Numerical investigation of the ignition delay time in black PMMA at high heat fluxes

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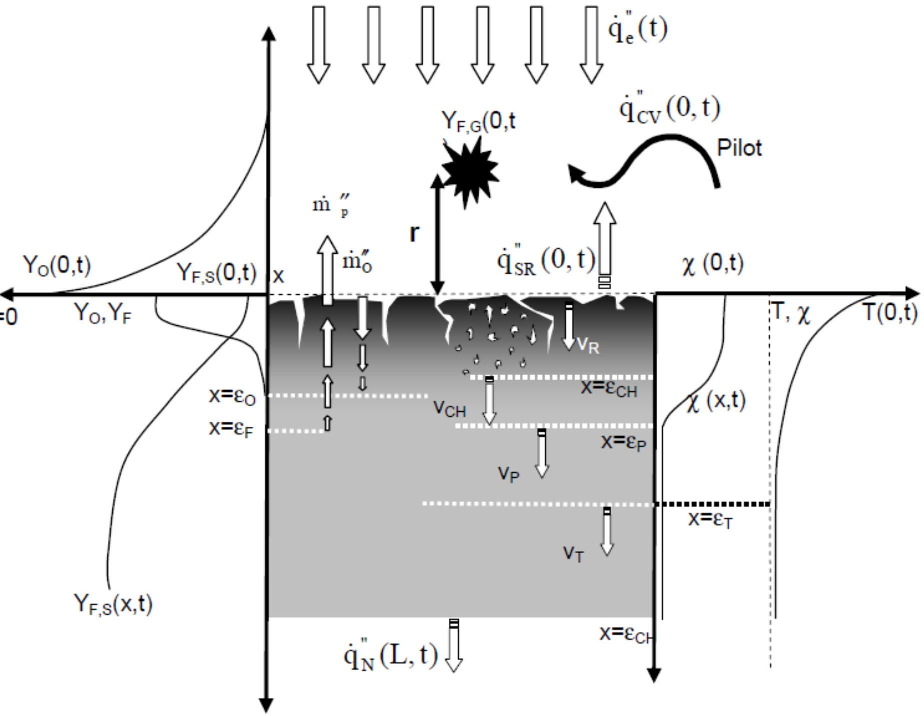
Solid ignition: black PMMA samples

Solid ignition = f(Many parameters)



Classical ignition theory:

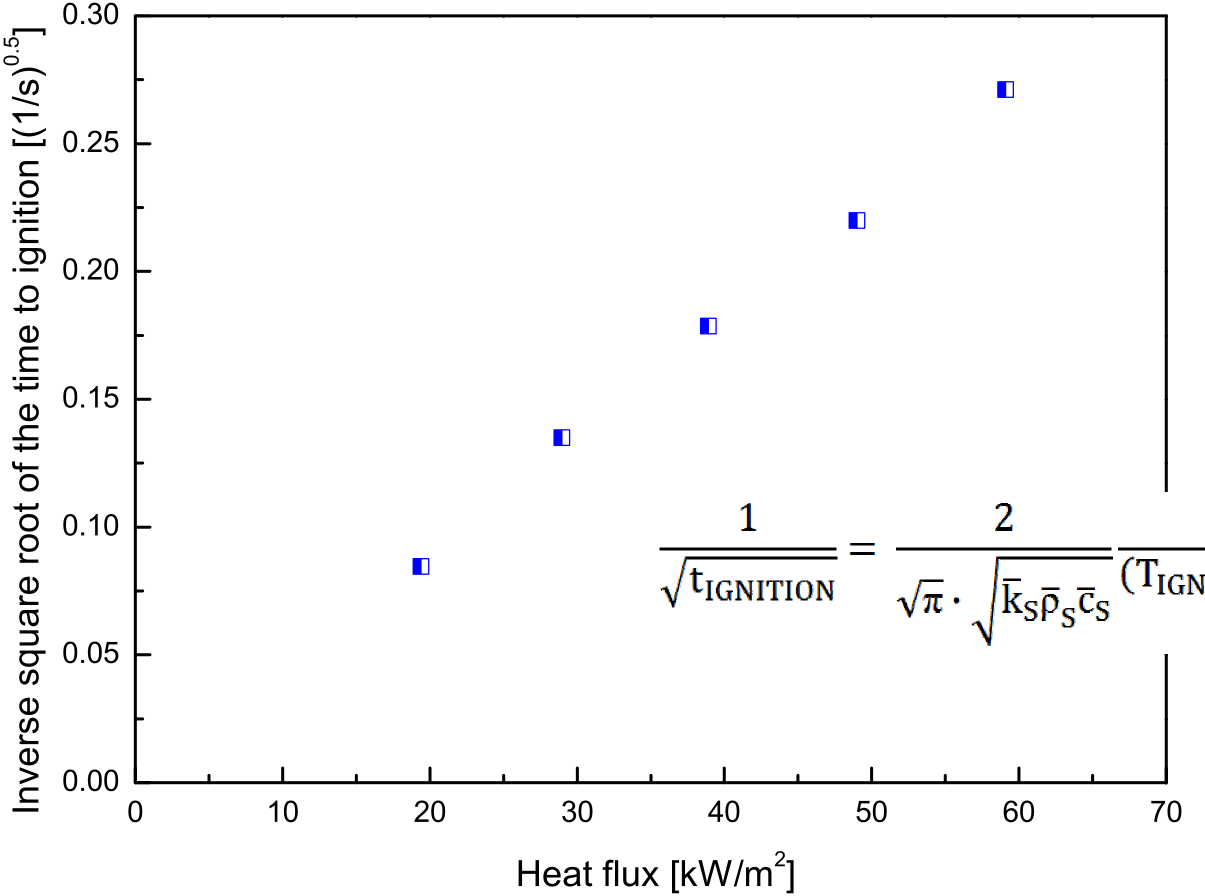
Main assumptions:

- Inert solid up to ignition;
- Surface temperature as ignition criterion;
- Material properties are temperature independent;
- Absorption of the radiation at the surface;
- Solid sample behaves as semi-infinite;
- …

$$\frac{1}{\sqrt{t_{IGNITION}}} = \frac{2}{\sqrt{\pi}\cdot\sqrt{\bar{k}_S\bar{\rho}_S\bar{c}_S}}\frac{\dot{q}_e''}{(T_{IGNITION} - T_{ambient})}$$

Ignition delay time for black PMMA samples

$$\frac{1}{\sqrt{t_{IGNITION}}}$$



$$\frac{1}{\sqrt{t_{IGNITION}}} = \frac{2}{\sqrt{\pi}\cdot\sqrt{\bar{k}_S\bar{\rho}_S\bar{c}_S}}\frac{\dot{q}''_e}{(T_{IGNITION} - T_{ambient})}$$

Ignition delay time

$$\frac{1}{\sqrt{t_{IGNITION}}}$$

Delay to ignition

WHY

?

