Numerical modelling of fire spread on wood cribs: parameter sensitivity analysis and conditions leading to travelling fires

UKCTRF Annual conference
29 March 2021

Xu Dai, **Stephen Welch**

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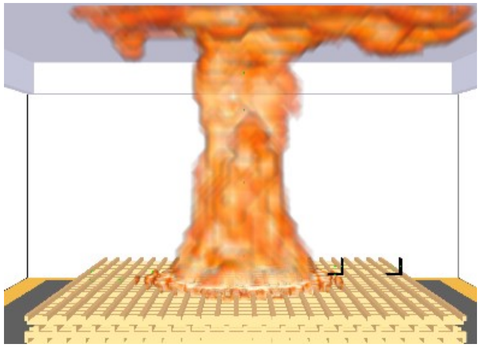

Travelling fires for structures

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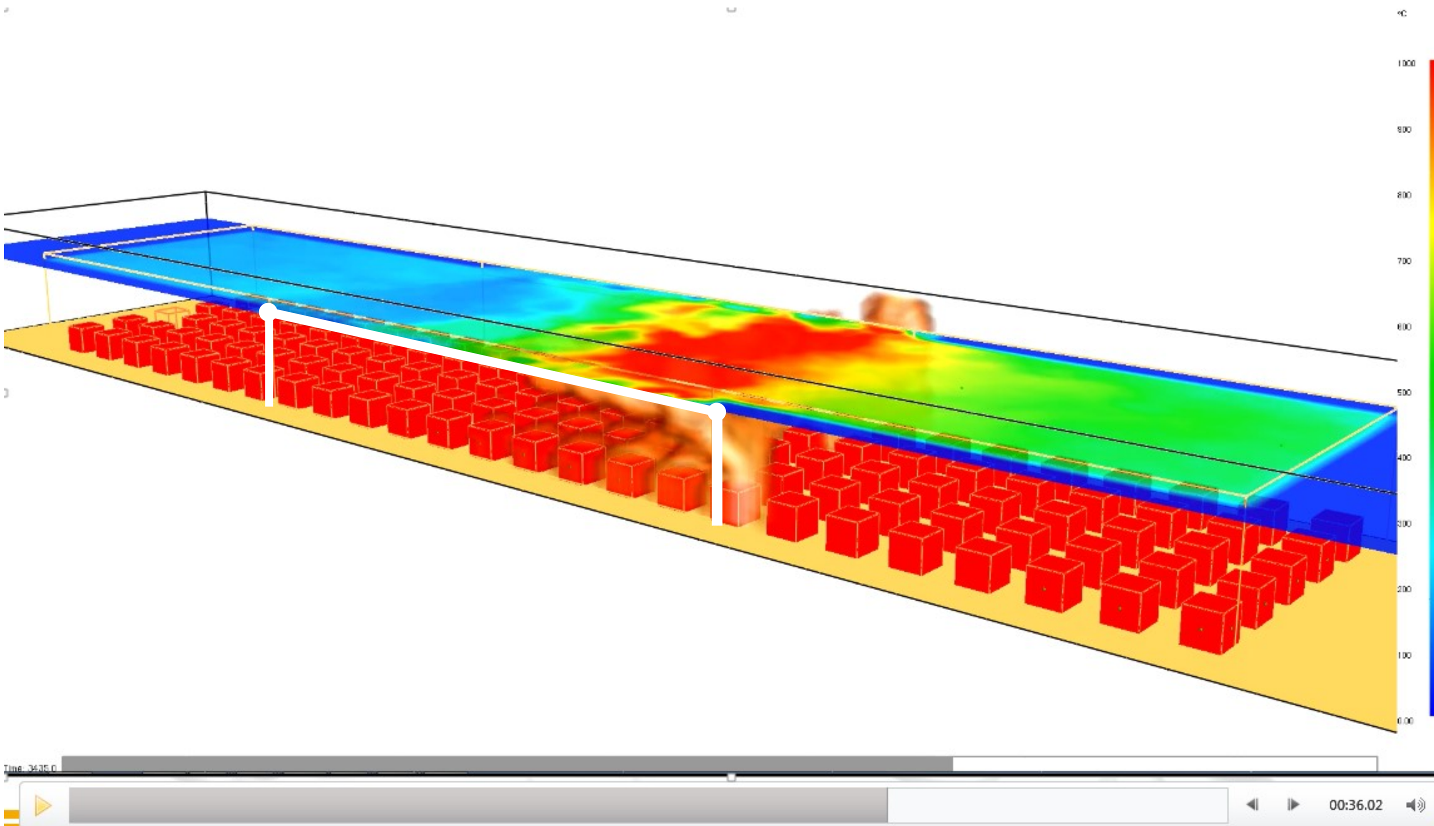

Charlier, M., Vassart, O., Gamba, A., Dai, X., Welch, S. & Franssen, J.-M. (2018) “CFD Analyses Used to Evaluate the Influence of Compartment Geometry on the Possibility of Development of a Travelling Fire”, SiF 2018, University of Ulster, 6-8 June 2018

Jose Torero*, Scaling-Up Fire:

“fire safety can only be quantitatively assessed if the **combustion process can be modelled within the context of its environment**. [This] will be referred to here as ‘fire modelling’.”

* Torero, J.L. (2013) “Scaling-Up Fire", Proc. Comb. Inst. 34: 99-124

Jose Torero*, Scaling-Up Fire:

"The link between refinements in the combustion processes involved in fire modelling and the potential improvements in a fire safety strategy is generally blurred by the complexity of the processes involved, the natural incompatibility of time and length scales and the unavoidable scenario uncertainty. **In this context the use of CFD as a basis for the Scaling-Up of fire has a very clear gain**.

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School of Engineering

Torero, J.L. (2013) "Scaling-Up Fire",
Proc. Comb. Inst. 34: 99-124

Burning rates

* Drysdale (2011) *An introduction to fire dynamics*, Wiley, 3rd ed.

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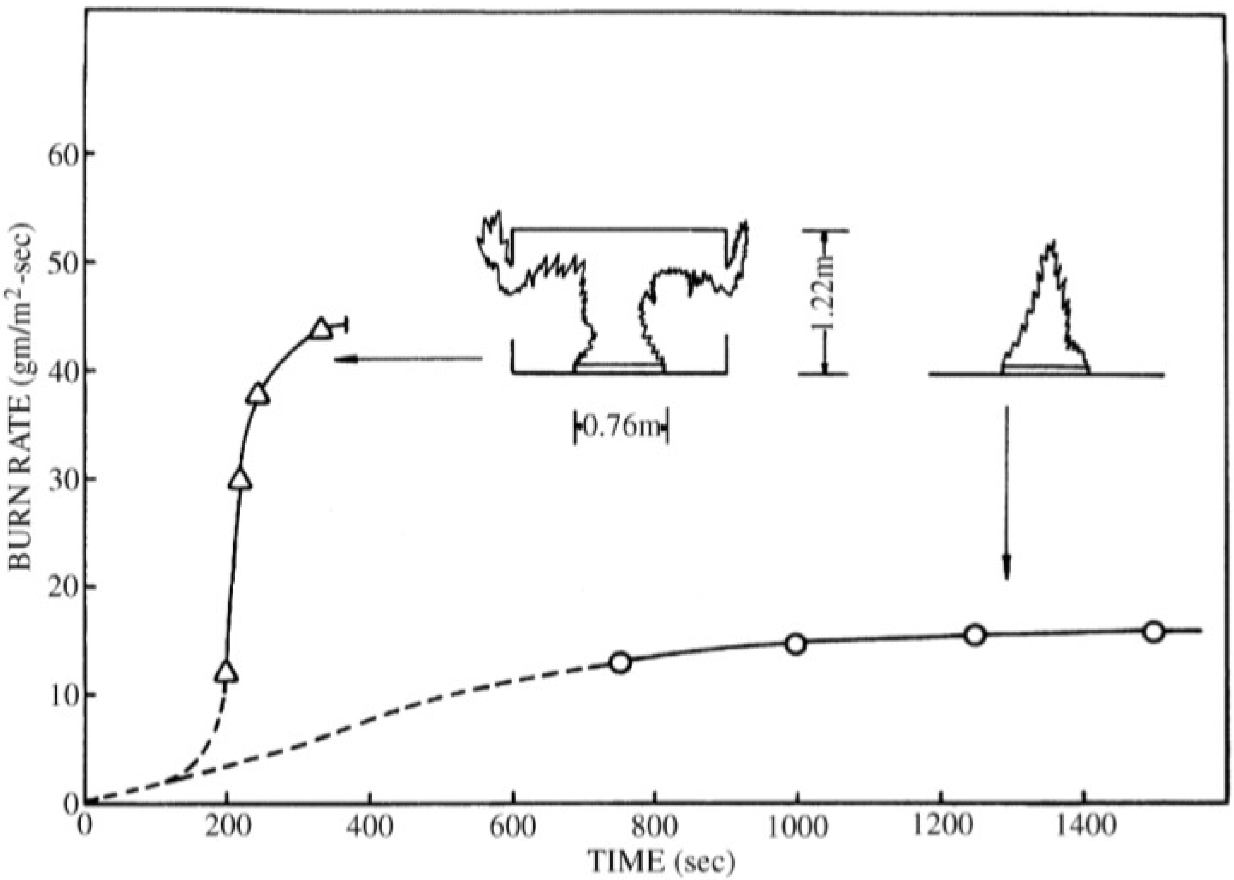

Figure 9.2 The effect of enclosure on the rate of burning of a slab of polymethylmethacrylate (0.76 m × 0.76 m) (Friedman, 1975)

Burning rates

* Drysdale (2011) *An introduction to fire dynamics*, Wiley, 3rd ed.

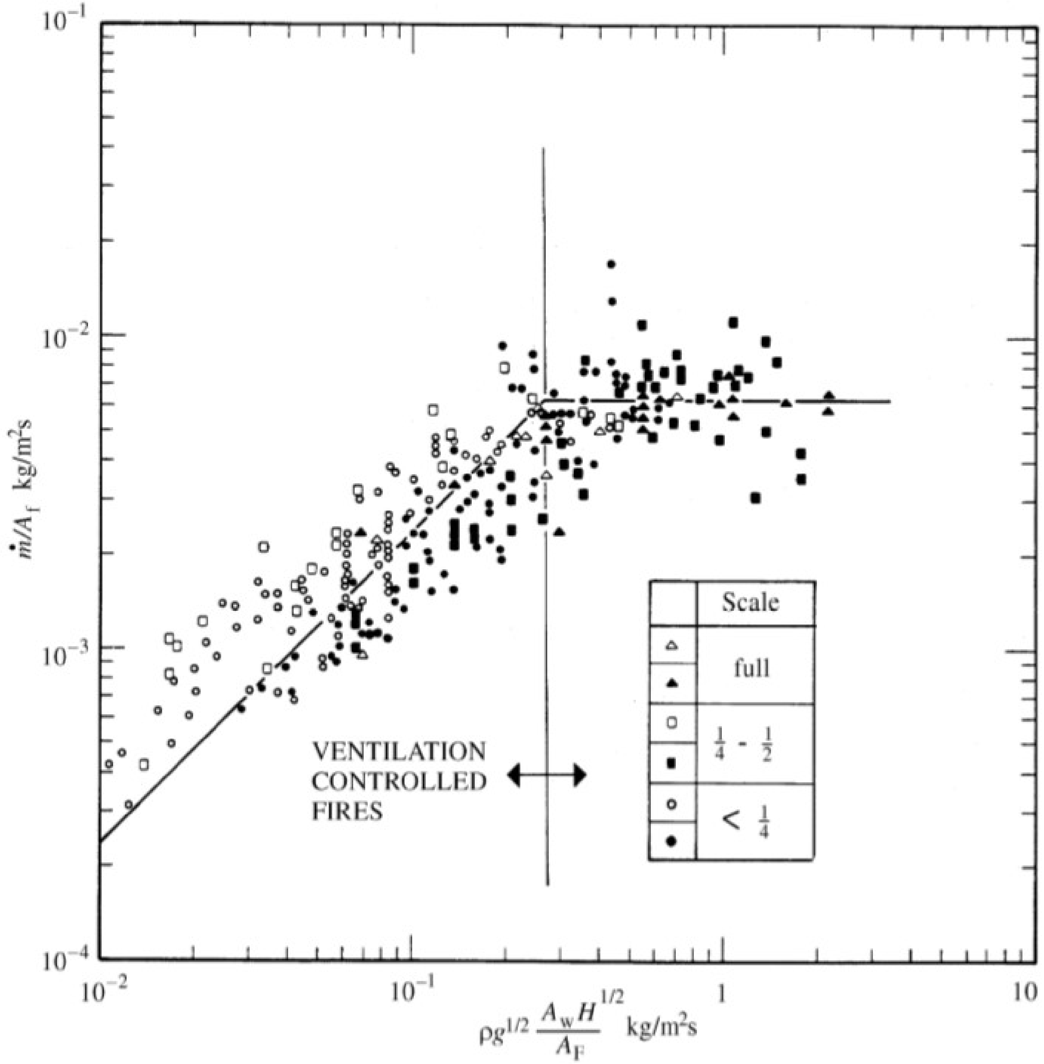

Figure 10.5 Identification of the transition between ventilation-controlled and fuel-controlled burning for wood cribs, according to Harmathy (1972)

Burning rates

* Drysdale (2011) *An introduction to fire dynamics*, Wiley, 3rd ed.

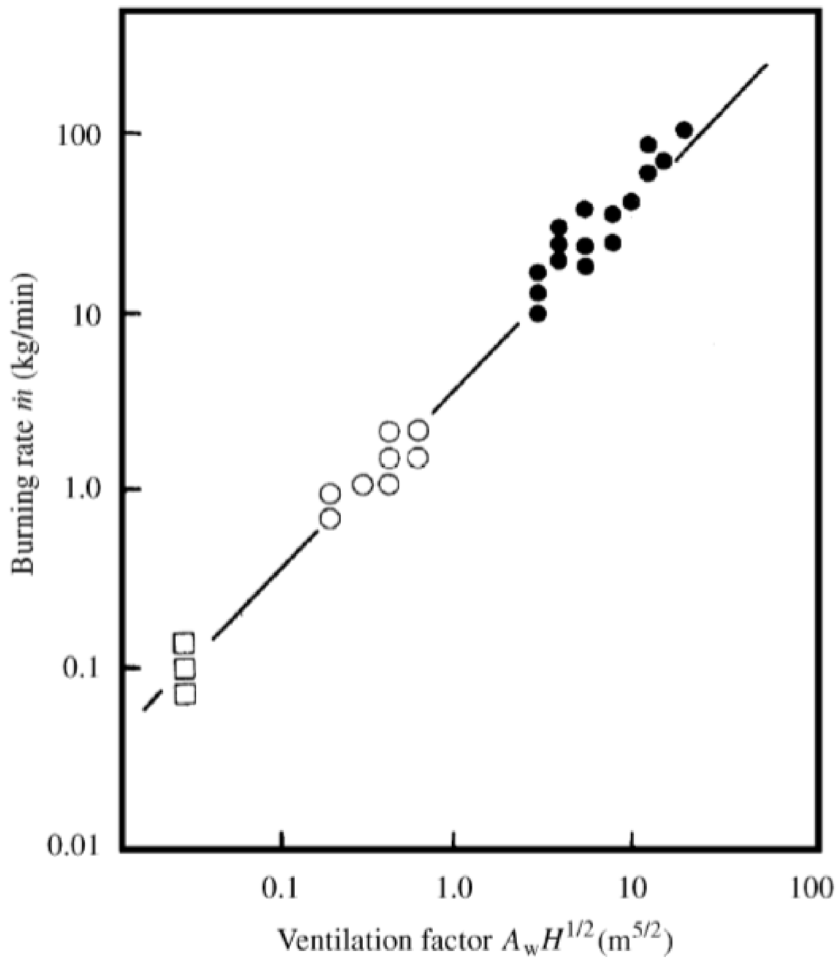

Figure 10.1 Mass burning rate of wood cribs in enclosures as a function of the ventilation factor, $A_w H^{1/2}$ for ventilation-controlled fires (Equation (10.1)): ●, full-scale enclosures; ○, intermediate-scale models; □, small-scale models (Kawagoe and Sekine, 1963). Reproduced by permission of Elsevier Applied Science Publishers Ltd

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Uni Liège LB7 Test Setup

Crib fire experiments

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Gamba, Charlier & Franssen (2020) Propagation tests with uniformly distributed cellulosic fire load FSJ 103213 .pdf - Adobe Acrobat Reader DC

Bookmarks

- Propagation tests with uniformly distributed cellulosic fire load
  - 1 Introduction
  - 2 First series of tests (LA)
    - 2.1 Ignition system
    - 2.2 Test description
    - 2.3 Measured quantities in the LA series
  - 3 Second series of tests (LB)
    - 3.1 Test description
    - 3.2 Measured quantities in the LB series
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  - 5 Conclusions
  - CRediT authorship contribution statement
  - Declaration of competing interest
  - Acknowledgements
  - Appendix A Supplementary data
  - References

Fire Safety Journal 117 (2020) 103213

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Propagation tests with uniformly distributed cellulosic fire load

Antonio Gamba [a,*], Marion Charlier [b], Jean-Marc Franssen [a]

[a] *Liege University, UEE Department, Belgium*
[b] *ArcelorMittal Global R&D, Luxembourg*

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Fire spread
Fuel arrangement

ABSTRACT

In the recent past, the necessity to have a better understanding of fire dynamics and of the full structural response under real fires was the motivation for several large-scale non-standard fire tests. Nowadays, the novel need to better comprehend the fire dynamics behind the so called "travelling fires" underlined the limitations of those non-standard fire tests. The lack of standardised procedures does not allow making effective comparisons and drawing scientific conclusion from these tests. The fire group of Liege University performed eleven non-standard or "natural fire" tests within the context of the RFCS research project TRAFIR sponsored by the E.U. Commission (grant N°754,198). The aim of this experimental campaign was to determine a uniformly distributed fuel arrangement that would lead to a medium fire growth as recommended for office buildings in Eurocode 1. This

* Gamba, A., Charlier, M. & Franssen, J.-M. (2020) "Propagation tests with uniformly distributed cellulosic fire load", Fire Safety Journal 117, 103213 doi:10.1016/j.firesaf.2020.103213

"Liege test series", LB7 Test, Marchienne, Belgium, 2018

- Photos regarding the experiment:

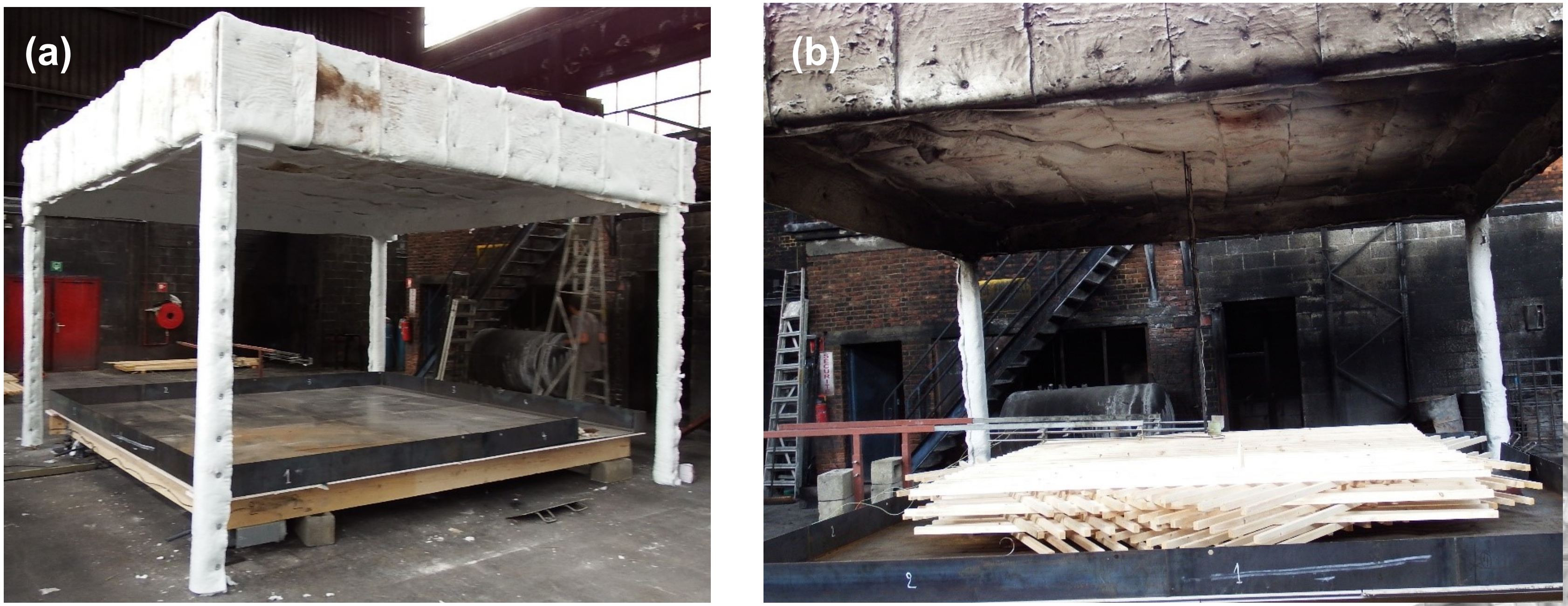

Figure 1. (a) Skewed view of test rig without wood sticks, and (b) Side view of test setup.

