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“SCALING-UP” FIRE SPREAD ON WOOD CRIBS TO PREDICT A LARGE-SCALE TRAVELLING FIRE TEST USING CFD

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ABSTRACT

Simulation-based approaches for characterising the fire behaviour of travelling fires in large compartments are a potentially valuable complement to experimental studies, providing useful insights on evolving boundary conditions for structural response. They are attractive in reduced costs and the possibility of carrying out systematic parametric studies free from some of the experimental uncertainties, but sufficiently general models have not been previously demonstrated. Here, we explore the potential for “scaling-up” a “stick-by-stick” CFD model which had been carefully calibrated against the results of experiments on an isolated crib, of 2.8 m diameter, to a uniformly distributed fuel bed of extent 4.2 × 14.0 m located within an open compartment 9 × 15 m in plan, with an internal height of 2.9 m. The results in terms of the fire spread and burn out predictions are very encouraging, and the heat release rate evolution is also consistent with the experimental value. There are some discrepancies in predicted gas phase temperatures, nevertheless, such discrepancies with this aspect of the model are unlikely to have any great significance in the prediction of fire spread on a horizontally orientated flat fuel bed, which is the prime interest of the current work. Thus, the established “numerical simulator” looks to have good potential as a tool to explore and characterise the behaviour of travelling fires subject to different compartment boundary conditions.

Keywords: Flame spread; CFD modelling; FDS; Large-scale wood crib fire tests; Travelling fires

1 INTRODUCTION

One of the key foundations in fire engineering is the compartment fire, which is used to describe a fire confined within an enclosure. Travelling fires are now regarded as a very relevant fire scenario in large compartments, following research in the past decade towards providing simplified design tools for performance-based structural fire design [1, 2]. Typical features of this fire scenario are the fire plume in the near-field and the hot smoke layer providing pre-heating in the far field. Once the fire is “travelling”,

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the near-field has a leading edge representing the fire spread, and a trailing edge representing the burnout of the fuel [3, 4].

In the long development history of experimental and theoretical treatments for compartment fires wood cribs were often adopted as the main fuel. Examples of this include: the pioneer compartment fire theory by Harmathy in the 1970s [5], the full-scale tests for Natural Fire Safety Concept for Eurocodes in 2000s [6], and various travelling fire test series in 2010s [2]. Nevertheless, the experimental costs for travelling fires are particularly high, as they require very large experimental compartments (usually > 100 m^2); time-consuming intensive test instrumentation work; and significant demands on resources and staffing, an example being the recent TRAFIR Ulster Travelling Fire Test series [7-9]. This is due to the essential nature of the travelling fires, with the requirement to adequately characterise the spatial and temporal variation of thermal boundary conditions for the extensive structural elements, inside the very large open-plan compartments which are of interest for structural fire engineering design.

2 RESEARCH OBJECTIVES AND METHOD

This paper aims to push the boundaries of fire modelling using CFD via "scaling-up" a calibrated model, to explore if an adequate level of fire spread prediction can be achieved at a large compartment scale for an idealised fuel bed (i.e., uniformly distributed wood crib). If the predictive capability could be demonstrated in the fire modelling field, it means "numerical experiments" can be potentially performed in the future for assessing underlying physical mechanisms that are currently out of reach through traditional large-scale onsite experiments. This would go some way to addressing the issues with the high expense of the large compartment fire tests for travelling fires.

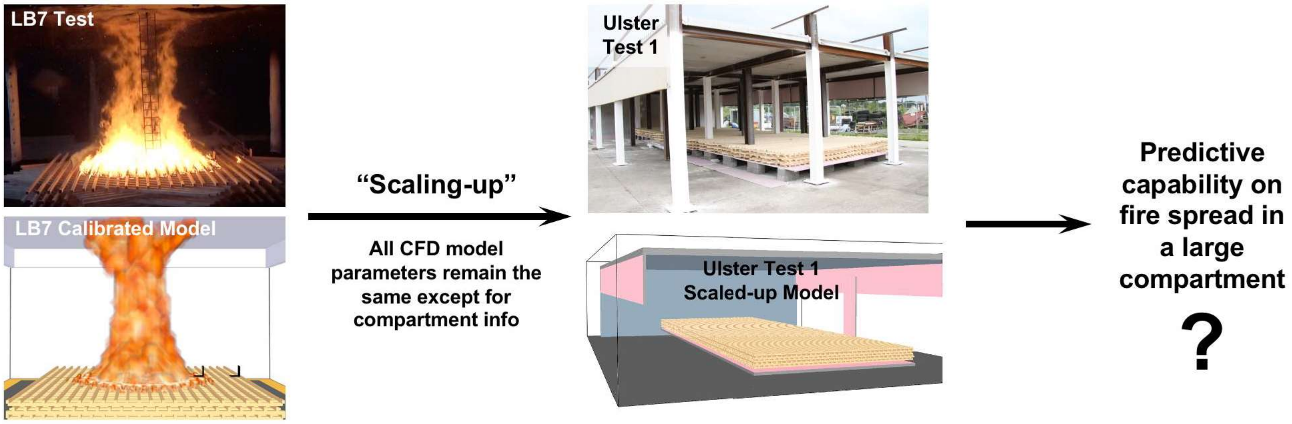

Figure 1. Research method in this paper.

The research method relies on "scaling-up" the model for fire spread calibrated on a single wood crib test (i.e., LB7 Test) [10], to a large-scale compartment travelling fire test with an extended wood crib distribution (i.e., Ulster Travelling Fire Test 1) [7]. Both the calibrated model and the scaled-up model have an identical high resolution for wood crib fuel bed representation (i.e., stick-by-stick). During the "scaling-up" exercise, all the CFD model setup parameters (e.g., wood characteristics) remain strictly the same except for updating the compartment dimensions (9 × 15 × 2.9 m in height). Then the method credibility could be assessed via comparing the scaled-up CFD model prediction against the large-scale compartment fire test measurements, as illustrated in Figure 1. The assessed parameters include fire spread, burn-away, heat release rate, gas phase temperatures, and incident radiant heat flux on the fuel bed.

Note that the CFD model presented in this paper is fundamentally different from that of one earlier publication [11], which used larger "wood block" objects to represent the fuel load as a simplification, with a direct model calibration against the same large-scale compartment travelling fire tests [7-9]. In theory the approach presented in this paper should result in a more general model, provided the wood crib specification is maintained, i.e., the one which does not require further calibration at a large compartment scale. It therefore provides a potential method with predictive capability on fire spread, as a cost-effective alternative to large-scale structural fire testing for travelling fires.

