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The Effect of Plan Corner Shapes on the Spread Speed of Fire in High-Rise Buildings

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ABSTRACT

This study investigates the impact of plan corner shapes on the propagation rate of fire in high-rise buildings. Employing the PyroSim fire simulation program, a systematic modeling approach was adopted to simulate fire spread in a 12-storey building with varying plan corner shapes. The findings reveal that plan corners exhibiting straight configurations devoid of protrusions or recesses exhibit a reduced risk of fire spread when contrasted with irregular shapes. Consequently, we propose the integration of regular plan shapes lacking protrusions or recesses in the design of high-rise buildings to effectively minimize the rate of fire spread. This research contribution facilitates the selection of an optimal design alternative with respect to the velocity at which fire propagates.

1. INTRODUCTION

The vertical expansion of urban areas has been driven by the increasing population density, resulting in the proliferation of buildings that serve as key indicators of urbanization [1]. High-rise buildings, accommodating a larger number of residents compared to low-rise structures, present an elevated risk of fires due to the increased occupancy requiring evacuation in the event of a fire, compounded by the mixed-use nature of such buildings [2]. The absence of design elements aimed at safeguarding lives against fire within buildings contributes to the rapid spread of fires and the challenges encountered in fire suppression, impact mitigation, control, and containment [3]. The safe design in the event of a fire involves employing all possible measures to mitigate its risks, which pose considerable challenges in high-rise buildings [4]. The significant loss of lives and property resulting from fires has generated increased interest in studies investigating fire incidents and their propagation within high-rise buildings [5]. It is an infeasible task to achieve absolute safety from fire and eliminate all potential threats, emphasizing that architects are not expected to attain complete fire risk elimination. However, they are responsible for reducing such risks [6]. This study aims to investigate the influence of different plan corner shapes on the vertical spread of fire in high-rise residential buildings through computational simulations. By modeling fire spread in buildings with identical floor areas but varying plan shapes using the PyroSim program, we seek to determine the impact of corner shapes on fire propagation and provide recommendations to enhance the fire safety design of high-rise buildings. The research encompasses an introduction, a comprehensive review of previous studies and research related to the research problem, the research methodology, the presentation of results, their analysis, and subsequent discussion, and the conclusion, which includes key findings and recommendations.

The findings indicate that the risk of fire spread in high-rise buildings decreases when the corners are straight and not protruding or recessed from the level of window openings, and vice versa. Hence, the research recommends utilizing corner shapes devoid of protrusions or recesses in high-rise buildings, as this reduction in fire spread velocity can increase the likelihood of successful evacuation and minimize fire-related losses.

2. PREVIOUS WORKS

The vertical spread of fire in high-rise buildings has been the subject of extensive research. Chow and Hung [7] examined the impact of designing inner courtyards in high-rise buildings for fire safety. Their findings indicated that the spread of fire through the courtyard to upper floors is influenced by the presence of openings overlooking the courtyard, as well as negative pressure in those floors resulting from mechanical ventilation. Cowlard et al. [8] emphasized the need to ensure an acceptable level of fire safety in light of the increasing number of high-rise buildings. They highlighted that open plan layouts tend to accelerate fire spread compared to closed plan configurations.

In investigating the geometric shape of high-rise building plans and its effect on fire spread, Onyenobi et al. [9] examined three shapes-square, triangle, and circle-with equal areas. Their results demonstrated that the square shape exhibited the highest resistance to fire spread, followed by the circle and then the triangle. Li et al. [10] compared fire risks in two areas representing different building floor areas and found no significant increase in risks when the building floor area was doubled.

Węgrzyński and Konecki [11] explored the influence of fire location and room area on the variation in smoke and heat spread within and outside the building. Their study revealed that the temperature of smoke escaping from a room varies with changes in room area and fire location, with higher temperatures observed in smaller rooms. Zhang [12] investigated the impact of spatial design in high-rise office buildings on fire prevention. The results highlighted the influential role of office area in the rate of smoke spread during a fire. Constructing an atrium on typical floors and extending the common edge between the atrium and the office area were found to effectively prolong the evacuation process.

Ali [13] aimed to identify the availability of safety controls and procedures for reducing fire accidents in residential complexes. The study revealed clear deficiencies in the application of safety systems, such as the lack of escape stairs in some residential complexes, posing a significant danger to residents during emergency evacuations. Abbas [14] focused on the design determinants of fire prevention facilities and their role in minimizing material losses and protecting lives. The study emphasized the importance of providing an adequate number of escape stairs, sufficiently wide corridors, and the division of buildings into fire sectors to contain and prevent the spread of fire.

