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Reduced-scale experiments and numerical simulations of informal settlement dwelling fires

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Category

Research Article

Abstract

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Keywords

Informal settlements, Enclosure fire dynamics, Reduced scale fire experiments, Computational fluid dynamics, Fire modelling

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Reduced-scale experiments and numerical simulations of informal settlement dwelling fires

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Abstract

Informal settlement dwellings (ISDs) house approximately one billion people in the developing world and this number is expected to double by the year 2030 [1]. Contemporary research on ISD fires has focused on understanding the fire dynamics within individual dwellings [2] (micro-scale) and fire spread in settlements consisting of multiple dwellings [3, 4] (macro-scale). This paper aims to do two primary things: investigate if scaling methods that were derived for compartments with thermally thick boundaries can be applied to ISDs (compartments with thermally thin boundaries), and if they can adequately represent the most important phenomena associated with full-scale ISD fires; and demonstrate Fire Dynamics Simulator (FDS) simulations against the Reduced-Scale Experiments (RSEs) conducted in this work by comparing the simulation results and fire behaviour to that of the RSEs. In this work, five RSEs—a 1/15 scale, 1/10 scale, 1/7.5 scale, 1/5 scale and a 1/4 scale experiment—were conducted. The RSEs are based on the full-scale ISD fire experiments done by Cicione, et al. [4], and were scaled using parameters such as Heat Release Rate (HRR) of the fuel packages, ventilation factors and the overall geometry of the dwellings. The full-scale experiment's geometry is based on the ISO 9705 compartment fire test. Temperatures, heat fluxes and flame heights for each of the RSEs were recorded and analysed to determine the correlation of the fire behaviour between the RSEs and the full-scale experiments [4]. The results from this study suggest that reduced-scale modeling with RSE models of 1/4 scale and 1/5 scale can be used to replicate an ISD fire with a reasonable level of certainty, depending on the parameter being studied. Limitations and challenges associated with the scaling methods employed are discussed, as not all fire phenomena can be accurately captured.

Keywords: Informal settlement dwelling fires; Scale modeling; Reduced scale experiment; Compartment fire; Fire dynamic simulation

Introduction

The African continent has experienced rapid growth in population over the past few decades. From a population of 630 million in 1990, the African population has increased to approximately 1.2 billion people in 2016 [5]. It is estimated that by the year 2035, half of the African population will be living in urban settlements [6]. The rapid growth in population and unplanned urbanization will give rise to various hazards such as floods, landslides, and fire risk, which have been growing at an equally alarming rate.

Informal settlements (ISs) can be found throughout the world today, and house millions of people who fall into the lower-income bracket. Currently, around one billion people live in informal settlements. These unplanned settlements are built over unoccupied lands and the informal settlement dwellings (ISDs), as shown in Fig. 1a) and 1b), are predominantly make-shift enclosures constructed from corrugated sheets, wooden materials, masonry, plastic sheets, or any available materials. Fires in ISDs are largely underestimated, despite being a frequently occurring event. In many instances, these fires only get significant attention by politicians during election campaigns and often dwellers feel neglected [7]. Informal settlements have a wide range of potential ignition sources, such as open flames, faulty electrical installations, candles,

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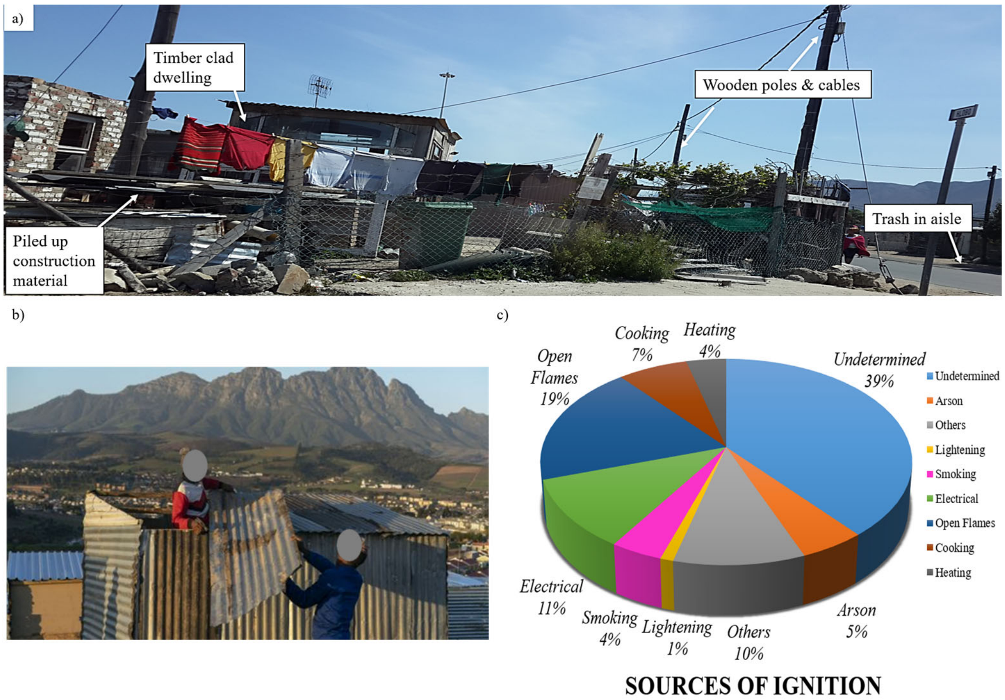

Fig. 1. a) Combustibles in the vicinity of a typical ISDs, b) Construction of an ISD [9], and c) Source of ignition in ISDs [2].

arson, and “other” or “undetermined” causes [2]. To mitigate the consequence of IS fires, understanding how these fires develop and spread between dwellings is paramount. Fires spread in informal settlements through three main processes: radiation, direct flame impingement, and fire branding (although negligible research is available on fire branding for informal settlement fires). A detailed analysis of footage from a real incident that destroyed around 40 homes is provided in [8].

Fire-safety interventions for ISD fires often prove to be ineffective due to incorrect technical performance, social challenges with their implementation, or poor implementation of projects. In recent years, numerous full-scale fire experiments have been conducted on ISDs [2, 4, 8, 9]. However, there are various challenges when conducting full-scale multi-ISD fire experiments to study settlement-scale spread, such as the financial and time cost of an experiment, meaning that only a limited number of experiments can be done; logistics, safety concerns, testing site complications; the significant influence of weather conditions, including wind and rain; and involvement of various stakeholders, such as the fire department and the local municipality. With the aforementioned challenges in mind, this paper seeks to develop Reduced-Scale Experiments (RSEs) and numerical simulations for ISD and IS fires. Parameters including overall geometry of ISDs, heat release rate (HRR), fuel load, and ventilation factors are scaled based on scaling laws for fire applications. This would offer a potential solution to the above problems when conducting Full-Scale Experiments (FSEs) and allow numerous parameters to be investigated.

The success of RSEs of ISDs could be used to study the fire spread behaviour of entire settlements; investigate slope, wind, material stored between dwellings, settlement density, etc.; and carry out forensic fire investigations by recreating actual events—and such events occur regularly in countries like South Africa. This will enhance our understanding of macro (settlement-scale) fire spread and contribute towards the development of guidelines to help prevent these large conflagrations in informal settlements. Furthermore, the work may be applicable for preliminary testing of interventions (e.g., spray-on vermiculite as is currently being considered) and the relative risk-assessment of different construction systems or products.

Ideally, the work could be expanded to be suitable for other low-income communities with high fire risk, such as refugee camps, where thousands can be left homeless in a single event, as seen in the recent Cox’s Bazaar incident in Bangladesh for the Rohingya people [10]. RSEs would allow for rapid and widespread testing of different construction systems and products prior to detailed full-scale testing being carried out. It is acknowledged that the scaling of fire behaviour will always be imperfect, and some phenomena may not be captured. Hence, care is required when interpreting results from RSEs, especially if trying to apply results to different home configurations, materials and when incorporating weather factors like wind and rain.