"Liege test series", LB7 Test, Marchienne, Belgium, 2018

- Wood sticks layout in elevation view:

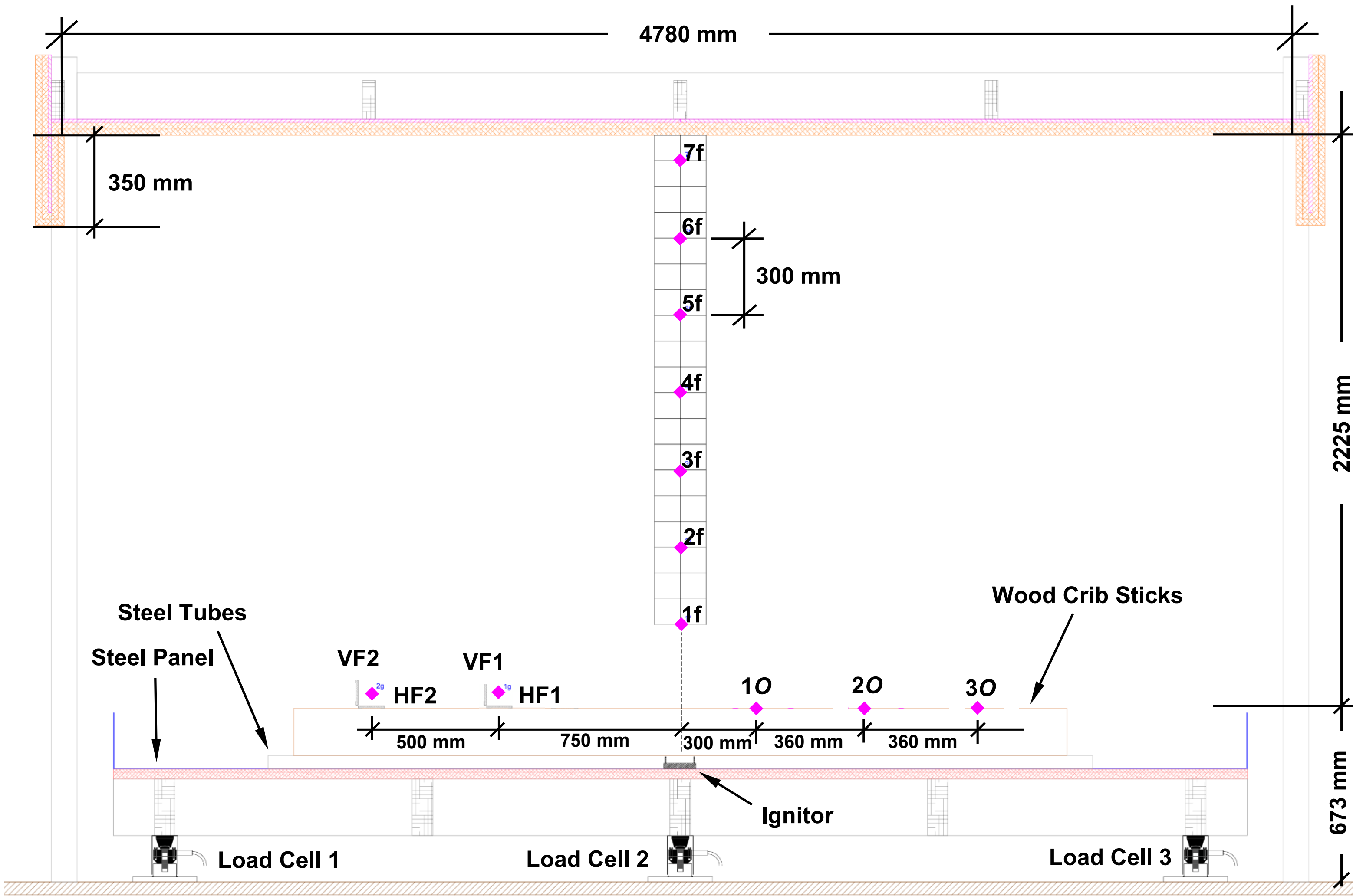

Figure 2. Overview of test setup in elevation: compartment structure, plate thermometer and thermocouple instrumentations (marked with pink square dot), and location of sticks.

“Liege test series”, LB7 Test, Marchienne, Belgium, 2018

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- **Photos regarding the experiment:**

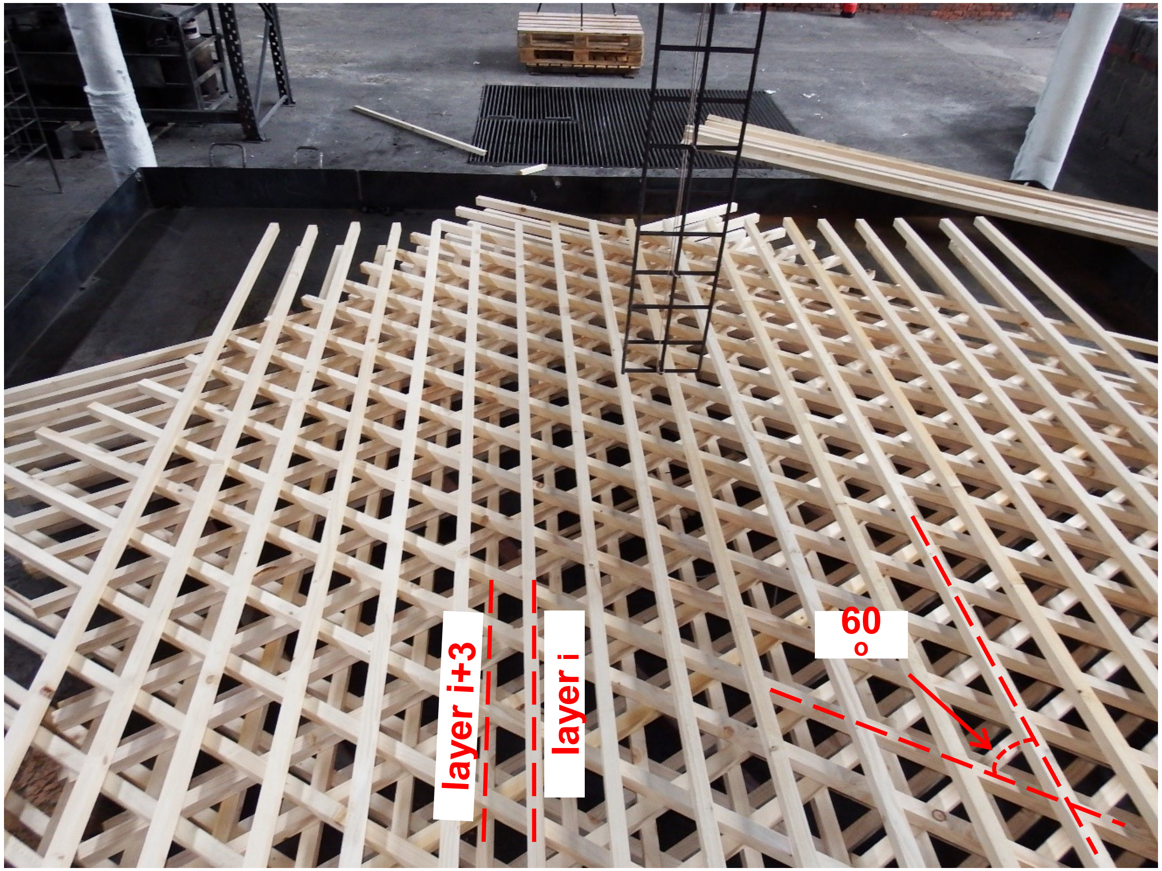

Figure 3. Wood stick arrangement in plan view: wood sticks orientation shifted 60° every layer, and every three layers wood sticks shifted horizontally for half of wood stick pitch.

“Liege test series”, LB7 Test, Marchienne, Belgium, 2018

- Wood sticks layout in plan view:

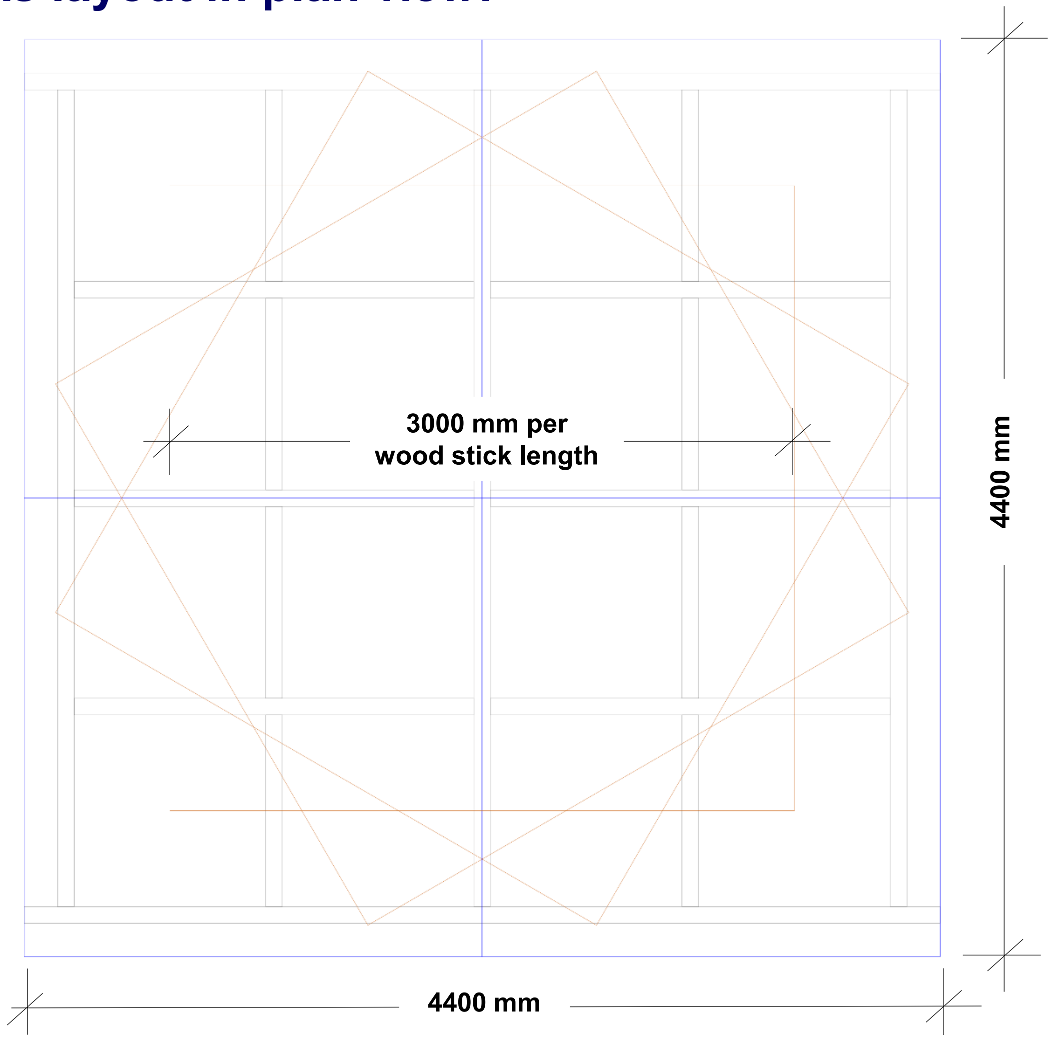

Figure 4. Test setup in plan view: wood stick orientation shifted 60º per layer.

A Calibrated CFD Model for LB7 Test

Model Setup

FDS modelling for calibration, “Liege test series”, LB7

- Grid cell resolution in elevation view

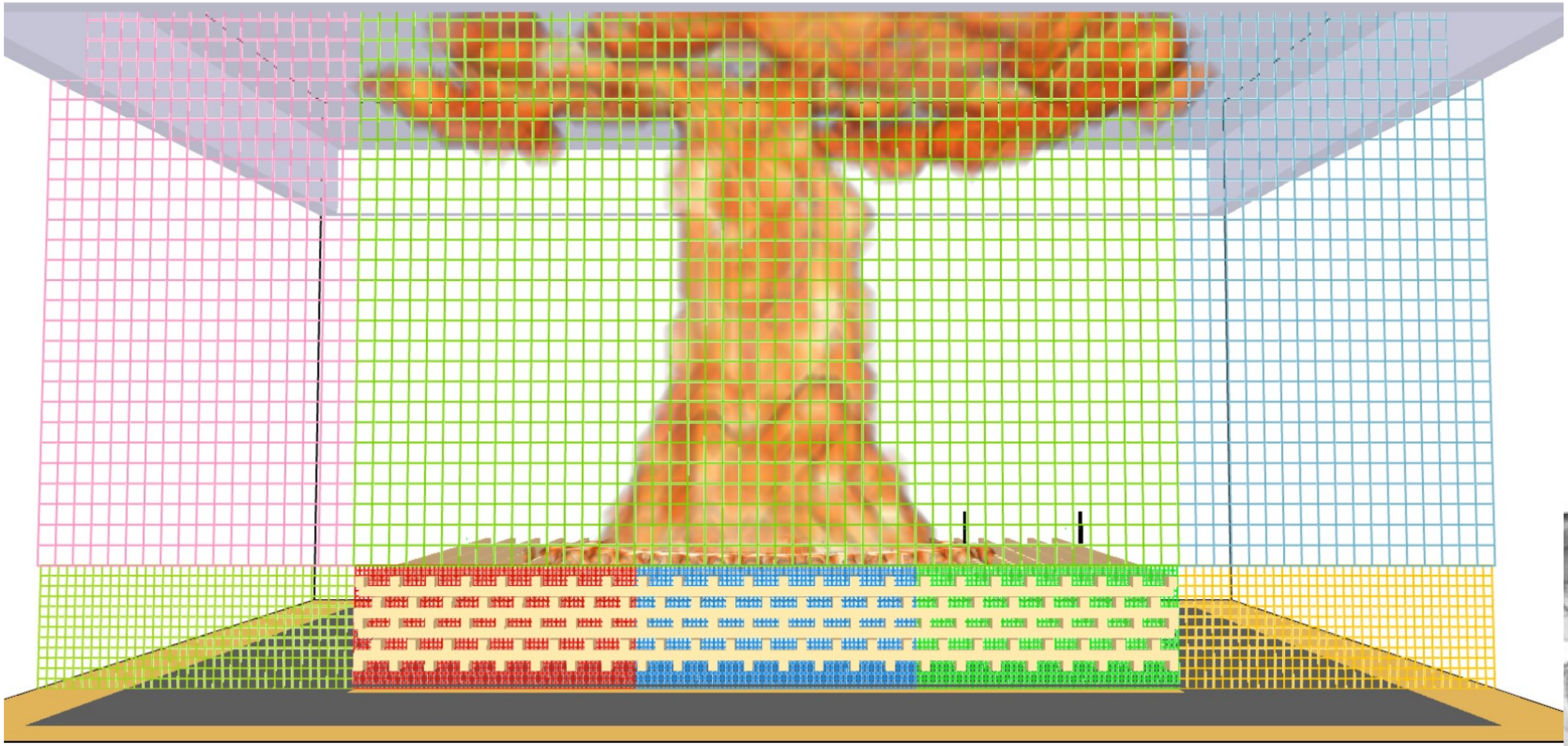

Figure 5. Grid cell resolution of the model: 1.5 cm × 1.5 cm × 1.75 cm per cell for wood sticks in porous crib structure, 6 cm × 6 cm × 7cm and 3 cm × 3 cm × 3.5 cm cell size in gas phase, total number of cells ~1.3 million.

FDS modelling for calibration, “Liege test series”, LB7

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- Wood sticks representation and coordinate system, in plan view:

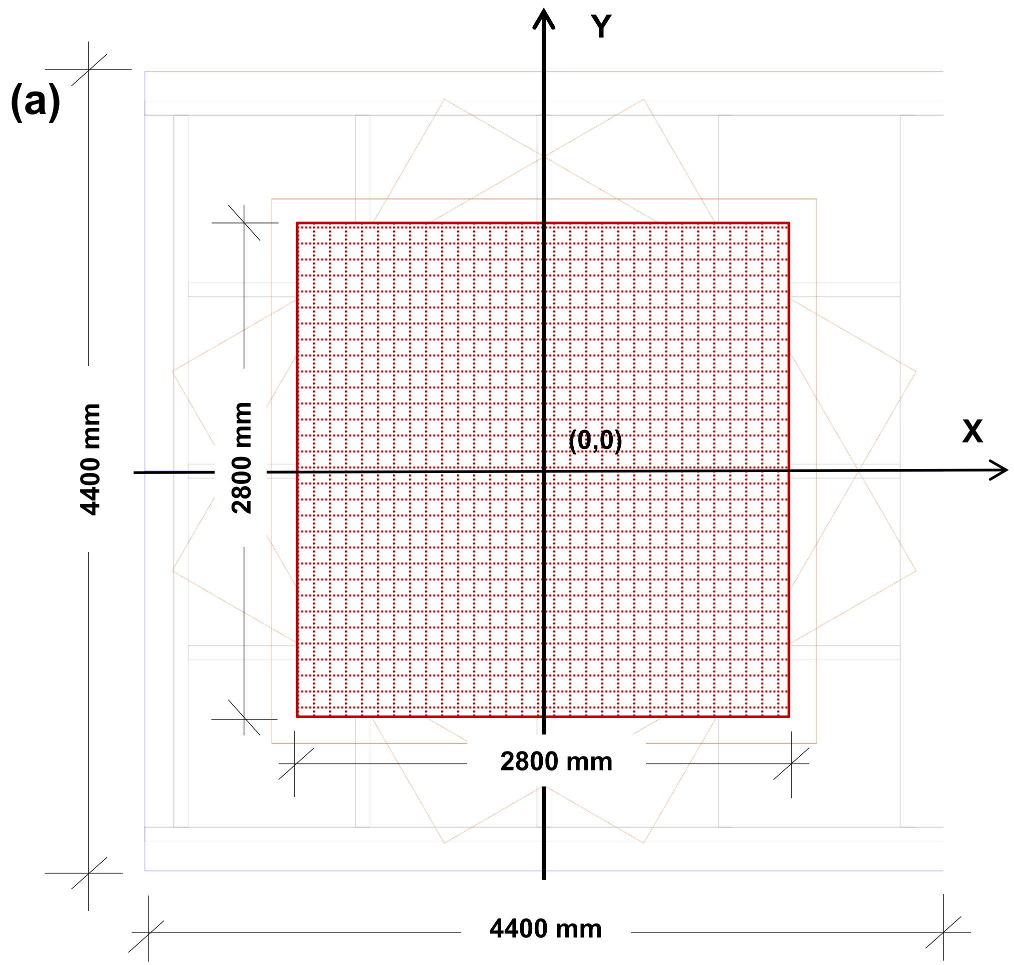
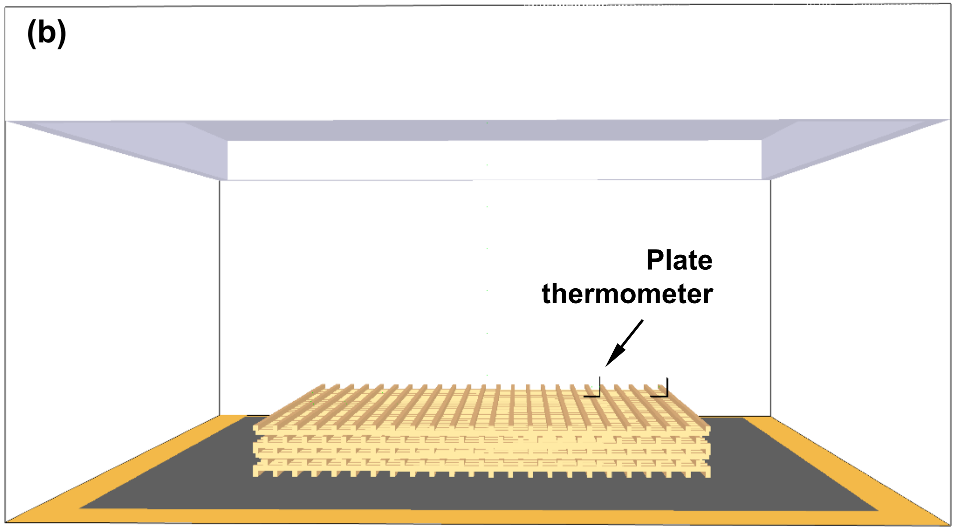
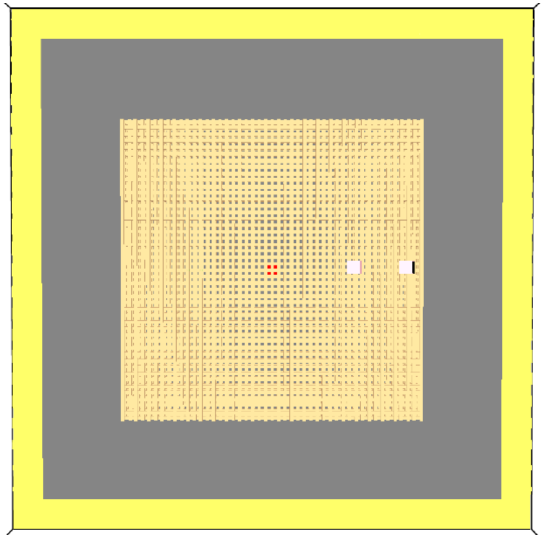


Figure 6. (a) Representation of the wood sticks in the model coordinate in plan view, simplified to a 2.8 m x 2.8 m square wood crib with sticks placed orthogonally.