Recognizing the existing weaknesses and shortcomings in safety measures within high-rise buildings, Ashour [15] aimed to assess the provision of safety measures aimed at reducing fire risks. The study revealed deficiencies in the engineering plans of these buildings, emphasizing the need to adhere to construction standards regarding escape routes and the division of buildings into fire sectors. Muhammad and Eze [16] found that while a high percentage of high-rise buildings adopt fire prevention strategies, there is a noticeable lack of fire escape routes in most buildings.

Konbr and Maher [17] conducted a study to determine the effect of stair design in multi-storey buildings on evacuation efficiency and speed. Their findings concluded that anti-clockwise stairs enable faster evacuation with less physical effort. Zhang et al. [18] conducted evacuation experiments in a university campus building, comparing four types of stairs. The study concluded that straight stairs with a platform and double-split parallel stairs offered smoother evacuation compared to curved double-run parallel stairs and L-shaped angle stairs.

3. METHODOLOGY

To clarify the effect of different models of high-rise building plan angles on the propagation fire speed, to solve the models was used the Fire Dynamics Simulator (FDS), and the PyroSim was used to draw the models, as well as the Smokeview was used for the purpose of presenting the results [19-21]. The importance of using computer modeling to simulate fire lies in the answers it provides to many questions for which we cannot find an answer by traditional descriptive methods [22, 23] without the high cost of experimental tests [21]. Simulations can also contribute to making safety recommendations to teach people what to do in the event of a fire [22].

3.1 Designing the building with different models for the plan corner shapes

The fire development by computer simulation was followed up for eight models of the plan corner shapes. Figures 1-4 show the plans and three-dimensional models of the shapes of the building's corners [A- B- C- D- E- F- G- H].

3.2 Fire scene design

The outbreak of fire on the lower floors poses a greater danger to the entire building in high-rise residential buildings [5], so the fire site that contains greater risks must be chosen, and accordingly the fire site was located in second floor at the apartment kitchen. The fire source area is 0.5 m×0.5 m, the fire source has 1000 kW/m^2 as a rate of heat release, the simulation object grid in the arithmetic domain is divided into 64*54*144, and the size of cell is 0.25 m×0.25 m×0.25 m, so that the cells total number of is 497,664. The simulation time is about 300 seconds. Thermocouples were placed on the second, fourth, sixth, eighth, tenth, and twelfth floors to measure the temperature change with time, and a 6-m Y-axis slice was used for measuring devices, and Figure 5 presents the arithmetic domain and the measuring devices. The polyurethane foam is a combustion reaction material, and the furniture differs in each residential apartment from the other. The same furniture was used for the entire building in order to simplify the computer simulation. General description of the computer model below:

- As a virtual material, the walls of the buildings were constructed with a thickness of 20 concrete walls
- As a default material, 10 cm of foam and 2 mm of fabric were used to upholster all sofas.
- Relative humidity 24% and initial temperature 44 degrees Celsius.

The default combustion energy that is chosen through the balance between the combustion energy source and the window openings, the energy source represents the furniture, which is uniform in all models and all floors of the building. The independent variable is the plan corner shapes in the different models, and the dependent variable is the speed of fire spread, while the constant parameters are the building area, the location of the fire source and the rate of heat release, furniture design and distribution, building materials, window area, as well as the smallest distance between furniture and window openings.