3 THE “SCALED-UP” CFD MODEL

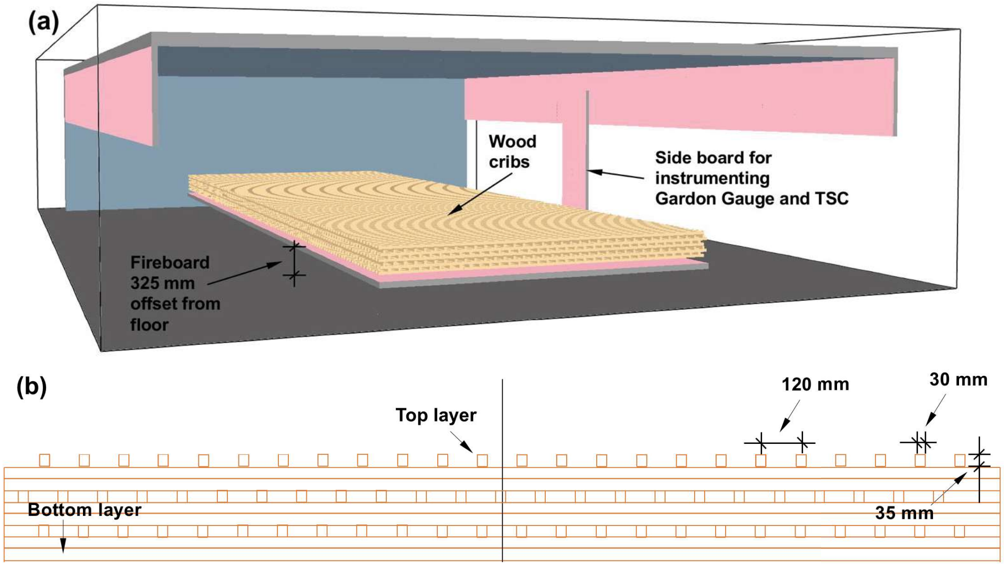

Figure 2. The “scaled-up” CFD model, (a) Skewed view, and (b) Representation of the wood sticks in side-elevation view.

As explained earlier, the “scaled-up” CFD model for the Ulster Travelling Fire Test 1 strictly inherited all the setup parameters from the calibrated model for the LB7 test (e.g., wood characteristics [10]), except for updating the dimensions of the compartment, fuel bed, and test rig, as shown in Figure 2 (a). The 2.8 m × 2.8 m square wood crib with nine layers of sticks in the calibrated LB7 model was extended to a 14.0 m × 4.2 m rectangular wood crib with the same wood sticks arrangement for the Ulster Test 1 [7]. Note that both the calibrated model and the scaled-up model had the same high resolution for wood crib fuel bed representation 30 mm (breadth) × 35 mm (height), referred as “stick-by-stick” models, see Figure 2 (b). Further, the cell size of the “scaled-up” model within the crib volume was 15 mm × 15 mm × 17.5 mm (i.e., half that of the physical dimensions of the sticks, the same as the calibrated LB7 model). Sensitivity studies on grid cell size for representing heat release rate (HRR) and the fire spread on the wood crib top layer were demonstrated in the calibrated LB7 model study [10].

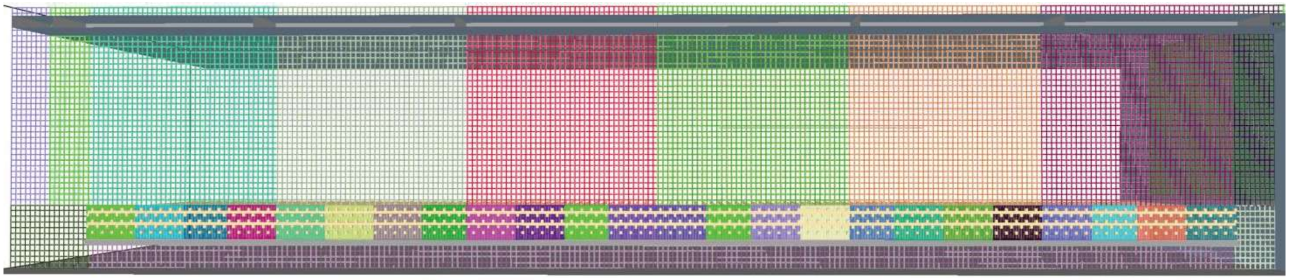

Figure 3. Grid cell resolution of the model: 15 mm × 15 mm × 17.5 mm per cell for the wood sticks at solid phase, 60 mm × 60 mm × 70 mm and 30 mm × 30 mm × 35 mm cell size at the gas phase, total number of cells ~8.3 million with 125 meshes.

The cell size of the gas phase in the horizontal surrounds of the crib, as well as above the top surface of the crib was 60 mm × 60 mm × 70 mm, see Figure 3. In addition, to better represent the heat transfer process at the crib top surface, an additional layer was inserted with two cells of identical size as in the fine mesh, functioning as a “transition layer” between the crib and the gas phase. The total computational domain size was 16.20 m × 10.20 m × 3.22 m, thus the total number of cells was approximately 8.3 million, which were divided into 125 meshes and each mesh was assigned to a single MPI process on the computational cluster. The simulations were performed using the compute cluster ARCHER2 [12], with the run taking around 40 days clock time of computation to complete a 7200 s simulation for the Ulster Test 1.

The compartment ceiling, back wall, downstands, and fireboard platform for supporting the wood sticks were all represented in the model according to the exact dimensions in the test. The material thermal properties for the compartment boundaries are summarized in Table 1. The moisture content of the normal weight concrete (NWC) was assumed to be 10%, which was equivalent to the water saturated status due to the consistent rain on the test day. Moisture migration, *per se*, was neglected in the model, but its energetic influence was considered via a modified specific heat value. In addition, the compartment test floor adopted the same NWC material, also with 10% moisture. The concrete blocks below the fireboard platform were not included in the model due to its limited impact on heat transfer for the wood cribs above. An elevated vertical fireboard screen located externally beside the wood cribs for Thin Skin Calorimeter (TSC) and Gardon Gauge (GG) instrumentation was also represented in the model, as shown in Figure 2 (a).

Table 1. Summary of the compartment thermal properties in the "scaled-up" model (Temperature, T, unit in ℃).