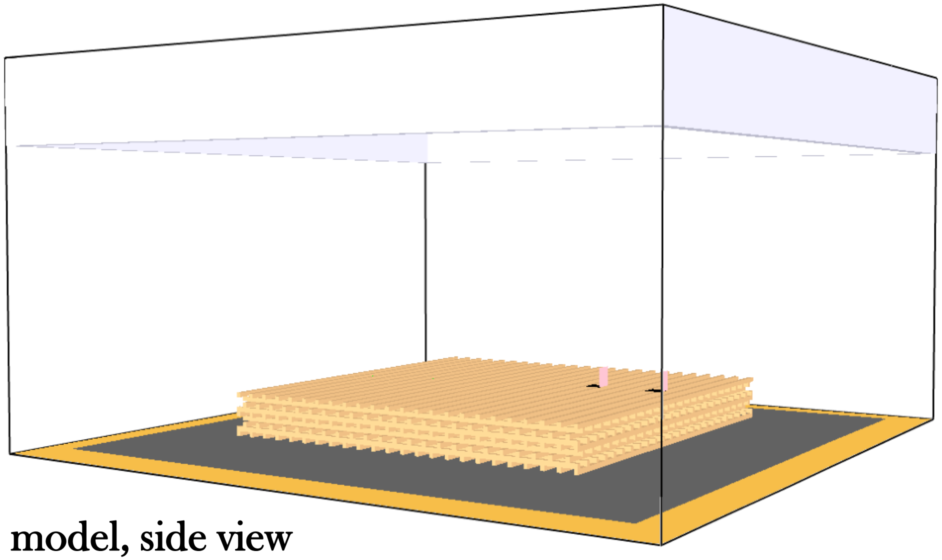
FDS modelling for calibration, “Liege test series”, LB7



FDS model front view



FDS model top view



FDS model, side view

- Wood sticks representation and coordinate system, in elevation view:

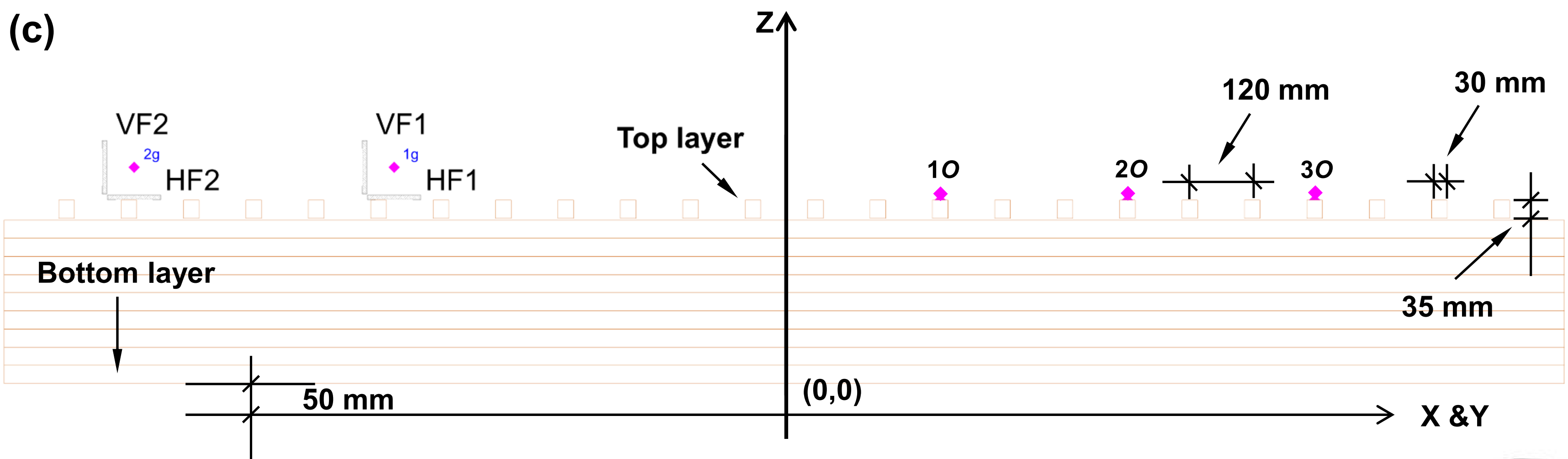


Figure 6. (c) Representation of the wood sticks in the model coordinate in elevation view, stick size 35 mm x 30 mm with stick pitch 120 mm, 24 sticks per layer, 9 layers in total, and 50 mm offset between the steel panel and the bottom wood stick layer for the ignition burner and steel tubes.

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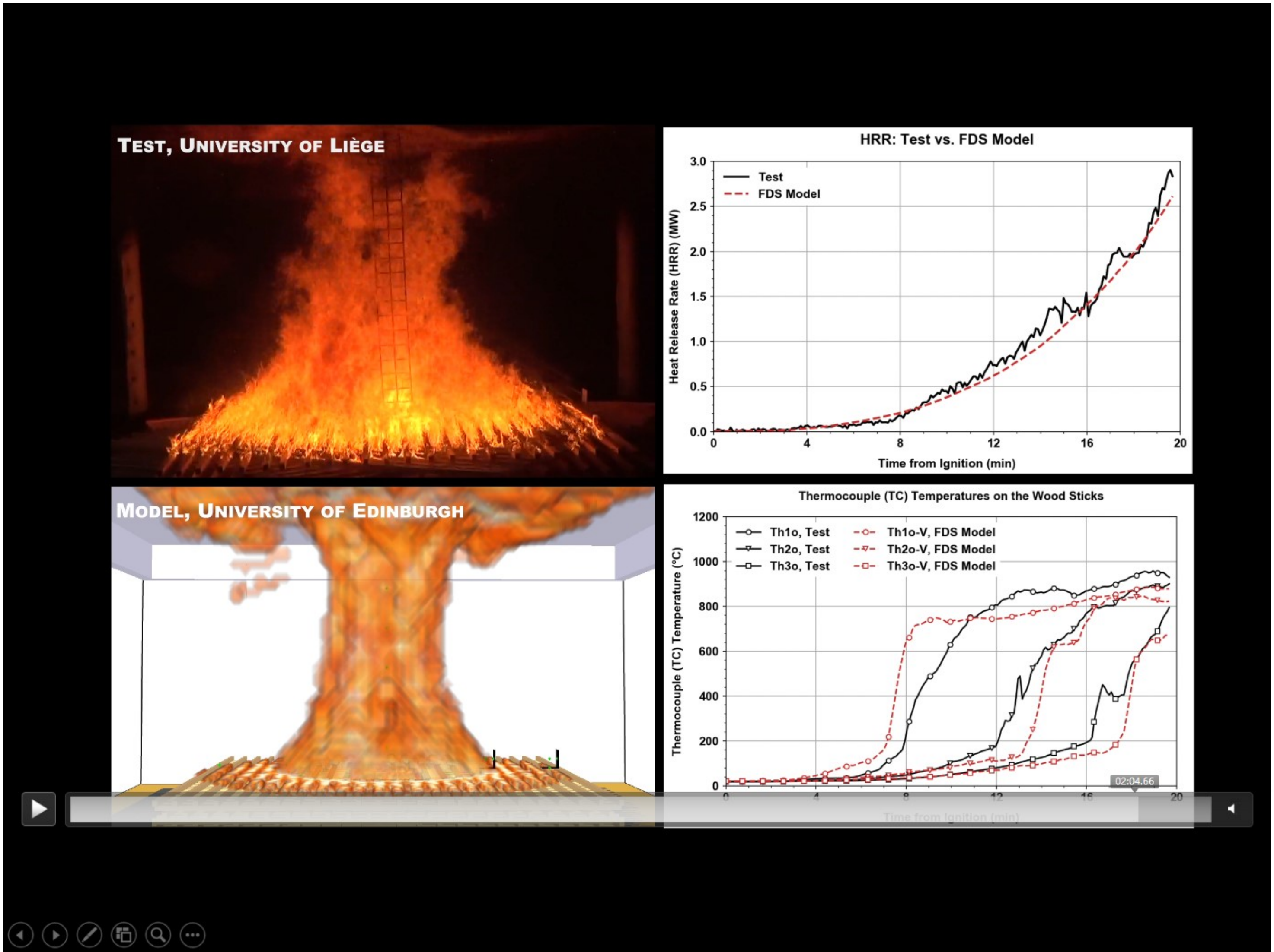
A Calibrated CFD Model for LB7 Test

Results

FDS modelling for calibration, “Liege test series”, LB7

- Full-calibrated model demo



FDS modelling for calibration, “Liege test series”, LB7

○ Fire development comparison

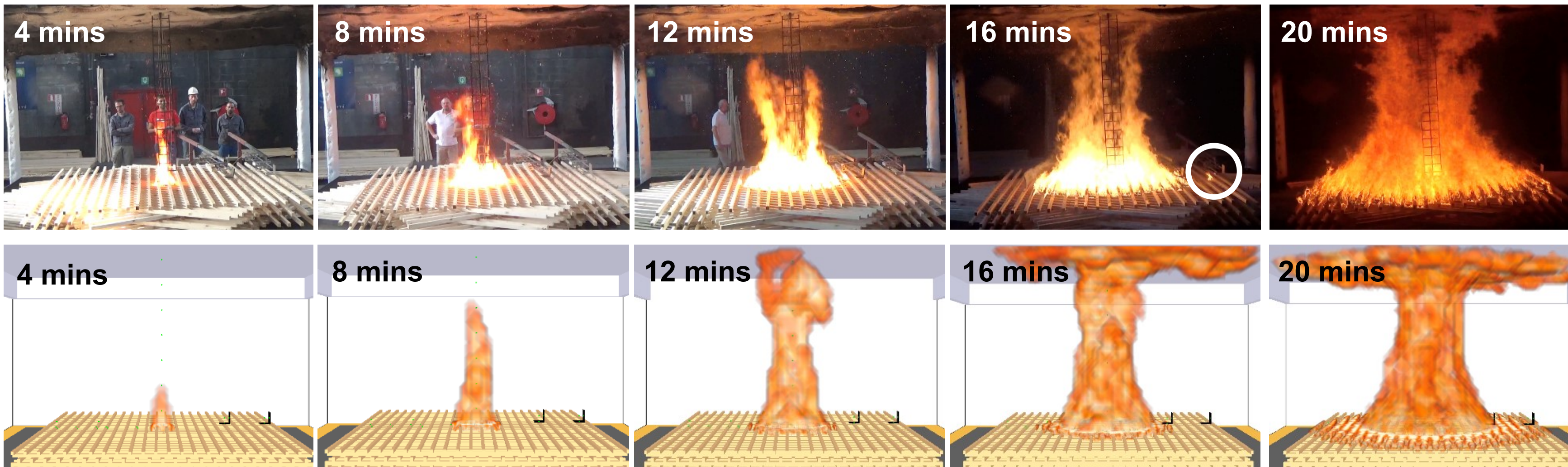


Figure 7. FDS simulated fire spread comparison with the test, at 4 mins, 8 mins, 12 mins, 16 mins, and 20 mins.

FDS modelling for calibration, “Liege test series”, LB7

- Fire spread rate comparison

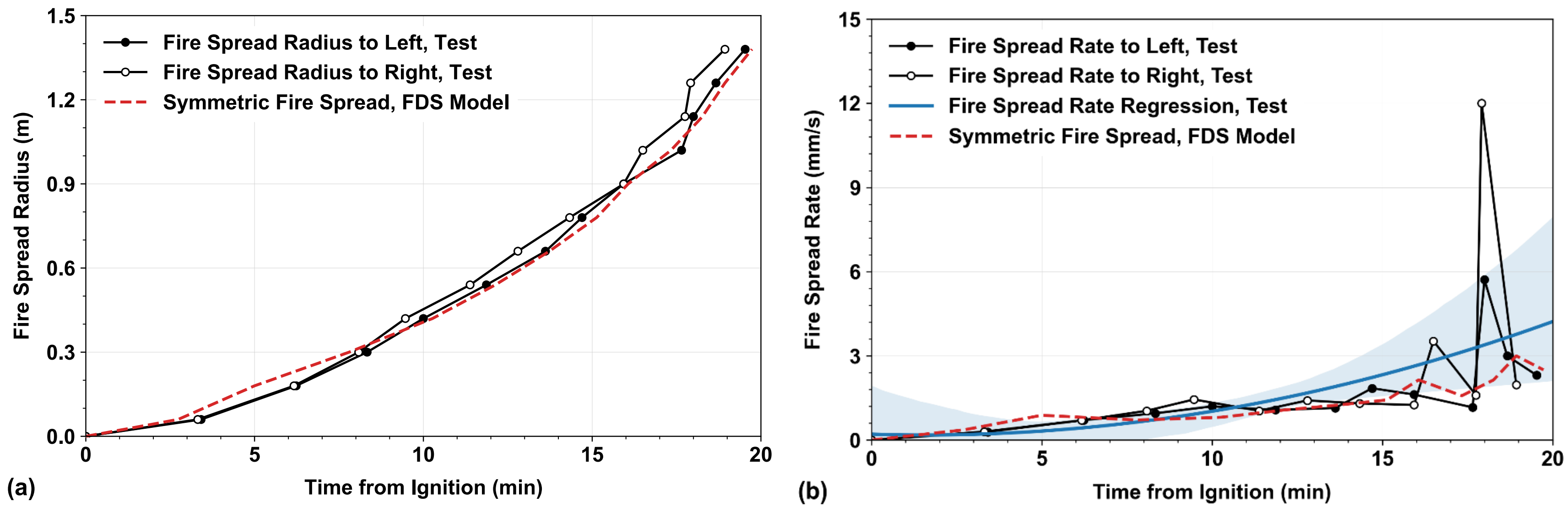
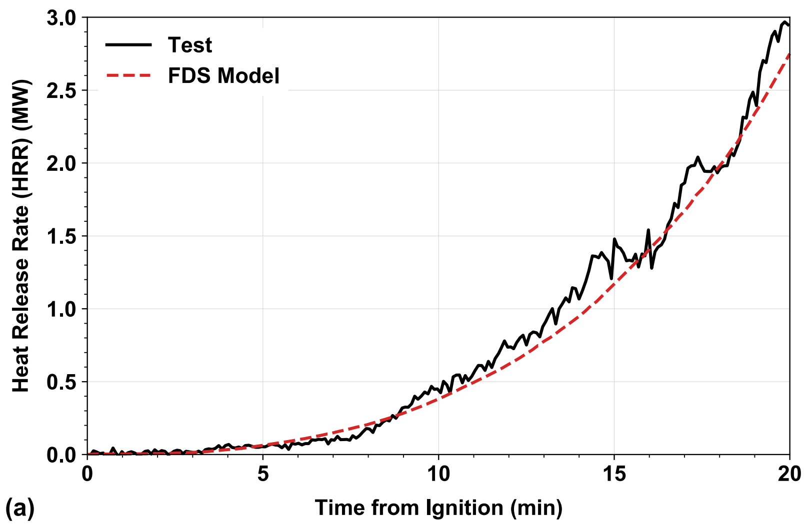


Figure 8. Comparison between the test and the model, (a) Fire spread radius from wood crib centre to edge, and (b) Fire spread rate from wood crib centre to edge.

FDS modelling for calibration, “Liege test series”, LB7

- **Heat release rate, and mass loss rate comparison**



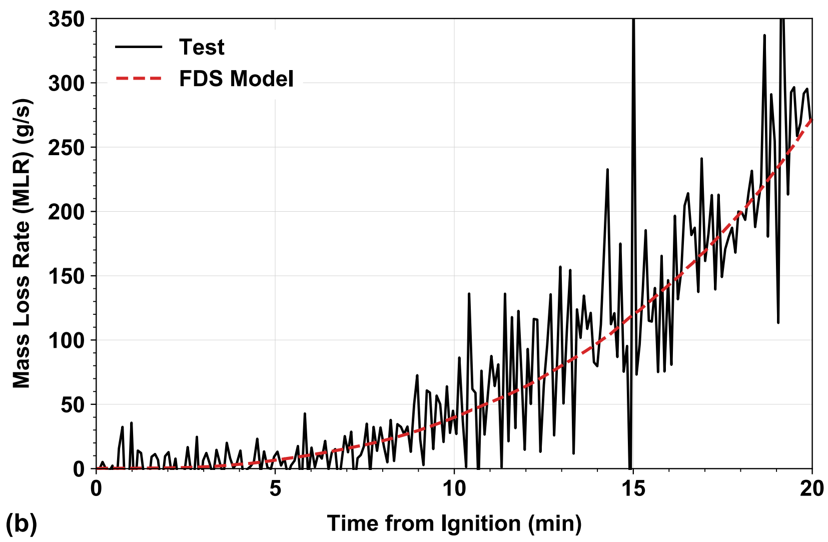


Figure 9. Comparison between the test and the model, (a) HRR, and (b) MLR.

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- Fire spread rate vs. HRR (decoupling time dependency)
- Fire height comparison

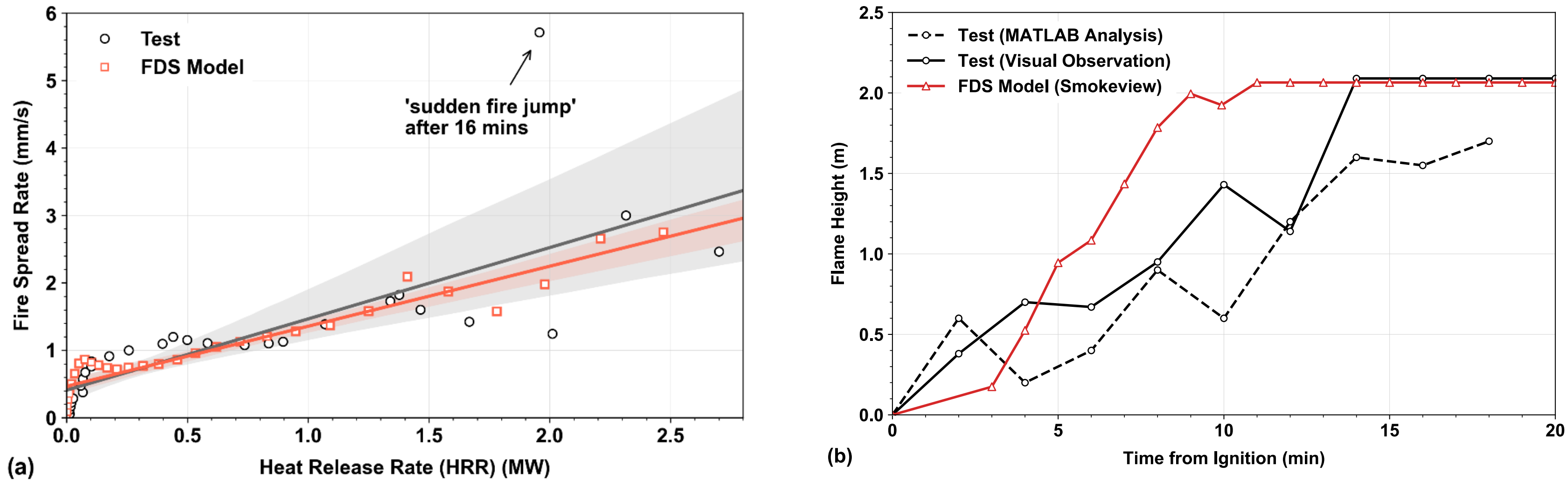

Figure 10. Comparison between the test and the model, (a) Change of fire spread rate with increasing HRR, and (b) Flame height.