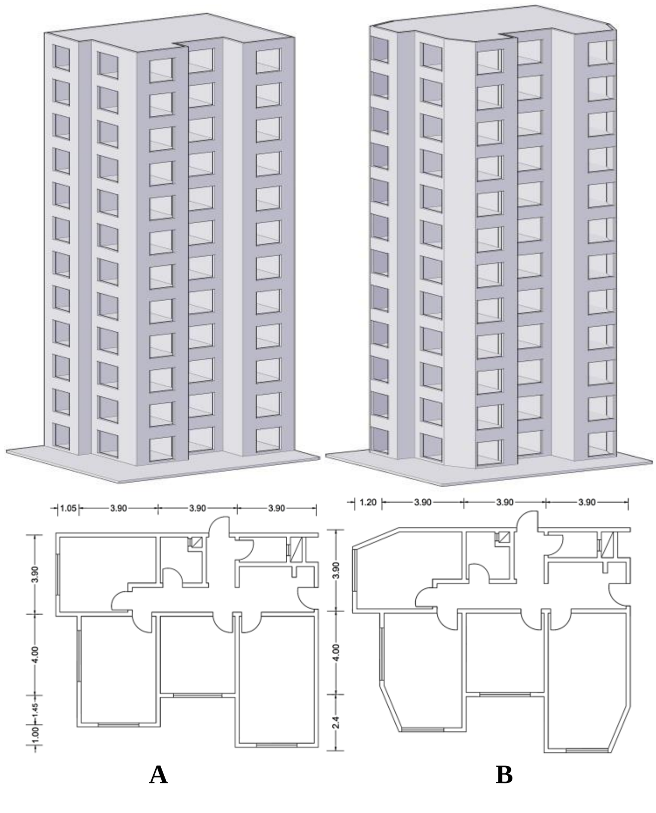

Figure 1. The plans and three-dimensional models of the plan corner shapes

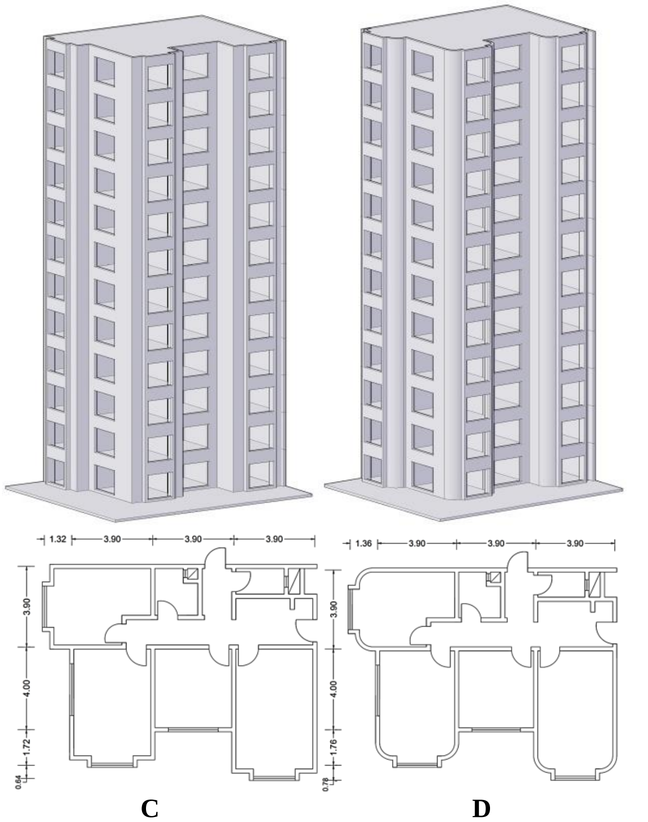

Figure 2. The plans and three-dimensional models of the plan corner shapes

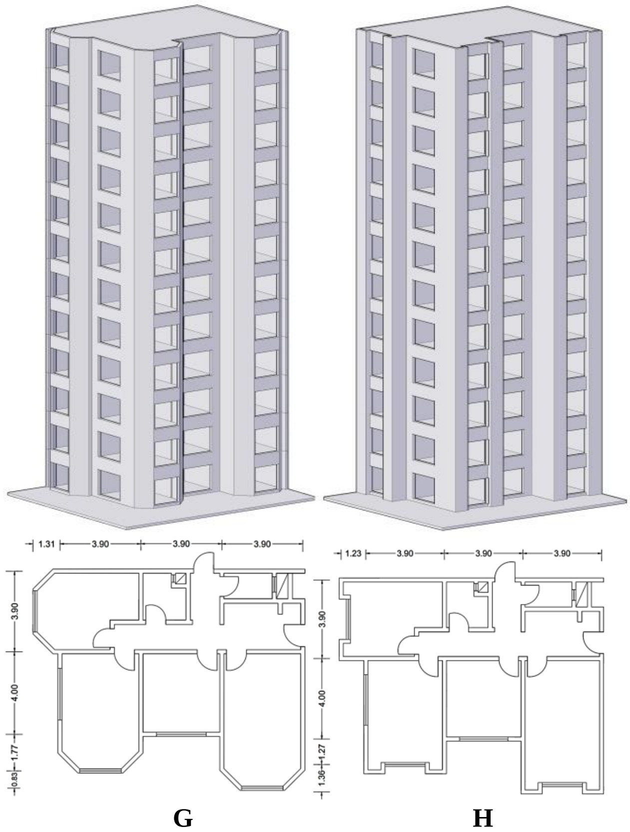

Figure 4. The plans and three-dimensional models of the plan corner shapes

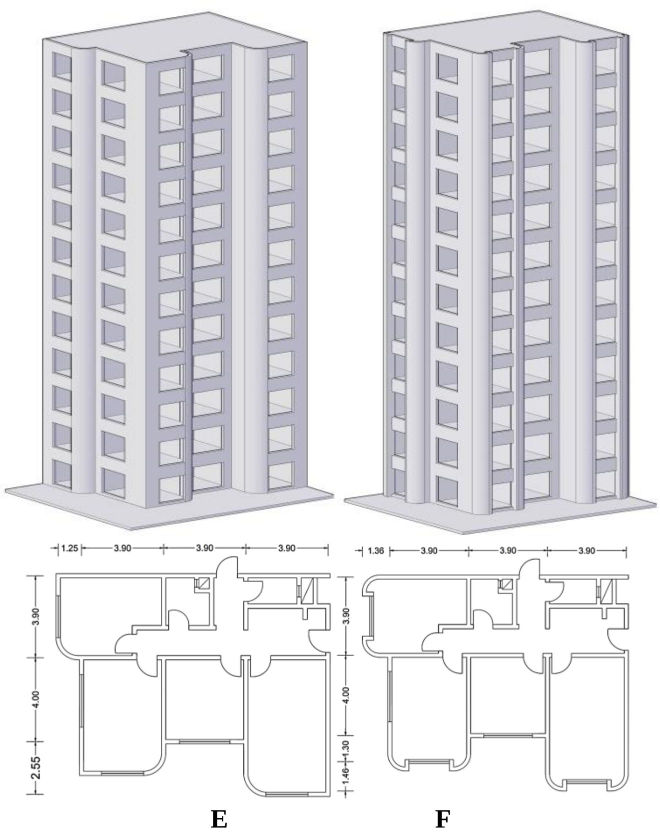

Figure 3. The plans and three-dimensional models of the plan corner shapes

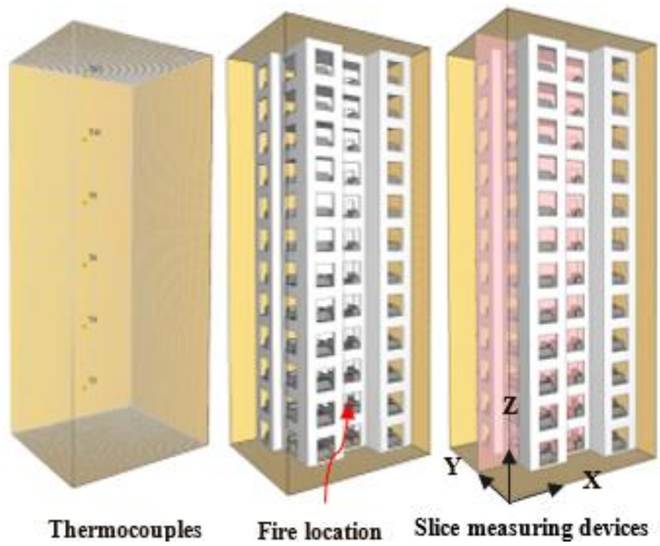

Figure 5. The arithmetic domain and the measuring devices

