U.P.B. Sci. Bull., Series D, Vol. 87, Iss. 4, 2025 ISSN 1454-2358

TOWARDS THE DEVELOPMENT OF AN FDS MODEL FOR EVALUATING THE EFFECTS OF CRITICAL PARAMETERS ON THE FLAME SPREAD BEHAVIOUR OF ISDS IN BANGLADESH

Swagata DUTTA [1], M. Muedul AHSAN [1], Mohammad Salim KAISER [2, *]

Fires in informal settlement dwellings (ISD) pose significant risks due to the nature of the structures, construction materials, fuel storage, and unplanned layouts. Computational Fluid Dynamics (CFD) models in the field of fire research have primarily focused on small-scale fire behavior and smoke movement in formal structures, with limited attention given to Informal Settlement Dwellings (ISDs). This paper addresses this research gap by developing a robust advanced numerical model on Fire Dynamics Simulator (FDS®) based solution to evaluate the flame spread characteristics of ISDs, and providing insights into the fire behavior of ISDs and the influence of different critical parameter (i.e. fuel load, fuel orientation, construction material), on the flame spread characteristics of ISDs. Higher values of ceiling temperature and back wall temperature have been found to correlate with construction materials having superior thermal conductivity and high ignition temperature. Also, observations show that, fuel load has significant effect on heat released per unit area. Understanding the correlation between various critical parameters and flame characteristics in ISD can lead to betterment of safe ISD design.

Keywords: fire dynamics, computational fluid dynamics, informal settlement dwellings, fire safety

1. Introduction

Informal settlements, including slums, shacks, and favelas, are highly vulnerable to fire incidents due to their lack of legal recognition and the prevalence of combustible materials [1-3]. The amalgamation of such materials, coupled with densely packed dwellings, significantly heightens the risk of fire initiation and rapid spread, leading to extensive damage and loss of life. Accurately categorizing and assessing fire risks in these settlements poses a considerable challenge due to the diverse range of materials present. Therefore, it is imperative to evaluate the typical materials found in these settlements and

[1] Institute of Appropriate Technology, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh
[2]Innovation Centre, International University of Business Agriculture and Technology, Dhaka-1230, Bangladesh
* Corresponding author: dkaiser.res@iubat.edu

compare them with existing literature to gain a comprehensive understanding of the fire risks they pose. This knowledge will facilitate effective fire incident management and aid in curtailing the further spread of fires [4]. Professional firefighters have observed the rapid escalation of fires in informal settlements, often reaching flashover within minutes due to the use of combustible materials in these homes [5]. Real-world tests on fire safety devices, conducted to evaluate their effectiveness in densely populated living quarters, underscore the critical need for tailored solutions. Furthermore, additional information on strategies to enhance individuals' responses during such emergencies and recommendations that could minimize losses are necessary.

Studies by A. Cicione et al. [6] and Y. Wang et al. [7] provide crucial insights into fire spread mechanisms within informal settlements, shedding light on separation distances required to prevent fire spread between homes and house-to-house fire spread dynamics. These studies represent significant strides in understanding fire behavior in these communities. In bustling urban areas like Dhaka, fires wreak havoc in slums constructed with flammable materials, underscoring the urgent need for effective fire safety measures tailored to the unique exigencies of informal settlements [8]. Further research by A. Cicione et al. [9] highlights the impact of physical characteristics of houses on fire spread dynamics, emphasizing the importance of context-specific interventions. While wood is a common building material within informal settlements, its inherent flammability poses challenges. However, with appropriate fire safety measures in place, wood can still be a viable choice [10]. Ensuring fire safety in congested areas, particularly informal settlements, is paramount. Investigations by I. Mbiggo et al. [11] underscore the critical role of fire safety in preventing the spread of fires and minimizing damage and loss of life. Despite these efforts, there remains a dearth of literature on Computational Fluid Dynamics (CFD) modeling tailored to Informal Settlement Dwellings (ISDs). This paper intends to fill this gap by creating a solution based on the Fire Dynamics Simulator (FDS) to assess the flame spread characteristics of Informal Settlements (ISDs) and offer significant insights for fire safety measures in these communities. By examining key parameters that affect fire behavior, this research aims to enhance the understanding of fire dynamics in informal settlements.