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- Fire development within the wood crib
- Temperature development within the wood crib

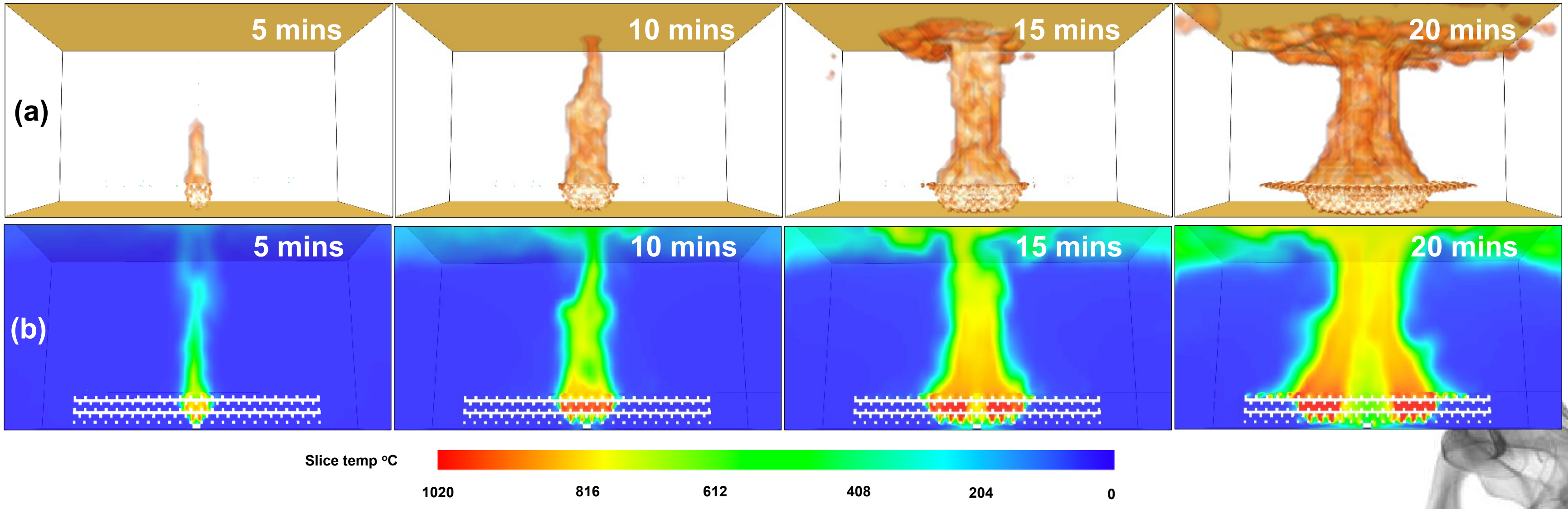

Figure 11. (a) Flame development within wood cribs (wood sticks “obstruction” removed in Smokeview for clearer flame demonstration), and (b) Temperature development at the compartment central ‘slice’.

FDS modelling for calibration, “Liege test series”, LB7

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- Cell size sensitivity in gas phase

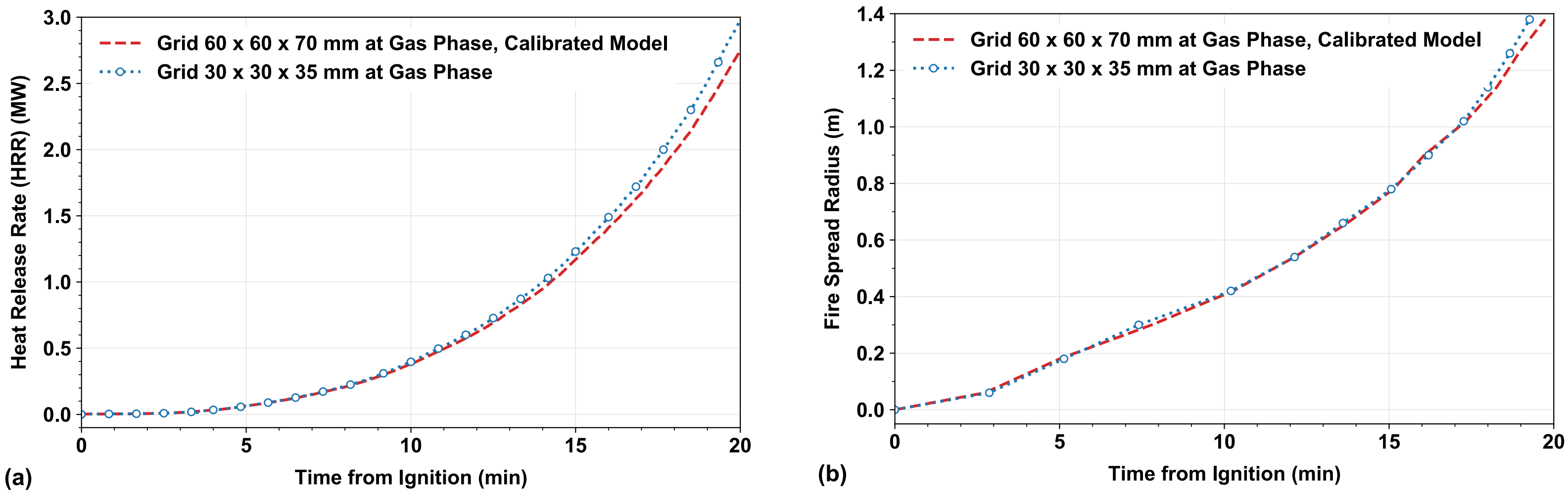

Figure 12. Cell size sensitivity at gas phase on (a) HRR, and (b) Fire spread radius.

FDS modelling for calibration, “Liege test series”, LB7

- Wood cribs burning away comparison

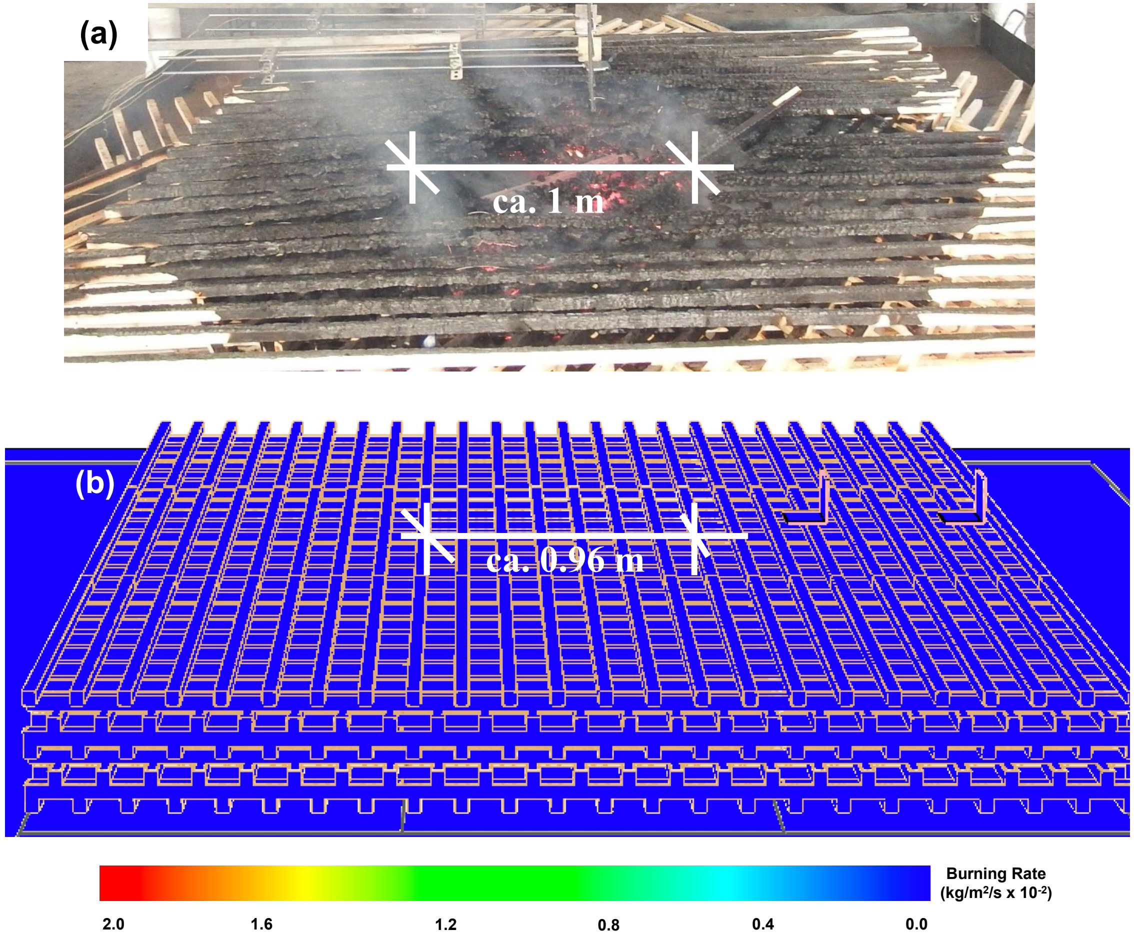

Figure 13. Burning away comparison between (a) the LB7 post-test photo, and (b) the model on burning rate at 20 mins.

FDS modelling for calibration, “Liege test series”, LB7

- Wood cribs “burn away” comparison

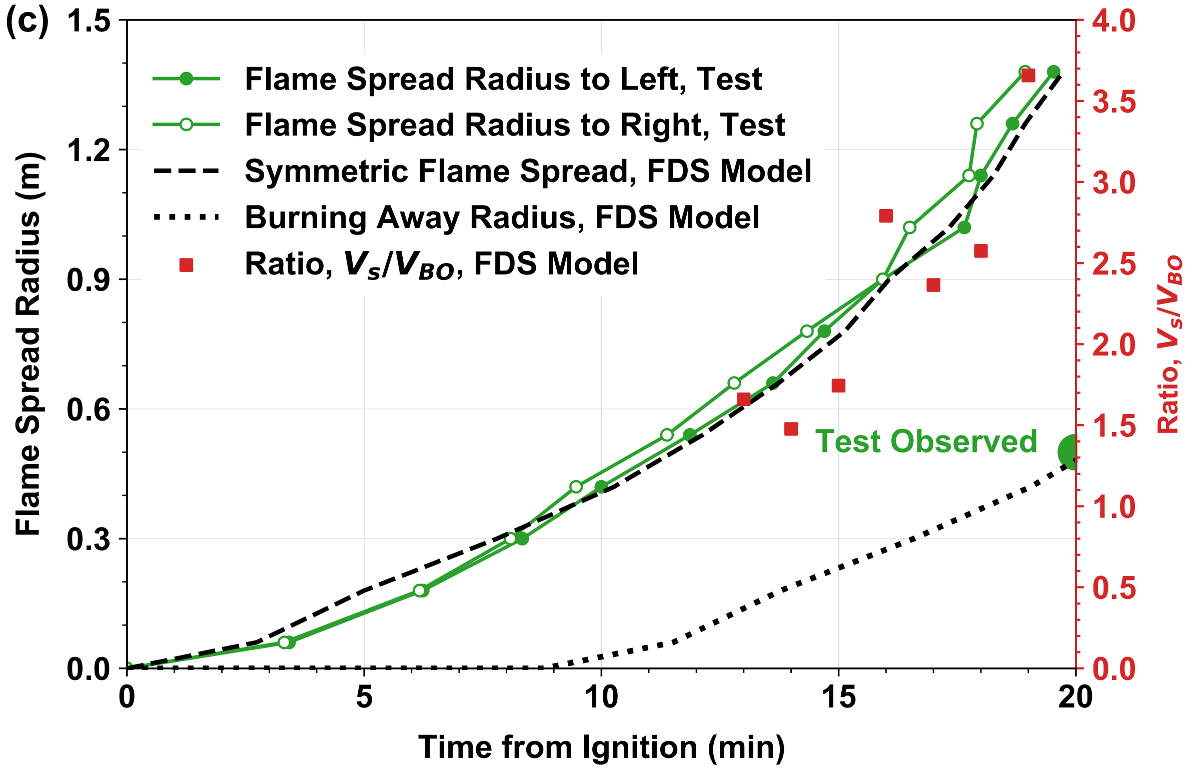

Figure 14. (c) Vs/Vb: velocity of flame spread front to velocity of flame burnout front.

FDS modelling for calibration, "Liege test series", LB7

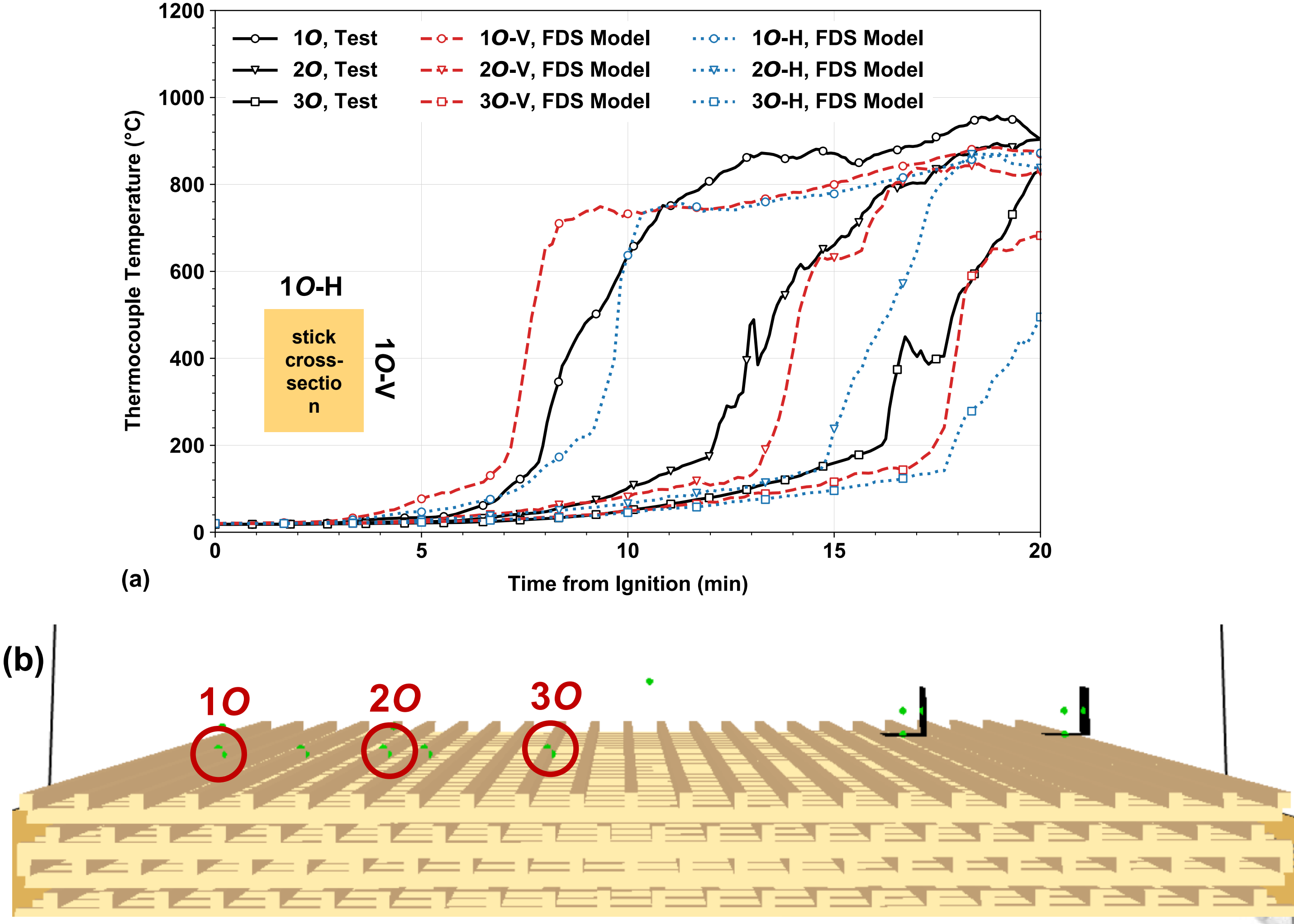

Figure 15. (a) Comparison of thermocouple temperatures on wood sticks top layer between model and test, and (b) Thermocouple instrumentation locations in model.

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FDS modelling for calibration, "Liege test series", LB7

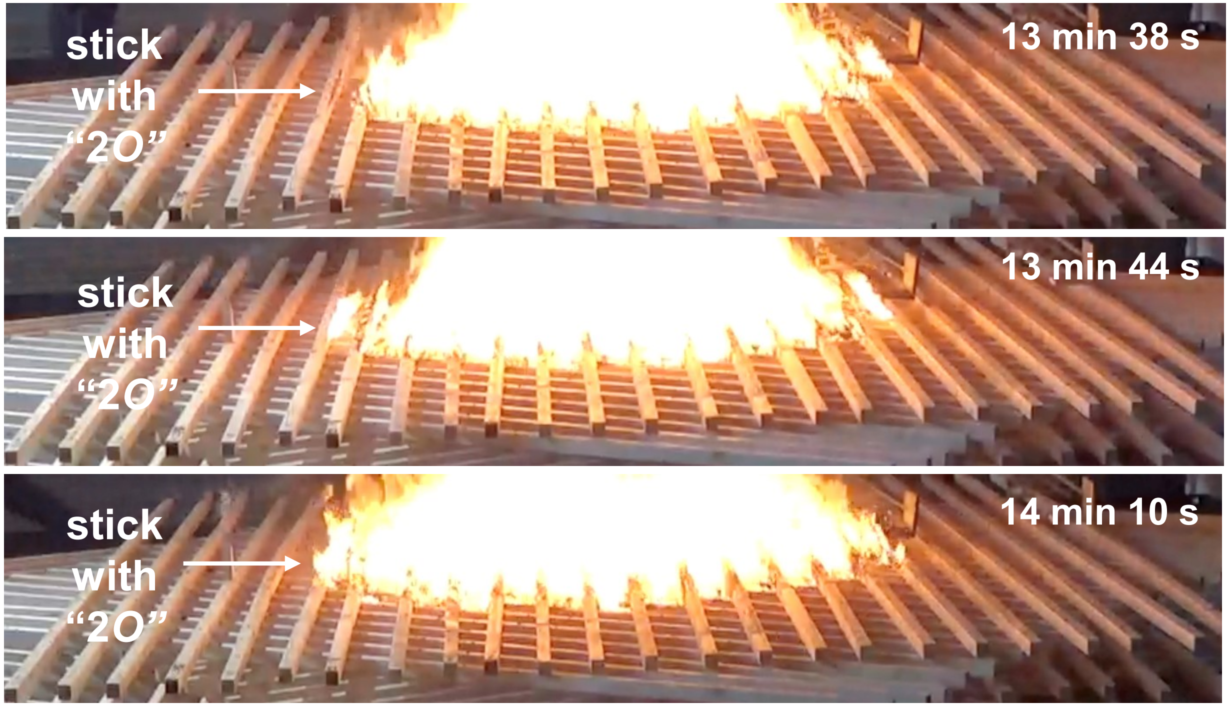

Figure 16. (c) Flame spread development on stick with thermocouple "2*O*".

