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Article

Effects of a Sprinkler on Evacuation Dynamics in Fire

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Abstract: A fire in an enclosed space, such as a room in a building, is generally called a compartment fire. To prevent the compartment fire, a sprinkler for first-aid fire-fighting is installed in rooms. However, it is difficult to determine the degree to which smoke generation and the fire spreading will be inhibited when sprinklers are on. In particular, demonstrating evacuation behavior assuming an actual fire is impossible. In this study, we evaluated an effectiveness of the sprinkler by numerical simulations. To consider evacuation dynamics, a real-coded cellular automata (RCA) was used, where we can freely set the direction and velocity of an evacuee based on a floor field model. To consider the situation in the room fire, we used a simulator called Fire Dynamics Simulator (FDS). Two cases with and without the sprinkler were compared to see the validity of the sprinkler on evacuation dynamics. The effect of smoke and the expansion of the fire-spreading region were discussed. Results show that, since the fire-spreading region disappears when the sprinkler is actuated, the evacuation time decreases. Even though the sprinkler is actuated, the smoke generated at the beginning of a fire diffuses inside the whole room. However, the duration of evacuees being overwhelmed by smoke is less, because the amount of smoke generated by the pyrolysis reaction is much decreased.

Keywords: fire; sprinkler; cellular automata; FDS; evacuation dynamics

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1. Introduction

When a fire breaks out, the spread of the fire must be inhibited as much as possible to prevent the building from being damaged. By this, the expansion of the fire (heat source) and the amount of smoke generated can be minimized [1–4]; consequently, safety of life can be secured [5]. A fire in an enclosed space, such as a room in a building, is generally called a compartment fire. The preparedness phase for fire is crucial in the emergency management process for reaching an adequate level of readiness to react to potential threats and hazards [6]. To set the proper evacuation route, some technically support systems have been developed [7]. To prevent a compartment fire, sprinklers installed in hotel rooms are effective for first-aid firefighting.

Sprinklers are actuated when a heat sensor detects a hot air flow generated by a fire. Generally, sprinklers are set to operate when the temperature reaches a predetermined value. However, it is difficult to determine the degree to which smoke generation and the spreading of a fire will be inhibited when sprinklers are on. In particular, demonstrating evacuation behavior assuming an actual fire is impossible. Therefore, the effectiveness of a sprinkler is difficult to assess from the perspective of evacuation behavior. Numerical simulations are useful in such situations [8–15]; hence, we have evaluated the safety of life in a fire by performing a numerical simulation of evacuation dynamics. Our method can freely set the direction and velocity of an evacuee based on a cellular automaton model. We call this method real-coded cellular automata (RCA).

Using the Fire Dynamics Simulator (FDS) [16], we simulated a fire in a room (compartment fire) when a sprinkler was and was not actuated. Using time-series data of a fire-spreading region, an evacuation behavior after a fire had broken out was reproduced through the FDS. Subsequently, the effects of a sprinkler on evacuation dynamics based on the flow of smoke and the expansion of the fire-spreading region were quantitatively evaluated.

2. Numerical Approach

2.1. FDS for Fire Simulation

This section briefly explains the simulation of the fire using FDS. The FDS was originally developed by the National Institute of Standards and Technology, and Smokeview which is visualization software for post-processing is attached to FDS [16]. We used Version 5.5.3 in this study. By solving the conservation equations of mass, momentum, and mixture fraction using large eddy simulation (LES), the combustion field can be determined.

Figure 1 shows the analytical domain to be examined. The numerical domain, including walls and a floor, was given in advance as input data. The size of the room was 16 m × 16 m, and an exit (width 2.4 m, height 2 m) was set at the center of the right wall. The width of the corridor adjacent to the room was 4 m, and the height of both the room and the corridor was 3.2 m. The floor was made of polyurethane with a thickness of 3 cm; the calorific value of polyurethane was set at 25,930 kJ/kg. A fire was generated using a heater placed in the center of the room, and the heater was removed 5 s after ignition. An equal grid spacing with a width of 40 cm was used for calculation. In the evacuation simulation, the mesh size of 40 cm is usually used [11–14]. Since it is typical shoulder width, each mesh can be occupied or empty by one evacuee. Accordingly, evacuees would not collide with or jostle each other. The same mesh size is used in the fire simulation to avoid complex interpolations.

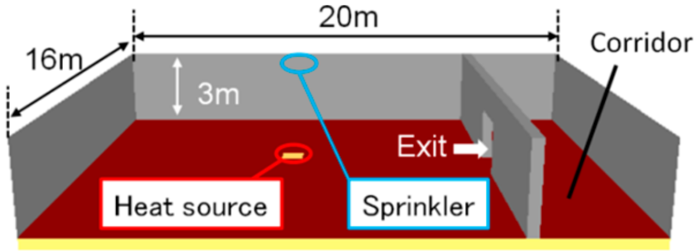

Figure 1. Numerical domain of room fire with sprinkler.