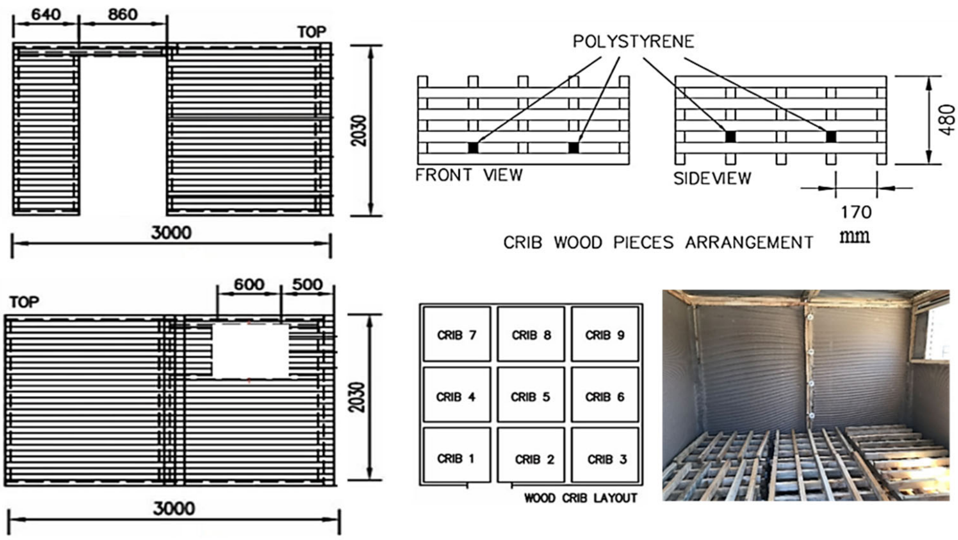

Fig. 2. The experimental set-up, wood crib configuration, and cardboard lining details of the full-scale experiment conducted by Cicione, et al. [4].

The scaling of fire behaviour is a complex task, as many phenomena, including temperature, heat release rates, heat fluxes, convection, mass flows, and geometry interact in a non-linear manner. Wang, et al. [11] demonstrated a method to use the laws of similitude for a fire in a compartment with small vents. The results showed that by using a scaling method, satisfactory results could be achieved in a small-scale test for a prototype fire. Quintiere, et al. [12] studied the fire and collapse of World Trade Centre (WTC) tower using scaled modeling, and they found that the scaled results were in harmony with the information of the fire. In another Quintiere, et al. experiment [13], a 1/4th scale fully furnished bedroom was set on fire to study the fire growth, flashover, and the fully developed fire stage. That study concluded that the scaled experiment results compared well with the full-scale experiments. Similar research on the 1/4th scale fire experiments was done to study the scaling of compartment fires [12, 13]. It was found that the results had high conformity with the full-scale experiments and the input data can be potentially used to validate numerical simulations.

In this paper, the RSEs developed are based upon data in the literature from previous full-scale experiments, which is introduced first in the section that follows. Afterward, the scaling methodologies employed in this work are discussed, followed by results from the RSEs that were conducted. Computational Fluid Dynamics (CFD) analyses of the RSEs are developed and compared with the experimental results to provide insights regarding the behaviour observed and whether the models can capture the fire phenomena of the burning dwellings. Conclusions and recommendations stemming from the work are provided, highlighting where the RSEs sufficiently capture full-scale fire behaviour and how to take the work forward.

Overview of the full-scale ISD fire experiment

This paper relies on two sets of experimental data: FSEs in the literature which are used as a benchmark, and new RSEs based on the aforementioned full-scale experiments. Cicione, et al. [4] conducted an FSE of a corrugated steel sheeting clad single dwelling to understand and characterize fire dynamics in informal dwellings as part of preliminary experimental work on the overall topic. Although the size, shape and fuel load of an informal settlement dwelling vary significantly based on construction material, population densities, personal belongings, etc., this experiment, with details shown in Fig. 2, has provided the basis for understanding the behaviour of fire in a typical ISD.

The ISD in question was constructed with corrugated steel sheet cladding and wooden frames. The fuel load in the ISD was represented using wood cribs of size (40×60×900 mm^3), evenly distributed inside the dwelling. Two polystyrene pieces were added per crib to increase the fire spread rate, although had a limited impact on fire behaviour. The dwelling was lined with 1.5 mm cardboard sheets to simulate the presence of any combustible lining materials such as curtains, nylon hangings, clothes, and internal divisions. The experimental set-up, wood crib layout and cardboard lining details of the full-scale experiment are shown in Fig. 2. Thermal data, such as temperatures and heat fluxes, were recorded using type-K thermocouples and thin skin calorimeters (TSCs). In addition, the experiments were analysed using video footage.

The fuel load was ignited with a paraffin source, placed in the middle of the front crib. The flames emerging from the wooden cribs took approximately

Table 1. Full-scale experiment results of steel clad ISD.

Parameters	Results
Maximum ceiling temperature	1032 °C
Time from the start of flashover to collapse	7 min
Heat flux (HF) at the door	95 kW/m^2
HF 1 m away from the door	32 kW/m^2
HF at the window	80 kW/m^2

Fig. 3. Steel clad dwelling after ignition [4].

11 minutes to ignite the cardboard lining in the ISD, and subsequently, the dwelling reached flashover and the fully developed stage was reached within a few seconds after the cardboard was ignited. At this point, flames with a height of 3-4 m from the ground were seen emerging from the door and window of the ISD. After 7 minutes, the structure collapsed. The results for the experiment are summarized in Table 1, and for more details regarding the results refer to Cicione, et al. [4]. Time-temperature curves and measured heat fluxes are provided in Section "RSEs results and discussion" when compared to the RSE data.

Scaling methodology

The Froude scaling technique is a widely accepted method for fire-related applications and has been used in this work. In scale modeling, it is not possible to preserve all the variables derived from the scaling theory simultaneously and only the most important dimensional terms are preserved. The scaling correlations of dimensional groups from the conservation equations are based on Quintiere [12] and Bryner, et al. [14].

In this work, the geometry of the Reduced-Scale Dwellings (RSDs) is based on the full-scale ISD experiment introduced above. For these purposes, five RSEs at 1/15th scale, 1/10th scale, 1/7.5th scale, 1/5th scale and a 1/4th scale experiment are conducted. The RSDs are geometrically scaled according to respective geometric ratios, and the vents (doors and windows) are scaled based on ventilation factor scaling as used by Bryner, et al. [14]. A fire load density in an informal settlement could range from 370 MJ/m^2 to 3000 MJ/m^2 [15]. An average fuel load of 780 MJ/m^2 was used in the FSE, which gave a total HRR of 10250 kW. For the RSEs, the HRRs were scaled according to $\dot{Q} \sim s^{5/2}$, and subsequently the average burning times were scaled according to $t \sim s^{1/2}$, where s represents the scaling ratio. The wood cribs were used as fuel such that it represents the anticipated fire load and burning time. The design details of the wood cribs for RSEs are discussed in the sections that follow. In addition, key parameters such as temperature, heat flux, and flame heights for all the RSEs were compared with FSE results.

The full-scale dwellings and model scale dwellings were constructed using thin steel between 0.6 and 0.8 mm, which neglected the influence of material thermal inertia ($\kappa\rho c$). The steel sheets are considered a thermally thin material (Biot number in order of $10^{-2} < 0.1$) thus, thermal properties can be assumed to be homogeneous, which allows the thickness of steel sheets to be scaled geometrically. Work on fire dynamics in compartments with thermally thin walls has been carried out by Beshir, et al. [16].

Convection scaling (i.e., scaling the convective heat transfer between the gas in the dwelling and dwelling boundaries) requires the convective heat transfer coefficient to be scaled. It is also practically difficult to find a material that could capture inconsistencies in fluid flow to match, and hence convective scaling was neglected in this work. Also, convective heat transfer is less dominant when studying fire spread in ISDs. Similarly, scaling of radiation involves either the gas emissivity to be modified or a change in ambient temperature. The change in ambient temperature is difficult to obtain even in laboratory conditions; however, change of gas emissivity can be possible by changing to a suitable fuel package in the scaled model. These aspects require investigation in the future. In RSEs, the same fuel (South African pine) was used as in the FSE for convenience and consistency. Hence, the gas emissivity was not changed with respect to the FSE.

Table 2 lists the scaling correlation for preserved parameters. The symbol S is the linear length scale while the subscript F represents full-scale, where $S_F = 1$. The subscript M represents the model-scale size ($S_M =$ 1/4, 1/5, 1/7.5, 1/10, 1/15 for each RSE) and the scaling ratio s can be defined as S_M/S_F. The tabulated correlations correspond to ideal conditions; however, perfect scaling of some parameters is not always possible and may induce some errors in relation to other interdependent parameters.