Material	Density (kg/m^3)	Emissivity	Conductivity ($W\ m^{-1}K^{-1}$)	Specific heat ($kJ\ kg^{-1}K^{-1}$)	References
Normal weight concrete (10% moisture)	2300	0.8	1.6	T=20, F=0.9 T=100, F=0.9 T=115, F=5.6 T=200, F=1.0 T=400, F=1.1 T=1200, F=1.1	Eurocode 2 [13]
Fireboard	900	0.89	0.24	1.25	SFPE Handbook [14], Kirby et al. [15]
Rockwool Flexi	45	0.9	0.09	0.66	Rockwool [16]

The igniter for the "scaled-up" model herein was simplified as being the same for the calibrated LB7 model, accounting for the fact that prediction of the initial ignition stage was not regarded as a prime research interest in this study, and also to minimise the modelling uncertainties for this "scaling-up" exercise due to the ignition difference between the Ulster Test 1 and the LB7 test. As explained in our earlier publication [10], the ignitor was modelled as a square burner with dimensions of 90 mm × 90 mm, prescribed with a 323 kW/m^2 HRRPUA (heat release rate per unit area) lasting for 240 s to ensure the energy and mass are conserved for the 40 ml of methylated ethanol at 96% used in the LB7 test.

Furthermore, thermocouples and incident radiant heat flux measurement devices (e.g., TSC/GG) in the model were placed at the same locations as the experimental instrumentations. Thermocouples were represented in FDS using a value of 1.5 mm bead diameter and emissivity of 0.85.

4 COMPARISON BETWEEN THE MODEL AND THE TEST

Due to the ignition difference between the Ulster Test 1 and the "scaled-up" model (inherited from the LB7 calibrated model), it should be noted that a 13 mins fire development delay was consistently applied to all the modelling results herein, including fire spread, burn-away, HRR, gas phase temperature, and incident radiant heat flux. This 13 mins offset was determined by matching the initial spread away from the burner, which itself is only represented approximately in the simulation.

4.1 Fire spread & burn-away

Figure 4 demonstrates the fire spread comparison captured from the video recording of the Ulster Travelling Fire Test 1 and the FDS Smokeview (a visualisation tool supplied with FDS) at 20-minute intervals. In the model, the fire spread was represented with the gas temperature "slice" at the centreline of the compartment along the fire trajectory (elevation view), and via the burning rate of the wood cribs fuel bed (plan view). Figure 4 suggests the simulated fire spread on the wood sticks top layer and the flame shape are both qualitatively comparable to the test observation.

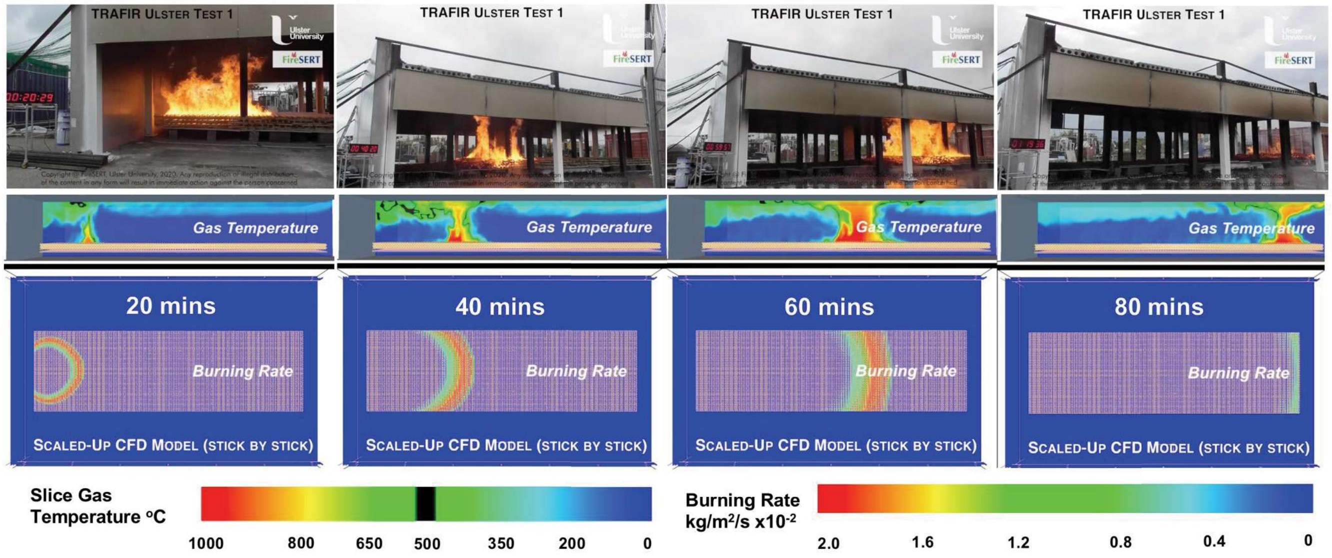

Figure 4. Scaled-up CFD model predicted fire spread comparison with the test, at 20 mins, 40 mins, 60 mins, and 80 mins.

Looking closely at the comparison of the fire spread and burn-away in Figure 5 (a), both the fire leading edge and the trailing edge of the model and the test are in remarkably good agreement, though for the stage after around 50 mins the model showed a slight 2-3 mins delay compared with the test until the fire reached 14.0 m, i.e. the fuel bed far end, at 67 mins. Figure 5 (b) shows the fire spread rate of the model gradually increased with the fire development, from 0 mm/s to 7 mm/s, generally in line with the trend observed in the test.

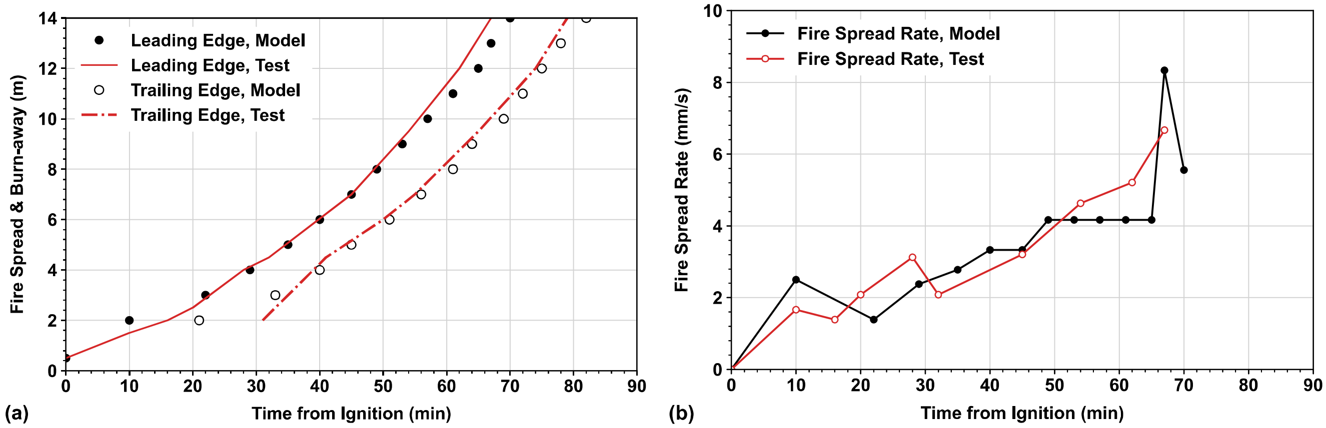

Figure 5. Comparison between the test and the model at compartment centreline along fire trajectory, (a) Fire spread distance & burn-away, and (b) Fire spread rate.