4. RESULTS ANALYZE AND DISCUSSION

The simulation process for each model took about 60 hours of different plan corner shapes [A- B- C- D- E- F- G- H] in order to secure a simulation time of about 300 seconds. The temperature measurement was adopted for the purpose of comparison as an indicator of the fire spread in the different models of the plan corner shapes

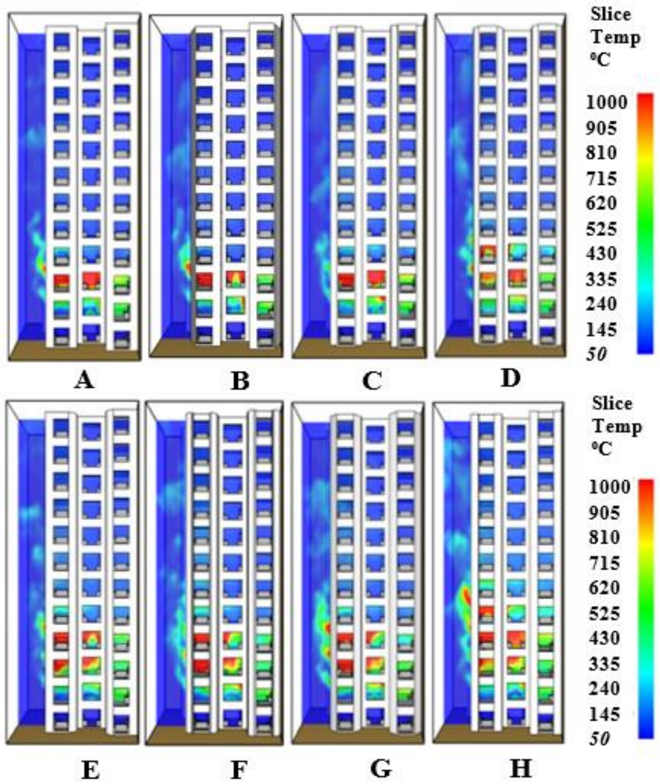

Figure 6. The distribution pattern of temperature vertically in the front view of a group of models for the plan corner shapes [A- B- C- D- E- F- G- H] at time of simulation (100 seconds)