Reduced-scale experiment methodology

In this work, five different scale models were used with the largest RSD being a 1/4th scale dwelling (compared to the full-scale dwelling introduced above) and the smallest being a 1/15th scale dwelling. Scale models such as 1/15th scale and 1/10th size were used to identify the possibility to replicate FSE with a plausible result at the smallest level, although it is

Table 2. List of scaling correlation for ISDs. M: model scale, F: full scale.

Scaling parameter	Unit	Scaling model	Eq. No.
Heat release rate [HRR] ($\dot{Q}$)	kW	$\dot{Q}_M = \dot{Q}_F * \left(\frac{S_M}{S_F}\right)^{5/2}$	(1)
Temperature (T)	K	$T_M = T_F$	(2)
Time (t)	s	$t_M = t_F * \left(\frac{S_M}{S_F}\right)^{1/2}$	(3)
Ventilation factor [$A(h)^{1/2}$]	$m^{5/2}$	$[A(h)^{1/2}]_M = [A(h)^{1/2}]_F * \left(\frac{S_M}{S_F}\right)^2$	(4)
Heat flux (q'')	kW	$q''_M = q''_F * \left(\frac{S_M}{S_F}\right)^{1/2}$	(5)
Flame height (h_{Flame})	m	$h_{M,Flame} = h_{F,Flame} * \left(\frac{S_M}{S_F}\right)$	(6)
Material thermal inertia ($\kappa\rho c$)	W^2s/m^4K^2	$(\kappa\rho c)_M = (\kappa\rho c)_F$	(7)
Material thickness (δ)	m	$\delta_M = \delta_F$	(8)

Table 3. Dimensions of reduced-scale dwellings (RSDs).

Dimension \ Scale	Full	1/4	1/5	1/7.5	1/10	1/15
Height H (m)	2.3	0.575	0.46	0.31	0.23	0.155
Length L (m)	3	0.75	0.6	0.4	0.3	0.2
Width R (m)	3	0.79	0.64	0.44	0.34	0.24
Door height (m)	2.03	0.51	0.41	0.27	0.2	0.14
Door area (m^2)	1.746	0.218	0.156	0.085	0.055	0.03
Door width (m)	0.86	0.37	0.33	0.27	0.23	0.19
Window area (m^2)	0.36	0.043	0.03	0.016	0.01	0.005
Window length (m)	0.6	0.161	0.135	0.098	0.078	0.056

inevitable that larger models will provide better correlations. All experiments were performed at Stellenbosch University with negligible wind conditions.

Reduced-scale dwelling geometry

The RSDs were built with a 1 mm flat steel sheet to provide ease in the construction of the dwellings, especially when constructing the smaller scale dwellings. For smaller dwellings, corrugated sheet profiles would significantly influence the shape and size of dwellings, which is why the flat steel sheet was selected. The metal sheets were cut, folded, and spot-welded to the desired dimension of each of the RSDs. The roof plates were fitted with bolts to allow adjustment of the roof height using bolts and nuts at the corners of the roofs. The roof height adjustment was to represent "leakages," (i.e., the gaps created by the corrugated sheets in the full-scale environment) although these openings are difficult to precisely quantify in real world application due to construction methods and the sheeting configuration. A constant spacing height, G_R, of 2 mm was used to account for these openings. These gaps will be important in future work when fire spread tests are investigated, as the gaps will open a path for piloted ignition to take place, which often occurs through these wall-roof joints in full-scale dwellings [17]. It was also assumed that leakages through the roof openings do not have a substantial effect on either the fire dynamics within the RSDs or the radiation emitted from the dwelling, which has recently been shown to be a suitable assumption [18]. The dimensions of individual RSDs are provided in Table 3.

Fuel source

Wood cribs were used as fuel for both the FSEs and RSEs. In this work, untreated South African pine wood (SAP) was used as fuel for all RSEs. Based on the HRR of the full-scale experiment, the representative HRR for each reduced-scale dwelling were calculated based on the scaling correlation in Table 2.

The HRR ($\dot{Q}$) of the cribs was calculated based on Babrauskas' method for wood cribs [19]:

$$\dot{Q} = \dot{m}\Delta H_{eff} \quad (9)$$

Table 4. RSE timber crib layouts and associated HRR values.

Dimension \ Scale	Full	1/4	1/5	1/7.5	1/10	1/15
No. of sticks n	40	48	28	15	9	6
No. of stick levels n_{level}	8	8	7	5	3	2
No. of Sticks per row n_{row}	5	6	4	3	3	3
Height of cribs h_c [m]	0.48	0.176	0.154	0.11	0.066	0.044
Mass of cribs m_0 [kg]	457	4.53	2.64	0.96	0.46	0.17
Spacing b/w cribs S [m]	0.17	0.074	0.137	0.137	0.102	0.042
Stick length [m]	0.9	0.5	0.5	0.34	0.27	0.15
Required HRR [kW]	10,250	320.31	183.4	66.54	32.41	11.76

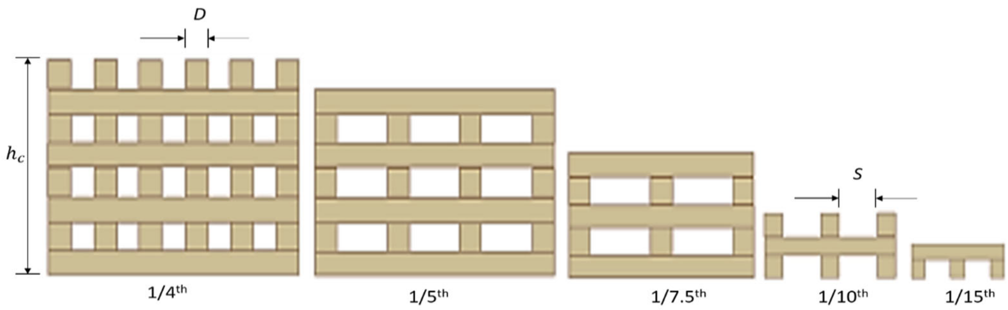

Fig. 4. Timber crib layouts used for RSE.

where $\dot{m}$ is the mass loss rate in kg/s and ΔH_{eff} is the effective heat of combustion in kJ/kg. The mass-loss rate ($\dot{m}$) for uniformly ignited cribs are governed by *the fuel surface-controlled mass loss rate,* which is the natural ability of the wood cribs to burn freely, determined by the following expression:

$$\dot{m} = \frac{4}{D} m_0 v_p \left(1 - \frac{2v_p t}{D}\right) \tag{10}$$

The crib porosity-controlled mass loss rate, where the maximum flow rate of air and combustible products through the crib holes determine the burning rate and can be calculated by:

$$\dot{m} = 4.4 \times 10^{-4} \left(\frac{S}{h_c}\right)\left(\frac{m_0}{D}\right) \tag{11}$$

where the regression velocity for wood is v_p = 2.2×10^{6} $D^{-0.6}$ according to Babrauskas and Peacock [19] and ΔH_{eff} = 18 MJ/kg. The least of Eqs. (10) and (11) is considered as the governing mass loss rate.

The FSE had a fuel load density of 780 MJ/m^2. The cribs consisted of 36 pieces of timber and 4 pieces of polystyrene sticks. The dwelling had a total of nine evenly distributed cribs. For all RSEs, the wood cribs were assigned a fixed cross-sectional dimension of 22×22 mm^2, whereas the length of each stick, number of sticks per level (n_{row}), and number of stick levels (n_{level}) were changed to obtain the desired HRR. The calculated stick layouts for each of the RSEs (as shown in Fig. 4) and their associated HRR values are given in Table 4. The HRR calculated from the scaling correlation is represented by $\dot{Q}_{reqd}$, where $\dot{Q}_{actl}$ is the actual HRR achieved by wood cribs in RSEs. At the time of the experiment, the cribs had a small quantity of accelerant (paraffin) applied and were ignited with the use of a blowtorch.