In the literature of the large-scale compartment fires, three fire "modes" were identified at the Malveira Fire Test [17] and similarly at the Tisova Fire Test [18], with both of them having a steady travelling fire, a growing fire, and a fully developed fire. Those three fire modes were quantified through the relationships between the velocity of the fire spread front, V_s, and the velocity of the fire burnout front, V_{BO}. Hence, a travelling fire mode refers to $V_s/V_{BO} \approx 1$, a growing fire mode means $V_s/V_{BO} > 1$, a decaying fire mode means $V_s/V_{BO} < 1$, and a fully developed fire mode is equivalent to $V_s/V_{BO} \rightarrow \infty$. Figure 6 demonstrates the fire mode comparison between the model and the test. It shows that the ratios of V_s/V_{BO} were both close but slightly higher than 1 at a later stage, indicating that the travelling fire mode was gradually trending towards a growing fire mode both in the model and the test.

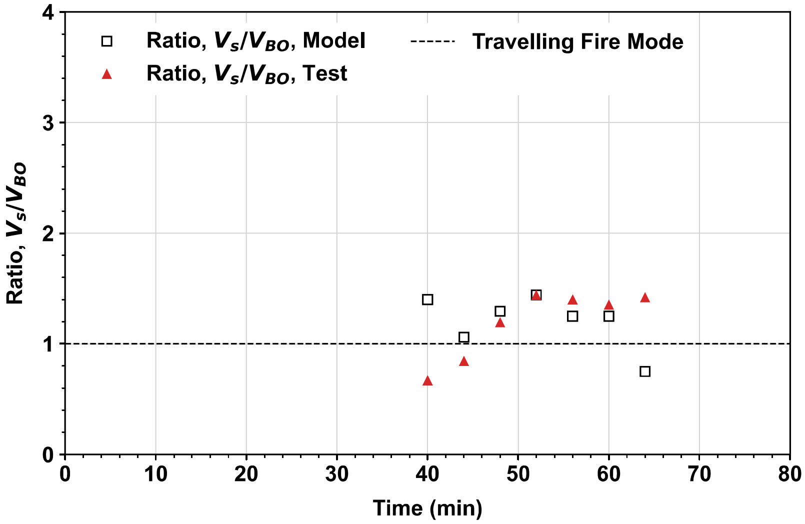

Figure 6. Comparison on fire mode, V_S/V_{BO}: velocity of the flame spread front to velocity of the flame burnout front.

4.2 Heat release rate (HRR)

In the experiment, the mass loss for *part* of the continuous fuel bed was measured to quantify the fire size development (i.e. HRR). A steel platform (3.0 m × 5.0 m) was placed below the centre of the continuous fuel bed with two layers of fireboards (3.6 m × 4.2 m) holding the wood cribs above, see Figure 7. Four load cells were used to support the steel platform to measure the total mass loss rate. Note that the fireboards border for the mass loss measurement area, 3.6 m × 4.2 m in dashed line shown in Figure 7 (a), was deliberately cut in order to separate the mass loss change from the neighbouring fireboard, holding another part of the extended wood crib [7]. Although only part of the continuous fuel bed was measured for mass loss, due to constraints on the experimental resources, a valuable HRR "data point" can be estimated while the fire was fully "sitting" on the platform at a specific time, for model validation purposes, i.e., at around 50 mins shown in Figure 7 (b).

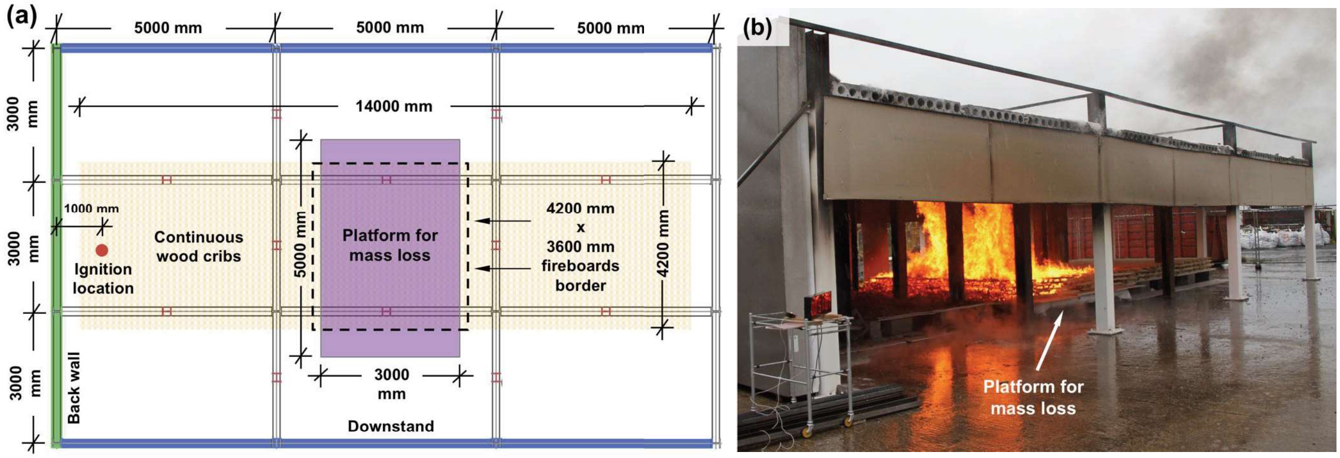

Figure 7. Mass loss measurement, (a) Position of platform for measuring mass loss (purple shaded area), and (b) Platform measuring mass loss at 51 mins.

Figure 8 compares the model HRR with the interpreted test data, based upon the measured mass loss while assuming the same effective heat of combustion of 10.84 MJ/kg as for the virgin fuel in the model. It is worth noting that the test HRR data was smoothed using a Savitzky-Golay filter with a low window length 5 and a medium window length 31, respectively, as advised by Morrisset et al. [19] who suggest that a high-order window length (e.g. 51) is likely to truncate up to 30% of the peak HRR for charring materials. Figure

8 shows that prior to the fire leading edge arriving to the mass loss platform at around 40 mins, the predicted fire size gradually increased to about 6.2 MW. When the fire was fully "sitting" on the platform at around 50 mins, the predicted HRR was about 7.9 MW, falling well in the range between 10.3 MW and 6.9 MW using the window lengths 5 and 31, respectively, for the interpreted test HRR, with an average value of 8.6 MW which is slightly higher than the predicted 7.9 MW. At around 63 mins, the fire left the mass loss platform and was predicted to reach its peak HRR of about 12.2 MW at around 72 minutes. Immediately thereafter the heat release rate declined due to the exhaustion of new fuel.