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- Thermocouples at the centre of the test compartment

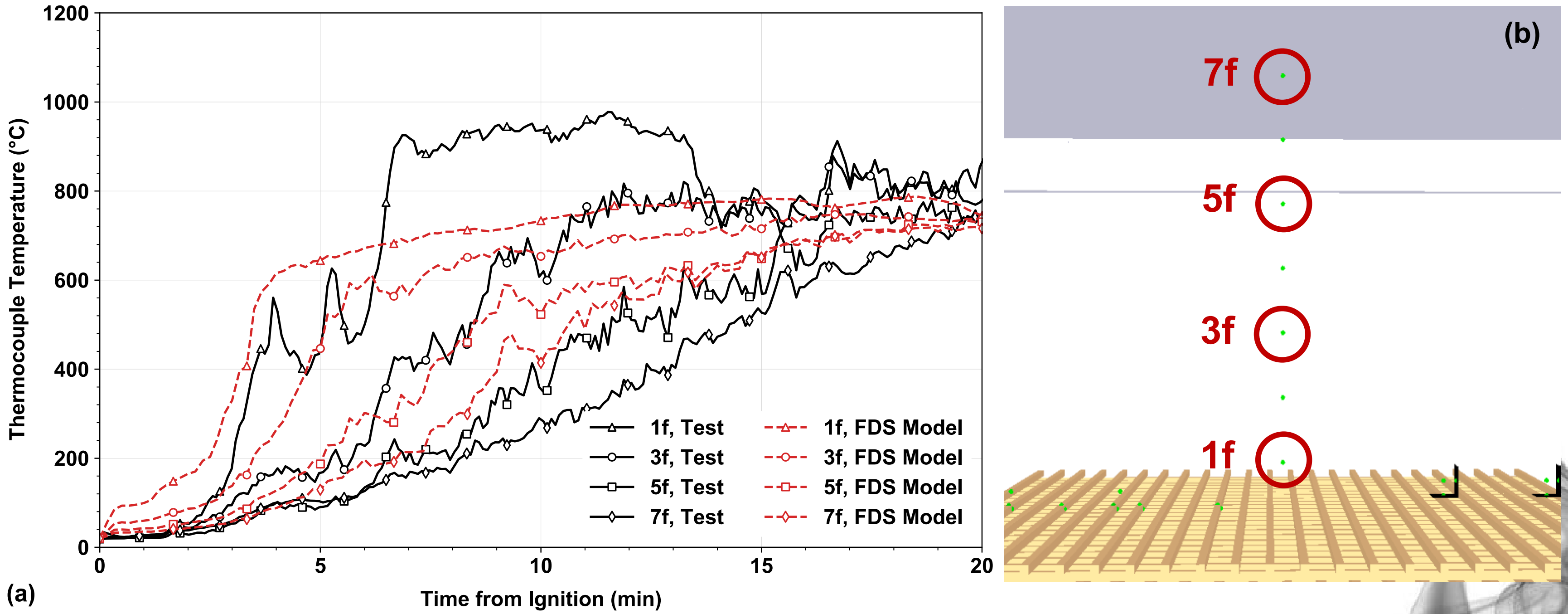

Figure 17. (a) Comparison of thermocouple temperatures at compartment centreline between model and test, and (b) Thermocouple instrumentation locations.

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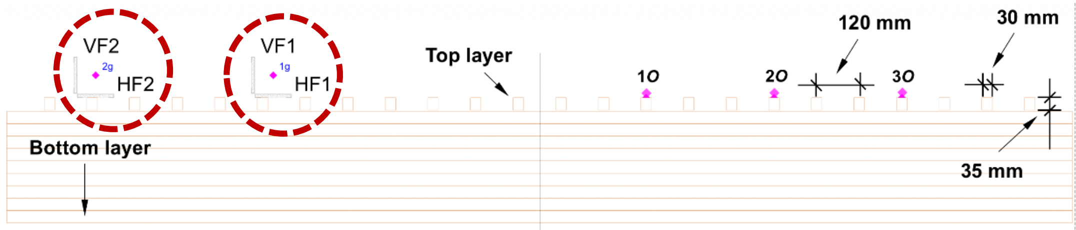
- **Plate thermometer comparison**



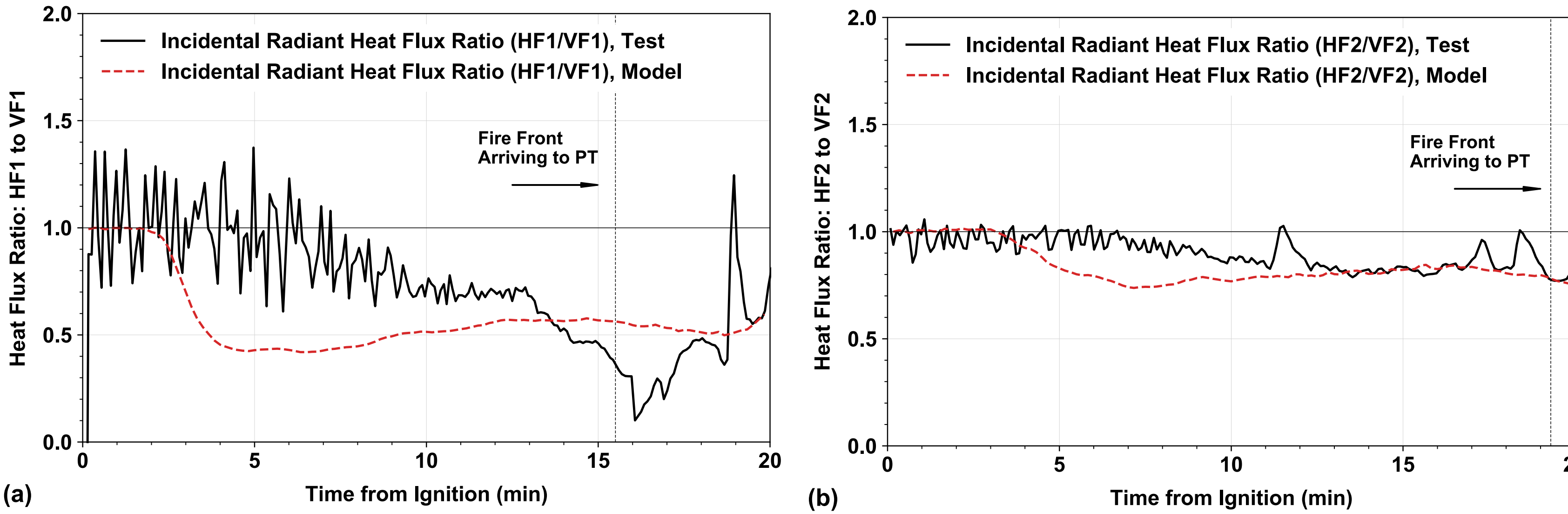
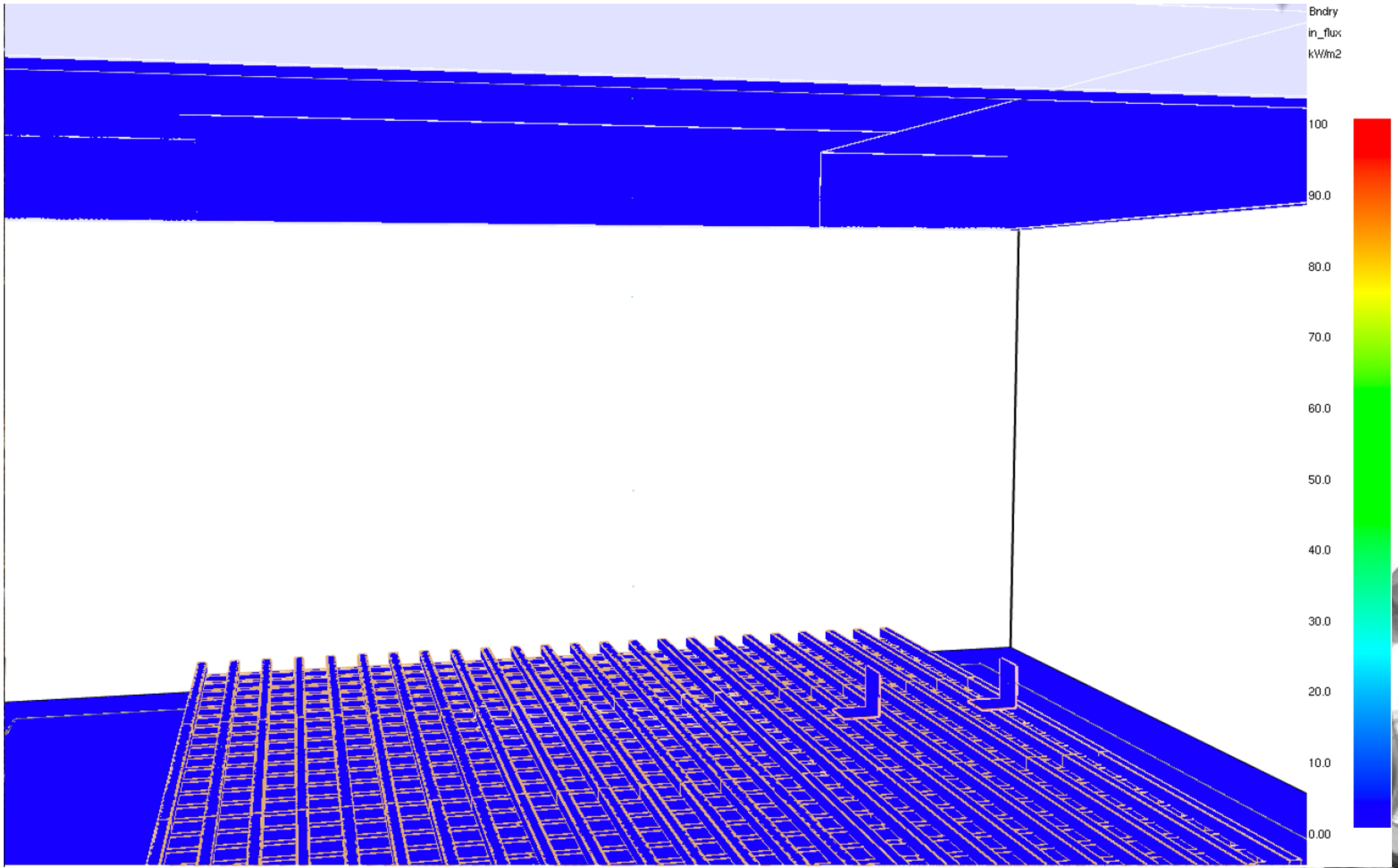


Figure 20. Comparison between test and model on incidental radiant heat flux ratio of (a) HF1 to VF1, and (b) HF2 to VF2.

FDS modelling for calibration, “Liege test series”, LB7

- Incidental radiant heat flux development in skewed elevation view



Video: top wood stick layer drives the fire spread mechanism (incidental radiant heat flux contour, black section - 13kW/m^2, measured critical heat flux using the cone calorimeter at UEDIN)

FDS modelling for calibration, "Liege test series", LB7

- Incidental radiant heat flux development on wood sticks

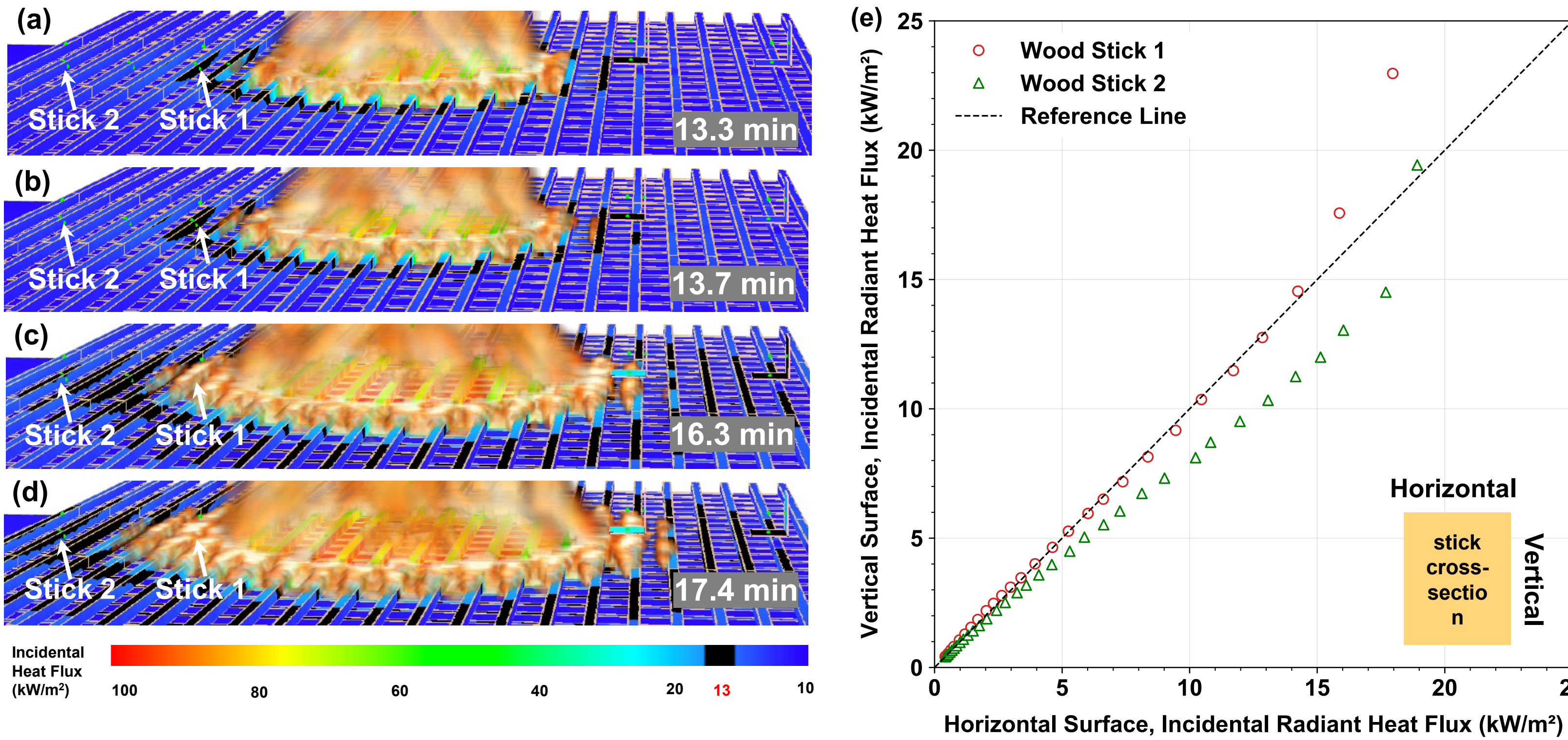


Figure 21. (a-d) Development of incidental radiant heat flux on top layer wood sticks, 13 kW/m^2 represented in black is critical heat flux for *Picea abies* wood ignition measured in Edinburgh fire lab using cone calorimeter, (e) Comparison of the heat fluxes on wood sticks 1 and 2 on horizontal surface vs. vertical surface.

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Parametric Studies

Proposed parameters for the parametric studies

Group 1:

- HRRPUA ✓
- Soot yield ✓
- Heat of combustion ✓
- Ignition temperature of wood ✓
- Thermal inertia of wood ✓
- Emissivity of wood ✓

Parametric study example – ignition temperature

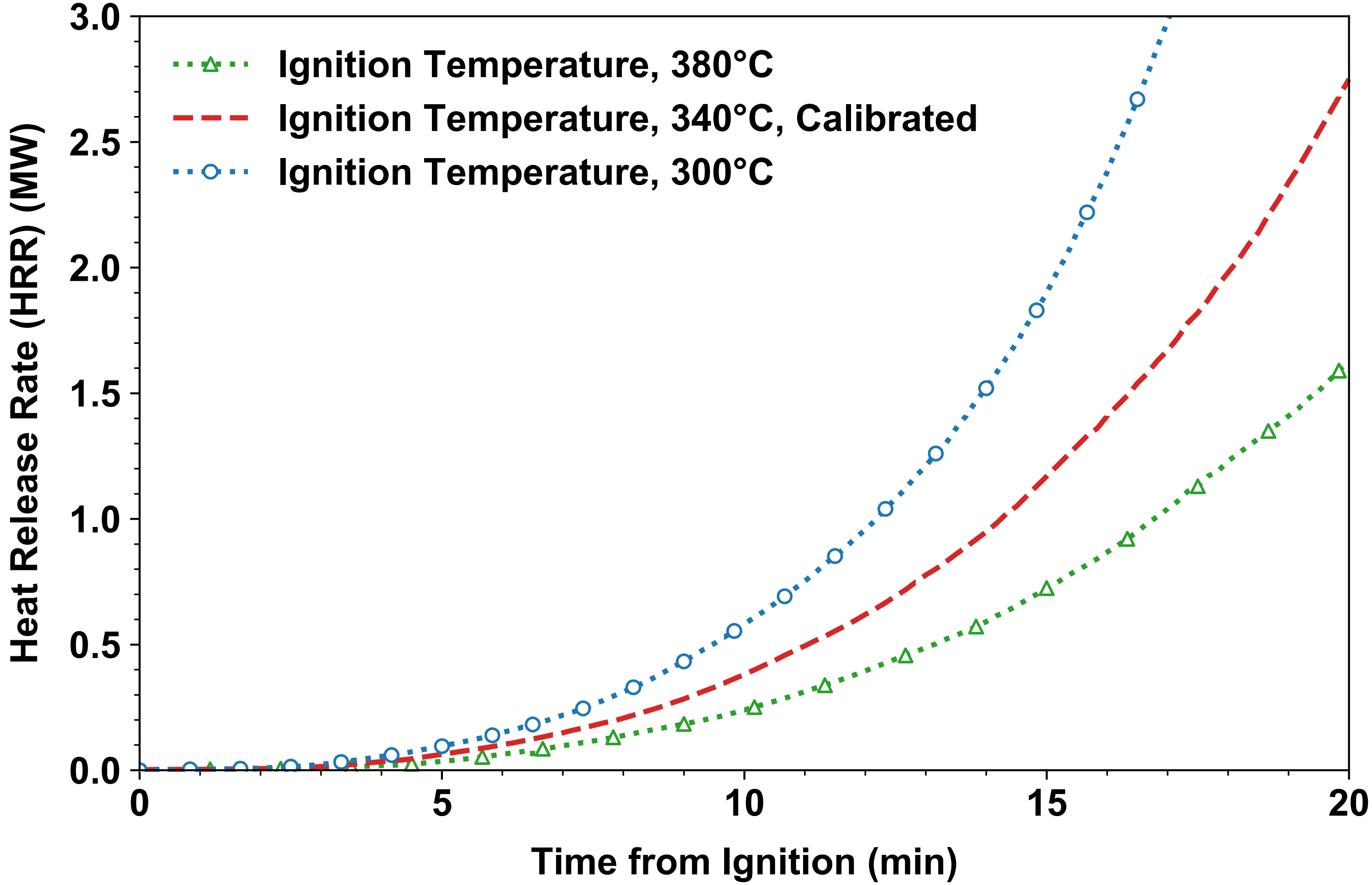

Figure 22. Parameter sensitivity on HRR: a) Ignition temperature of wood

- Ignition temperature
- Soot yield
- Thermal inertia
- HRRPUA
- Emissivity
- Heat of combustion

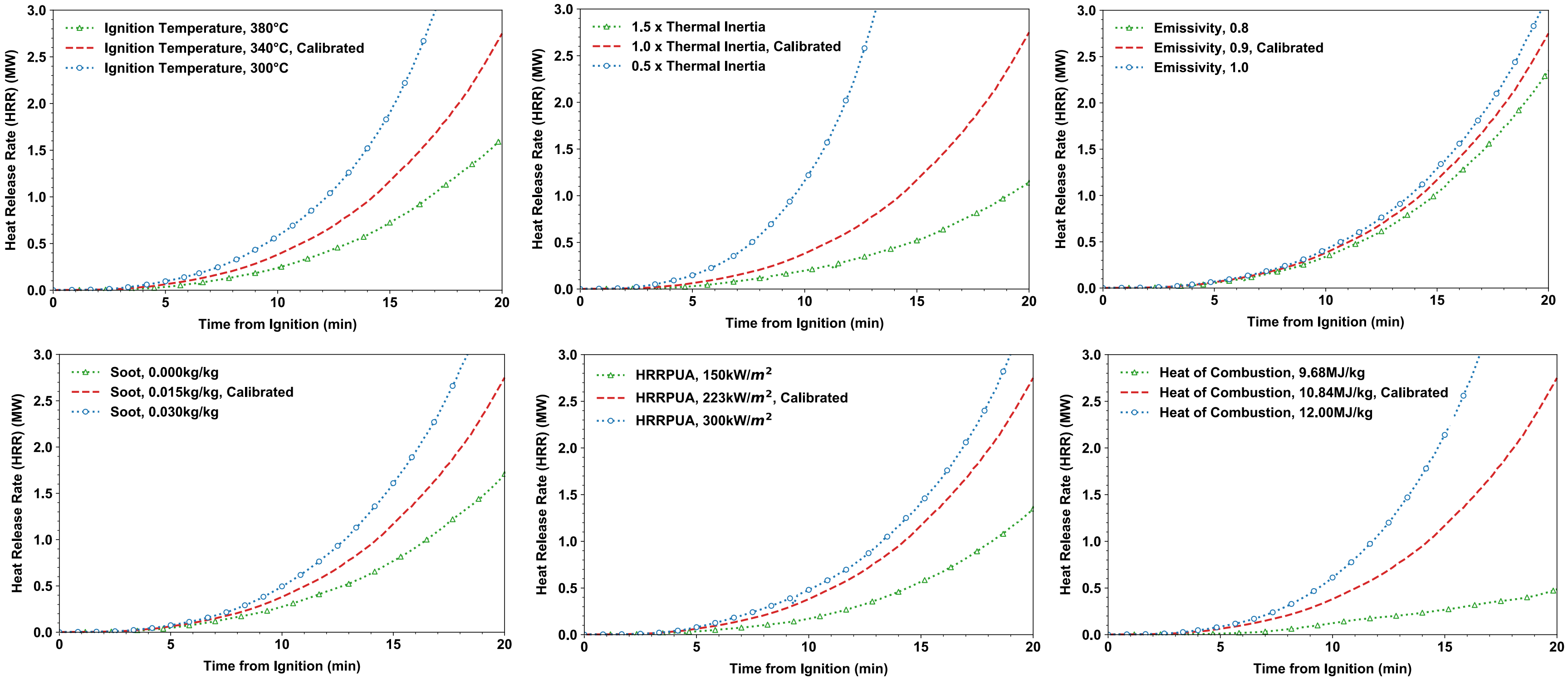

Figure 22. Parameter sensitivity on HRR: a) Ignition temperature of wood, b) Thermal inertia, c) Emissivity of wood, d) Soot concentration (prescribed), e) HRRPUA, f) Heat of Combustion