Instrumentation

Temperatures inside the RSDs were recorded using 1.5 mm diameter tip type-K thermocouples (TCs). All the thermocouples were positioned inside the RSDs, at the ceiling level near the left side of the adjacent wall (when viewed as shown in Fig. 5), the rear wall, and the center of the roof plate. A water-cooled heat flux gauge (HFG) was used to record the incident radiative heat fluxes at a distance (b) away from the door and at the height of the door soffit (H_D). Hence, the HFG was placed at 0.133 m, 0.2 m, 0.267 m, 0.4 m and 0.5 m away from the doorways of the 1/15, 1/10, 1/7.5, 1/5, and 1/4 RSEs, respectively. The video recordings were used to estimate flame heights emerging from the doorways and windows of RSDs. Estimates were based upon

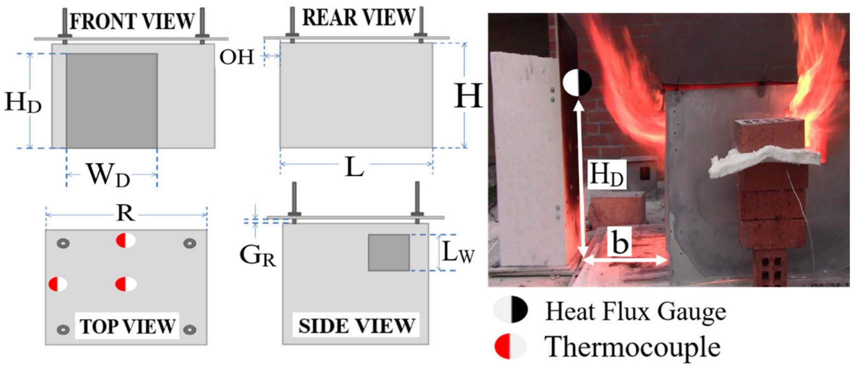

Fig. 5. Experimental set-up of the RSEs (left), 1/4 scale model at the fully developed fire stage (right).

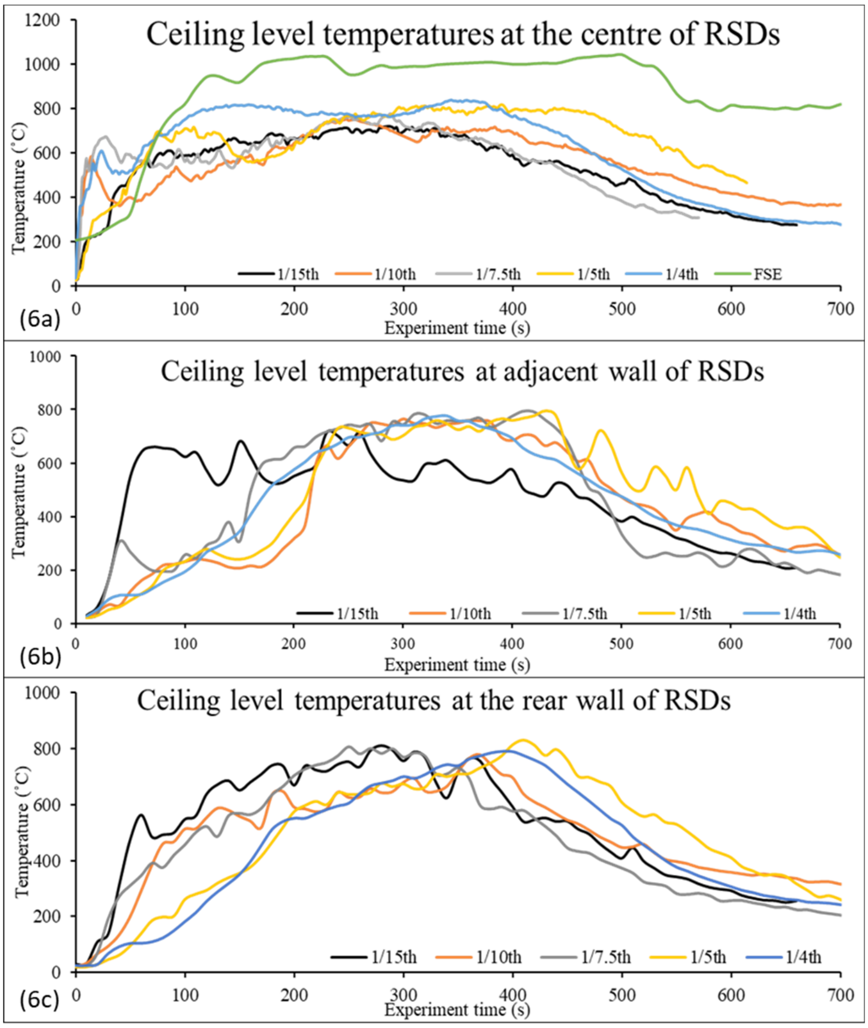

Fig. 6. a) Center ceiling temperatures (top graph), b) Temperatures measured at the adjacent (side) wall (middle graph), and c) Temperatures measured at the rear wall (bottom graph).

manually analyzing video imagery from experiments using demarcations in the experiment to scale values. Also, a thermal imaging camera was used to obtain a thermal profile of flames emerging from the RSEs (but not to measure temperatures). Fig. 5 shows the symbolic dimensions (left) and location of instrumentation (right) of RSEs, with further information of each RSE given in the sections that follow.

RSEs results and discussion

In this section, ceiling temperatures, incident heat fluxes, and flame heights of the RSEs are presented and compared to the FSE.

Table 5. Time comparison of RSEs with FSE.

Scale size	Experimental time [s]			Time to flashover [s]		
	Real time	Scaled time	Error (%)	Scaled time of FSE	Real time of RSEs	Error (%)
Full	1500	–	NA	420	420	0
1/4	750	1500	0	210	349	66
1/5	620	1386	8	188	226	20
1/7.5	490	1342	10	153	229	49
1/10	440	1391	7	132	130	2
1/15	395	1530	2	108	110	1

Table 6. Peak heat flux at 2 m from the door.

Scale		Full	1/4	1/5	1/7.5	1/10	1/15
Experiment time [s]		1500	750	620	570	440	395
Peak heat flux at 2 m from the door [kW/m²]	Unscaled	60	14.85	12.61	11.27	Error	10.17
	Scaled	60	29.7	28.42	30.87	–	39.74

Ceiling temperature

The temperature profiles at the ceiling level for all the RSEs are shown in Fig. 6. The curves in Fig. 6 represent the development of the fires inside the RSEs, which follows a trend similar to that of a typical enclosure fire of similar to the FSE. Within approximately 2 minutes, all the RSEs reached flashover point. Fig. 6a primarily represents the flame temperature impinging onto the ceiling due to burning wood cribs and Fig. 6b and 6c represents the average temperature of the hot smoke layer at the ceiling level. The initial spike in the RSE temperatures is due to the paraffin that was used to ignite the cribs.

Theoretically, the temperature profile for FSE and RSEs should be the same and the temperature-time curves for all RSEs generally correlate well with the FSE curve. The maximum ceiling temperatures increase with an increase in the geometric scale of RSDs, as reflected by the results shown in Table 5. The peak temperatures for all RSEs were found to be similar, but the temperature profile in FSE was 20% higher than the RSEs. Besides, the smaller-scaled models had wider openings based on the scaling methodology above, leading to less smoke accumulation inside the RSDs. As a result, the larger scaled models had a thicker smoke layer, thus increasing the temperature within the compartment.

Considering Fig. 6b and 6c, it is possible to see that the hot gas temperature for RSEs was fluctuating during the steady-state phase, indicating the movement of cold air and hot gases in that region. The temperatures are higher at the adjacent wall compared to the rear wall, due to the influence of incoming cold air through the door, which indicates a mixture of cold air and hot gases.

The experiment time for all the RSEs was defined as the duration between ignition and collapse of the wood crib during the decay phase. The total experiment time was obtained from the visual data captured through video footage. It was seen that the time followed the scaling correlation $t \sim s^{1/2}$ and the experiment time was found to be similar to the FSE. The time to flashover for the smaller models (1/15th and 1/10th) correlated well with the time to flashover of FSE. On the other hand, the larger RSD models (1/4th, 1/5th, 1.7.5th) took longer to reach flashover. Further work is required to study the time to flashover based on these results. It appears that the paraffin ignition source in RSEs had a significant influence on the growth rate, leading to a correlation inverse to what would be expected, since smaller dwellings had a smaller error percentage compared to FSE when considering the time to flashover.