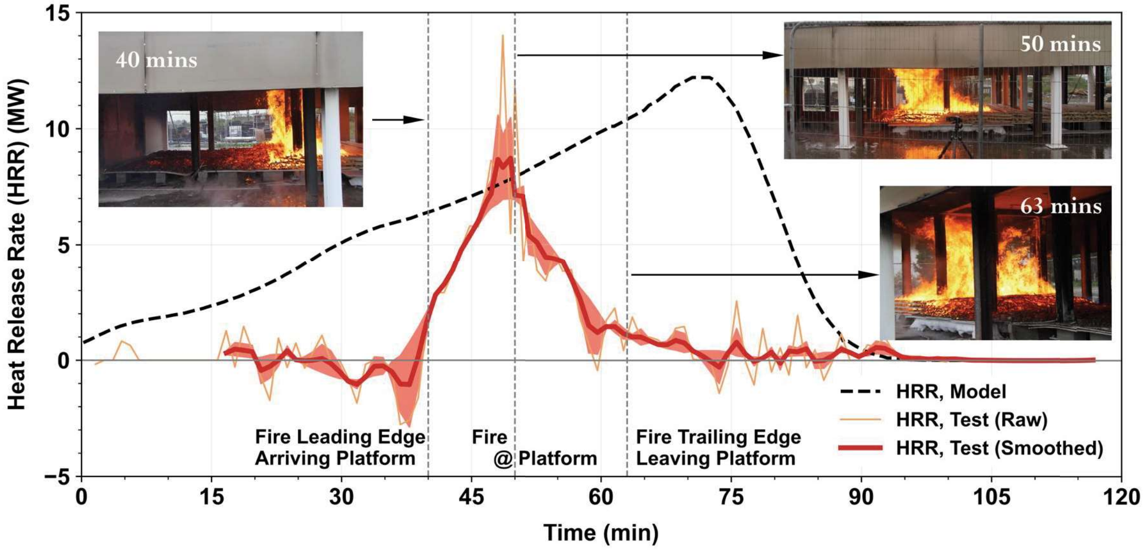

Figure 8. Comparison between the test and the model on HRR
(The translucent pink band represents the range of smoothing sensitivity via using Savitzky-Golay filter with a low window length, 5, and a medium window length, 31).

4.3 Thermocouple temperatures

To further characterise the gas phase temperatures and fire spread, thermocouple trees "TRL-1" to "TRL-11" were placed above the wood cribs, as presented in Figure 9. In addition, six thermocouples "TC-1" to "TC-6" were instrumented 200 mm beneath the ceiling level to quantify the travelling fire "far-field" temperatures. The thermocouples were modelled with the same diameter as the test, i.e., 1.5 mm bead diameter and assuming emissivity of 0.85.

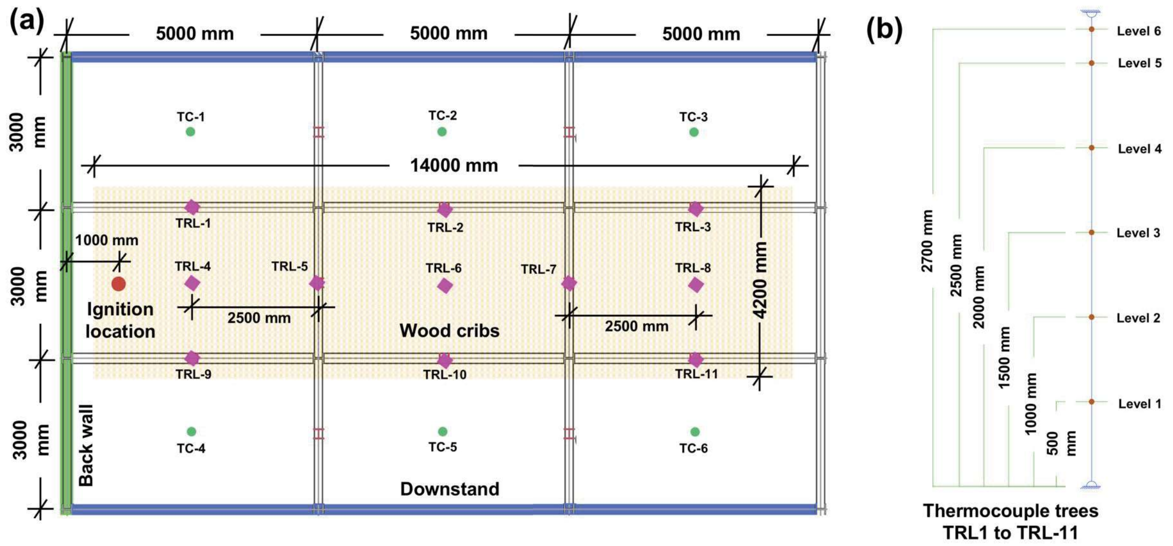

Figure 9. Location of the thermocouples for measuring gas phase temperatures, (a) plan view, TC-1 to TC-6 were thermocouples 200 mm below ceiling, (b) elevation view, TRL-1 to TRL-11 were thermocouple trees above the wood cribs.

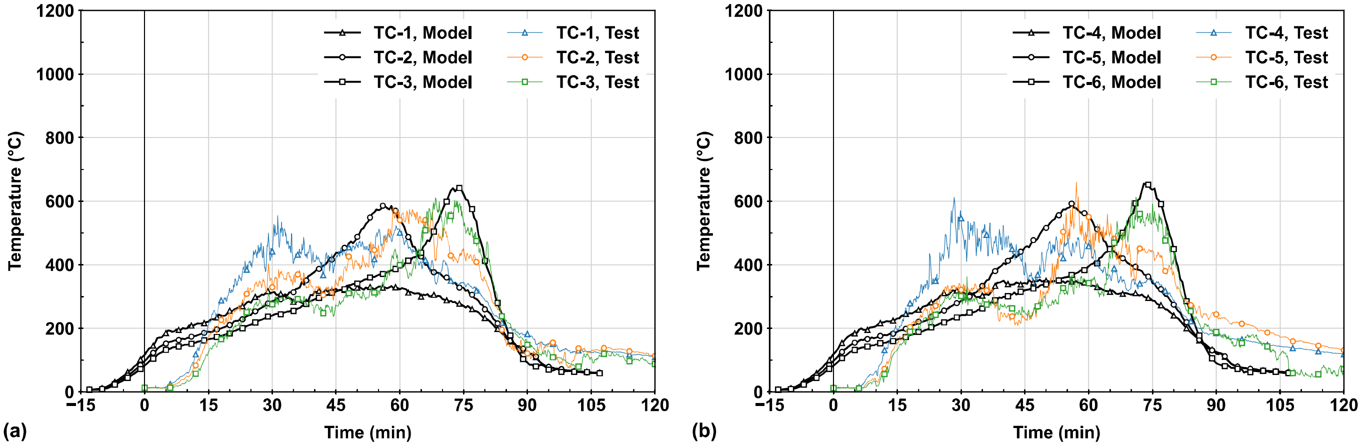

Figure 11. Comparison of the thermocouple temperatures, 200 mm from the ceiling level at side bays, (a) TC-1 to TC-3, and (b) TC-4 to TC-6.