2. Numerical model

In this research study, the detailed geometric configuration of the timber-clad Informal Settlement Dwelling (ISD) model, as visually represented in Figure 1, was meticulously developed using a domain size measuring 5 meters in width, 5 meters in breadth, and 3 meters in height. This translates to a significant total of 75,000 individual cells, each with a precise volume of 0.1 cubic meters. To simplify cell size ratios, the timber pieces in the cribs were modeled as 0.1 m x 0.1 m. This adjustment allowed for a consistent cell size of 0.1 m x 0.1 m x 0.1 m throughout the models, facilitating computational efficiency without compromising the simulation of informal settlement fires. The density of the timber/wood used in the simulations was adjusted to 520 kg/m³ to account for the change in volume resulting from the modified cell size. In a similar vein, the cardboard thickness was intentionally set to 100 mm to guarantee that its depth was at least equivalent to the size of one cell, thereby securing its capacity to function effectively. Additionally, adjustments were made to the cardboard's density to align with these specifications and maintain its structural integrity.

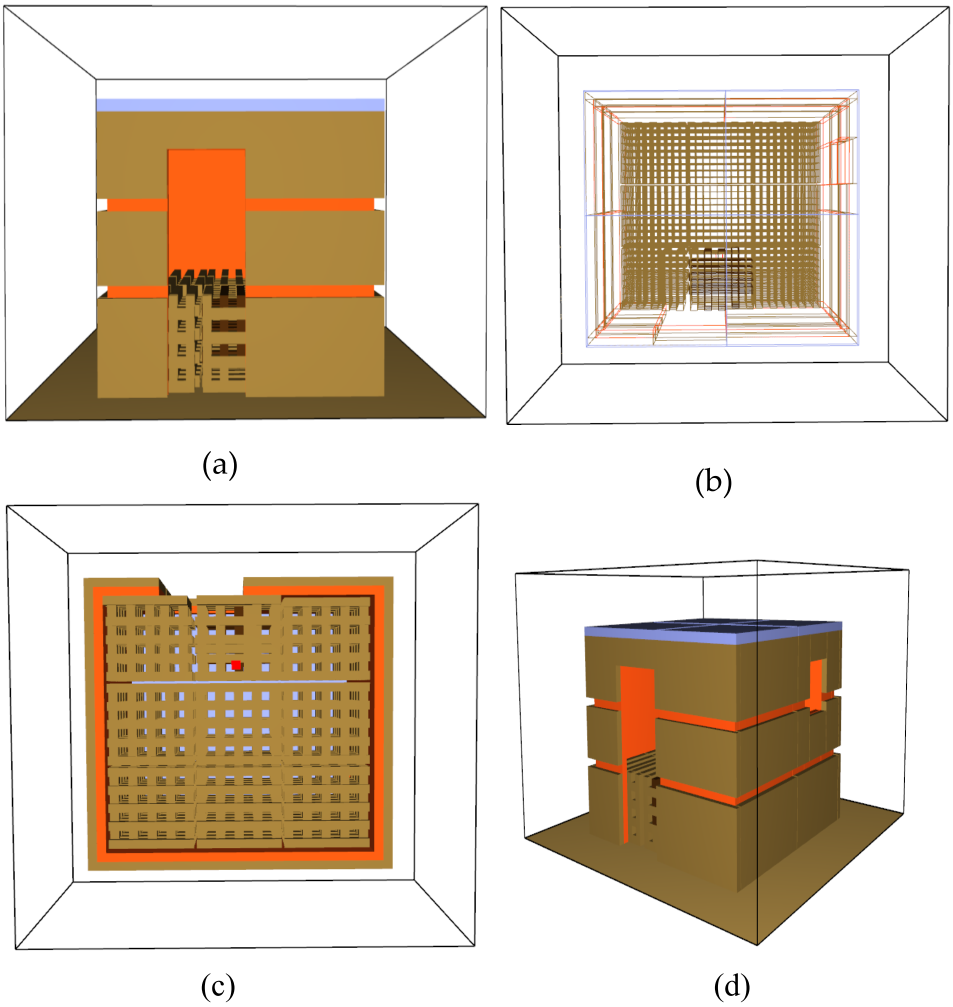

Fig. 1. FDS model of the timber cladded ISD (a) front view [solid object], (b) top view [wireframe], (c) Bottom view - showing timber cribs and ignition location (red zone), (d) Isometric view of the ISD.

The setup of the models, depicted in Fig. 1 as a Smoke view image, includes various components that were carefully designed for accurate representation. It is crucial to emphasize that the models were constructed without factoring in wind effects, an aspect that bears significance due to its potential impact on the overall results. The model was constructed according to the details in [6]. The cell size employed in the models developed in this study is notably smaller than 0.1 times the theoretical value for the maximum cell size recommended for plume fires. In a previous study [9], the authors conducted a cell sensitivity analysis on a model consisting of multiple ISDs with similar cladding materials and cardboard lining. The authors determined that a cell size of 0.1 m (which was used in this study) was adequate for capturing ceiling temperatures, heat fluxes emitted from the dwellings, and the behavior of the cardboard. Considering all the aforementioned factors, it can be reasonably assumed that the cell size employed in this study is sufficiently accurate in capturing the fire behavior. The material properties of cardboard and wood/timber were sourced from previous studies [12-14] to ensure accurate representation in the models. The walls were simulated with a thickness of 0.1 m, ensuring they were at least one cell size thick. The density of the timber material was adjusted to account for the change in volume resulting from the modified thickness. A surface thickness of 0.25 m was applied to all surfaces, and an air gap was set as the backing condition. Additionally, horizontal gaps with a width of 0.1 m were incorporated into the walls at heights of 800 mm and 1500 mm from the ground level, as illustrated in Fig. 1. The heights were chosen according to [6]. It is worth mentioning that the door and window in all cases were kept open throughout the whole duration of the simulation.