Incident heat flux

The peak heat flux measured during the FSE and the scaled-up heat flux values for each RSE are shown in Table 6. Graphical representations of heat flux curves for RSEs are shown in Fig. 7. The heat flux curves were scaled based on Eq. 5, as listed in Table 2. The 1/10th scale experiment was excluded from the results due to an error in results, which the authors believe is as a result of incorrect placement and operation of the heat flux gauge.

The scaled heat flux curves of RSEs are shown in Fig. 7. The curves obtained for the RSEs did not scale well when compared with heat fluxes of FSE. When the results from the RSEs were scaled up and compared with the FSE result, the magnitude of the modified heat flux at the door in the RSEs was half of the heat flux values recorded during the FSEs. However, the smaller models had higher accuracy among the RSDs since they had larger openings as a result of the ventilation scaling: Heat flux during the experiments are predominantly from the flames emerging from the openings. It should also be noted that for the smaller models, the ratio of the area of the openings to the area of the wall in-

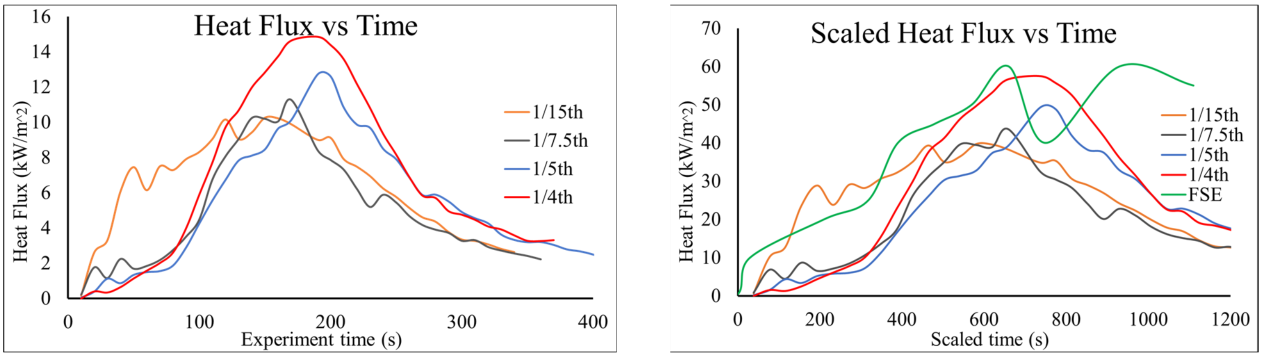

Fig. 7. Heat flux curves for RSEs showing the unscaled (left) and scaled (right) results.

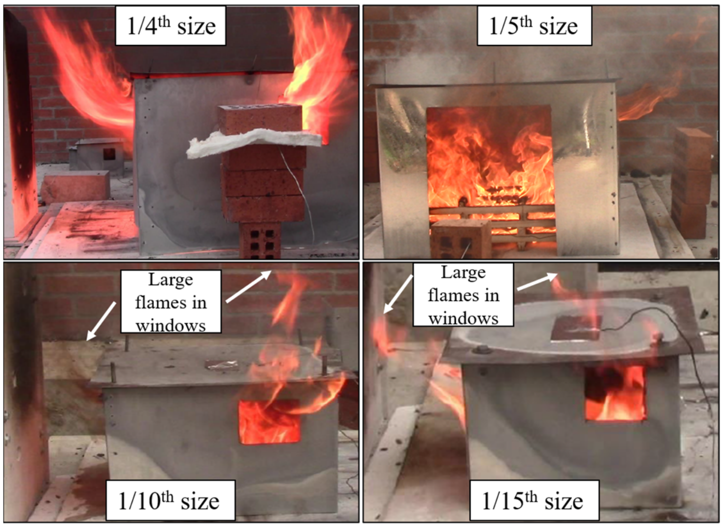

Fig. 8. Flames ejecting out of the openings in various reduced-scale models.

creases with a decrease in the size of RSDs. As a result, smaller RSDs have wider vents compared to larger scaled models through which fire/smoke plumes leave the dwelling, which contributes to higher heat fluxes.

The heat flux received by a heat flux gauge at a distance from the dwelling will consist of multiple components, due to the energy emitted by the flames, wall sheets and from flames inside the dwelling, i.e. $\dot{q}'' = \dot{q}''_{flames} + \dot{q}''_{walls} + \dot{q}''_{dwelling}$. From fundamental thermodynamics, the radiation received from each is a function of the view/configuration factor, $\emptyset$; temperature difference of the emitter and receiver to the 4th power, $(T_e^4 - T_r^4)$; and emissivity of each component, ϵ. The emissivity of gas on a reduced scale is smaller compared to full scale as the emissivity is a function of absorption coefficient κ. For optically thick or sooty flames, the emissivity approaches unity; for optically thin cases, it approaches zero. In a compartment fire, the flames are optically thin in the beginning and transition to optically thick, thereby making the absorption coefficient κ a time-dependent function. However, the ignition of a target material is typically not affected by its size (unless thermal thickness influences the heat balance, and the critical heat flux is assumed to remain constant for a material. Hence, when simulating fire spread due to radiation, heat fluxes must reach the magnitude of critical heat fluxes required for materials and cannot be scaled.

Based on the discussions above it can be seen that geometric and Froude number scaling does not capture radiation well. Parameters influencing radiation could range between being linear and to the fourth power, as well as being time-variant. Thus, when ignition by radiation is critical, the equation for the flux received, $(\dot{q}'')$ should be calculated and parameters adjusted until the flux from the different components sums to that required for ignition. This will make scaling very sensitive to geometry and will also need to be done for each configuration investigated.

Flame heights

A fire within a compartment induces pressure difference across the openings. This allows cold air to enter the compartment, which then supplies oxygen to sustain the fire and drive hot gases out of the compartment. In a ventilation-controlled fire, unburnt combustible gases tend to ignite at the openings as soon as fresh air is introduced, which also causes

Table 7. Summary of RSE model tests.

Scale		Full	1/4	1/5	1/7.5	1/10	1/15
Experiment time [s]		1500	750	620	570	440	395
Peak ceiling temperature [°C]		1037	836	817	776	867	719
Peak heat flux at 2m from the door [kW/m²]	Unscaled	60	14.85	12.61	11.27	Error	10.17
	Scaled	60	29.7	28.42	30.87	–	39.74
Flame heights [m]	Experiment	4	0.98	0.7	0.46	0.33	0.24
	Analytical	3.996	1.043	0.838	0.552	0.411	0.285
	Scaled from Exp.	–	3.92	3.5	3.45	3.3	3.6
	%Error of scaled and FSE	–	2	12.5	13.8	17.5	10

external flaming. In RSEs, the flame height (h_{flame}) was defined as the vertical length measured from the ground level to the tip of the external flame, as discussed below. For ISs, flames ejecting from openings (as seen in Fig. 8) enhance fire spread by igniting combustibles in close proximity, i.e., the flames from the openings impinge on adjacent dwelling and enhance the fire spread rate. Hence, the ability to scale flame lengths is an important factor if one wants to recreate settlement-level spread in future work. During the RSEs conducted in this work, the fresh air entering through bottom of the doors pushed the hot gases inside the dwelling through the windows and door tops. Hence, large flames emerging from windows and doors were visible. This was predominantly visible in smaller models, which had wider door openings in relation to the dwelling width, compared to the larger models.

The flame heights (h_{flame}) were obtained from analysis of the video footage and photographs recorded during RSEs. The peak values of h_{flame} and scaled flame heights ($h_{flame\ scaled}$) of each of the RSEs, as well as the value of h_{flame} for the full-scale single ISD experiment, are shown in Table 7. The length of flames for a wood crib fire can be expressed by the following approximate correlation:

$$h_{flame} + H_o = 12.8\left(\frac{R}{w}\right)^{2/3} \quad (12)$$

where H_o and w are the height and width of the opening [m], respectively. R is the estimated mass loss rate of the wood cribs burning inside a post flashover compartment [kg/s], which can be defined as:

$$R = \frac{5.5}{60} A_o \sqrt{H_o} \quad (13)$$

where A_o is the total area of all openings for an enclosure. When the above flame height calculations are compared to the flame heights measured during the RSEs, it shows that the calculated flame heights are slightly overpredicted compared to the experimental flame height. The closest match was found in the 1/4th RSD with an error margin of 2%. For other cases, the error margin was between 10–20%. This shows that the flame height from the opening in a compartment fire was linearly proportional to the scaling factor and the that the larger scaled models have a higher accuracy. It is also necessary to note that the peak flame height was an approximated value, and the error might reduce or increase if the flame heights were measured accurately.