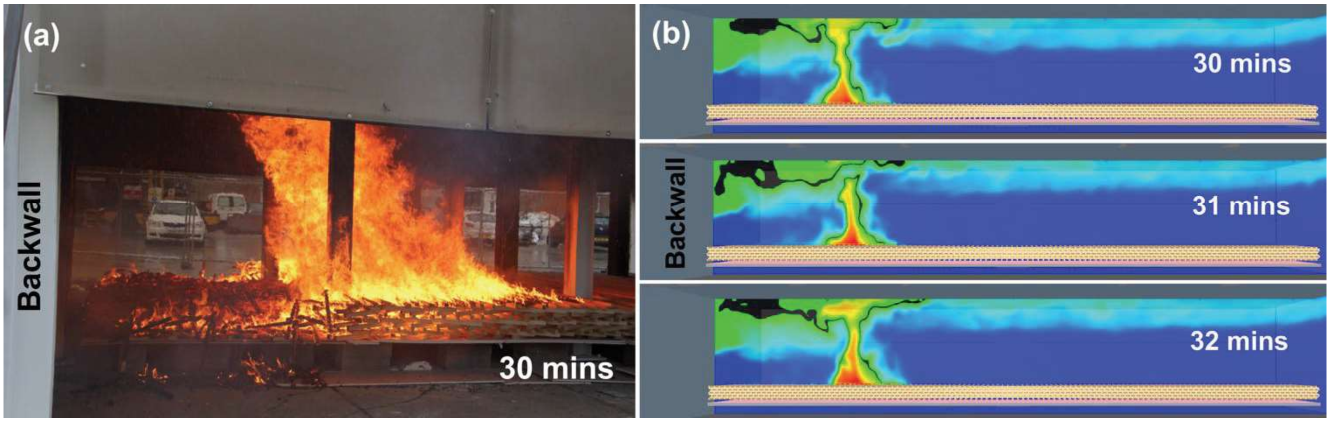

Figure 10. Fire plume shape at around 30 mins, (a) experiment showing the fire plume “leaning” (photo reversed), and (b) scaled-up model.

Figure 11 shows the comparison of the thermocouple temperatures “TC-1” to “TC-6”, located 200 mm beneath the ceiling at the side bays of the large compartment. Apart from the temperatures discrepancy due to the aforementioned initial ignition difference from 0 – 15 mins, thermocouple temperatures of the model show good agreement with the test data for the rest of duration except for “TC-1”/“TC-4”, which presented an under-prediction of around 250 °C compared with the test data at about 30 mins.

This discrepancy is likely associated with: 1) the absence of glowing char representation for heat transfer in the model; 2) the “leaning” fire plume in the first bay during the test affected by the external wind, in combination with the local effect of air entrainment and recirculation due to the presence of the backwall, see Figure 10 (a). Such external wind effect was not considered and explored in the scaled-up model, as shown in Figure 10 (b). Note that the TRAFIR Ulster Travelling Fire Test series were undertaken outdoors due to the large test scale [7].

Further, once the fire size grew from 5 MW at 30 mins to larger sizes, (i.e., 10 MW and 12 MW at 60 mins and 75 mins, respectively, as illustrated in Figure 8), the maximum discrepancy of the thermocouples at “TC-2”/“TC-5” and “TC-3”/“TC-6” was greatly improved. This is because the flame extension and smoke flows beneath the ceiling level became more dominant at “TC-2”/“TC-5” and “TC-3”/“TC-6”.