In the coordinate system, the center of the room was set as the origin, and the location of the ignition source was at 40 cm height from a floor in the center of the room. Smoke was generated by the combustion reaction of thermal decomposed gas of the polyurethane. The amount of smoke generated was determined as 10% of the pyrolysis gas in a mass ratio. A sprinkler was installed in the center of the ceiling of the room, and water sprinkling began when the room temperature reached 50 °C. The angle of water sprinkling was 65°−75° (vertical downward direction was defined as 0°), the amount of water sprinkling was 80 L/min, and the water particle size was fixed at 200 μm. In FDS, the water droplet or pyrolysis smoke is treated as Lagrangian particle. Since the heat of water evaporation was included in the numerical model, the water droplet can cool the flame region. Any interactions between water droplets and the smoke were not considered.

2.2. Evacuation Simulation

The following briefly explains the analytical model for evacuation behavior. Our method can freely set the direction and velocity of an evacuee based on the RCA model. The direction of movement of an evacuee was determined using the static floor field [9–14], which is the distance from the exit. Although the velocity of movement of an evacuee could be freely set, we set this at a fixed value of 1.6 m/s. However, when a fire (fire-spreading region) exists on an evacuation route, evacuees must avoid it. To maintain a certain evacuation distance from the burning area, a dangerous area was set outside of the burning area [14]. When evacuees enter these regions, they must perform avoidance behavior. In the present study, the burning area was defined as the region engulfed in flames predicted by FDS.

The avoidance behavior of evacuees is explained using Figure 2. When evacuees entered the burning area in Zone 1, which comprised the upper half of the room and the danger region, they avoided the area so that they moved in a direction 45° counterclockwise from the direction of the original floor field (dotted-line vector in Figure 2). In Zone 2, which was the lower half of the room, evacuees moved in a direction 45° clockwise from the direction of the original floor field. In addition, when evacuees entered the region of smoke that was reproduced using the FDS, they were considered to be overwhelmed by the smoke. The velocity of movement of an evacuee was determined based on the value [6] obtained when an evacuee moved while kneeling down. The width of the dangerous area was fixed as 1.2 m. The simulation was performed five times with different initial allocations of evacuees, and the average evacuation time was obtained.

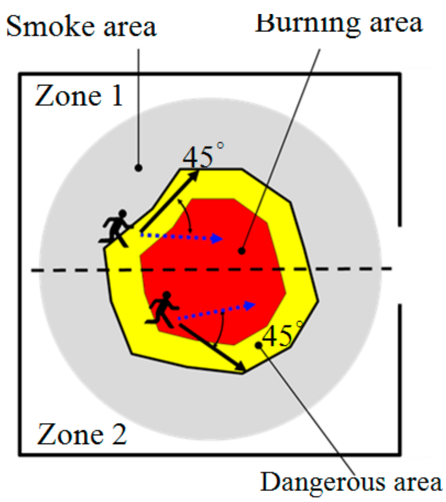

Figure 2. Evacuation model in fire.

3. Results and Discussion

3.1. Fire Dynamics

We simulated the spread of the room fire when the sprinkler was not actuated and examined the change in temperature and flow of smoke in the room. Figure 3 shows the distribution of heat release rates 10.5, 14.1, 16.8, and 19.8 s after the time (*t*) when the heater was set. As shown in this figure, it took some time from the point the heater began to heat to when a fire broke out. However, after ignition, the fire-spreading region rapidly expanded because the polyurethane floor was flammable.

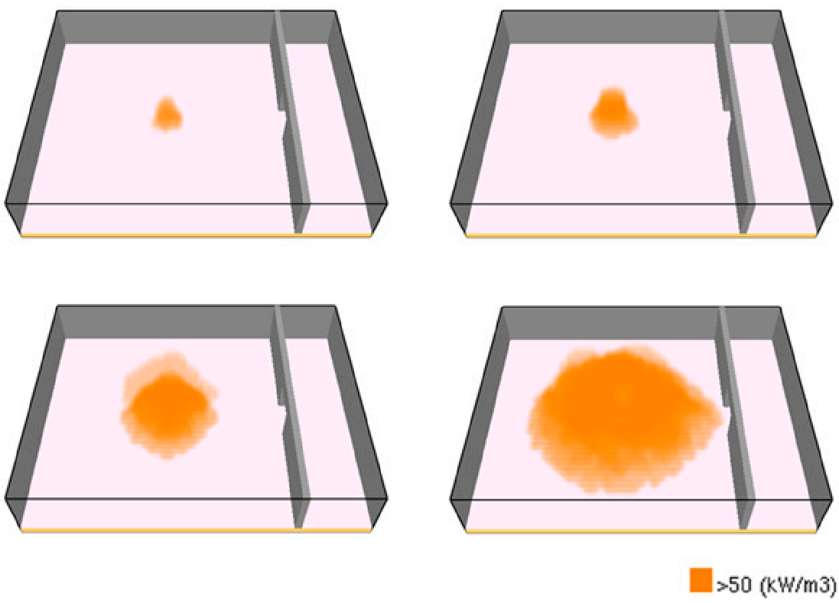

Figure 3. Profiles of heat release rate; from left to right and from top to bottom at t = 10.5, 14.1, 16.8, 19.8 s.

