universal simple, rather than complex, model that can generally simulate the performance of intumescent coatings. Given the high complexity of the intumescent reaction and the many influencing parameters, empirical approaches like the effective thermal conductivity appear as the way to proceed. The approach is rather simple, and it enables the correct prediction of the temperature evolution of intumescent-coated substrates, disregarding any heat transfer consideration (e.g. swelled coating thickness and in-depth temperature profiles). The approach is also suitable for commercial FEM software.

However, the approach requires to be deeply researched and generalised for the vast variety of available commercial products and potential conditions. By analysing the numerous recently-published literature reviews (Lucherini and Maluk, 2019b; Dreyer *et al.*, 2021; Puri and Khanna, 2017; Mariappan, 2016; Weil, 2011; Bourbigot *et al.*, 2004), it is possible to see how many coatings, substrates, heating/fire and external factors affect the insulating effectiveness of intumescent coatings (refer to Table 2). The numerous research studies published in the last few decades should be combined, profoundly compared to achieve an overall understanding on the response of intumescent coatings as fire protection measure. This analysis should be also linked and supported by more detailed and fundamental studies (Hsu, 2018; Kang *et al.*, 2017; Griffin, 2010; Lucherini *et al.*, 2021), as well as new research studies focused on comprehending unresolved issues related to intumescent coatings (e.g. behaviour in natural fires, long-term durability, physical hindered swelling). Thanks to the increasingly-available computational power, advanced computational tools can also be employed, for instance involving machine learning techniques (e.g. deep neural networks). These modern methods can offer innovative ways to combine large amounts of existing data and produce highly reliable models to predict the thermal behaviour of swelling intumescent coatings. These techniques would also offer important advantages in the treatment of uncertainties of various natures (e.g. approach-specific, numerical, experimental, etc.) and possibly enable optimisation processes (Samaniego *et al.*, 2020).

As an outcome, a universal modelling approach should be generalised and regulated. In particular, clear guidelines should be produced for fire safety engineers, in which rules and suggestions related to the modelling of intumescent coatings are explained. Of key importance, the uncertainties related to each technique and estimated material property should be made it explicit and careful treated, in away such to provide a clear understanding on the reliability of the various proposed design methodologies. In addition, the analysis and combination of the published research should provide information related to the potential challenges related to modelling swelling intumescent coatings and how to produce safe designs. Indeed, nowadays, in many projects which involve performance-based design approaches, intumescent coatings are sometimes not selected as appropriate fire protection solution due to the limited modelling capabilities, the large uncertainties, and the discomfort of fire safety engineers around this topic, still facing significant investments, compared to traditional fire protection solutions (e.g. boards).

Coating	Substrate	Heating/Fire	External
• Intumescent formulation • Composite components (e.g. primer and topcoat) • Initial thickness (Dry Film Thickness – DFT)	• Boundary conditions (thermo-physical properties) • Shape (concave vs convex edges, holes)	• Heat fluxes, heating rate, temperatures • Oxygen content • Turbulence and convective flows • Physical obstructions • Gravity	• Physical damages • Exposure environment (i.e. ageing, weathering, aggressive environments) and long-term durability

Source(s): Author's own creation

Table 2.
Main factors affecting the effectiveness of intumescent coatings

5. Conclusions

The presented literature review analyses and discusses the various modelling approaches to describe and predict the behaviour of swelling intumescent coatings as fire protection for structural materials, such as steel. Due to their reactive behaviour, intumescent coatings are a particularly complex material to be modelled and predicted because of the many influencing parameters and the challenges related to the definition and quantification of their thermal, physical and optical properties. The study underlines the most critical modelling aspects and suggests where further research is needed.

From the analyses of the available modelling approaches, a countless amount of mathematical and numerical models of various complexities was found. However, a universal simple, rather than complex model that can simulate the performance of intumescent coatings has not yet been developed or it has not been generalised for a wide range of products and testing conditions.

Most available models are based on the assumption that the coating properties are defined as constant or temperature-dependent only, while only few works consider the important influence of other factors on the material properties (e.g. substrate, initial thickness, fire conditions). In addition, the majority of the reviewed models have many uncertainties related to the input parameters and material properties. This is the case for empirical models, in which many parameters are highly case-dependent, also given the vast variety of available commercial intumescent products and their very sensitive performance to many conditions. Similarly, FEM software typically only solve simplified conductive heat transfer problems for inert materials (fixed geometry), and they rely on several simplifications. As a consequence, all these models must be used with great care and critical eye, and numerical predictions should always be supported by experimental evidence.

As regards to the definition and quantification of the material properties of swelling intumescent coatings, the available literature rarely offers research studies in which the evolution of the swelled coating thickness is explicitly predicted and implemented in heat transfer models. This is mainly related to the fact that instantly measuring the coating thickness is experimentally challenging and, consequently, experimental data are often missing for comparisons. Similarly, thermal, physical, and optical properties of swelling intumescent coatings are rarely experimentally measured using dedicated techniques (e.g. thermal transport equipment for thermal conductivity).

As a consequence, most of the research studies suggest the use of effective properties based on well-known initial parameters, like the concept of effective thermal conductivity based on the initial dry film thickness (DFT) of the virgin coating. In this way, extensive experimental research has produced a large amount of data for the quantification of effective properties of intumescent coatings. However, due to the vast variety of available commercial products and potential testing conditions, these data are rarely compared and combined to achieve an overall understanding on the response of intumescent coatings as fire protection measure.

In conclusion, the research and fire safety engineering communities are in need of a universal modelling tool that can generally simulate the performance of intumescent coatings and reliably produce fire-safe performance-based designs. As an outcome, an engineering approach should be extended and regulated, supported by comprehensive and thorough comparisons and combinations of all the research efforts made during the last decades.

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