The numerical model in this study is built using PyroSim (Version 2021.4.1201), a graphical user interface based on Fire Dynamics Simulator (FDS) version 6.7.6. The model employs the Large Eddy Simulation (LES) approach to simulate low-speed, thermally driven flow. LES solves the Navier-Stokes equations with a low Mach number approximation suitable for low-speed, thermal convective processes. To solve LES equations, the numerical model applied is the finite volume method, which integrates the equations over the control volume inherently applying implicit filter. In FDS [15], the filter width is taken to be cubic root of the cell volume, $\Delta = V_C^{\frac{1}{3}}$, where $V_C = \partial x \partial y \partial z$. For any continuous field, φ is defined as,

$$\overline{\varphi}(x, y, z, t) = \frac{1}{V_C} \int_{x=-\partial x/2}^{x=+\partial x/2} \int_{y=-\partial y/2}^{y=+\partial y/2} \int_{z=-\partial z/2}^{z=+\partial z/2} \varphi\,(x', y', z', t)dx'dy'dz' \qquad (1)$$

Computational Fire Dynamics (CFD) based models utilized to solve fire related phenomena imply the conceptual framework provided by the Reynoldsaveraged form of Navier-Stokes equations (RANS). The equation defining conservation of mass is as follows:

$$\frac{\partial(\rho \boldsymbol{u})}{\partial t} + \nabla.(\mathrm{p}\mathbf{uu}) = -\nabla p + \rho \boldsymbol{f} + \nabla.\tau_{\mathrm{ij}} \tag{2}$$

In the above equation the terms used are as follows, $\rho\boldsymbol{u}$ is momentum per unit volume, $\partial(\rho\mathbf{u})/\partial t$ is local time rate of change of momentum, $\nabla\cdot(\rho\boldsymbol{uu})$ is convective transport of momentum (momentum flux), $-\nabla p$ is pressure gradient force per unit volume, τ_{ij} is viscous stress tensor and $\rho\boldsymbol{f}$ is body force per unit volume. The above equation is derived from Newton's second law of motion. The forces acting on the fluid body are surface forces like pressure gradient ? p , and friction in the form of viscous stress along with the buoyancy. The equation governing the energy at different states, which is the equation of conservation of energy is stated below:

$$\frac{\partial(\rho h)}{\partial t} + \Delta.(\rho \mathrm{h}\mathbf{u}) = \frac{\mathrm{Dp}}{\mathrm{Dt}} + q''' - \nabla.\boldsymbol{q} + \varepsilon \tag{3}$$

$$\rho\frac{\mathbf{Du}}{\mathrm{Dt}}.\boldsymbol{u} = \rho\frac{D(\frac{|\boldsymbol{u}|^2}{2})}{Dt}. \tag{4}$$

Here, the terms used are as follows, h is sensible enthalpy, ρh is energy per unit volume, $\partial(\rho h)/\partial t$ is local time rate of change of enthalpy, $\nabla\cdot(\rho h\boldsymbol{u})$ is convective transport of enthalpy, $\mathrm{D}p/\mathrm{Dt}$ is material derivative of pressure, q''' is volumetric heat source, $\boldsymbol{q}$ is heat flux vector, $-\nabla\cdot\boldsymbol{q}$ is divergence of heat flux, ε is viscous dissipation, $\mathrm{D}\boldsymbol{u}/\mathrm{Dt}$ is material derivative of velocity, $|\boldsymbol{u}|^2/2$ is kinetic energy per unit mass, ρ $\mathrm{D}(|\boldsymbol{u}|^2/2)/\mathrm{Dt}$ is rate of change of kinetic energy per unit volume. The sensible enthalpy, denoted as h, is a function that varies from point to point within a small control volume. It represents the net energy flow across the boundary of the control volume, with the point of consideration typically located at the center of the control volume. In the context of fire dynamics, certain terms in the governing equations can be neglected without significantly compromising the accuracy of the model, unless the physical system involves sealed compartments with significant pressure rise. Therefore, for most fire scenarios, the pressure term and dissipation term can be disregarded. In Large Eddy Simulation (LES), the flow field is resolved on a numerical grid, where flow structures, such as swirling eddies, may span only a few grid cells. To account for the effects of smaller, unresolved eddies, a sub-grid scale (SGS) model is employed. The goal of the SGS modeling is to maintain a small eddy viscosity that prevents the filtering of small-scale features while ensuring numerical stability. The eddy viscosity model can be understood in the context of the Navier-Stokes equations. One of these equations describes the conservation of momentum and defines the kinetic energy of the gas. This equation involves the dot product of the velocity field and the gradient of velocity, resulting in terms that represent the transport and dissipation of kinetic energy. In summary, the sensible enthalpy is a function of the net energy flow across a control volume, and its variation at different points within the volume. In fire dynamics, certain terms in the governing equations can be neglected unless the system involves sealed compartments with substantial pressure rise. LES resolves the flow field on a numerical grid and employs a sub-grid scale model to account for unresolved eddies. The eddy viscosity model plays a role in the conservation of momentum equation, representing the transport and dissipation of kinetic energy. The physical, thermal, and chemical properties of the materials, including detailed of each property, are comprehensively outlined in Table 1 for easy reference and comparison.