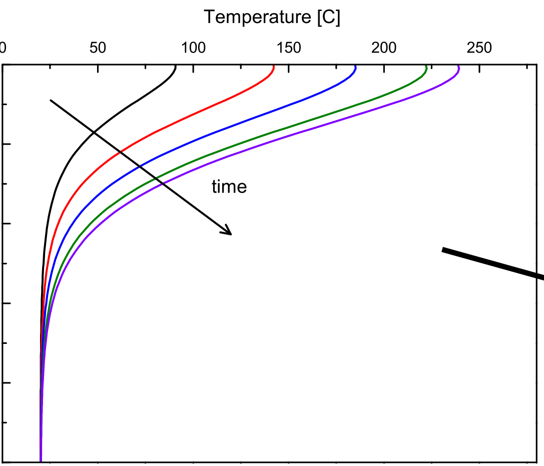
$$t_{ign}^{Experimental} \neq t_{ign}^{Classical\ theory}$$

$\dot{q}_e$

Pyrolysis model

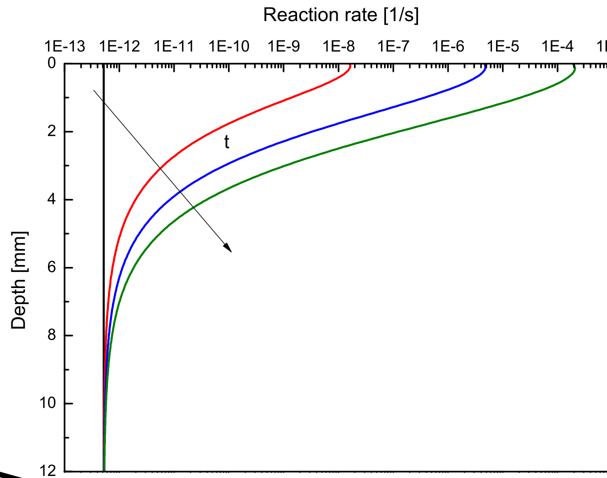
Heat transfer

$$\rho c\frac{\partial T(y,t)}{\partial t} = k\frac{\partial^2 T(y,t)}{\partial x^2} + (1-r)(1-\gamma)\dot{q}_e \kappa \exp(-\kappa y)$$



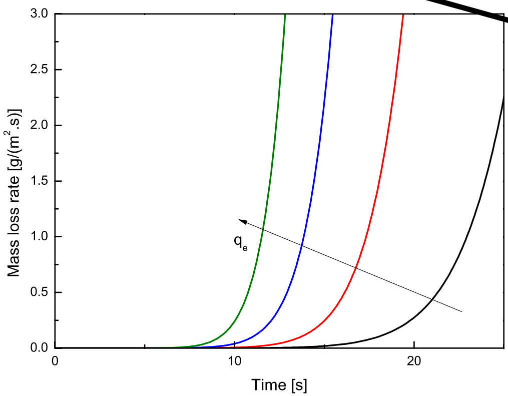
Pyrolysis reaction

$$PMMA \rightarrow \upsilon_{MMA} MMA + (1-\upsilon_{MMA}) residu$$



$$\dot{w}_{GAS} = \frac{dw_{GAS}}{dt} = A\exp\left(\frac{-E}{RT(x,t)}\right) w_{GAS}^n$$

$$\dot{m}'' = \rho \int_{y=0}^{y=L} \dot{w}_{GAS} dy$$



~~ΔH_g~~

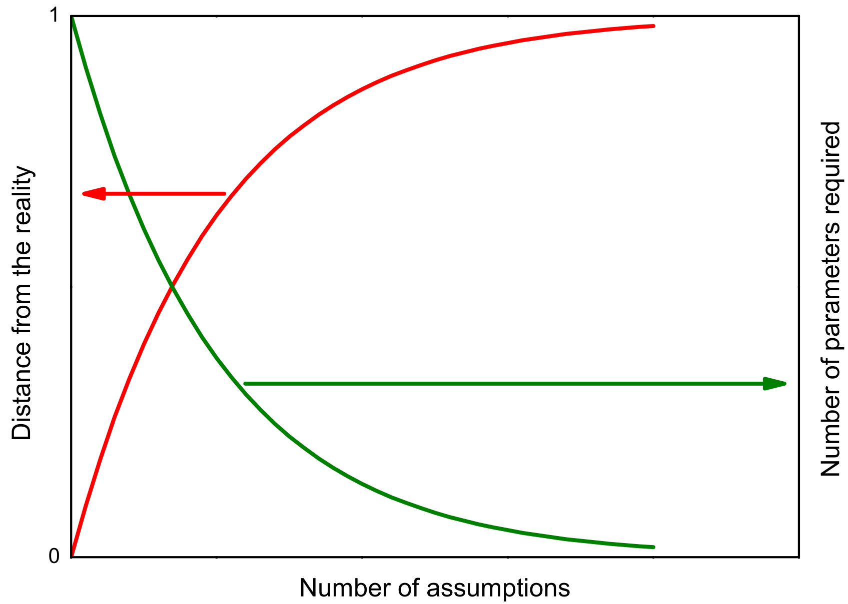
Error:

40 kW/m² => 10%

200 kW/m² => 2%

Why develope a new pyrolysis model?

Excessive Simplicity?



Disproportionate Complexity?

What is the minimum set of mechanisms that explains the experimental observations?

Comparison assumption

Classical theory

Inert solid up to ignition;

Surface temperature as ignition criterion;

Absorption of the radiation at the surface;

Solid sample behaves as semi-infinite;

Material properties are temperature independent;

Heat losses combined in a total heat transfer coefficient;

Pyrolysis model

Pyrolysis reaction controlled by $\{A;E\}_{SOLID}$;

Mass flux criterion;

In-depth radiation absorption possible;

Solid sample behaves as semi-infinite;

Material properties are temperature independent;

Pyrolysis gases flow well out of the sample;

Endothermic contribution from pyrolysis reaction ignored ;

Oxidation reaction ignored;