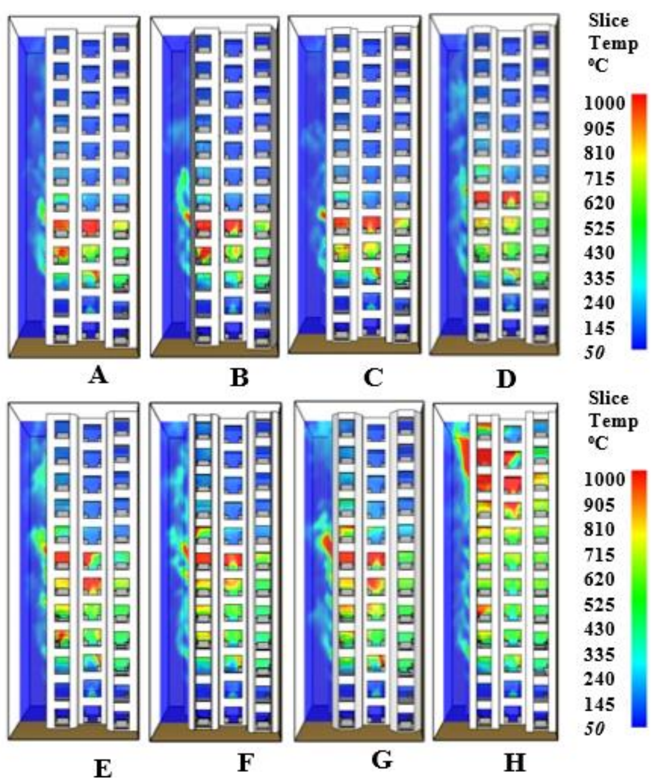

Figure 7. The distribution pattern of temperature vertically in the front view of a group of models for the plan corner shapes [A- B- C- D- E- F- G- H] at time of simulation (150 seconds)

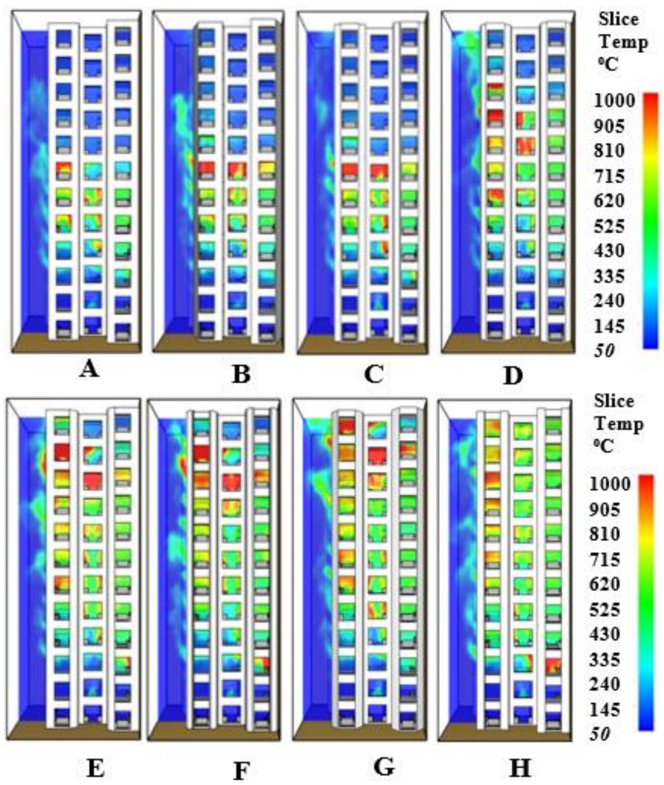

Figure 8. The distribution pattern of temperature vertically in the front view of a group of models for the plan corner shapes [A- B- C- D- E- F- G- H] at time of simulation (200 seconds)