Table 1: **Physical, thermal and chemical properties of the materials [6, 16]**

Material Properties	Steel	Wood	Cardboard	Foam	Cotton	PVC	Rubber	Plywood
Density [kg/m^3]	7850	520	4.8	158	754	70	120	580
Specific Heat [kJ/(kg K]	0.6	1.3	2.7	1.0	2.9	1.8	1.8	1.2
Thermal Conductivity [W/(m K)]]	45	0.14	0.42	0.03	0.17	0.03	0.039	0.12
Emissivity	0.42	0.9	0.9	0.22	0.88	0.9	0.88	0.88
Ignition temperature [^{o}C]	NA	355	290	225	115	70	80	120
Heat of Combustion [x104kJ/kg]	NA	2.38	0.057	0.007	0.007	0.008	NA	0.001
Absorption Coefficient [x104 1/m]	5.0	5.0	5.0	4.0	5.0	5.0	5.0	5.0

3. Results and discussion

3.1 Effect of Fuel Load

In this study, three distinct fuel loads, namely 700 MJ/m^2, 1750 MJ/m^2, and 2000 MJ/m^2, were investigated. The initial four graphs, Figure 2(a)-(d), illustrate the impact of varying fuel loads on flame characteristics, while other parameters were kept the same. Analyzing the variation in heat release rate (HRR) depicted in Figure 2(a), it can be inferred that a lower fuel load leads to a quicker attainment of flash-over. This observation aligns with expectations, as a smaller amount of fuel requires less time to reach the ignition temperature. Moreover, a lower fuel load enhances combustion efficiency by ensuring sufficient oxygen for burning the combustibles. With increasing fuel load, ignition time also increases and more heat and oxygen are required for flash-over. Figure 2(b) illustrates the effect of fuel load on back and ceiling temperatures. In the case of a lower fuel load, the temperature rapidly reaches its peak and starts declining shortly thereafter. However, no such peak is observed with higher fuel loads. The peak in the case of a lower fuel load serves as an indicator of flash-over attainment. As the fuel load increases, the