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- Ignition temperature
- Soot yield
- Thermal inertia
- HRRPUA
- Emissivity
- Heat of combustion

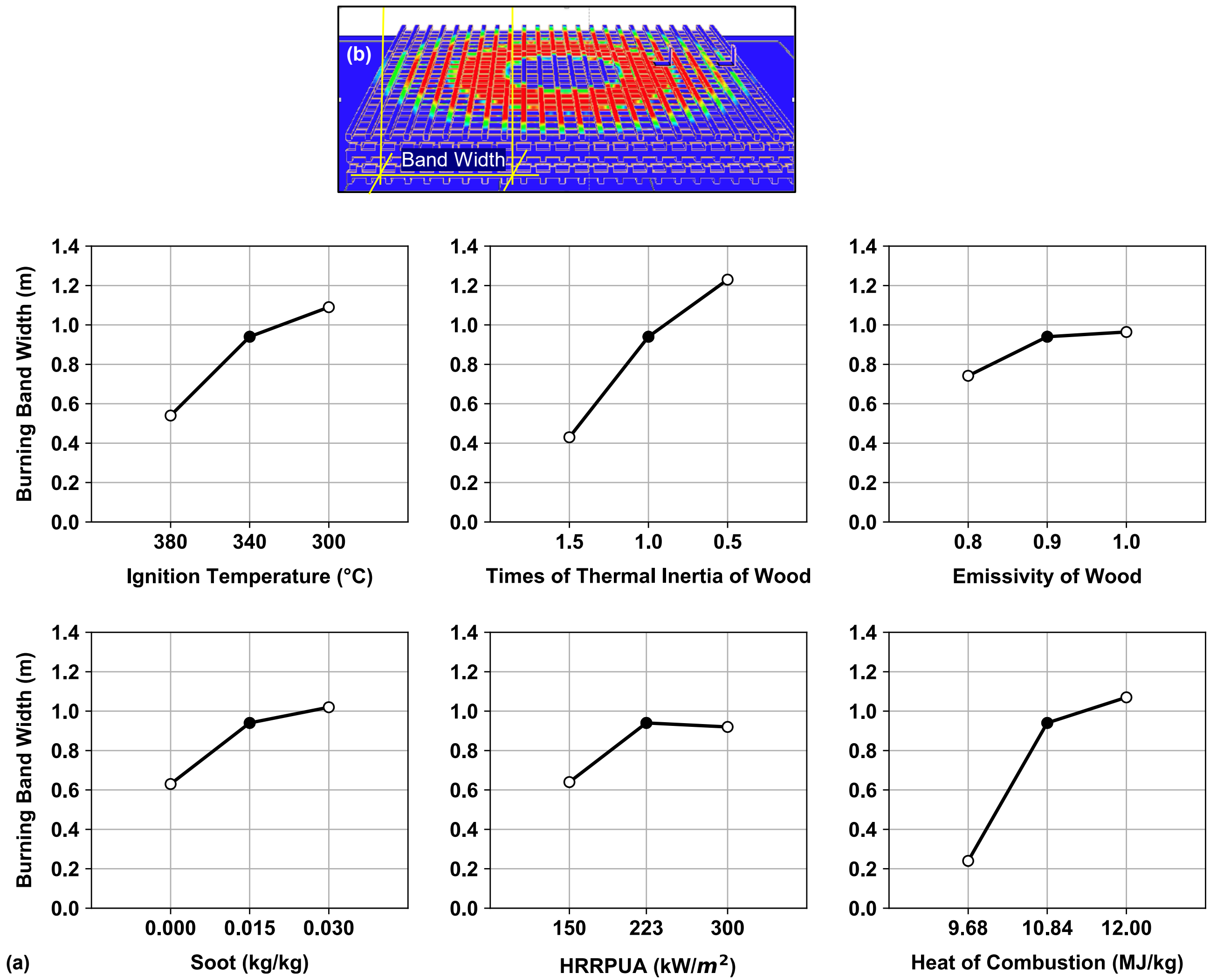

Figure 23. Maximum burning band width with 20 mins simulation (solid black dot: calibrated model).

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- Ignition temperature
- Soot yield
- Thermal inertia
- HRRPUA
- Emissivity
- Heat of combustion

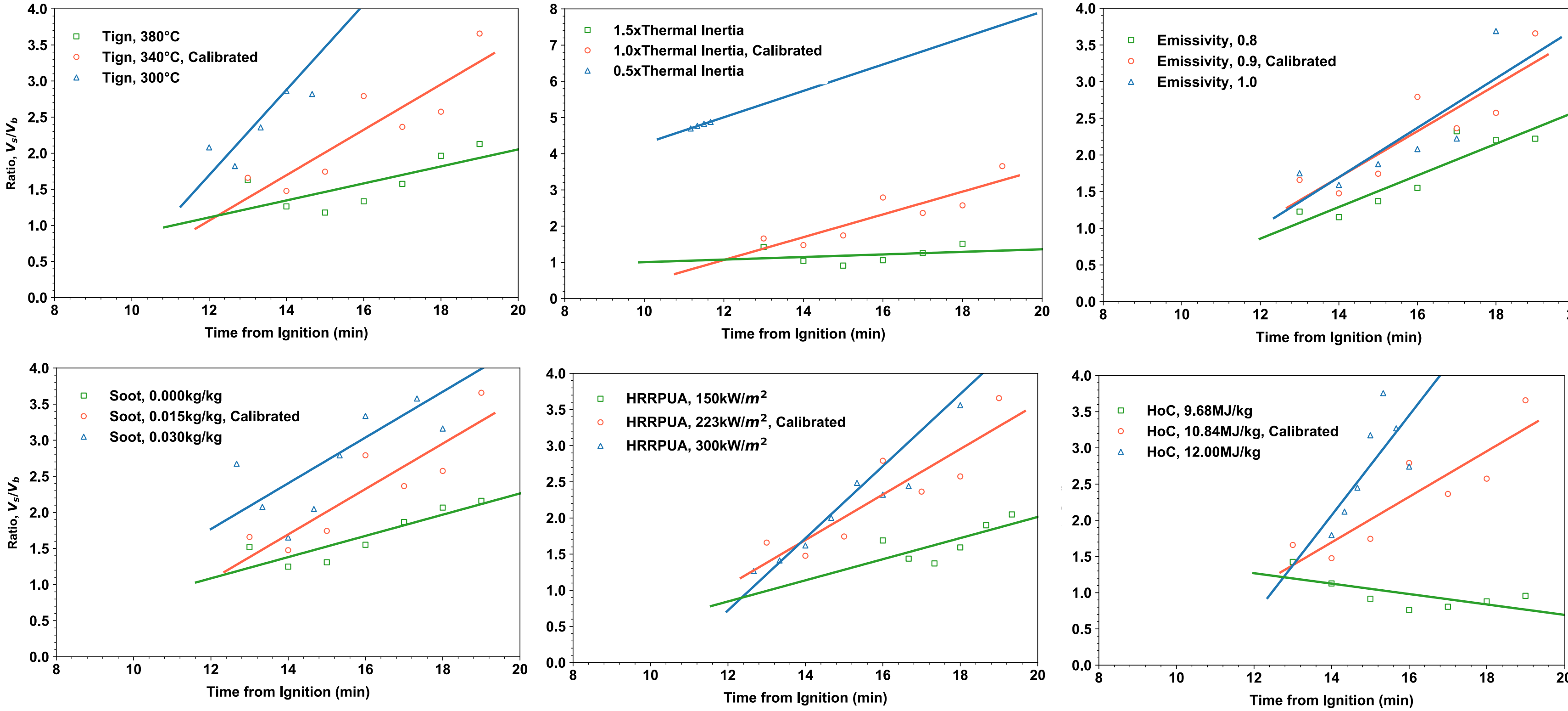

Figure 24. Physical parameter sensitivity on different fire modes.

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- Ignition temperature
- Soot yield
- Thermal inertia
- HRRPUA
- Emissivity
- Heat of combustion

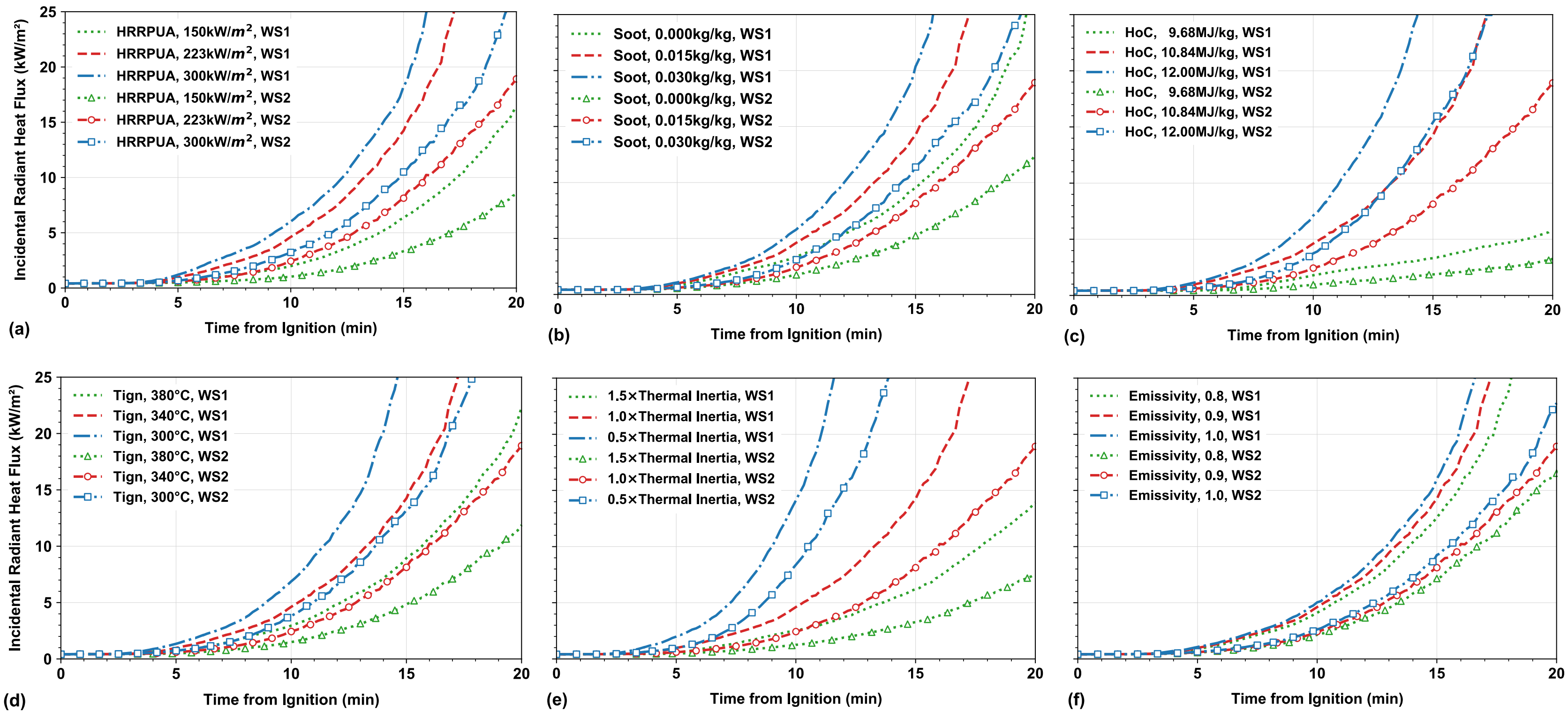

Figure 25. Parameter sensitivity on incidental radiant heat flux at horizontal surface of wood stick 1 (WS1), and wood stick 2 (WS2).

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- Ignition temperature
- Soot yield
- Thermal inertia
- HRRPUA
- Emissivity
- Heat of combustion

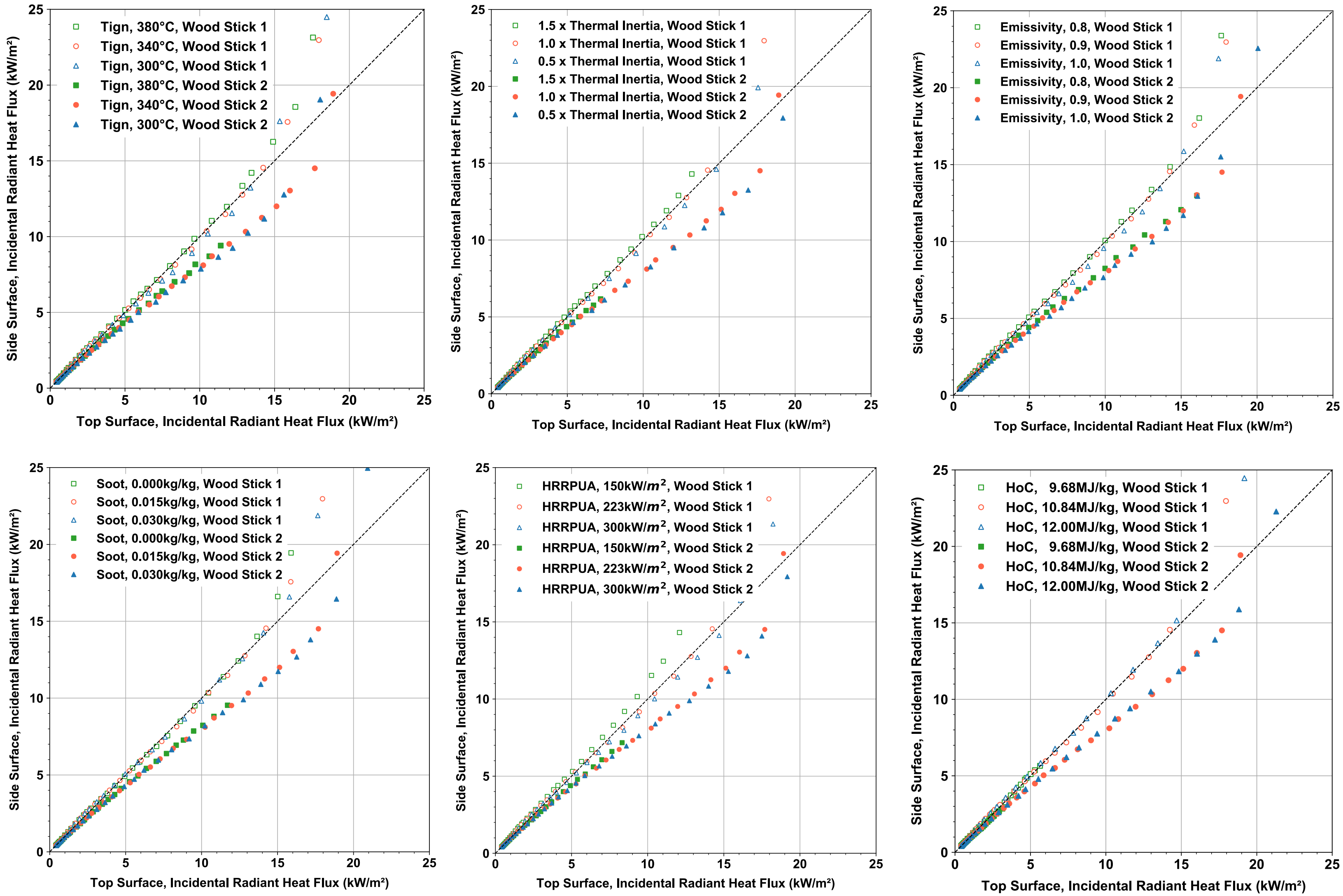


Figure 26. Parameter sensitivity on heat flux comparison between top surface and side surface of wood sticks 1 and 2.

Proposed parameters for the parametric studies

Group 2:

- Ceiling height ✓
- Fuel load density ✓
- Downstand depth ✓

- Ceiling height
- Fuel load density
- Downstand depth

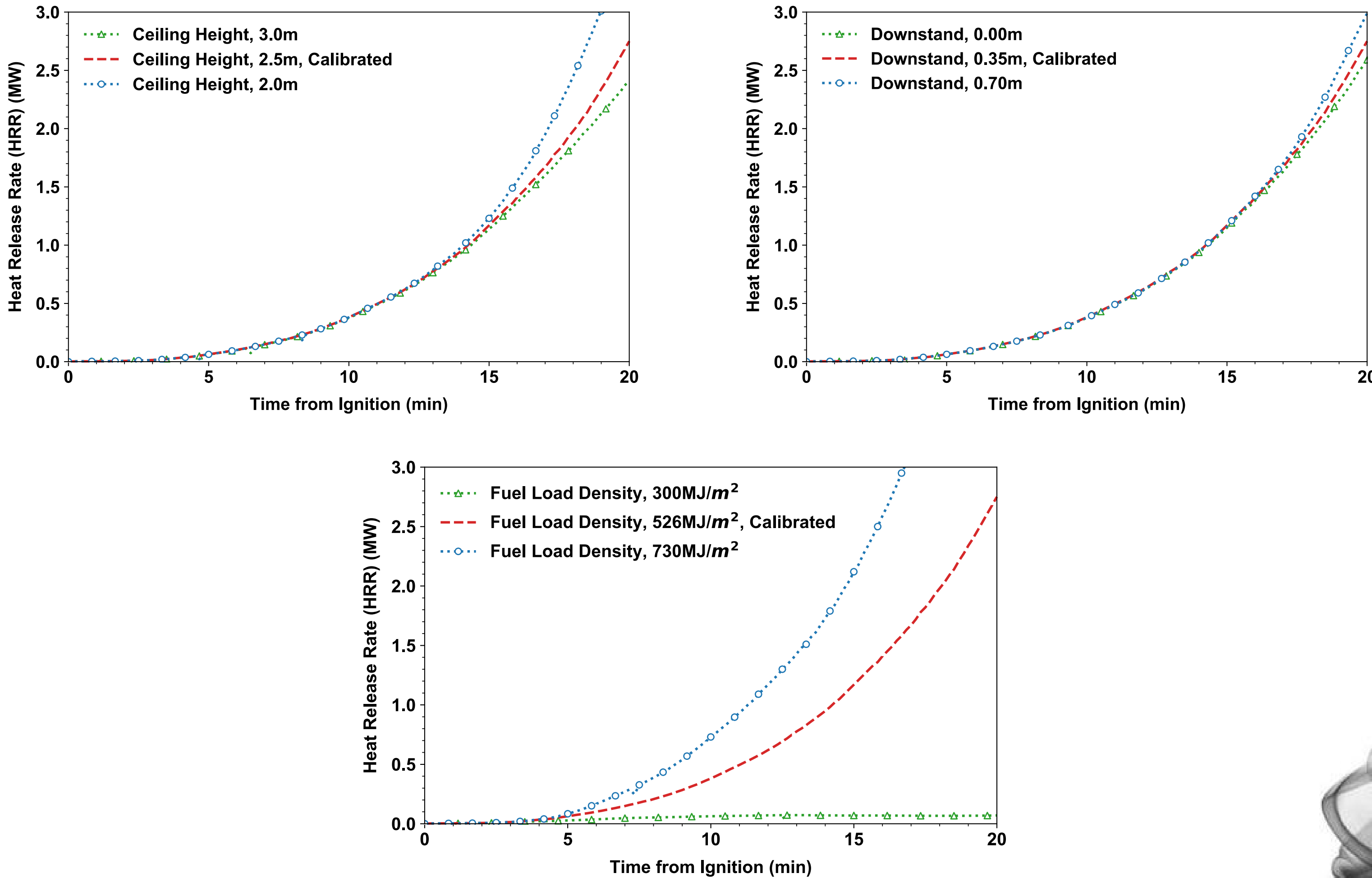
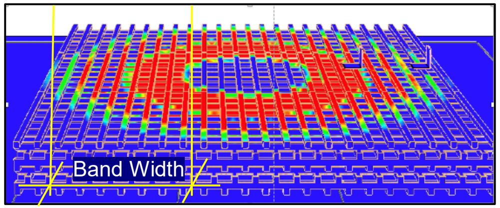


Figure 27. Structural design parameter sensitivity on HRR.