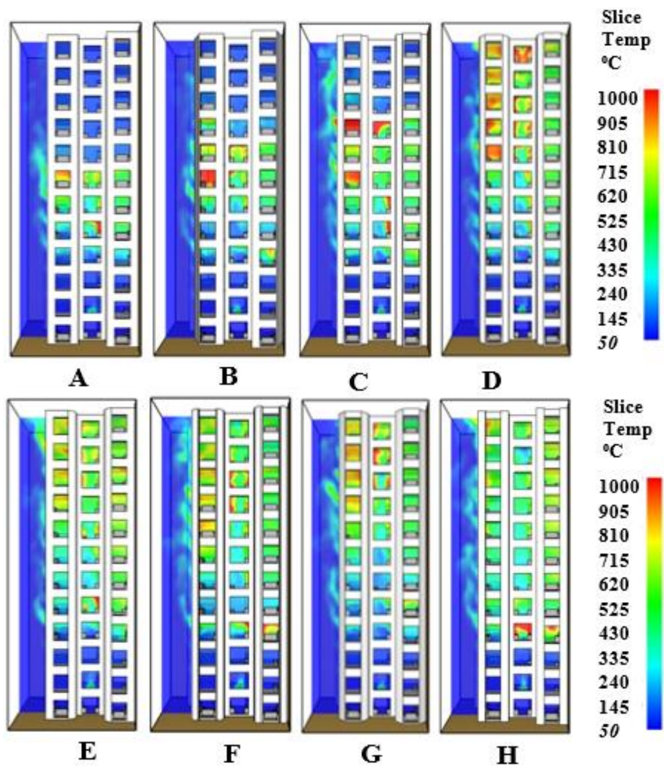

Figure 9. The distribution pattern of temperature vertically in the front view of a group of models for the plan corner shapes [A- B- C- D- E- F- G- H] at time of simulation (250 seconds)

4.1 The distribution pattern of temperature at time of simulation 100 seconds

Figure 6 presents the distribution pattern of temperature vertically in the front view of a group of models for the shapes of the plan corner shapes [A- B- C- D- E- F- G- H] at time of simulation 100 seconds. It is clear from the figure that the fire spread progression covered the fifth floor in model H with a temperature rise in the sixth floor, and the fire covered the fourth floor in the cases of models D, E, F, G, with a rise in temperature in the fifth floor in the cases of models E, F, G, the fire covered the third floor in the cases of models A, B, and C.

4.2 The distribution pattern of temperature at time of simulation 150 seconds

Figure 7 presents the distribution pattern of temperature vertically in the front view of a group of models for the plan corner shapes [A- B- C- D- E- F- G- H] at time of simulation 150 seconds. It is clear from the figure that the fire spread progression covered the eleventh floor, started on the twelfth floor, and vanished from the second floor in model H, while the fire covered the seventh floor and started on the eighth floor in models G and F, with a slight increase in model G over what is it model F, the fire has vanished on the second floor for both models. The fire has also covered the seventh floor with a slight rise in temperature on the eighth floor and it has faded from the second floor in of model E, the fire has covered the sixth floor with a slight rise in temperature on the seventh floor and faded from the second floor in model D, but in the cases of model A, B and C, the spread of the fire covered the fifth floor with a rise in temperature in the sixth floor, and the fire also faded from the second floor.

4.3 The distribution pattern of temperature at time of simulation 200 seconds

Figure 8 presents the distribution pattern of temperature vertically in the front view of a group of models for the plan corner shapes [A- B- C- D- E- F- G- H] at time of simulation 200 seconds, and it can be seen from the figure in the model H, the progression of the fire's spread covered the twelfth floor early and continued in most floors, and it faded from the second floor and began to fade in the third floor, while in model G, the fire began to spread in the twelfth floor and the fading of the fire continued to the fourth floor, in Model F, the fire covered the eleventh floor with its complete vanishing on the second floor, partially on the third floor, and continued to the fourth floor. It is also evident that the fire spread on the eleventh floor, with its complete disappearance on the second floor and partially on the third floor, in model E. As for model D, the spread of the fire began on the tenth floor, with its complete disappearance on the second and third floors, and continues to fade from the fourth floor. The fire also covered the seventh floor in both models B and C, and it faded in the second and third floors, and partially in the fourth. It also turns out that on the seventh floor, the fire started to spread with its fading in the second, third, and partly on the fourth floor, in model A.