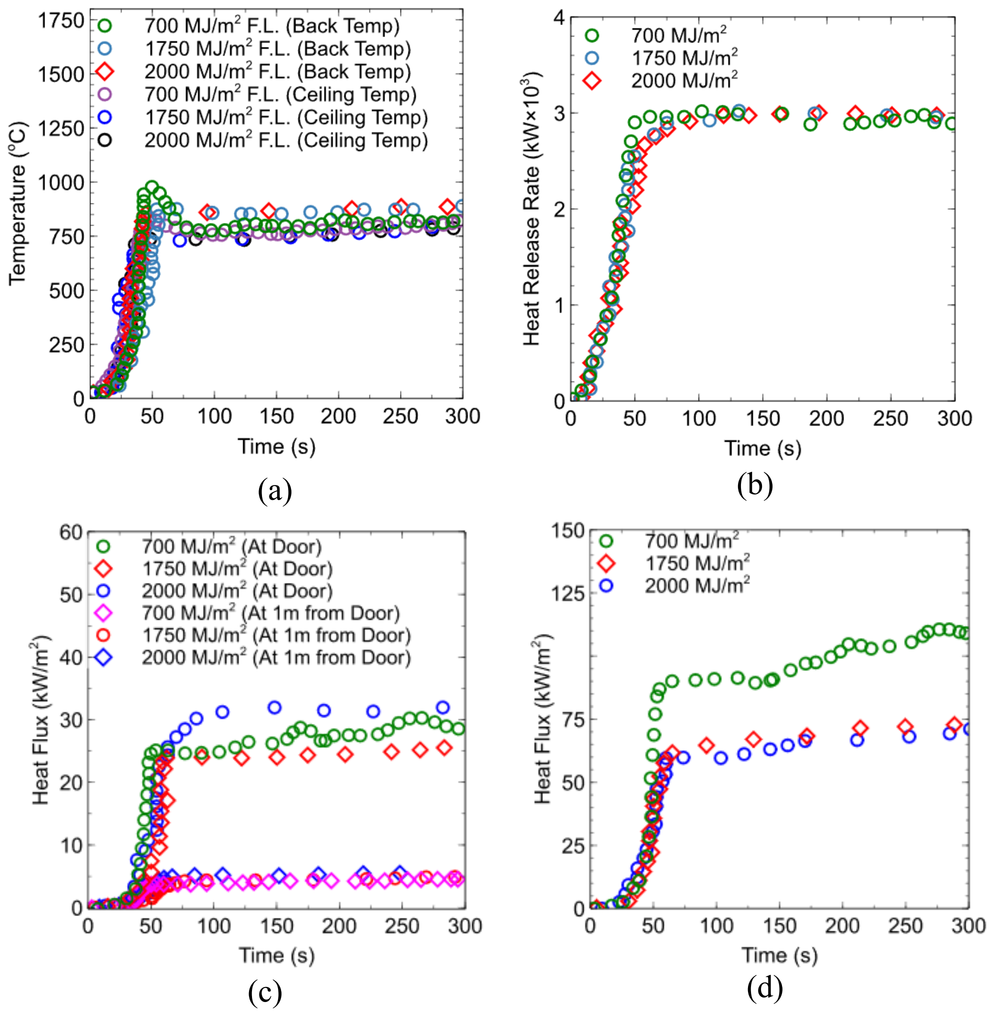

Fig. 2. For different fuel load (a) comparison of temperature (b) comparison of heat release rate (c) comparison of heat flux at door (d) comparison of heat flux at window.

overall impact on flame characteristics becomes independent of the fuel load. In scenarios with less fuel, the fire is predominantly fuel-controlled; however, with increased fuel, the fire transitions to being ventilation-controlled. This shift in dependency from fuel load to ventilation is notable as fuel increases. Observations from Figure 2(c) indicate that the heat flux at the door exhibits less sensitivity to variations in fuel load. However, less fuel load correlates to relatively high heat flux, due to faster rate of fuel burning through flash-over attainment. Furthermore, heat flux experiences a significant drop 1 meter away from any openings in the dwelling. Figure 2(d) indicates that, heat flux at the window is significantly larger than the heat flux at door, for the same fuel load. Thus, area of the opening has an inverse relationship with the heat flux through the opening. Heat escape from a compartment with hot exhaust gas is influenced by fluid flow continuity, where the velocity of fluid from smaller openings is greater than that from larger ones, resulting in higher heat flux at the smaller openings.

3.2 Effect of Construction Material

When examining the impact of construction material on fire behavior, it becomes evident that the fuel load's constancy plays a crucial role in determining the heat release rate, as indicated in Figure 3(a). The amount of heat generated during the fuel combustion process heavily relies on both the composition and the