Summary of experimental results

The summary of the experimental results for the RSEs, consisting of the peak ceiling temperatures, peak heat fluxes, flame heights, and total experimental time, are detailed in Table 7. The unscaled RSE results were also scaled-up, using the scaling correlation, to compare the results to the FSE; these are also in Table 7. From the results it can be seen that using a 1/4-scale RSE will provide good behavior when simulating fire spread due to flame impingement.

Fire Dynamics Simulator model set-up

In this work, Fire Dynamics Simulator (FDS version 6.7.4) models were created for all the RSEs, and the results were compared to the experimental data. This has been done to further study the RSEs and to provide insight into whether FDS models may provide good predictions for identifying which scale may be suitable for experiments prior to developing RSEs, and for conducting parametric studies in future work.

Experimental setup in FDS

The FDS model setup corresponds to the RSEs as explained in the above sections. The dimensions of the RSDs in FDS were set according to Table 3. The surface thickness of the sheet walls for the models was assigned to be 1 mm; however, the obstruction thickness was adjusted to a single cell and a void backing condition was applied.

The properties of materials used in the simulations are listed in Table 8. The fire was modeled by burning wood cribs using a simple pyrolysis model. The wood

Table 8. Material properties used in FDS models.

Properties	Steel	Wood
Density [kg/m^3]	7850 [20]	450
Specific heat [kJ/(kg·K)]	0.46	1.3
Conductivity [W/(m·K)]	45.8	0.14
Emissivity	0.90 [21]	0.9
Ignition Temperature [°C]	NA	350 [9]
Surface backing	Exposed	Air gap

Table 9. Mesh size calculation and wood crib dimensions of different scaled models.

Scale size		1/4	1/5	1/7.5	1/10	1/15
HRR [kW]		320	183	67	33	12
D^*		0.608	0.486	0.325	0.245	0.163
Mesh sizes [m]	Coarse [$D^*/4$]	0.152	0.122	0.081	0.061	0.041
	$0.1D^*$	0.061	0.049	0.033	0.025	0.016
	Fine [$D^*/16$]	0.038	0.03	0.02	0.015	0.01
Applied mesh [m]	Fire	0.01	0.01	0.006	0.005	0.0025
	Other domain	0.02	0.02	0.012	0.01	0.005
Wood crib size [m]	Width/height (RSE 0.022 m)	0.02	0.02	0.024	0.02	0.02
	Length	0.5	0.5	0.3 (In RSE 0.34)	0.3 (In RSE 0.27)	0.16 (In RSE 0.15)

cribs were assigned a heat release rate per unit area (HRRPUA) curve for the South African pine as obtained from fire propagation apparatus (FPA) tests conducted for previous FSE work [4]. The wood pieces soaked in paraffin were modeled by allowing those pieces of the crib to burn immediately.

In this work, the radiation transport equation for a grey gas was solved using finite volume method. The radiation parameters, namely radiation fraction and the number of radiation angles, were set to the default values of 0.35 and 100 sr respectively.

Computational domain, cell size, and mesh sensitivity

The size of the computational domain for each model was dependent on the size of the respective RSDs. The domain was kept sufficiently large to capture necessary data from the door and window of the RSDs. The computational domain was assigned with uniform meshing except that a finer meshing was used for the wood cribs. The dimensions of wood cribs were marginally adjusted to accommodate the meshing process; however, the total HRR of the cribs was maintained close to the experimental value.

The cell size (δ_x) for each simulation was determined using the D^* method, as shown in the following equation [20]:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty C_p T_\infty \sqrt{g}}\right)^{\frac{2}{5}} \qquad (14)$$

where D^* is the characteristic fire diameter; $\dot{Q}$ is the heat release rate [kW]; ρ_∞, T_∞ and C_p are the ambient air density [kg/m^3], specific heat of air [kJ/(kg K)] and ambient temperature [K], respectively; and g is the gravitational acceleration [m/s^2]. A maximum cell size of $0.1D^*$ for a plume fire is widely accepted in the fire simulation; thus, a significantly finer mesh than the recommended $0.1D^*$ was used for each case. In this work, a mesh size of $0.02D^*$ was applied to the wood cribs and $0.04D^*$ was applied on remainder of the computational domain. The details of mesh sizes and wood crib sizes for all reduced-scale models are listed in Table 9.

A mesh sensitivity analysis for each scenario was carried out by refining the cell size by a factor of 2. The refinement of the computational domain increased the computational time significantly such that the simulation did not reach a considerable time step even after running for weeks on high-performance computing at the University of Stellenbosch. The computational cost with such a refined mesh is uneconomical and impractical. The HRR and cell size is governed by the size of wood cribs; hence, the coarser mesh was avoided to carry out the mesh sensitivity analysis. Since the modeling was already carried out with an overly refined mesh, the sensitivity analysis was not carried out for all the cases. However, with the considerable data that was obtained from the 1/4th and 1/15th scale models, temperatures of various locations at different heights within the compartment were compared. The temperature curves shown in Fig. 9 for both 1/4th and

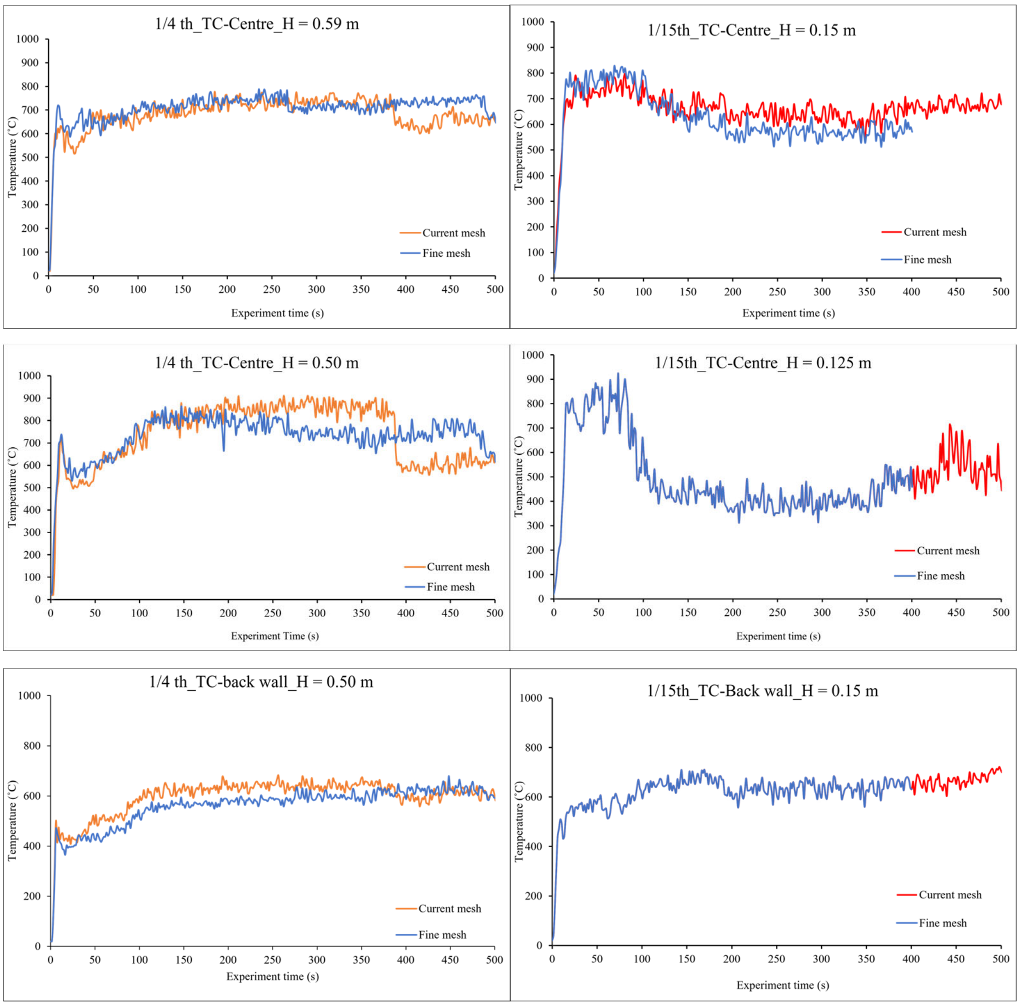

Fig. 9. Mesh sensitivity analysis—temperatures of various locations at different heights for 1/4th and 1/15th scale.