Mechanism responsible for the ignition delay at high heat fluxes

Kinetics, heat losses and critical mass flux

Reaction scheme

$$t_{ign}^{Experimental} \neq t_{ign}^{Classical\ theory}$$

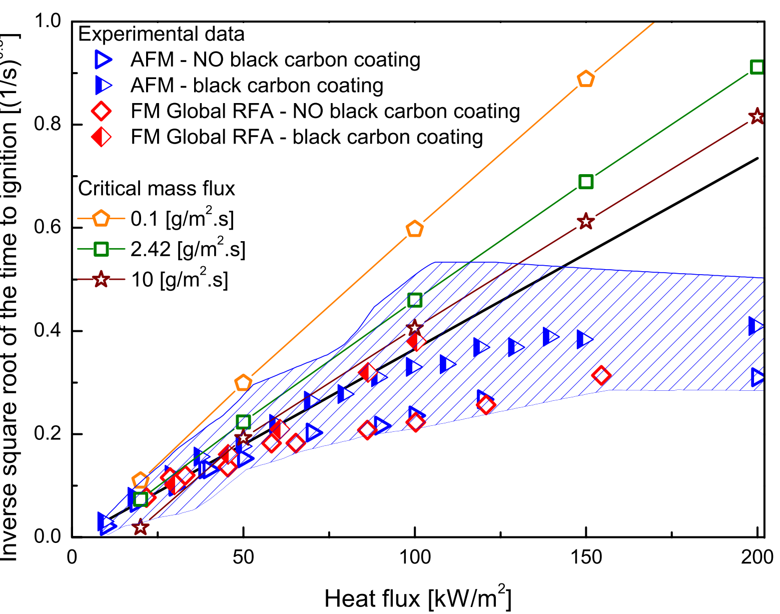
temperature dependency of the material properties

In-depth radiation absorption

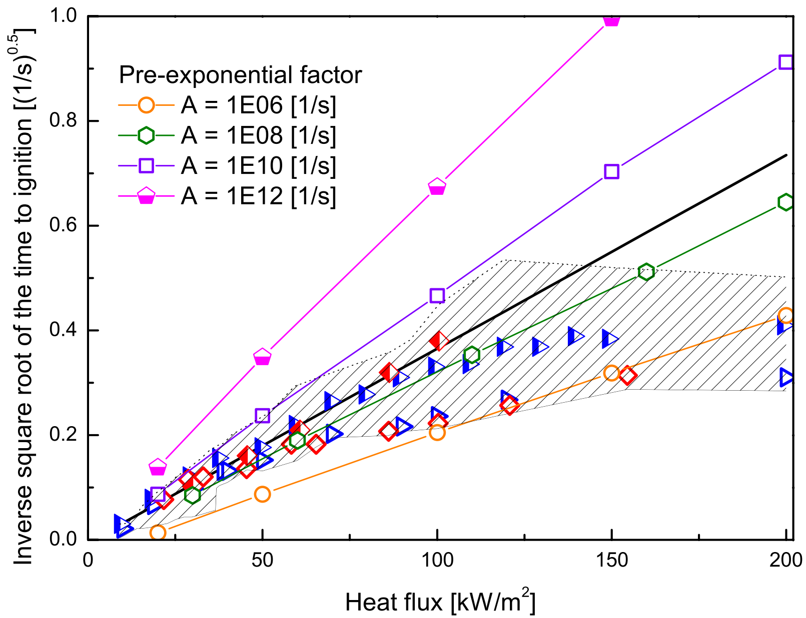
Mechanism responsible for the ignition delay at high heat fluxes

Kinetics, heat losses and critical mass flux

$\dot{m}_{critical}\ [g/(m^2.s)]$



$A\ [1/s]$



Mechanism responsible for the ignition delay at high heat fluxes

Reaction scheme

ne step:

$$MMA \rightarrow \upsilon_{MMA}MMA + (1 - \upsilon_{MMA})residue$$

vo steps reaction:

nsecutive

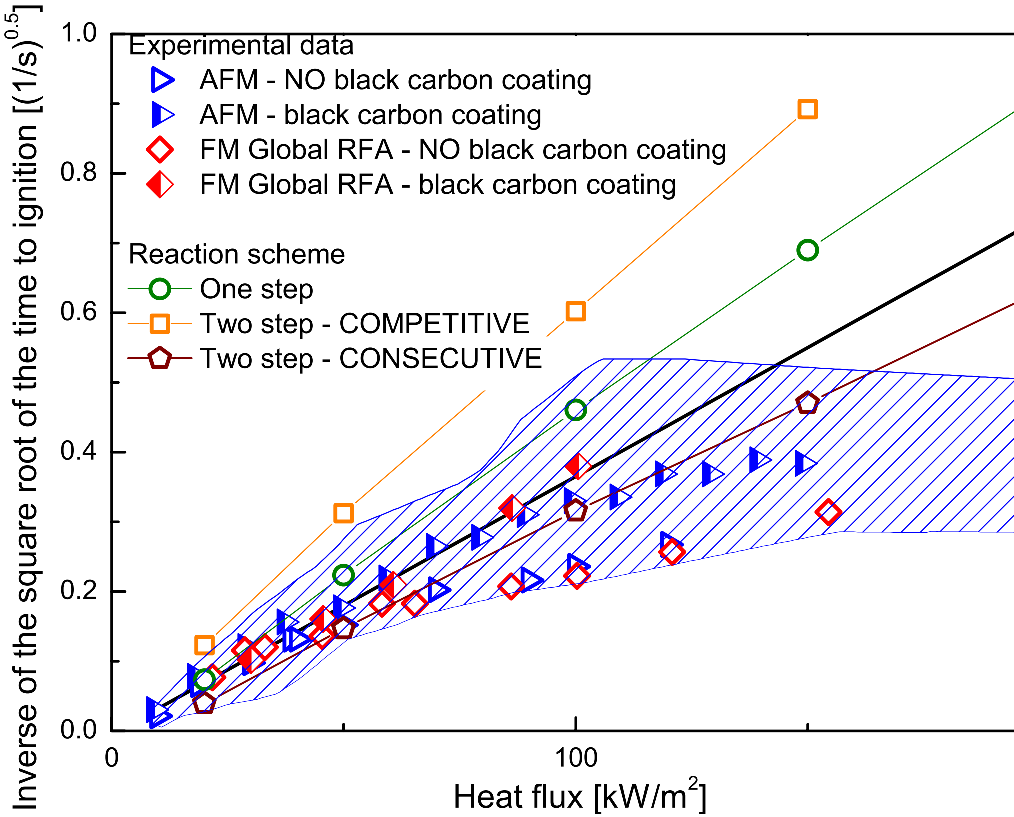
$$MMA \rightarrow \beta - PMMA$$

$$- PMMA \rightarrow \upsilon_{MMA}MMA + (1 - \upsilon_{MMA})residue$$

mpetitive

$$MMA \rightarrow \beta - PMMA$$

$$MMA \rightarrow \upsilon_{MMA}MMA + (1 - \upsilon_{MMA})residue$$

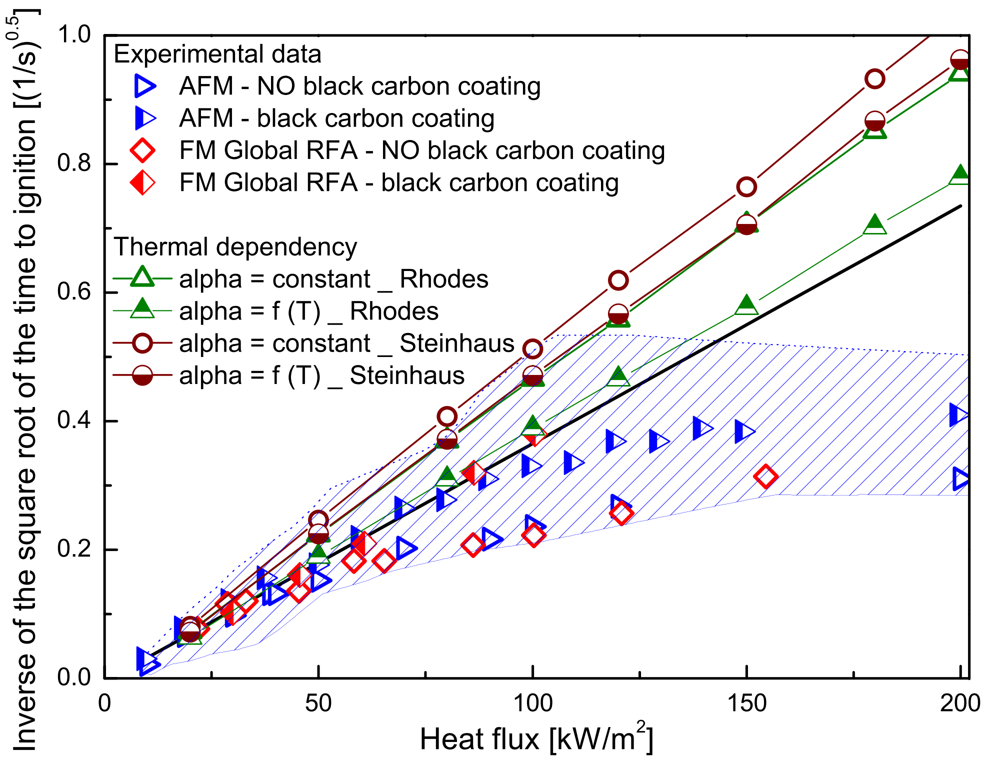


Mechanism responsible for the ignition delay at high heat fluxes

temperature dependency of the material properties

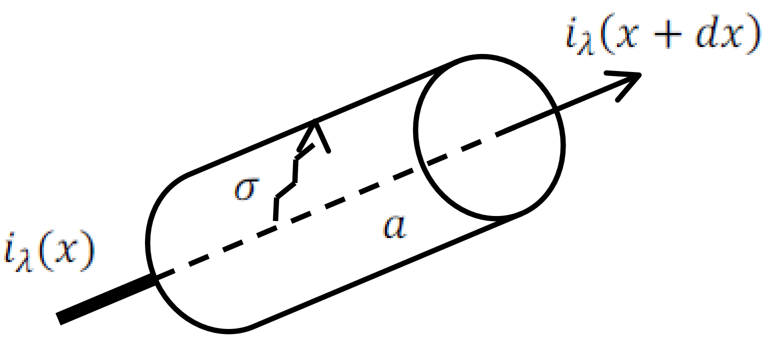
$$k\rho c = f(T)$$

Rhodes   Steinhaus



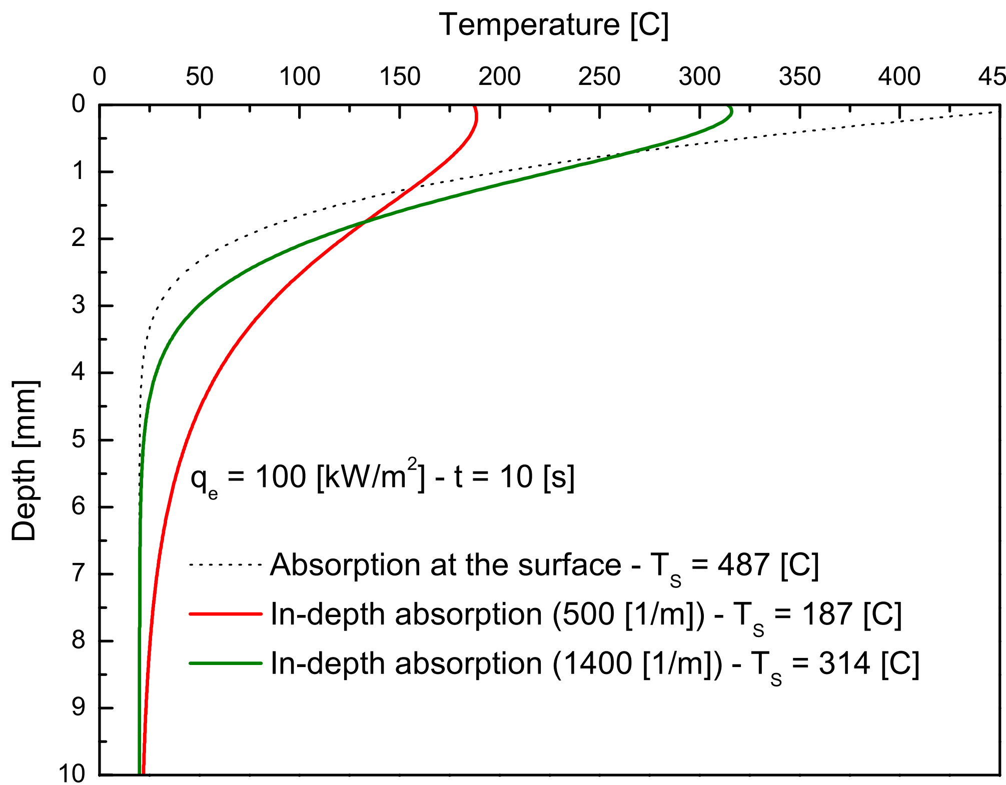
Mechanism responsible for the ignition delay at high heat fluxes