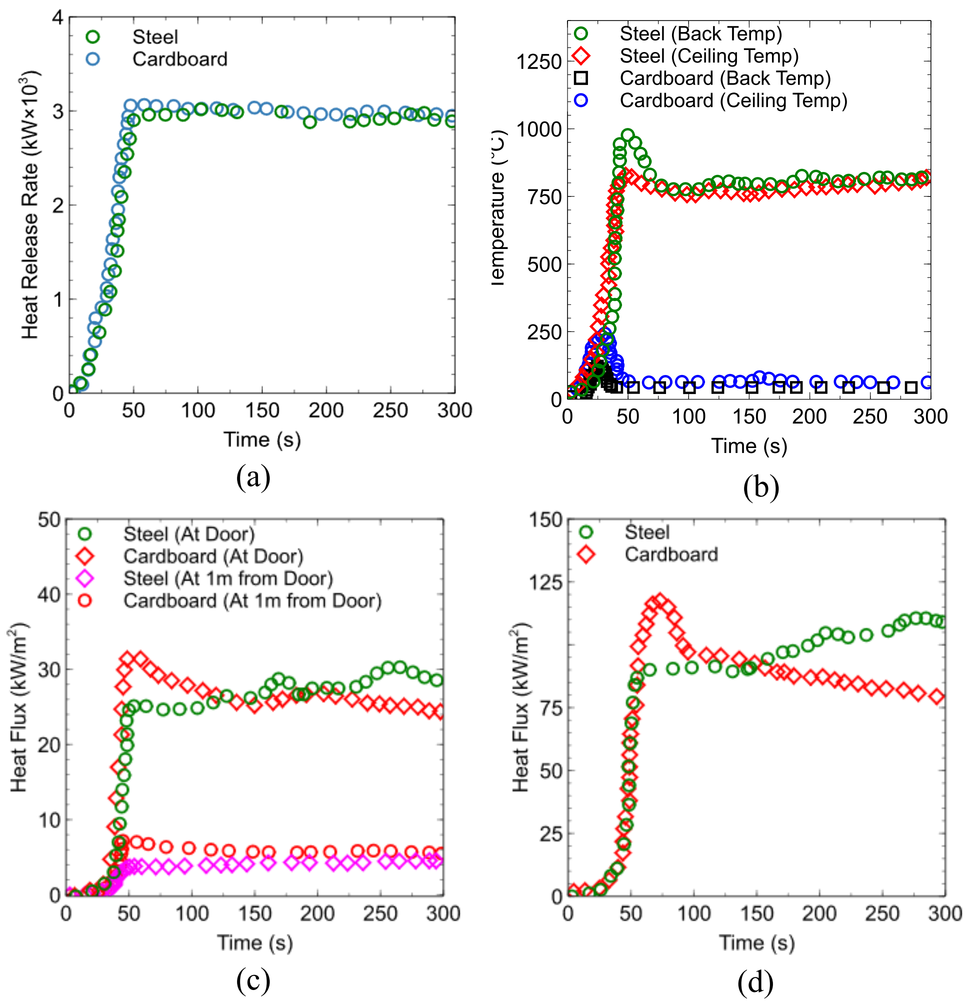

Fig. 3. For different fuel load (a) comparison of temperature (b) comparison of heat release rate (c) comparison of heat flux at the door (d) comparison of heat flux at the window.

quantity of fuel within the dwelling. Interestingly, the internal temperature of a dwelling can decrease rapidly if constructed using materials like cardboard, as highlighted in Figure 3(b). This swift decrease in temperature can be attributed to the quick ignition of cardboard once the internal temperature of the dwelling approaches the flash-over point, resulting in a rapid and hazardous fire escalation. Consequently, the structural stability of the dwelling is compromised, ultimately leading to the collapse of the entire structure and exposing the interior to external elements [17-18]. In contrast, structures built with steel sheets demonstrate a slower collapse rate, which allows for the accumulation of more hot combustion by-products within the dwelling, subsequently causing a rise in internal temperature. The influence of construction materials on heat flux mirrors that of the fuel load, as demonstrated by the data presented in Figures 3(c) and 3(d) within the specified context.

3.3 Validation of Numerical Model

In order to validate the precision and reliability of the numerical model that has been employed throughout the scope of this research endeavor, a comprehensive and meticulous analysis was conducted. This analysis involved a thorough examination of two particularly crucial experimental inquiries that specifically focused on the architectural dynamics inherent to informal settlement dwellings. Notably, Cicione and Bashir [6] were responsible for conducting experiments that involved two distinctly different setups of informal settlement dwellings. Each setup utilized different cladding materials, allowing for an in-depth comparison and analysis of how these variations influenced fire responses recorded for each configuration.

To appropriately evaluate the predictive capability of the computational model utilized within this study, particular attention was given to one experimental setup that employed timber cladding. This specific setup was meticulously reconstructed within the Fire Dynamics Simulator (FDS), ensuring that all relevant parameters were accurately represented. Following this reconstruction, the resultant fire responses generated from the numerical simulation underwent an exhaustive comparison with the corresponding experimental findings obtained from the empirical observations.

The comparisons were visually represented in Figures 4(a)-(d), which illustrate that the results derived from the numerical simulation display a close alignment with the experimental observations. This close correspondence signifies a satisfactory agreement between the two data sets, thereby reinforcing the validity and reliability of the numerical model for predicting fire behavior in informal settlement dwellings.