○ **Ceiling height** ○ **Fuel load density** ○ **Downstand depth**



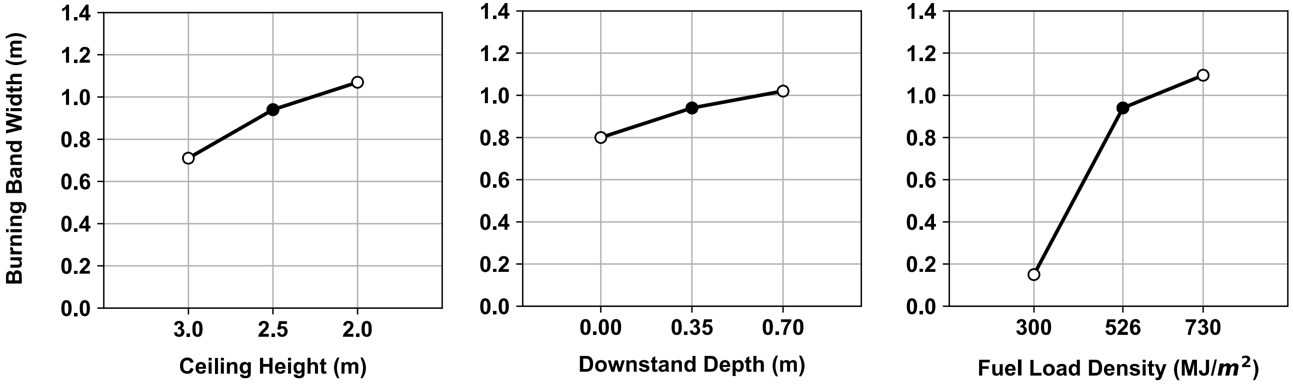


Figure 29. Structural design parameter sensitivity on maximum burning band width with 20 mins simulation (solid black dot: calibrated model).

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○ **Ceiling height** ○ **Downstand depth** ○ **Fuel load density**

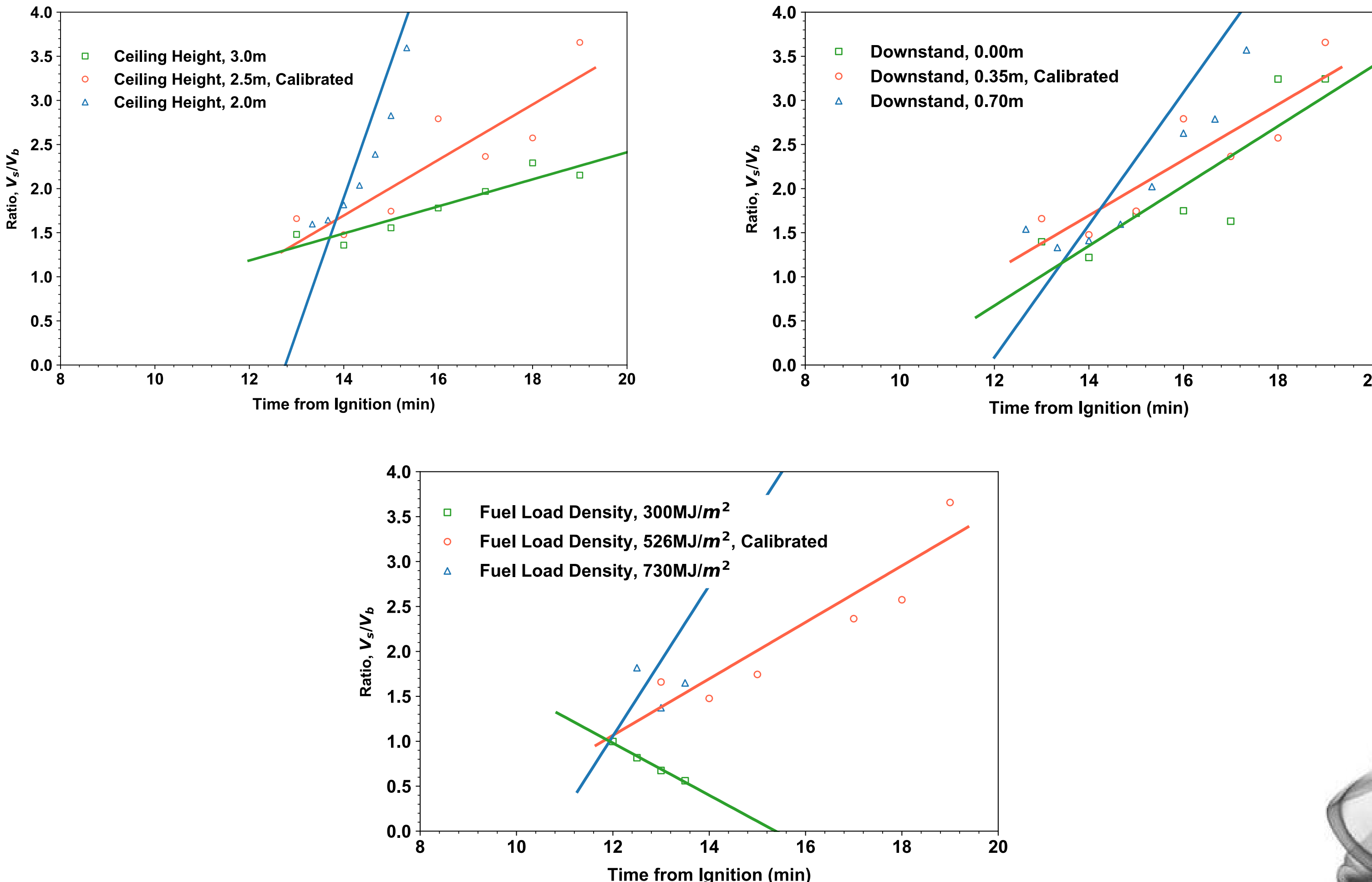

Figure 30. Structural design parameter sensitivity on fire modes.

- **Ceiling height**
- **Downstand depth**
- **Fuel load density**

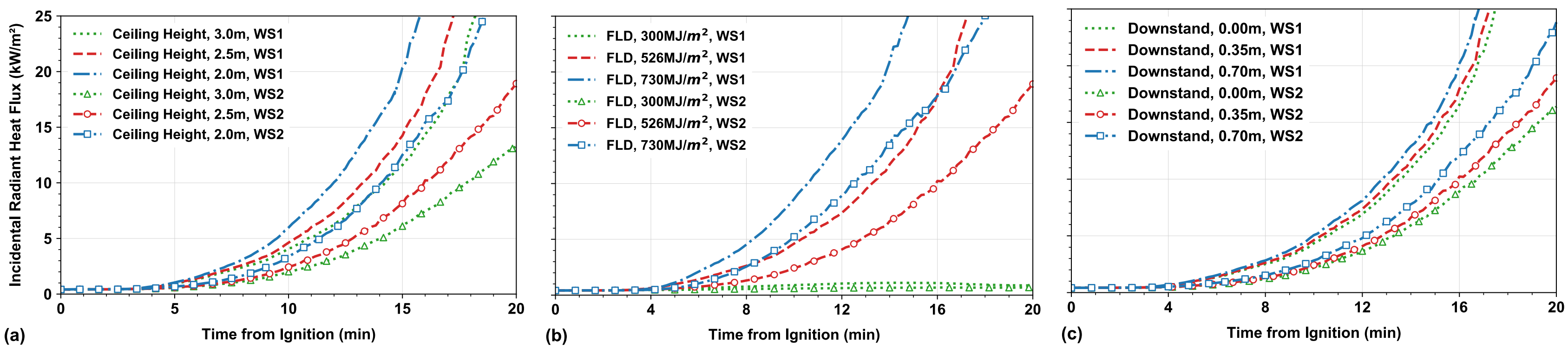

Figure 31. Design parameter sensitivity on incidental radiant heat flux at horizontal surface of wood stick 1 (WS1), and wood stick 2 (WS2).

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- Ceiling height
- Downstand depth
- Fuel load density

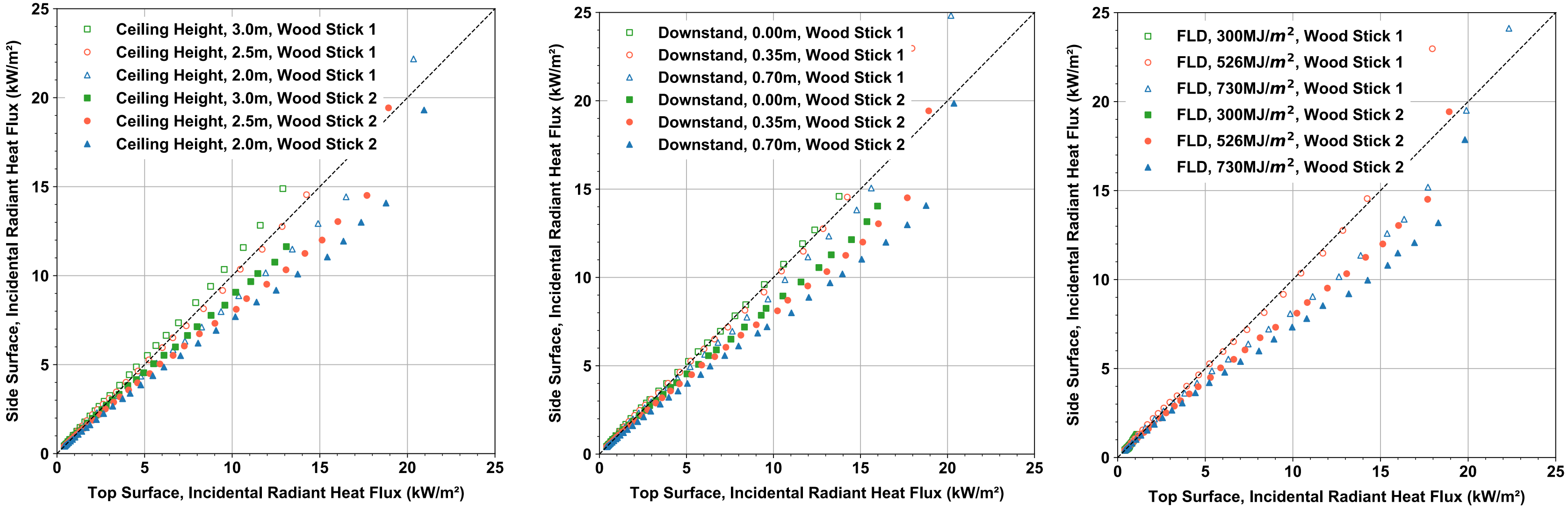
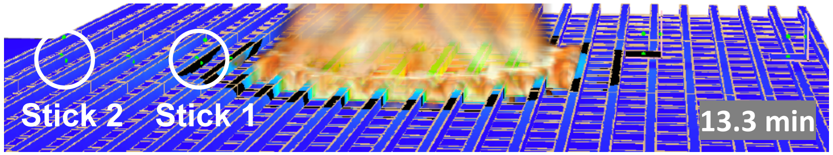


Figure 32. Structural design parameter sensitivity on heat flux comparison between top surface and side surface of wood sticks 1 and 2.

Conditions Leading to Different Fire Modes

Conditions leading to fire modes (summary all 19 cases)

- **heat flux on wood sticks horizontal surface**



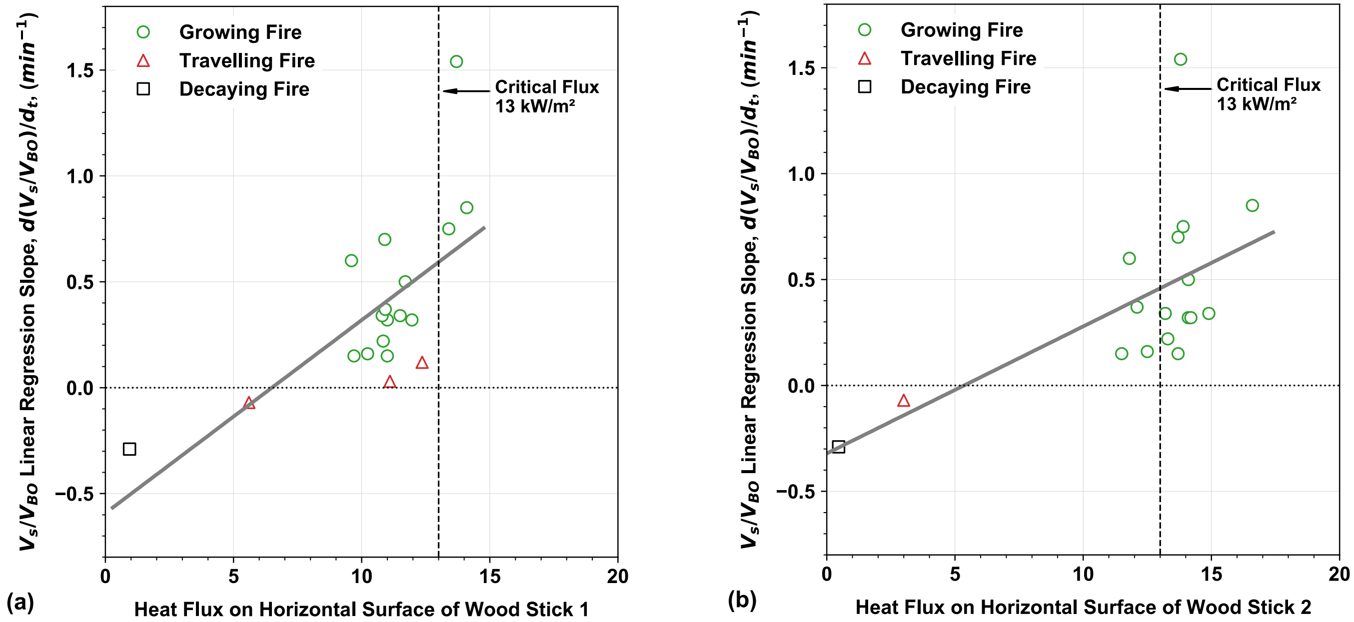


Figure 33. Relationship between fire modes development and heat flux on horizontal surface of (a) wood stick 1, and (b) wood stick 2, 1 min before ignition (summary all 19 cases).

Full scale experiments

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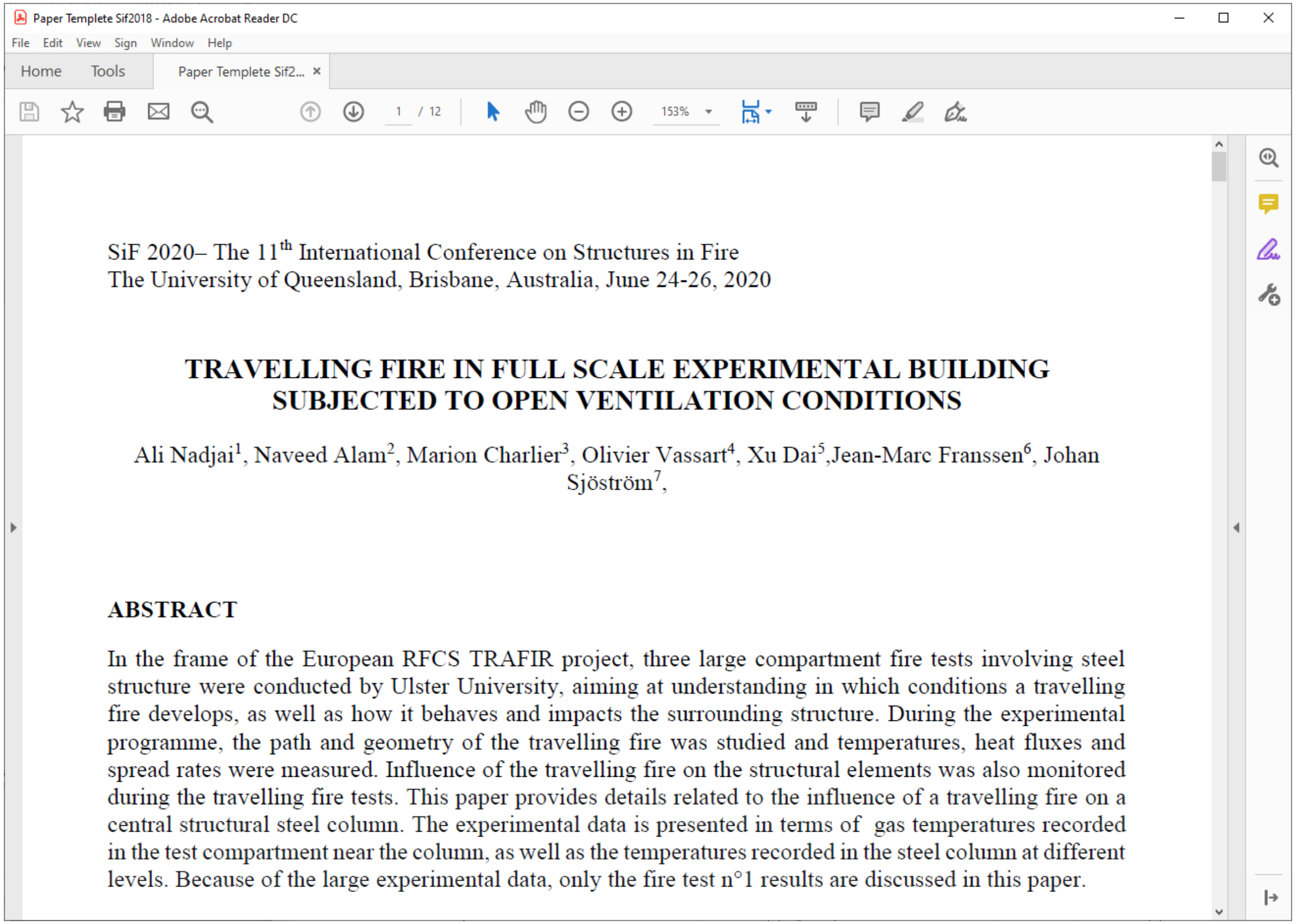

SiF 2020– The 11th International Conference on Structures in Fire
The University of Queensland, Brisbane, Australia, June 24-26, 2020

TRAVELLING FIRE IN FULL SCALE EXPERIMENTAL BUILDING SUBJECTED TO OPEN VENTILATION CONDITIONS

Ali Nadjai[1], Naveed Alam[2], Marion Charlier[3], Olivier Vassart[4], Xu Dai[5],Jean-Marc Franssen[6], Johan Sjöström[7],

ABSTRACT

In the frame of the European RFCS TRAFIR project, three large compartment fire tests involving steel structure were conducted by Ulster University, aiming at understanding in which conditions a travelling fire develops, as well as how it behaves and impacts the surrounding structure. During the experimental programme, the path and geometry of the travelling fire was studied and temperatures, heat fluxes and spread rates were measured. Influence of the travelling fire on the structural elements was also monitored during the travelling fire tests. This paper provides details related to the influence of a travelling fire on a central structural steel column. The experimental data is presented in terms of gas temperatures recorded in the test compartment near the column, as well as the temperatures recorded in the steel column at different levels. Because of the large experimental data, only the fire test n°1 results are discussed in this paper.