In-depth radiation absorption



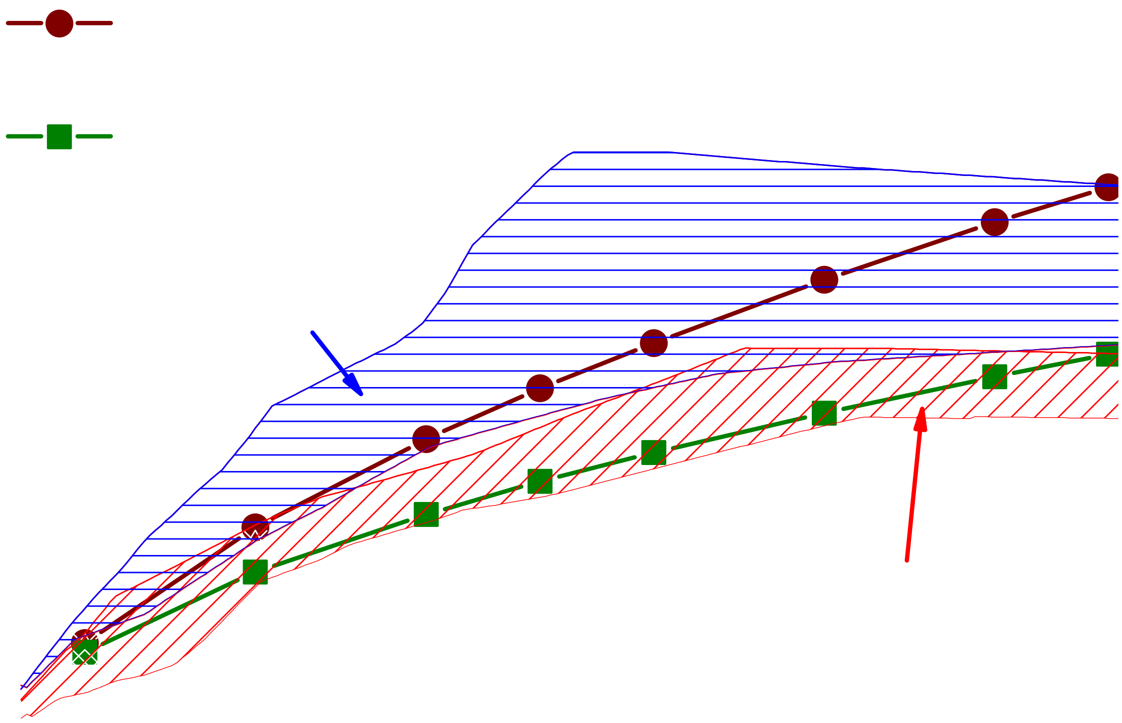
$$\kappa_{(\lambda,T,P)} = a_{(\lambda,T,P)} + \sigma_{(\lambda,T,P)}$$

$$\dot{q}'''_{absorbed} = \dot{q}''_{incident}\ \kappa\ exp(-\kappa\ x)$$



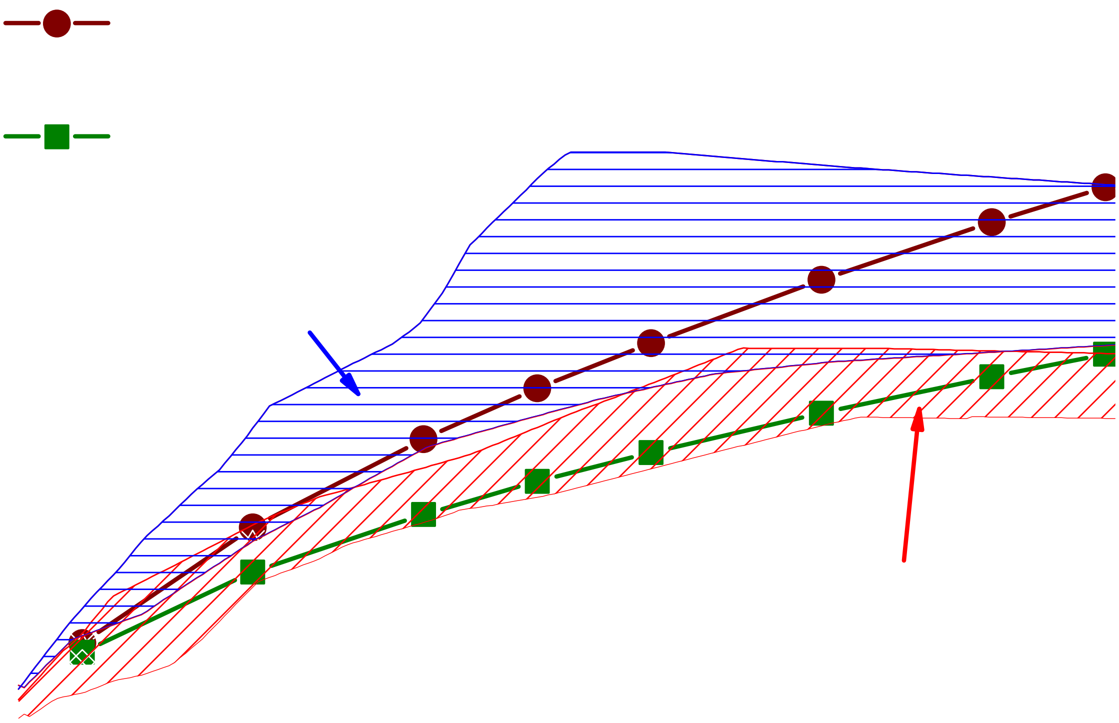
Mechanism responsible for the ignition delay at high heat fluxes

In-depth radiation absorption



Impact of the black carbon coating

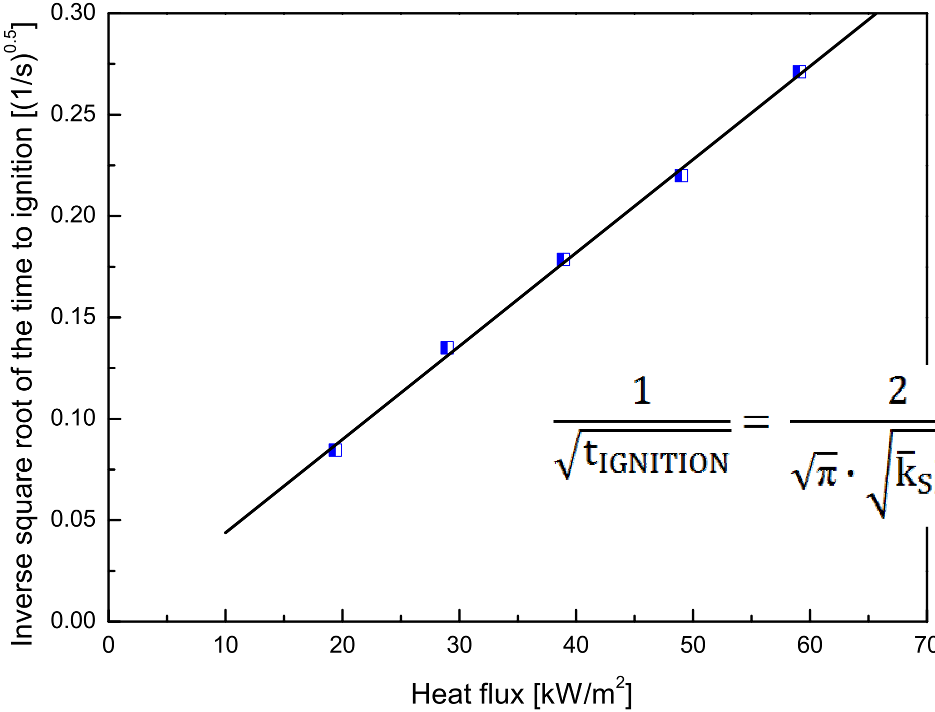
κ: 500 [1/m] → 1400 [1/m]