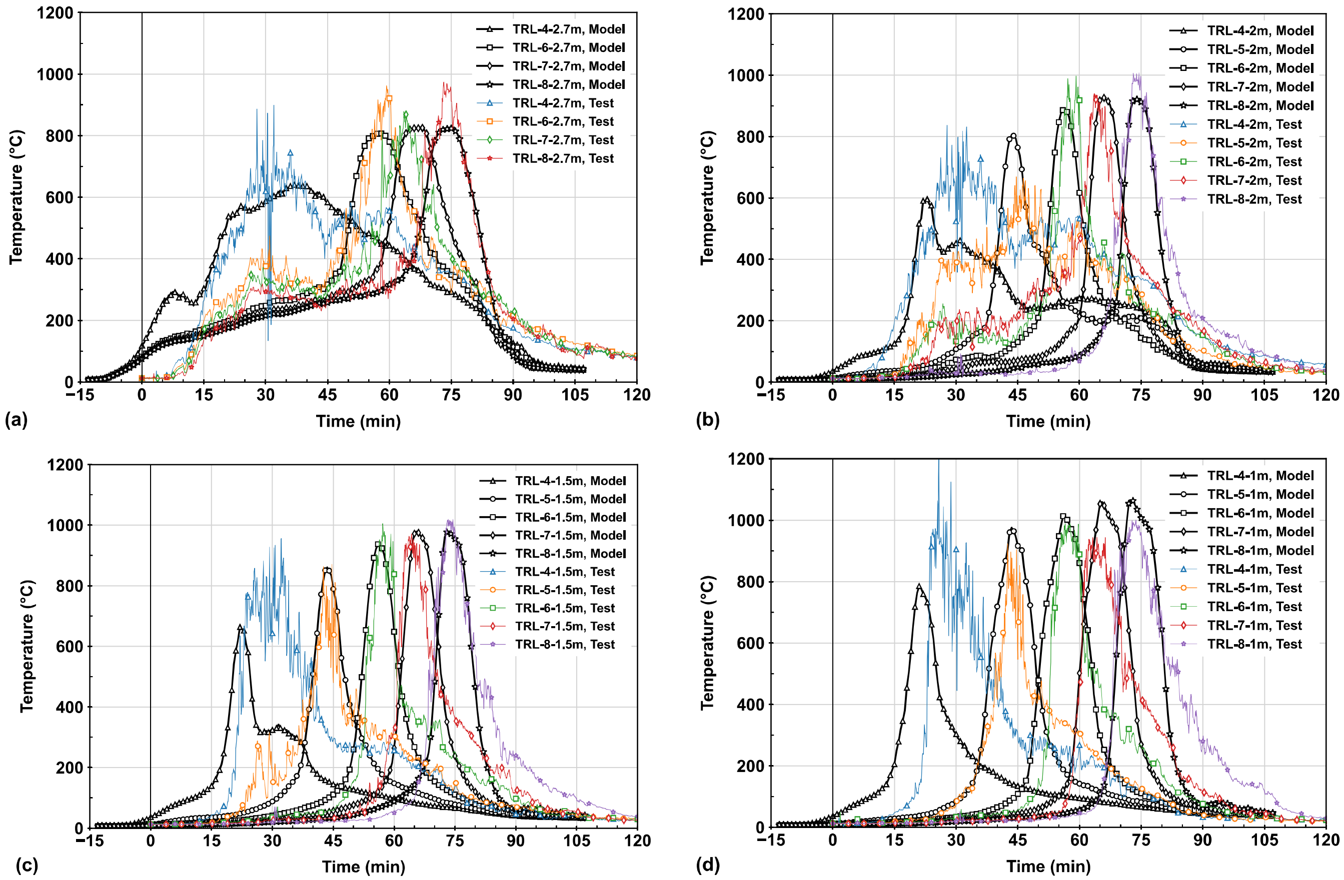

Figure 12. Comparison of the thermocouple temperatures at compartment centreline along fire trajectory, TRL-4 to TRL-8, (a) ceiling level (note: TRL-5-2.7m failed during test data acquisition), (b) 2 m from floor level, (c) 1.5 m from the floor level, and (d) 1 m from the floor level (i.e., 0.265 m from the fuel bed top level).

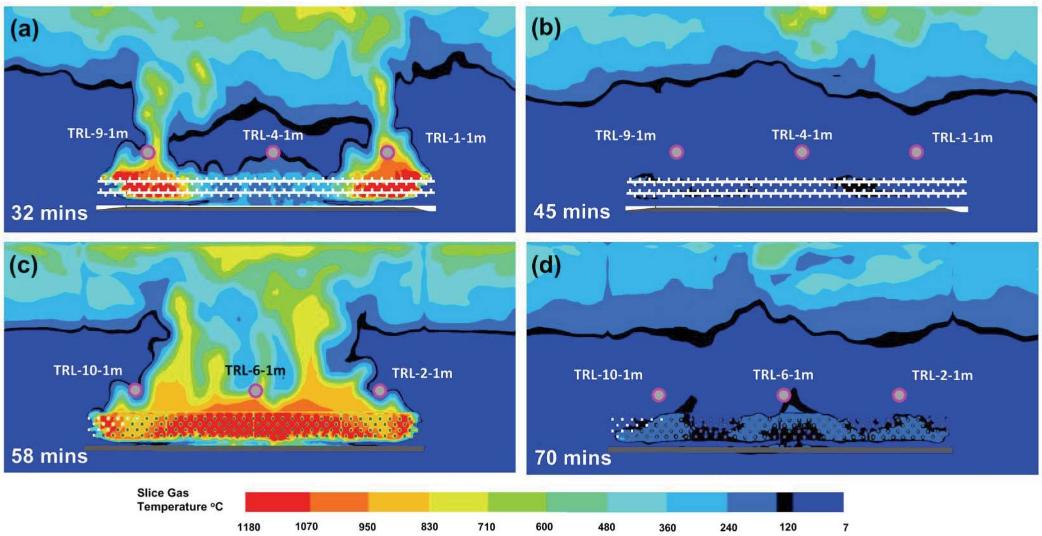

Figure 13. Gas phase temperature contour of the compartment 'slice' at specific time, (a) TRL-1/4/9 'slice' at 32 mins, (b) TRL-1/4/9 'slice' at 45 mins, (c) TRL-2/6/10 'slice' at 58 mins, and (d) TRL-2/6/10 'slice' at 70 mins.

Figure 12 demonstrates an excellent capability of the model in predicting the evolution of fire spread and burn-away, and in reproducing the gas phase temperatures along the fire travelling trajectory. Nevertheless, a discrepancy is still presented in the thermocouple temperatures close to the ignition location at a lower level (e.g., TRL-4-1m), because of: 1) the ignition difference between the model and the test; and 2) deficiencies in the model representation of the heat transfer for the radiation from the glowing embers, with high surface temperatures to the thermocouples close to the fuel bed (see Figure 13 (a) and (b) for TRL-4-1m at 32 mins and 45 mins respectively); a similar issue was also identified in the calibrated LB7 model [10]. Also, the fire at an early developing stage is more susceptible to sources of disturbance, e.g., wind.