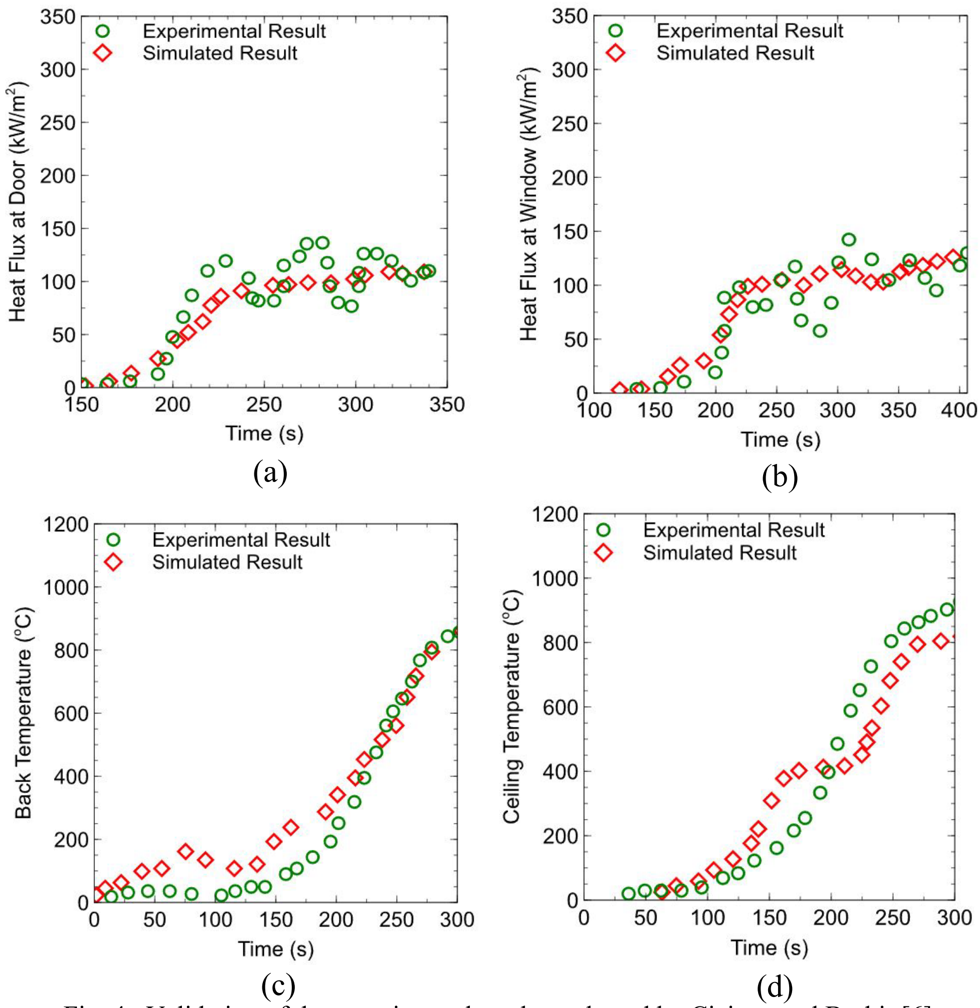

Fig. 4. Validation of the experimental work conducted by Cicione and Bashir [6].

4. Conclusions

This study investigated the influence of varying fuel loads on flame characteristics in informal settlement dwellings, utilizing three different fuel loads: 700 MJ/m², 1750 MJ/m², and 2000 MJ/m². The analysis revealed that lower fuel loads lead to quicker flash-over attainment, attributed to the smaller amount of fuel requiring less time to reach ignition temperature. Additionally, lower fuel loads enhance combustion efficiency due to sufficient oxygen availability for combustion. The examination of heat release rate (HRR) indicated that the fire dynamics shift from fuel-controlled to ventilation-controlled as the fuel load increases. The effect of fuel load on back and ceiling temperatures was observed, with lower fuel loads exhibiting a quick peak followed by a decline, indicative of flash-over attainment. In contrast, higher fuel loads did not show a distinct peak, suggesting an independence of flame characteristics from fuel load. The study also found that heat flux at the door exhibited less sensitivity to variations in fuel load, and heat flux dropped significantly 1 meter away from any openings in the dwelling. Furthermore, the research explored the impact of construction materials on fire dynamics, revealing that changing construction materials did not affect heat release rate if the fuel load remained constant. However, structural materials influenced the rate of temperature change inside the dwelling, with cardboard-made dwellings collapsing quickly, leading to a rapid decline in internal temperature, while steel-sheet structures took longer to collapse, resulting in prolonged elevated temperatures. To validate the numerical model employed in this study, comparisons were made with experimental investigations conducted by Cicione and Bashir on informal settlement dwellings. The simulations closely aligned with the experimental observations, confirming the accuracy and predictive capability of the computational model.

Acknowledgments

The authors express their deep appreciation to the Directorate of Advisory, Extension, and Research Services office of Bangladesh University of Engineering and Technology, Dhaka for the invaluable assistance and unwavering support throughout the duration of the project.

REFERENCES

[1] *S.H. Amirnordin, A. Khalid, S. Sulaiman, D.W. Jacob, M. Fawzi, S.M. Seri*, Combustion analysis of multi-circular jet plate in internal mixing air-assisted atomizer of burner system, Journal of Advanced Manufacturing Technology, Vol. **17,** No. **2,** pp. 1-15, 2023.