Temperature profiles

CONCLUSION AND SCOPE OF PROGRESS

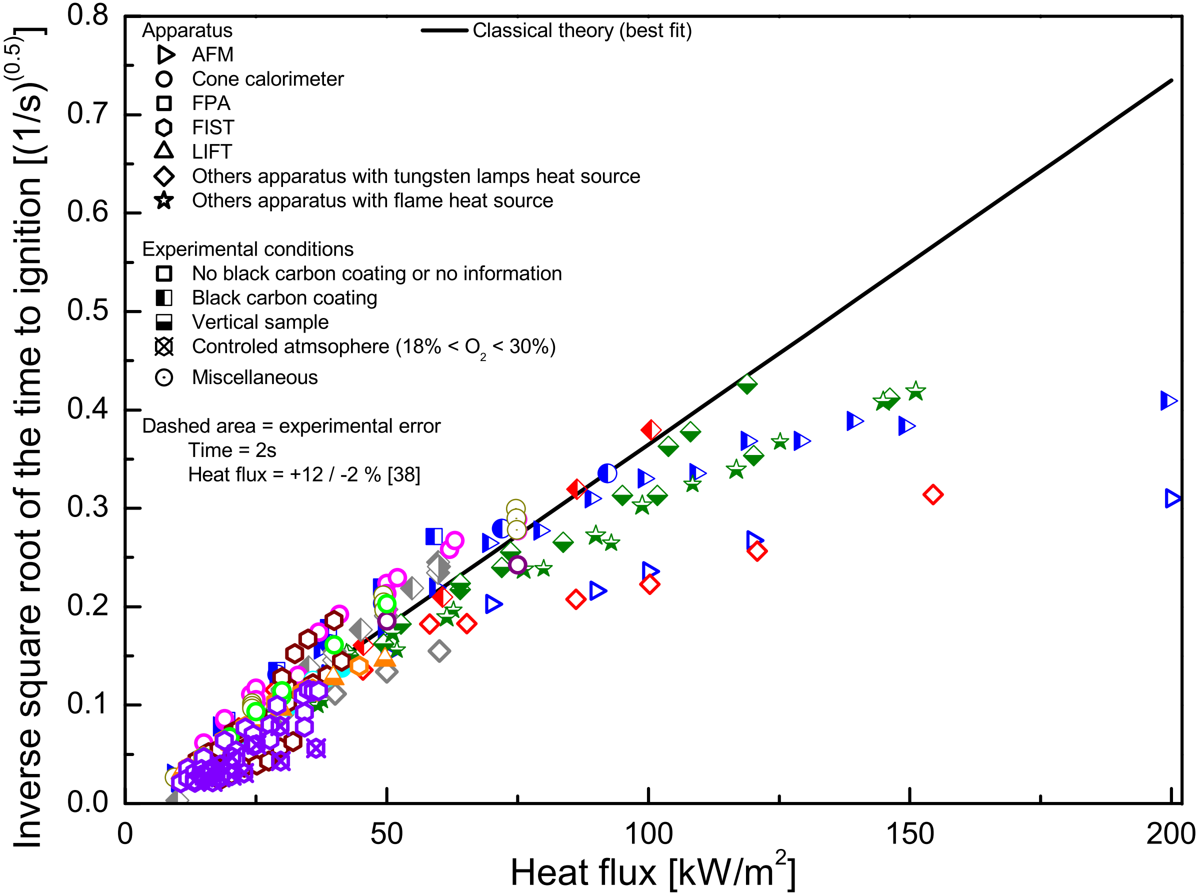
Time to ignition measurements match perfectly with the classical theory up to 50 -60 kW/m² for black PMMA samples.



$$\frac{1}{\sqrt{t_{IGNITION}}} = \frac{2}{\sqrt{\pi} \cdot \sqrt{\bar{k}_S \bar{\rho}_S \bar{c}_S}} \frac{\dot{q}_e''}{(T_{IGNITION} - T_{ambient})}$$

CONCLUSION AND SCOPE OF PROGRESS

For heat fluxes higher than 70 kW/m², a delay is observed in comparison with the classical ignition theory prediction.