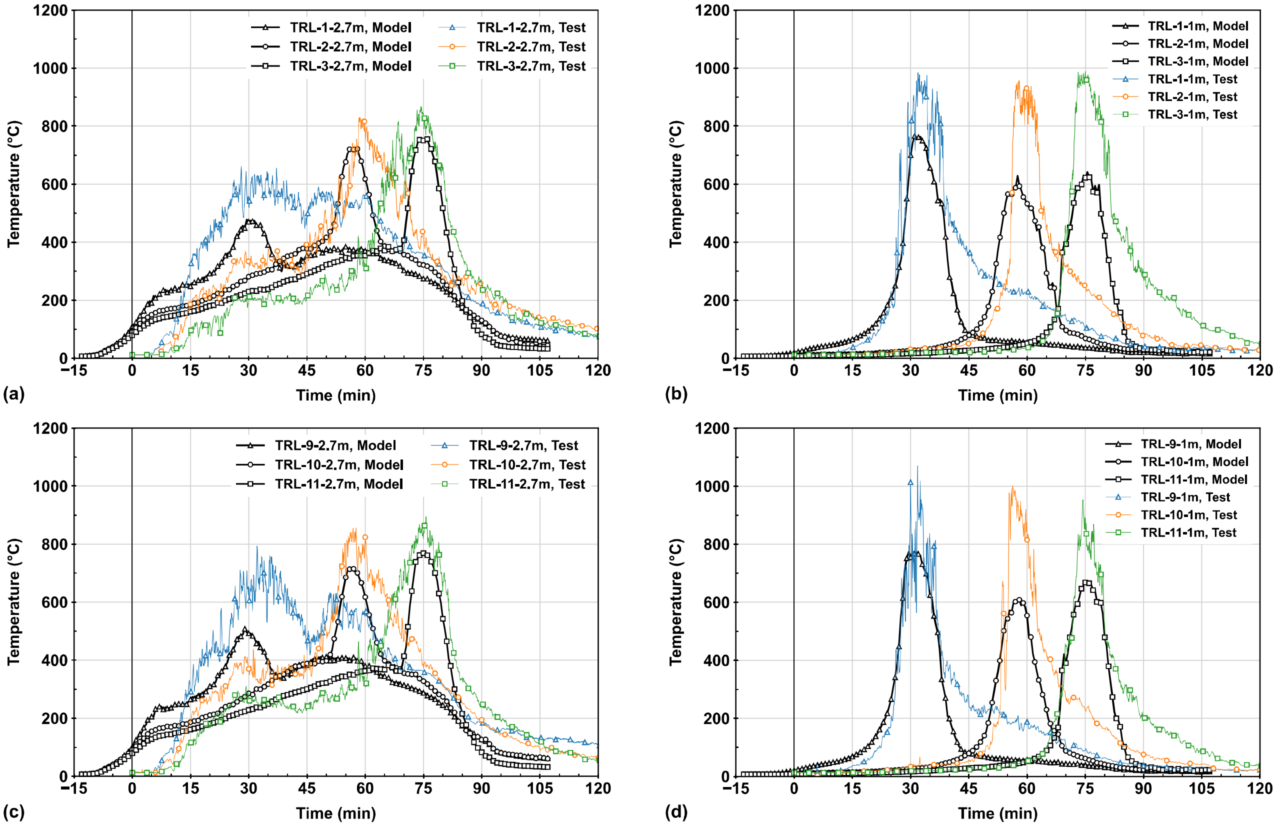

Figure 14. Comparison of the thermocouple temperatures along fire trajectory and the longitudinal fuel bed edges, (a) TRL-1 to TRL-3 at ceiling level, (b) TRL-1 to TRL-3 at 1 m from the floor level (i.e., 0.265 m from the fuel bed top level), (c) TRL-9 to TRL-11 at ceiling level, (d) TRL-9 to TRL-11 at 1 m from the floor level (i.e., 0.265 m from the fuel bed top level).

Figure 14 (a) and (c) demonstrate a good level of fire spread model prediction, but a similar discrepancy (as Figure 11) for the thermocouple temperatures along the longitudinal edges of the continuous fuel bed, but close to the ceiling level, was identified. Again, such a discrepancy might be induced by a slightly different shape of the fire plume, especially while those thermocouples were not engulfed in the extended flame or smoke at ceiling level (i.e., TRL-1-2.7m; TRL-9-2.7m) for the fire size of 5 MW at 30 mins.

For the thermocouples close to the fuel bed longitudinal edges presented in Figure 14 (b) and (d), the model predicted TRL-1-1m maximum temperature around 220 °C, which is lower than the test at 30 mins, while it was engulfed into the flame due to the “ring” like fire development (see Figure 4, and Figure 13 (a)). At 58 mins, the maximum temperature difference between the model and the test at TRL-2-1m reached an even higher level, around 380 °C, while it was “beside” the fire plume due to the entrainment of the cold air, see Figure 13 (c). Further, the missing element of the model representation in heat transfer for the radiation from “hot” glowing embers, was again manifested in the “local” cooling phase on thermocouples close to the fuel bed level. For example, at TRL-1-1m at 45 mins, the model predicted a temperature of 80 °C whereas the experimentally measured value was 350 °C, see Figure 13 (b) and Figure 14 (b).

5 CONCLUSIONS

Porous wood cribs, with shielding of internal surfaces, are recognised as a rather artificial fire source, hence with different fire spread sensitivities than many real-world fuels, but have been a dominant choice in fire experiments over many decades and are an important steppingstone towards more complex scenarios. Gaining a proper understanding of the sensitivities of fire spread over distributed fuel beds in large compartments would be greatly facilitated by the availability of validated models that could be used for parametric studies.

In this work, the potential for "scaling up" a "stick-by-stick" CFD model which had been carefully calibrated against the results of experiments on an isolated crib, of 2.8m diameter, to a distributed fuel bed in a full-scale compartment, has been demonstrated. With no changes of any model parameters between these two scenarios of very different scale, fire spread and burn out predictions were found to be in excellent agreement, and the single experimental data point for heat release rate also fits very well with the evolution of the predicted value.

Some differences in gas phase temperatures were seen, and the reasons for them have been carefully considered. Firstly, there is some uncertainty associated with the representation of the ignitor and the initial fire development – an identical ignitor was used in both cases in the model, while a bigger fuel tray located higher in the fuel bed was adopted in the experimental compartment test. But it is important to stress that the modelling of the early fire development is not a prime concern since it is subject to many uncertainties but is largely irrelevant to the evolution of fire conditions of interest for structural response – nevertheless the differences at the very start do introduce uncertainties in matching up the evolving fire timelines. Other temperature discrepancies seen early in the fire, when the main plume is located only halfway along the first bay, are likely to derive substantially from differences in the shape of the fire plume, with the model significantly underpredicting the peak temperatures at ceiling level at the compartment edge, and outside, the fuel bed. However, the test values reveal some asymmetry, and it is likely that the shape of the plume was affected to some degree by the prevailing wind, with an observed deflection towards the back wall, and this is not represented in the model. But as the fire size increases, more than doubling before the end of the test, it will be more robust to external disturbances.

The final temperature discrepancy is the most noticeable, with an acknowledged inability of the model to properly represent the heat transfer effects of the glowing char, resulting in a very significant underprediction of peak thermocouple temperatures near the fuel bed and the failure to capture the extended "cooling phase" seen in the test. This issue is known to have broadly affected previous model comparisons in the literature, but is particularly clear for this travelling fire where its impact can be seen progressively at each measurement location, i.e., there is effectively a local "cooling phase" for each sector of the extended fuel bed, in addition to a final cooling once all the fuel is burning out. Though potentially important for local structural elements, various avenues might be explored to remedy the discrepancies with this aspect of the model, but it is unlikely to have any great significance in the prediction of fire spread on a horizontally orientated flat fuel bed, which is the prime interest of the current work.

Thus, the established "numerical simulator" looks to have good potential as a tool to explore and characterise the behaviour of travelling fires subject to different compartment boundary conditions, including, but not limited to, the effects of 1) compartment geometry, opening locations and sizes, 2) extent and location of fuel bed, and 3) thermal properties of the boundaries. The equivalent experimental studies of this range of parameters would be infeasible, and would also be subject to significant uncertainties including the effects of varying ambient conditions (temperature and wind) as well as differences in fuel moisture.

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