Modeling of intumescent coatings growth : simulations from lab-scale to the large one

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Background

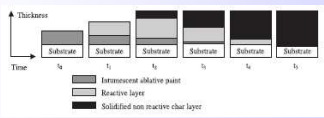
- In military applications, intumescent paints are commonly used as an IM technology to protect the munitions against fires (increasing the reaction time)
- Up to now plenty of experimental data but few numerical studies have been carried out to calculate heat transfer in the intumescent coated munitions

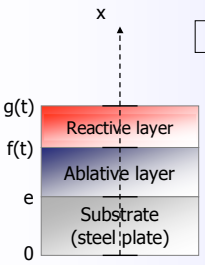
Main Objectives

- To accurately calculate heat transfer in the intumescent coated munitions
- To predict the reaction time when coated munitions are faced with thermal aggressions such as fuel fires
- To get validated models **from lab scale to the large one**

1D modeling of intumescent coatings growth under high flux

Steps of the intumescent process under radiative heat flux





Thermal modeling

$$\rho_{gr} C_{gr} \frac{\partial \theta(x,t)}{\partial t} - \lambda_{gr} \Delta\theta(x,t) = 0$$

$$\text{If } \theta(x,t) < \theta_{ins} \quad \begin{Bmatrix} \rho_{gr} \\ C_{gr} \\ \lambda_{gr} \end{Bmatrix} = \begin{Bmatrix} \rho_{ins} \\ C_{ins} \\ \lambda_{ins} \end{Bmatrix}$$

$$\text{If } \theta(x,t) \geq \theta_{ins} \quad \begin{Bmatrix} \rho_{gr} \\ C_{gr} \\ \lambda_{gr} \end{Bmatrix} = \begin{Bmatrix} \rho_{char} \\ C_{char} \\ \lambda_{char} \end{Bmatrix}$$

$$\rho_{ablat} C_{ablat} \frac{\partial \theta(x,t)}{\partial t} - \lambda_{ablat} \Delta\theta(x,t) = -\rho_{ablat}\, \kappa(\theta(x,t))\, H_v$$

$$\kappa(\theta(x,t)) = \begin{cases} A\exp\left(-\dfrac{E}{R\theta(x,t)}\right) & \text{if } \theta(x,t) \geq \theta_v \\ 0 & \text{else} \end{cases}$$

$$\rho_{steel} C_{steel} \frac{\partial \theta(x,t)}{\partial t} - \lambda_{steel} \Delta\theta(x,t) = 0$$

Moving boundaries modeling

$$\dot{f} = \frac{df(t)}{dt} = -\int_0^{f(t)} \kappa(\theta(x,t))\,dx \quad \text{and} \quad \dot{g} = k_g \dot{f} \quad \text{with } k_g < -1$$

Boundary and initial conditions

$$x = g(t) \qquad -\lambda_{gr} \frac{\partial \theta(x,t)}{\partial x} = h(\theta(x,t) - \theta_{ext}) + \varepsilon_{gr}\sigma(\theta^4(x,t) - \theta_{ext}^4) - \alpha_{gr}\Phi(t) \qquad \text{(Irradiated face)}$$

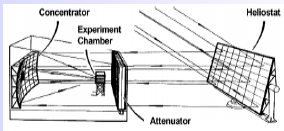
$$x = 0 \qquad \lambda_{steel} \frac{\partial \theta(0,t)}{\partial x} = h(\theta(0,t) - \theta_{ext}) + \varepsilon_{steel}\sigma(\theta^4(0,t) - \theta_{ext}^4) \qquad \text{(Back face)}$$

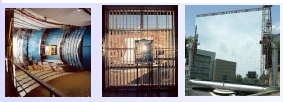
Flux and temperature continuity at the interfaces

Initial conditions : at $t = 0$ $\quad \theta(x,0) = \theta_{ext} \quad f(0) = e_p + e \quad$ and $\quad g(0) = f(0)$

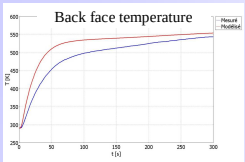
Test results and validation of the 1D model

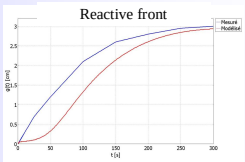
Test facilities in Odeillo: the Main Solar Furnace (a 45 kW furnace with adjustable flux)





Experimental test setup

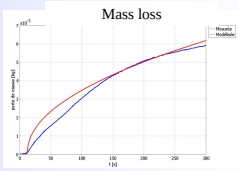




Intumescent painting: 1 mm thick

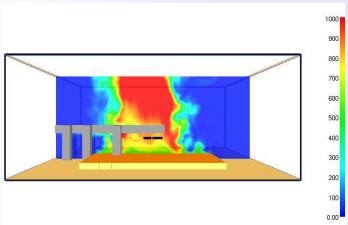
Steel plate: 2 mm thick

Incident heat flux: 170 kW/m²



Upgrading the 1D model to a 3 dimensional domain

Liquid Fuel Fire Simulation



Liquid Fuel Fire Test Facilities at CAEPE

Comparison of results

Motor Type	Experimental Reaction Time (s)	Computed Reaction Time (s)
Motor 1 *not intumescent coated*	1min37s	1min40s
Motor 2 *0,3 mm intumescent coated*	2min24s	2min32s
Motor 3 *2 mm intumescent coated*	4min18s	4min25s

Numerical simulation of a large scale standard liquid fuel fire test (STANAG 4240 ed.2) using Fire Dynamics Simulator (NIST)

Intumescent coatings taken into account for these large scale simulations

⇨ **To predict the reaction time of an intumescent coated Solid Rocket Motor**

Conclusion & Future Works

- Effect of ageing on intumescent coatings efficiency
- Numerical efforts on 2D and 3D modeling of intumescent coatings
- Experimental investigation about intumescent painting efficiency when deposed on composite materials

References

[1] Mathieu Gillet « Analyse de systèmes intumescents sous haut flux : Modélisation et identification paramétrique », phD Thesis, Angers University (2009)

[2] K. McGrattan et al., NIST Publication (2004).