4.4 The distribution pattern of temperature at time of simulation 250 seconds

Figure 9 presents the distribution pattern of temperature vertically in the front view of a set of models for the plan corner shapes [A- B- C- D- E- F- G- H] at time of simulation 250 seconds, and it is clear from the figure that the fire has completely covered the top of the building in the models H, G, F, E and D, and there are the beginnings of a general fading and decay of the fire in most parts of the building. It also turns out that the spread of the fire covered the ninth floor of model C, the eighth floor and began on the ninth floor in model B, and the seventh floor in model A. It also shows that there is a fading and decay in the fire that began to progress through the fourth and fifth floors to the top in model A, B and C. From the follow-up simulation of all models for the shapes of the corners of the plan of the building up to the highest floor that the fire reaches, we mention that the arrival of the fire to the twelfth floor was at a simulated time of 152 seconds, 197 seconds, 210 seconds, 210 seconds, and 225 seconds in the models H, G, F, E, and D respectively, and that the fire reached the tenth floor at a time of 275 seconds in model C, and reached the ninth floor at a time of 256 seconds in model B, and reached the seventh floor at a time of 200 seconds in model A. Thus, the average time it took for the fire to spread to one floor was 13.8 seconds in the model H, 17.9 seconds in the model G, 19.9 seconds in the F and E models, 20.5 seconds in the model D, 34.4 seconds in the model C, 32 seconds in the model B, and 33.3 seconds in the model A. It is clear from the foregoing that the speed of fire spread was greatest in model H, followed by G, then in model F and E, followed by D, then slowest in model C, then model B, then model A. And from the comparison between all models of the forms of the corners of the plan of the building, it is clear that the model in which the corners are straight first and the corners are not protruding or recessed secondly is the best among the model under research, as the less and slower spread of fire across the floors of the building. From the comparison between the two models with straight corners C and H, and from the comparison between the two models with round corners D and F, it is clear that the best model is with recessed corners compared to protruding corners for less and slower spread of fire.

4.5 Change of temperature with time

Figures 10 and 11 represent temperature changes with time for several floors of the plan corner shapes models [A- B- C- D- E- F- G- H], at the second floor, the temperature pattern change with the time progression is similar for all models where the onset of the fire is close in this floor, and at the fourth floor as well, the temperature pattern change is similar for all models, but it varies with the beginning of the progression of time, as the arrival of the fire to the floor varied in these models, then this disparity increases between the models. Here, in addition to what was mentioned, the development of the fire as a result of the effect of the movement of air currents in different models, and at the sixth floor, the pattern of temperature change in general is also similar, with an increase in the variation between patterns with time, and there is agreement between models A, B, and C at a simulation time of about 150 seconds, and at the eighth floor, the temperature pattern change is generally symmetrical with the increase in the discrepancy between these patterns with time for all models except for model A and the spread of fire on this floor for these models in a simulation time that does not exceed 200 seconds and there is a correspondence between the temperature patterns change for models B and C as well as between models E and F, the pattern of model A lagged significantly from the rest of the models and did not reach the level of incandescence, meaning that in this model the temperature rose on the eighth floor without combustion, and at the tenth floor the temperature pattern change in general is also similar with the increase in the variation between these patterns with time for models D, E, F, G and H, and the fire spread on this floor for these models in a simulation time that does not exceed 200 seconds, also, there is still a match between the temperature patterns change for models E and F, and the pattern of model C lagged significantly from the rest of the models, as the fire spread in it at a simulation time of about 275 seconds. The pattern of temperature change for model B did not reach the level of incendiary, that is, in this model, the temperature rose in the tenth floor without burning, and finally at the twelfth floor, the temperature pattern change in general is also similar with the increase in the variation between the temperature patterns with time for models D, E, F, G and H, where the fire spread in this floor at a simulation time between 150 seconds to 225 seconds.

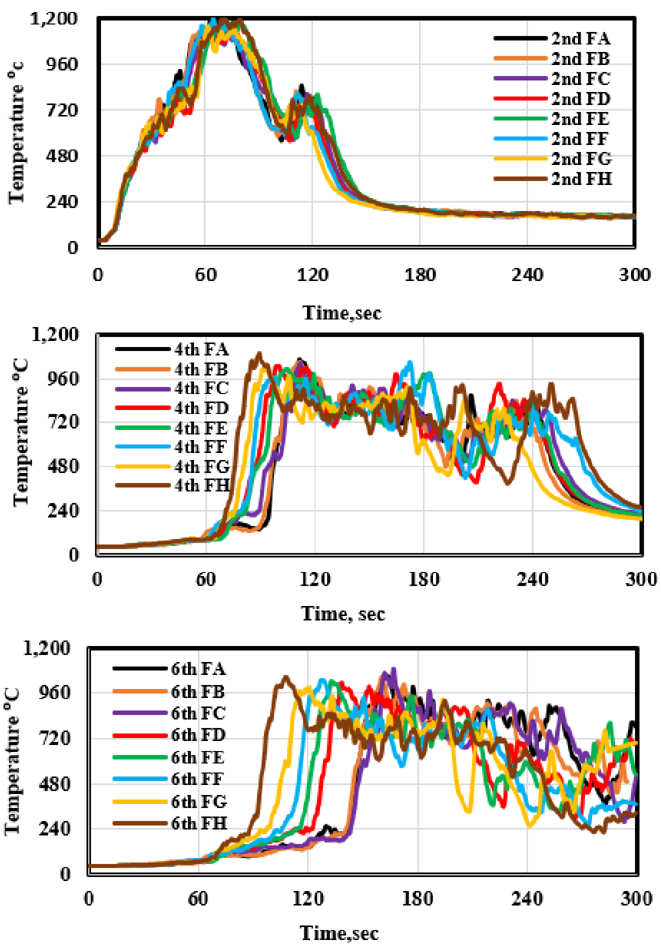

Figure 10. The change of temperatures with time for 2nd, 4th, and 6th floors in the different plan corner shapes models [A- B- C- D- E- F- G- H]