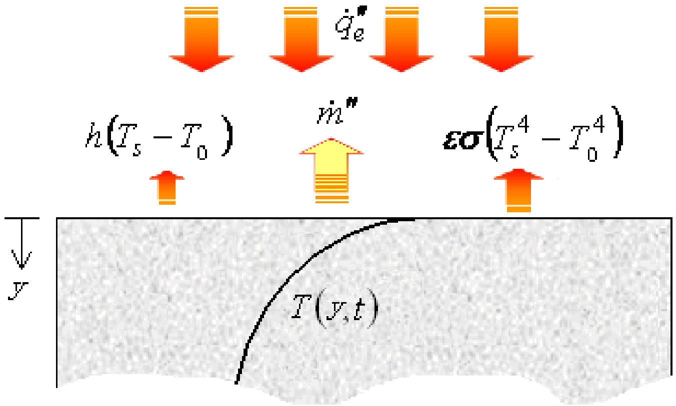


CONCLUSION AND SCOPE OF PROGRESS

A simple pyrolysis model was developed

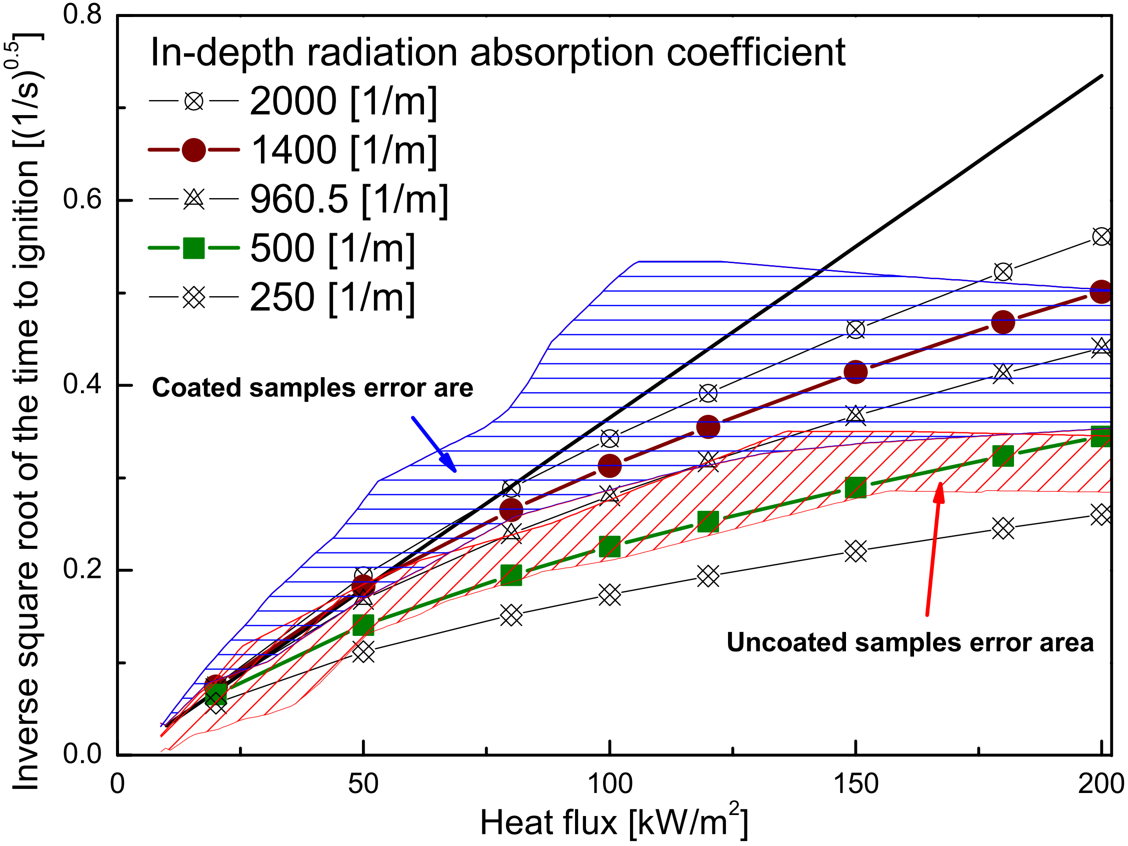
Main assumption:

SIMPLIFICATIONS ARE REQUIRED WHERE THE PRECISION DOES NOT WARRANT THE INCLUSION OF HIGHER LEVELS OF COMPLEXITY



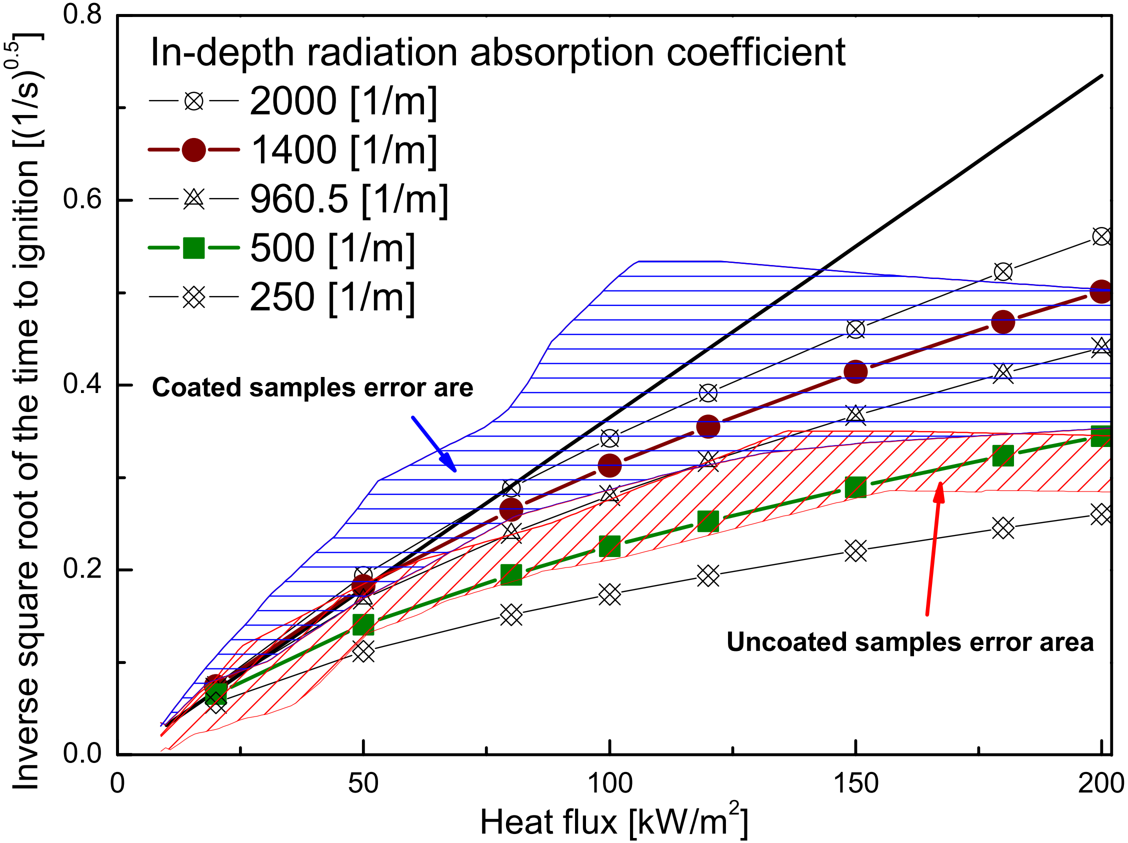
CONCLUSION AND SCOPE OF PROGRESS

The only mechanism which enables to describe the delay on the classical theory prediction was the in-depth radiation absorption.