[2] *C.L. Atkinson,* Informal Settlements: A New Understanding for Governance and Vulnerability Study Urban Science, Vol. **8**, No. **158,** pp. 1-18. 2024, https://doi.org/10.3390/urbansci8040158

[3] *S. Dutta, F. Ahmad, R. Islam, M.S. Kaiser*, Evaluating the fire-reaction properties of building materials used in informal settlements in Dhaka, Bangladesh, Asia-Pacific Journal of Science and Technology, Vol. 29, No. 6, 2024, pp. 1-14. https://doi.org/10.14456/apst.2024.89

[4] *R. Walls, A. Cicione, R. Pharoah, P.J. Zweig, M. Smith, D.G. Antonellis*, Antonellis D. "Fire Safety Engineering Guideline for Informal Settlements: Towards Practical Solutions for a Complex Problem in South Africa, Editor: Richard Walls, Published by FireSUN Publications, Stellenbosch University, South Africa, 2020.

[5] *L. Wang, W. Li, W. Feng, R. Yang*, "Fire Risk Assessment for Building Operation and Maintenance Based on BIM Technology, Building and Environment, Vol. **205,** No. **108188,** 2021. https://doi.org/10.1016/j.buildenv.2021.108188

[6] *A. Cicione, M. Beshir, R.S. Walls and D. Rush*, Full-Scale Informal Settlement Dwelling Fire Experiments and Development of Numerical Models, Fire Technology, Vol. **56**, 2020, pp. 639-672. https://doi.org/10.1007/s10694-019-00894-w

[7] *Y. Wang, M. Beshir, R. Hadden, A. Cicione, M. Krajcovic, L. Gibson, D. Rush,* Laboratory Experiment of Fire Spread Between Two Informal Settlement Dwellings, International Journal of Thermal Sciences, Vol. **171,** 2022, 107195. https://doi.org/10.1016/j.ijthermalsci.2021.107195

[8] *F. Sharmin, M.R. Hossain, M.M. Rahman*, Causes and Consequences of Fire Hazard in Slum Settlements in Dhaka City: A Case Study on Basbari and Kawran Bazaar Slum, Dhaka, Bangladesh," European Academic Research, Vol. **7,** No. **1**, pp. 78-92, 2021.

[9] *A. Cicione, R.S. Walls, C. Kahanji*, Experimental Study of Fire Spread Between Multiple Full-Scale Informal Settlement Dwellings, Fire Safety Journal, Vol. **105,** 2019, pp. 19-27, https://doi.org/10.1016/j.firesaf.2019.02.001

[10] *B. Ostman, A. Voss, A. Hughes, H.P. Jostein, O. Grexa*, Durability of Fire-Retardant Treated Wood Products at Humid and Exterior Conditions: Review of Literature, Fire and Materials, Vol. **25**, No. **3**, 2001, pp. 95-104. https://doi.org/10.1002/fam.758

[11] Mbiggo I, Ssemwogerere K. "An Investigation into Fire Safety Measures in Kampala Slums—A Case of Katanga-Wandegeya," civil and Environmental Research, Vol. **10,** No. **3,** pp. 30-34, 2018.

[12] *A. Lonnermark, H. Ingason*, Fire Spread in Large Industrial Premises and Warehouse, BRANDFORSK project 630-021, SP Swedish National Testing and Research Institute, Sweden, 2005.

[13] *C. Eichler,* Flame Flashback in Wall Boundary Layers of Premixed Combustion Systems, Ph.D. Dissertation, Technische Universität, München, Germany, 2011.

[14] *G. Rein,* Smouldering Combustion Phenomena in Science and Technology, International Review of Chemical Engineering, Vol. **1**, pp 3-18, 2009.

[15] *K.B. McGrattan*, “Fire Dynamic Simulator (Version 6) Technical Reference Guide, National Institute of Standards and Technology, Washington, DC, USA, 2019.

[16] *M.J. Hurley*, SFPE Handbook of Fire Protection Engineering, 5th ed. Springer, New York, USA, 2016.

[17] *W. Zheng, F. Wei, S. Su, J. Cai, J. Wei, R. Hu*, Effect of the envelope structure on the indoor thermal environment of low-energy residential building in humid subtropical climate: In case of brick–timber vernacular dwelling in China, Environmental Technology & Innovation, Vol. **28**, No. **102884**, pp. 1-14, 2022, https://doi.org/10.1016/j.eti.2022.102884.

[18] *J. Teare, A. Mathee, N. Naicker, C. Swanepoel, T. Kapwata, Y. Balakrishna, D.J. Preez, D.A. Millar, C.Y. Wright*, Dwelling Characteristics Influence Indoor Temperature and May Pose Health Threats in LMICs. Annals of Global Health, Vol. **86(1)**, No. **9**, pp. 1-13, 2020, https://doi.org/10.5334/aogh.2938.