Nadjai, A., Alam, N., Charlier, M., Vassart, O., Dai, X., Franssen, J.-M. & Sjöström, J. (2020) “Travelling fire in full scale experimental building subjected to open ventilation conditions”, Structures in Fire 2020, University of Queensland, Brisbane, Australia, 30 November – 2 December 2020 doi:10.14264/987a305

Full scale experiments

Nadjai, A., Alam, N., Charlier, M., Vassart, O., Dai, X., Franssen, J.-M. & Sjöström, J. (2020) “Travelling fire in full scale experimental building subjected to open ventilation conditions”, Structures in Fire 2020, University of Queensland, Brisbane, Australia, 30 November – 2 December 2020 doi:10.14264/987a305

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Wind effects

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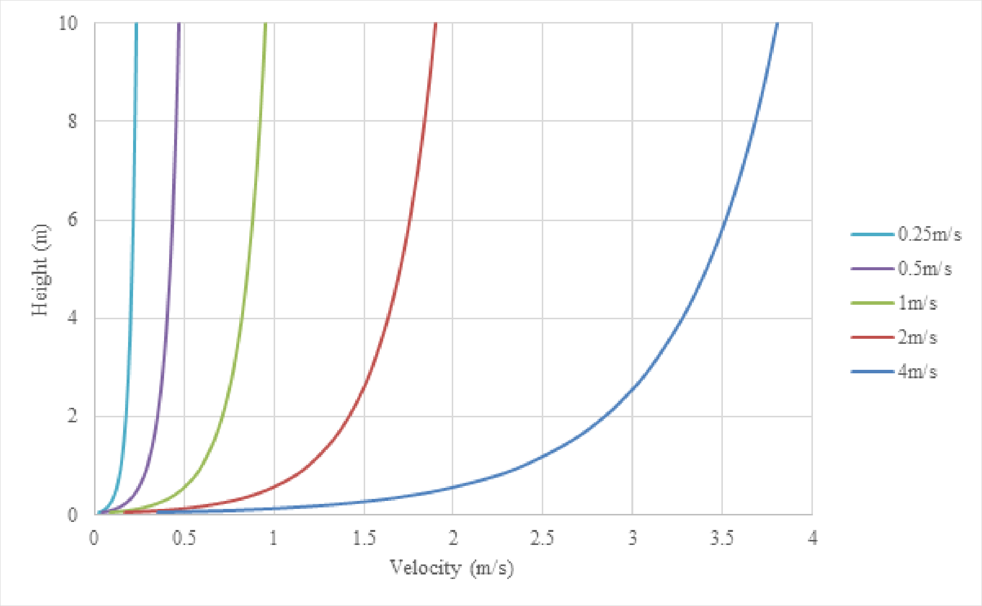
Monin-Obukhov similarity theory for atmospheric boundary condition, including wind speed, u, and corresponding temperature, θ, each are a function of height, z:

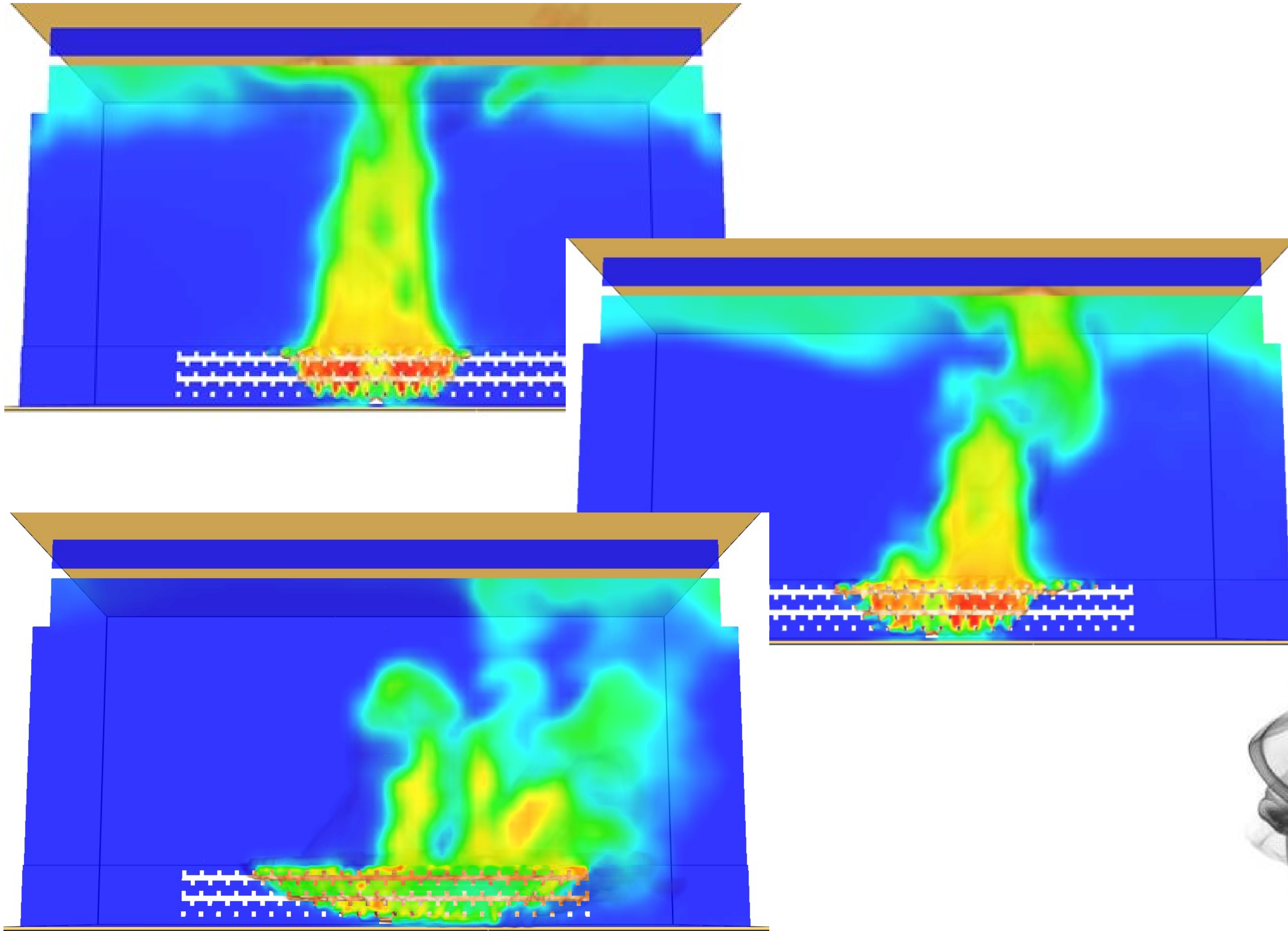
$$u(z) = \frac{u_*}{\kappa}\left[\ln\left(\frac{z}{z_0}\right) - \psi_m\left(\frac{z}{L}\right)\right]$$

$$\theta(z) = \theta_0 + \frac{\theta_*}{\kappa}\left[\ln\left(\frac{z}{z_0}\right) - \psi_h\left(\frac{z}{L}\right)\right]$$



* McGrattan, K., Hostikka, S., Floyd, J., McDermott, R. & Vanella, M. (2017) Fire Dynamics Simulator, User's Guide, NIST Special Publication 1019, 6th ed., National Institute of Standards and Technology (NIST), Gaithersburg, Maryland, USA/VTT Technical Research Centre of Finland, Espoo, Finland.

Wind effects (0, 2, 4 m/s)



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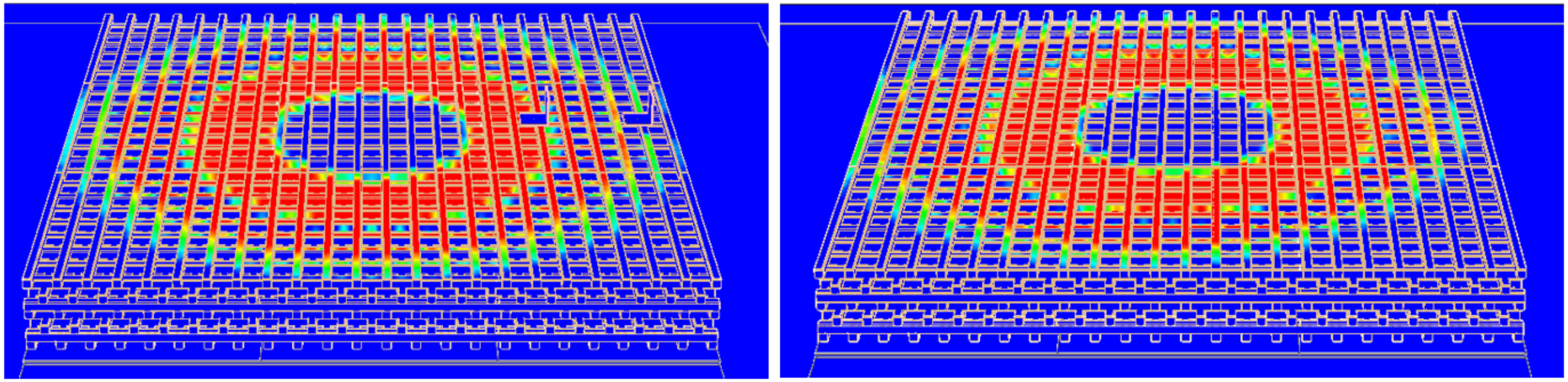
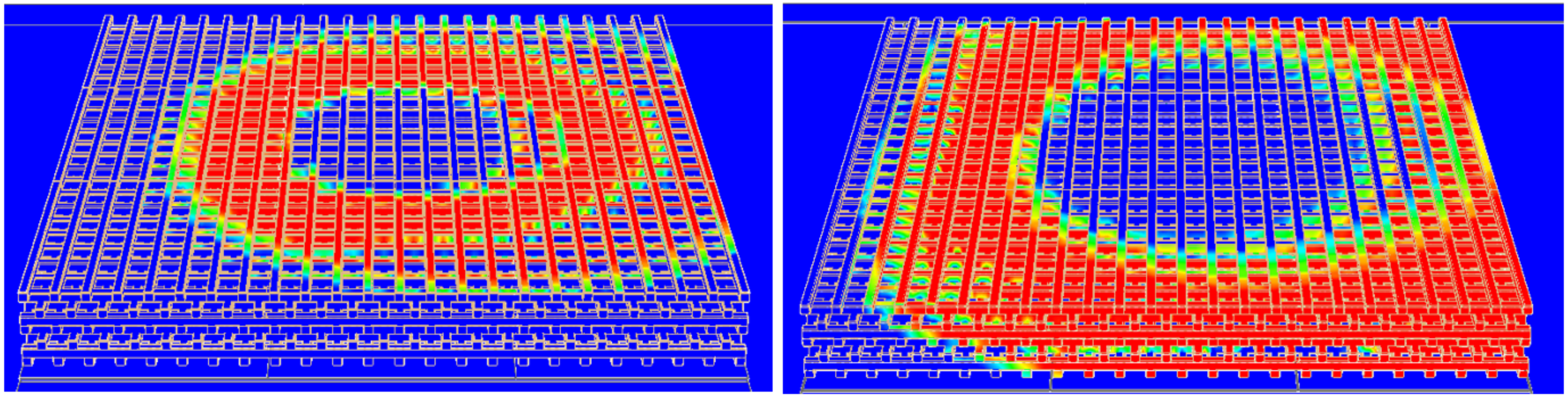
Wind effects – flux analysis


(a) (b)


(c) (d)

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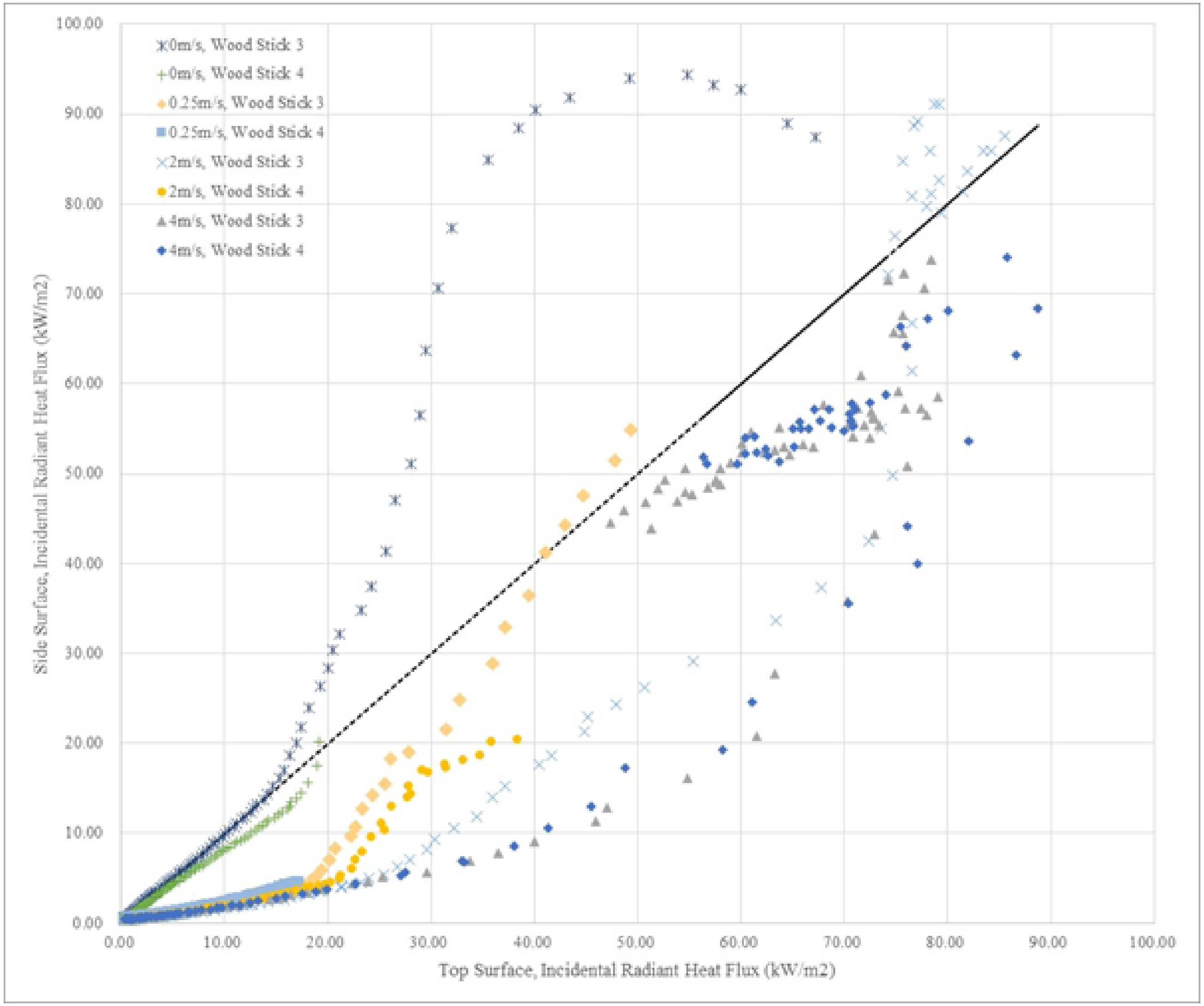
Wind effects – flux analysis



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Conclusions (1)

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- Downstand tends to play a role when the fire proper develops, i.e. when it impinges the ceiling; lower ceiling height is more likely to drive the fire to run away, as wood stick ignition mechanism shifts from side surface-driven to top surface-driven, in which the heat flux is larger
- Soot is a very important input parameter on affecting heat flux magnitude on wood stick surfaces
- Results are strongly related to adopted Heat of combustion via a mass transfer number (cf. Gupta *et al*. 2020)
- Thermal inertia is a crucial input parameter which may determines fire spread mechanism, from travelling, to spreading, and even to flashover
- Emissivity: the heat flux relationship analysis suggests may promote a travelling fire when $top_{heat\ flux}/side_{heat\ flux} < 1$
- Fuel load density, higher value => spreading/flashover fire
- HRRPUA, lower value tends to yield a travelling fire

Conclusions (2)

- Reconstruction of a uniform wood fuel bed for fire spread, is achieved through using a stick-to-stick model with simple pyrolysis and an ignition temperature setup. Compared with previous research the results show more parameters being comparable to the full suite of test data, suggesting potential credibility of the model for predicting fire spread rate, flame temperature, incidental radiant heat flux, burning away, and most importantly, the total HRR.

- The mesh scheme was implemented using finer mesh at the solid phase and relatively coarse mesh at the gas phase, provides an alternative solution for modelling such crib fires, with potential for scaling up to compartment level.

Acknowledgements (1)

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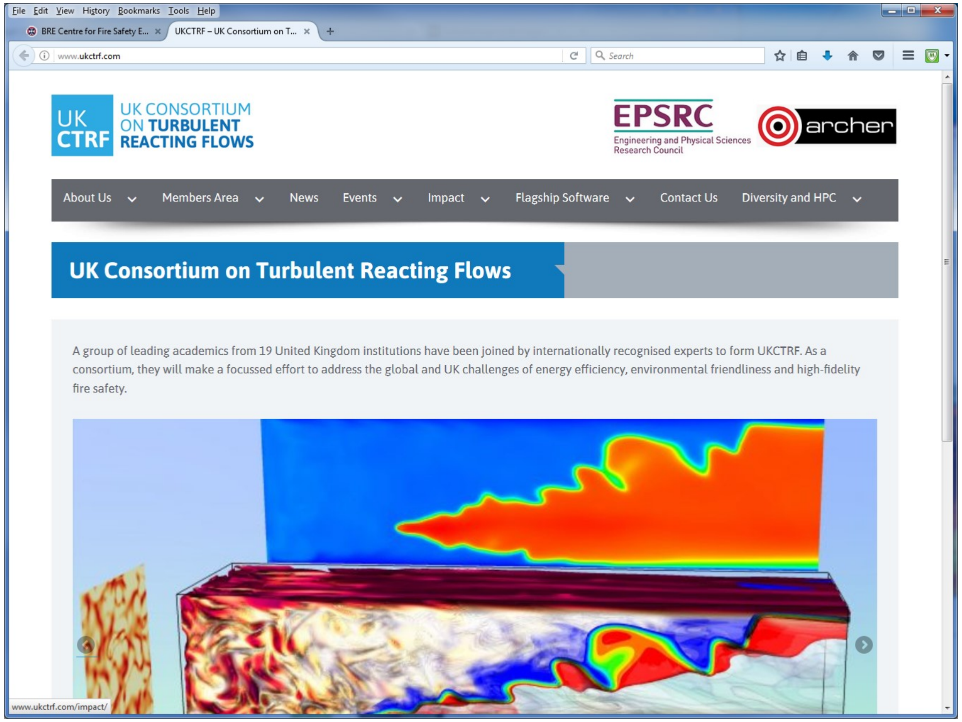
UK CTRF UK CONSORTIUM ON TURBULENT REACTING FLOWS

EPSRC Engineering and Physical Sciences Research Council

archer



EPSRC EP/R029369/1: Addressing Challenges Through Effective Utilisation of High Performance Computing – a case for the UK Consortium on Turbulent Reacting Flows (UKCTRF)

https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/R029369/1

Acknowledgements (2)

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Fire degree project students

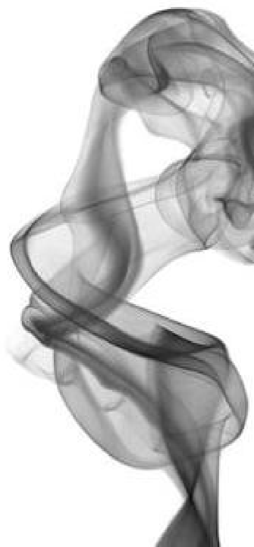
Structural and Fire Safety Engineering Dissertation (90 credits)
MEng thesis (50 credits)

19/20 students

- **Chang Liu (SAFE), Yang Xu (SAFE)**

20/21 students

- **Peter Charley (MEng), Chang Liu (SAFE)**



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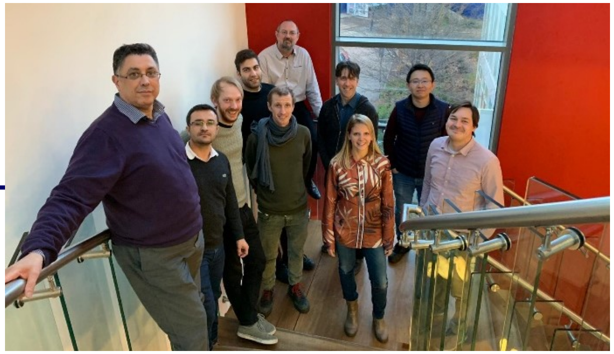
Acknowledgments (3)



TRAFIR Project

Characterization of TRAvelling FIRes in large compartments

Funding from the Research Fund for Coal and Steel (RFCS) - European Commission

European Commission

Industrial led – ArcelorMittal
(1/07/2017 → 31/12/2020)

- **testing** (isolated elements and simplified fire progression, as well as a full-scale large compartment)
- **modelling** (both simplified analytical/phenomenological models and CFD).

Project partners:

ArcelorMittal

Université de Liège

RI. SE

Ulster University

The University of Edinburgh

Edinburgh fire

BRE Centre *for* Fire Safety Engineering

- Colleagues and students:
  - 8 Academic Staff (+1 retired)
  - 6 Research staff
  - c. 20 PhD Students
  - 25+ MSc students
  - ~10 pa UG students
  - Visiting researchers
- External Relationships:
  - EPSRC
  - ArcelorMittal (RFCS TRAFIR project)
  - BRE Trust (FireGrid, PhD Intelligent Egress)
  - Fire & Rescue Services
  - International academic/research partn
    - UQ (Hidalgo, Maluk, Lange, Gupta…)
    - CVUT Prague (Wald, Horová…)
    - RISE (Sjöström, …)
    - Liege (Franssen, Gamba…)
    - Ulster (Nadjai, …)


Questions?