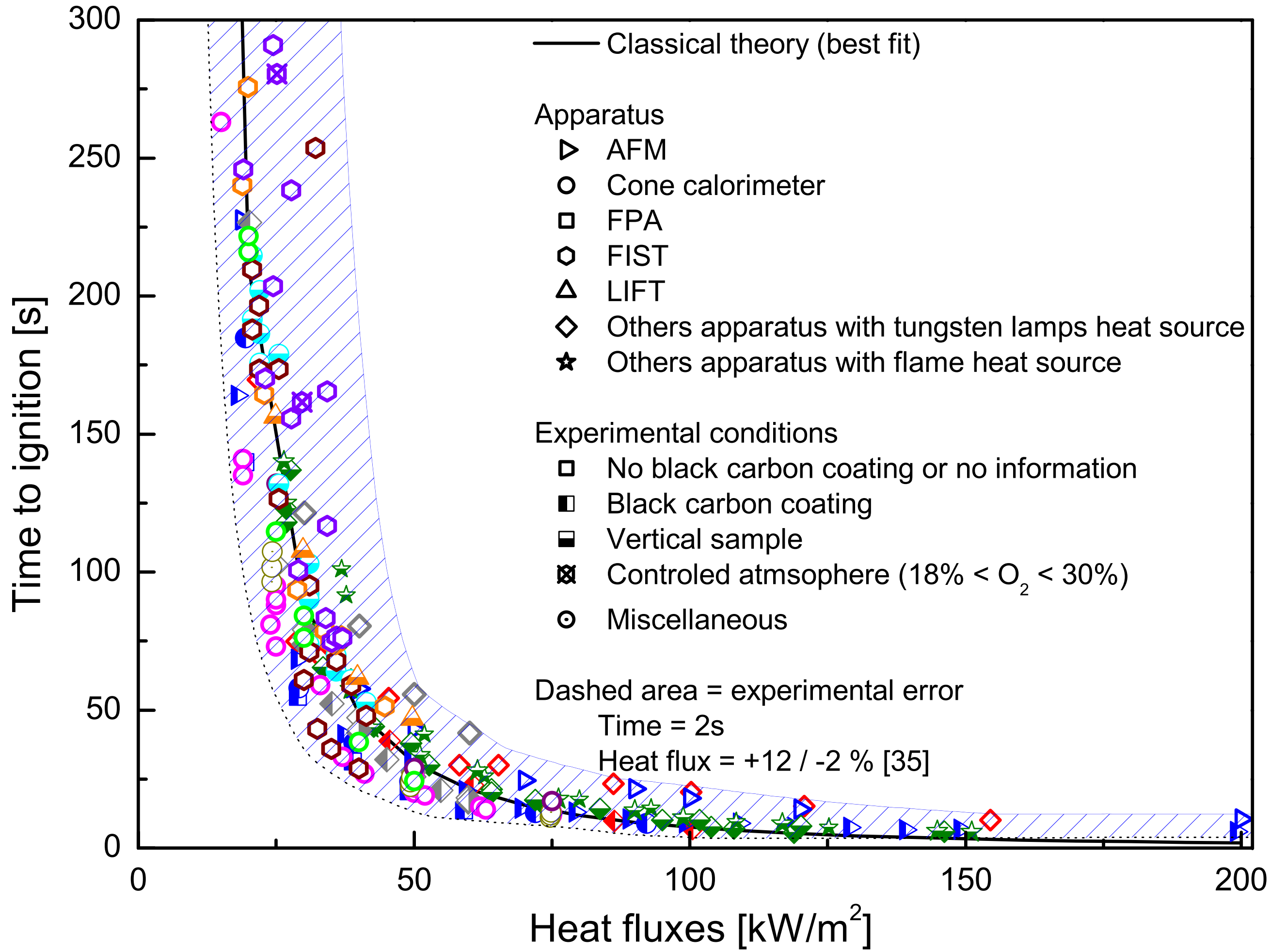


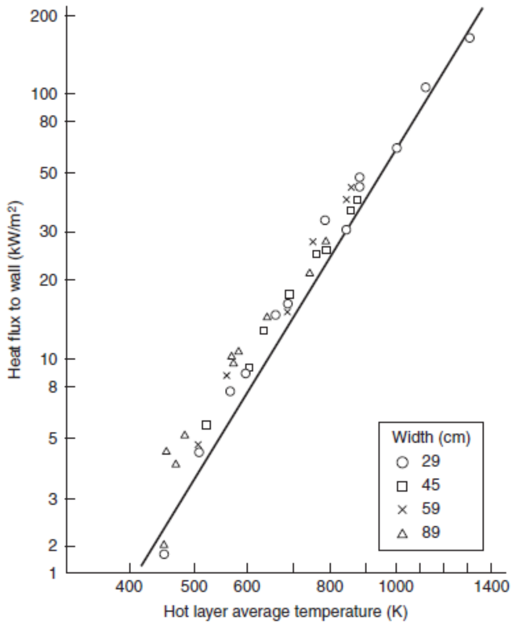
CONCLUSION AND SCOPE OF PROGRESS

By applying a black carbon coating on the top surface of the sample, the effective in-depth radiation absorption increases.



QUESTIONS


Classical theory (best fit)
Apparatus
AFM
Cone calorimeter
FPA
FIST
LIFT
Others apparatus with tungsten lamps heat source
Others apparatus with flame heat source
Experimental conditions
No black carbon coating or no information
Black carbon coating
Vertical sample
Controled atmsophere (18% < O2 < 30%)
Miscellaneous
Dashed area = experimental error
Time = 2s
Heat flux = +12 / -2 % [35]
Time to ignition [s]
Heat fluxes [kW/m2]
0
50
100
150
200
250
300
0
50
100
150
200



Heat flux to the walls inside a compartment containing a hot gas layer

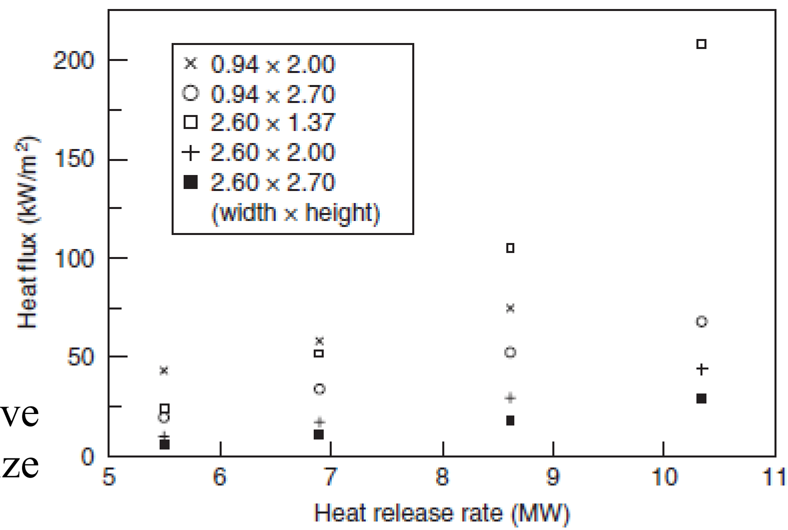
Flame at 2000 K: 907 kW/m^2

Pool fire (0.5 m x 9.45 m) Kerosene: Peak heat flux to object immersed: 150 kW/m^2 (HRR_rad ≈ 45 kW/m^2)

Peak HRR polystyrene keyboard: 22 kW (HRR_rad ≈ 6.6 kW/m^2)

Peak HRR wooden desk (0.6 * 1.2 *0.8 m) : 650 kW (HRR_rad ≈ 195 kW/m^2)

Bench scale mattress Polyurethane :400 kW/m^2 (HRR_rad ≈ 120 kW/m^2



Heat fluxes from a window flame 0.5m above the top of the window for different size propane fires inside the compartment