1/15th FDS model were identical with minimum fluctuations. This demonstrates the grid independence of the model and, based on these results, it can be assumed that the cell size used in this work for all the models can be sufficient to capture fire behaviour with reasonable accuracy.

Fire Dynamics Simulator results and discussion

Ceiling temperature

The ceiling time/temperature curves of the FDS simulations for the various RSEs are depicted in Fig. 10. The ignition of wood cribs sprinkled with paraffin was modelled in FDS using burn immediately condition. This choice of ignition could not capture the initial growth phase of the reduced scale FDS models. Due to this reason, an immediate peak was observed a few seconds after ignition of the RSDs, which gave way to the fire slowly becoming a ventilation-controlled fire with a continuous steady phase. In the RSEs, however, the wood cribs, despite being enhanced with paraffin, took longer to reach a steady-state phase; thus, in some cases the graphs were shifted by up to 3 minutes for ease of comparison.

The fire development curves were divided into two parts based on the burning pattern inside the RSDs. The smaller scales—1/10th and 1/15th size—had smooth transitions between the stages of fire, whereas the larger compartments had a distinct burning pattern in which a significant change in the temperature curve was visible. The stepwise drop in the time-temperature curve of the FDS models for the larger models could be a result of the fuel burn away property. This fuel property allows the wood cribs layers to disappear when they are exhausted, and for temperatures to drop immediately in simulation models; as a result, these RSEs form a unique pattern. This behavior was continued until the fuel was largely consumed by the fire; then the curves became smooth, as seen in the smaller scaled models. The smaller RSEs also have a smaller number of wood crib layers, meaning that the change in fuel availability was not sufficient to form a similar pattern.

The FDS models of the RSEs typically predict the experimental results with a suitable level of accuracy and provide the correct trend. However, for the 1/7.5th and 1/10th case, the maximum ceiling temperatures

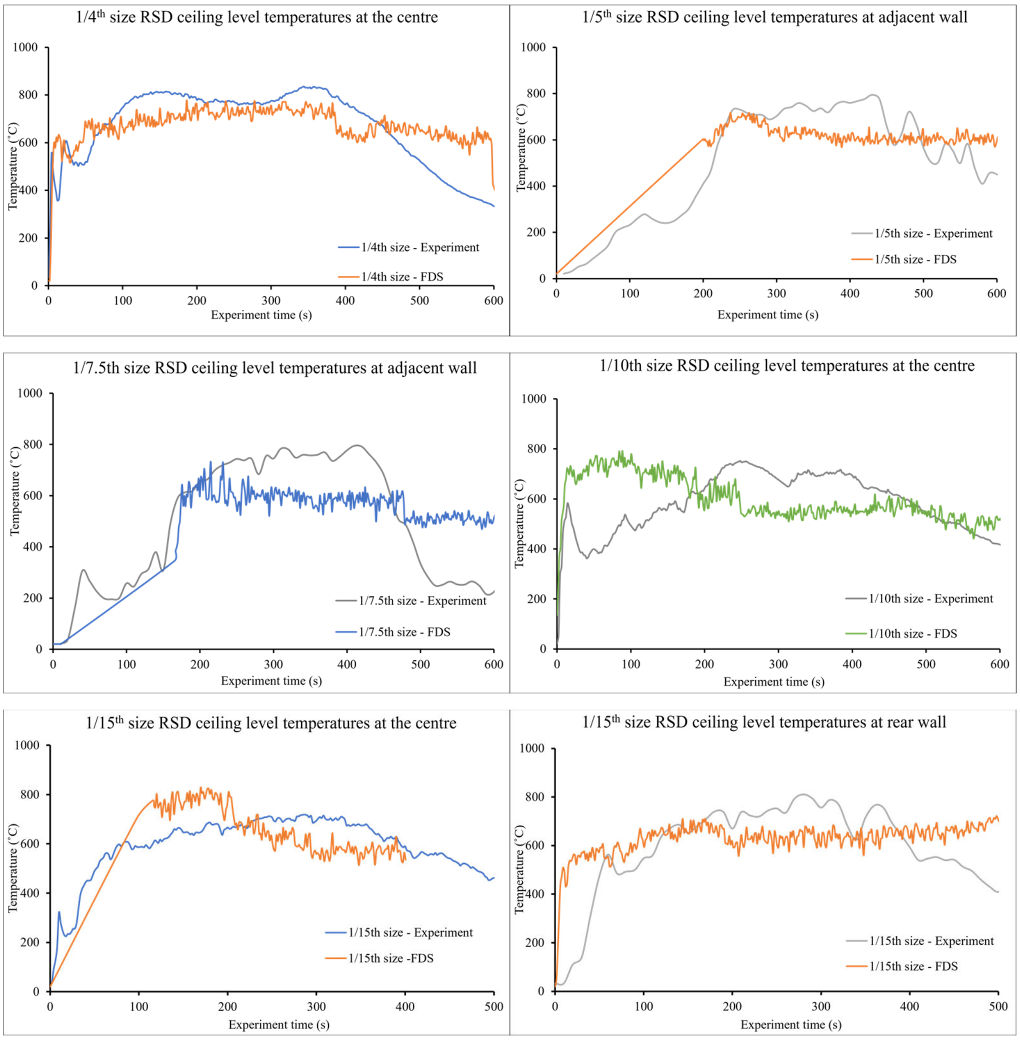

Fig. 10. Top: ceiling level temperatures at the centre of RSDs in RSEs; middle, bottom: experimental and FDS results in comparison of ceiling level temperatures.

varied with an error of 10–15% when compared with the RSEs as shown in Fig. 10. The burning time for the 1/4th and the 1/15th scale was in good agreement with the experimental time with an error of less than 3%, but for all the other cases, it was over predicted in the FDS models by between 10 and 25 %.

Incident heat flux

The heat-flux curves for the FDS simulations and the RSEs are shown in Fig. 11. In some cases, the maximum heat fluxes were offset by up to 3 minutes for comparison reasons. Additionally, for some scenarios, the peak heat fluxes were seen at the early stage in the simulations due to the immediate burning of wood cribs. The peak heat fluxes at a 2m distance from the door compared well with the experiment results. After the peak, the fire immediately reached a steady-state phase. The heat fluxes in the FDS scenarios were lower than the RSEs, but the FDS simulation times compared well with experiment durations. Additionally, the FDS results for the heat fluxes at the windows were scaled up and compared with the FSE. The results from FDS underestimated the FSE results, resulting in a deviation of up to 30%.

Flame height

The flame heights of the simulations were obtained through visual interpretation using Smokeview. The maximum flame heights for all the cases are listed in Table 8, and Fig. 12 shows the projections of flame of the FDS RSEs. The flame heights predicted by the FDS simulations are higher than the experimental flame heights, except for the 1/4th scale model which has a good correlation. It should also be noted that the flame height from the experiments was visually recorded, meaning that a more detailed study is required to accurately quantify flame lengths.