4.6 Percentage of building area

It represents the percentage of the building area to the area of the smallest rectangular shape that the building contains, which was used as a geometric factor to distinguish some characteristics of the different models [24]. The building area is fixed in all the different models for the shapes of the corners of the plan [A- B- C- D- E- F- G- H] and the amount is 117 square meters. Table 1 shows the values of the building area percentage coefficient for the different models of the corners' shapes. The table shows that with the decrease in the percentage of building area, the spread of fire increases. This means an increase in the percentage of the free area of the building relative to the area of the smallest rectangle that includes the building, i.e. an increase in protrusions and cavities, which have a direct impact on air movement.

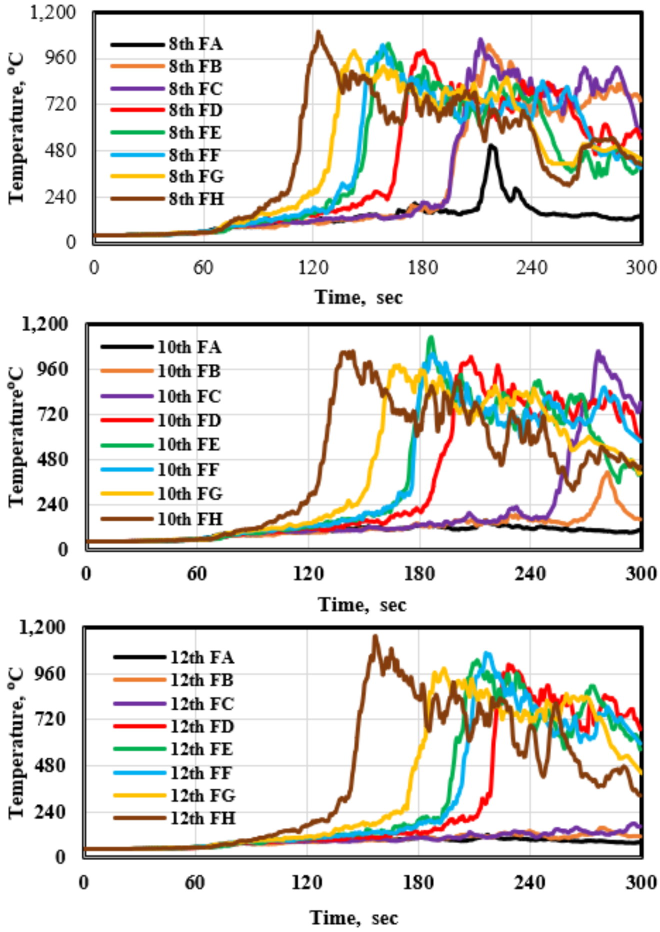

Figure 11. The change of temperatures with time for 8th, 10th, and 12th floors in the different plan corner shapes models [A- B- C- D- E- F- G- H]

Table 1. The values of the building area percentage coefficient for the different models of the corners' shapes

Models for the plan corner shapes	A	B	C	D	E	F	G	H
Building area percentage coefficient	85.6	85.1	84.6	83.8	83.5	83.4	83.3	83.1

5. CONCLUSIONS AND RECOMMENDATIONS

1. The research showed, through the comparison of different models of the shapes of the corners of the plan, that there are clear differences in the performance of each model in the speed of spread and progression of the fire.

2. The results revealed that the fire spreading risk in high-rise buildings decreases as long as the corners are straight and not protruding or recessed from the level of window openings, or with an increase in the percentage of the building area, and vice versa.

3. Depending on the average time for fire to spread to one floor, the time required for fire to spread to one floor for models A, B, and C is more than twice the time required for

fire to spread to the floor for model H, and there is a significant convergence in the performance of models D and E, F, G and H as a result of congruence in the building area percentage value of these models.

The conclusions of the research may contribute to determining the special criteria according to the shape of the corners of the plan and choosing the best design in terms of the spread of fire, by using shapes free of protrusions or cavities in the corners of the plan for tall buildings. In order to limit the spread of fire, the overlap between the effect of the shape of the corners of the plan and other factors such as changing the window area, the rate of heat release and the height of the building can be studied in order to confirm and generalize the research conclusions.

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