Summary of FDS results

The summary of the FDS results, comprising of peak ceiling temperatures, peak heat fluxes, and flame heights, for all scaled models are given in Table 10. The

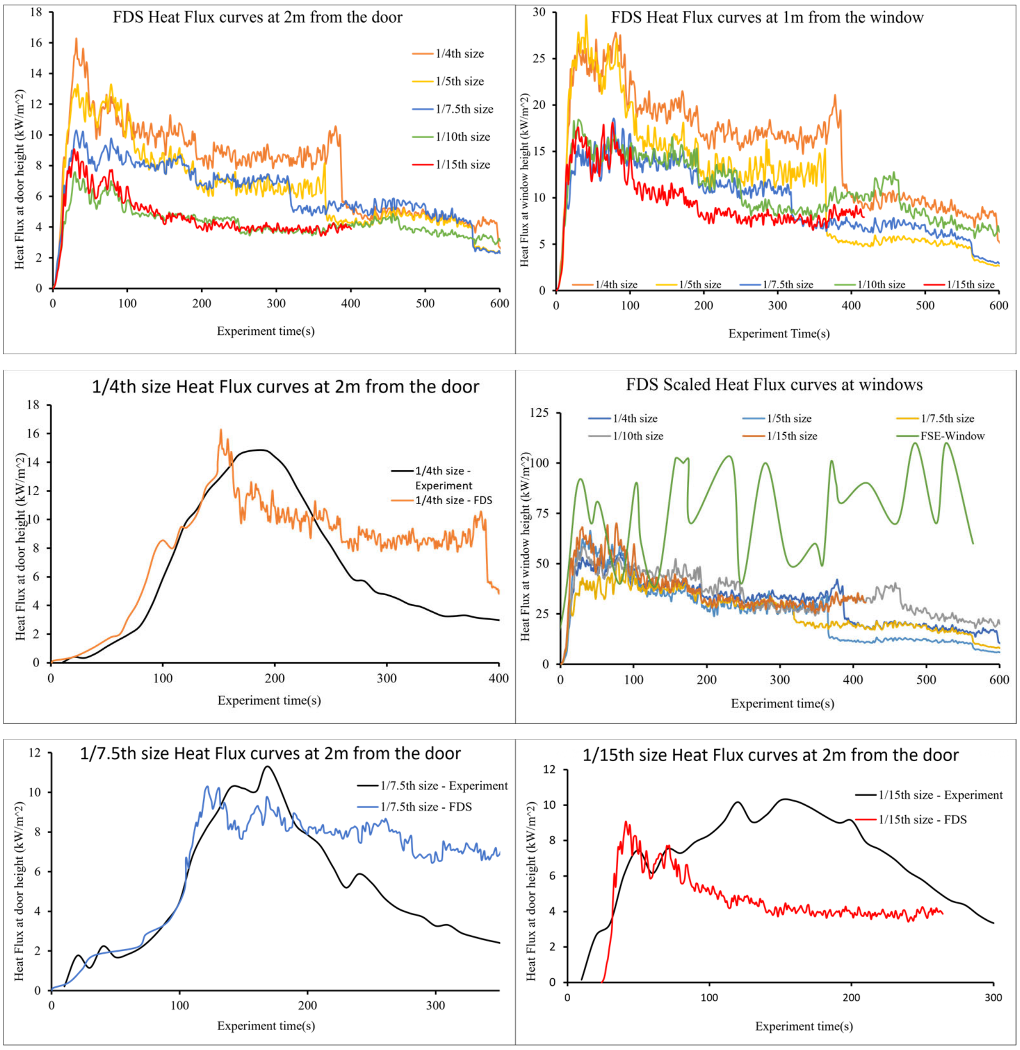

Fig. 11. Heat flux curves comparison from RSEs and FDS simulations. (The 1/5 RSE is not excluded due to an equipment error.)

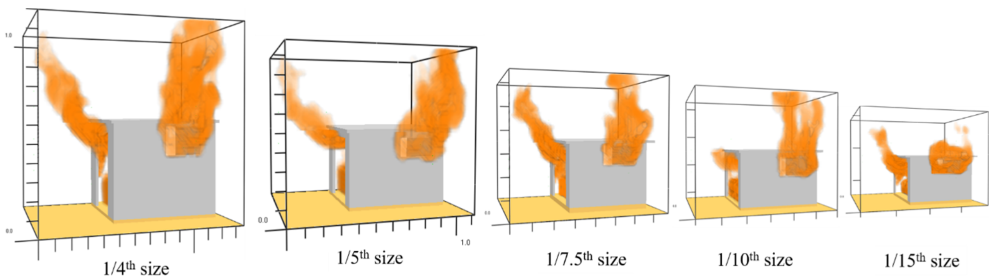

Fig. 12. Peak flame heights of RSD FDS models.

experimental results in the table are also provided to compare with the FDS simulation results.

Conclusion

This paper investigated the application of scaling methods for thermally thin compartment fires, such as the ones that can occur in informal settlement dwellings (ISDs), through reduced-scale experiments (RSEs) and Fire Dynamics Simulator modeling. The RSEs in this work were based on a full-scale experiment of a steel clad dwelling previously conducted [4]. Different sizes—1/4 scale, 1/5 scale, 1/7.5 scale, 1/10 scale, 1/15 scale—were used to assess the behaviour of the RSEs, and the results obtained were compared with the full-scale ISDs results.

Each RSE had clear stages of fire growth, flashover, a fully developed blaze, and decay. A trend of increase in time to flashover with an increase in dwelling scale (i.e.,

Table 10. Summary of FDS results and RSE data.

Scale size	Experimental results			FDS simulation results		
	Maximum ceiling temperature [°C]	Heat flux at 2 m from the door [kW/m²]	Flame heights [m]	Maximum ceiling temperature [°C]	Heat flux at 2 m from the door [kW/m²]	Flame heights [m]
Full	1037	60	3.5	990	60	3.5
1/4	836	14.85	0.98	911	16.3	1.1
1/5	817	12.61	0.70	817	12.7	0.80
1/7.5	776	11.27	0.46	856	10.3	0.60
1/10	867	Error	0.33	792	7.16	0.49
1/15	719	10.17	0.24	827	8.89	0.30

resulting in a small dwelling) was observed during testing, which requires more research. Recorded temperatures in the RSEs were considerably lower than those recorded in the previous full-scale experiment, with a difference of 20–25% being observed between the RSEs and the FSE. The incident heat fluxes for the RSEs did not correlate well with the FSE, where the error margin in all scales was substantially high: up to 50% in few cases. Scaled flame heights of the 1/4 and 1/5 scale experiments were within 15% of the FSE, with the 1/5 scale matching the approximate flame height of the full-scale experiment.

FDS simulations for each RSEs were carried out and the results were compared. The FDS models appear to predict the experimental results with a relatively good agreement and show similar peaks and the correct trend. However, there was an offset in the time to flashover of a maximum of 3 minutes in some cases, due to the choice of igniting wood cribs. The ceiling temperatures from FDS matched well against the experimental results, where the maximum deviation was found to be 10% for the 1/15 size model. The burning times in FDS were also similar to the RSEs. The peak heat flux predicted by FDS for all the scaled models compared well with the experiments, whereas the heat flux reached during steady-state in all models were lower: a significant deviation of up to 30% was seen in the 1/15th scale FDS model. The flame heights for the RSEs were overpredicted in FDS. The closest correlation was found only in 1/4th scale models, while all other models had significantly higher flame heights. A more quantitative approach would provide a detailed understanding of scaling flame heights in compartment fires. In addition, the length of the flame is also an important factor that has the potential to ignite flammable materials in its vicinity, meaning that it is necessary to study this aspect in future work.

The comparison between RSEs and FDS results shows that larger RSEs would more closely match the behavior of the full-scale for recorded temperature, flame heights, and burning time, but the heat flux is underpredicted in all the cases. This preliminary study has given a indication that the rate of heat loss through the boundaries is more prevalent in RSEs than through the vents, meaning that a more robust approach must be considered to study the properties of these heat fluxes in future experiments. It should also be noted that an RSE larger than 1/4 scale would be inefficient, as it would increase the material cost, labor requirements, and handling of the RSE before testing. The results from this study suggest that reduced-scale modeling with RSE models of 1/4 scale and 1/5 scale can be used to replicate an ISD fire with a reasonable level of certainty, depending on the parameter being studied. Nonetheless, a more detailed analysis on a 1/4 scale is necessary to understand the workability of this scaled model as a replication of an informal settlement dwelling from a fire-spread perspective.

This work forms the foundation for future experimental testing where the fire spread between dwellings and parameters, such as slope, flammable items stored between dwellings, construction materials, wind, dwelling density and the material that is first ignited can be studied. Furthermore, the scaling methodology may be suitable to be applied to other combustible dwellings, such as refugee camp shelters, temporary shelters for the homeless in some cities and traveller camps. Studies involving combustible cladding would require significant research as the scaling methodologies provided here may not be suitable when compartment boundaries are flammable.

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