Figure 4 shows the temperature distribution at 1.6 m above the floor 6.3, 13.5, 16.2, and 19.8 s after initiating the calculation. The temperature of the entire room increased as the fire-spreading region expanded, and high-temperature combustion gas flowed out to the corridor through the door.

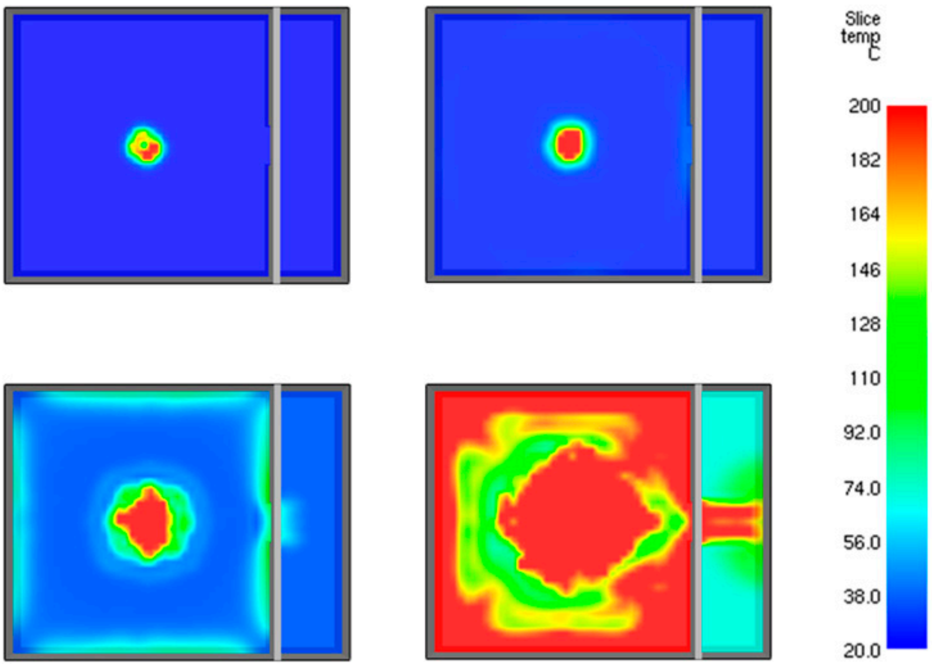

Figure 4. Profiles of temperature at z = 1.6 m; from left to right and from top to bottom at t = 6.3, 13.5, 16.2, 19.8 s.

Next, the time-variation of smoke region was examined (Figure 5). Smoke was generated around the center of the room. Because of the high temperature, the smoke ascended due to its buoyancy. After reaching the ceiling of the room, the smoke diffused in a horizontal direction along the ceiling. The amount of the smoke increased as the fire-spreading region expanded. After diffusing to the walls of the room, the smoke subsequently descended along the walls.

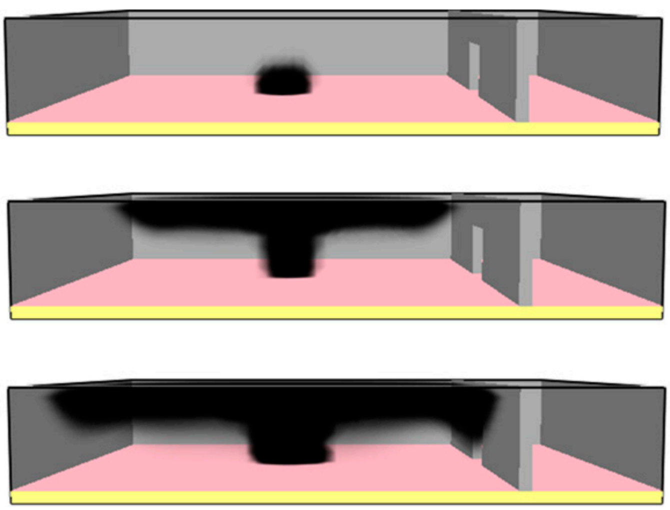

Figure 5. Profiles of smoke region; from top to bottom at t = 5.4, 10.5, 14.1 s.

Figures 6 and 7 show the smoke concentration distribution 6.3, 10.8, and 15.9 s after initiating the calculation without and with installing a sprinkler, respectively. The extinction coefficient K (1/m) was obtained from the following Formula (1).

$$K = K_m \cdot M \tag{1}$$

In this formula, M represents the mass concentration of soot (kg/m^3), K_m represents the extinction coefficient per unit mass (m^2/kg), where K_m of 10,000 (m^2/kg) was used and the area where the extinction coefficient K exceeded 0.1 was defined as the region of smoke in this study [17]. Since the fire was extinguished when the sprinkler was actuated, the diffusion of smoke was greatly inhibited.

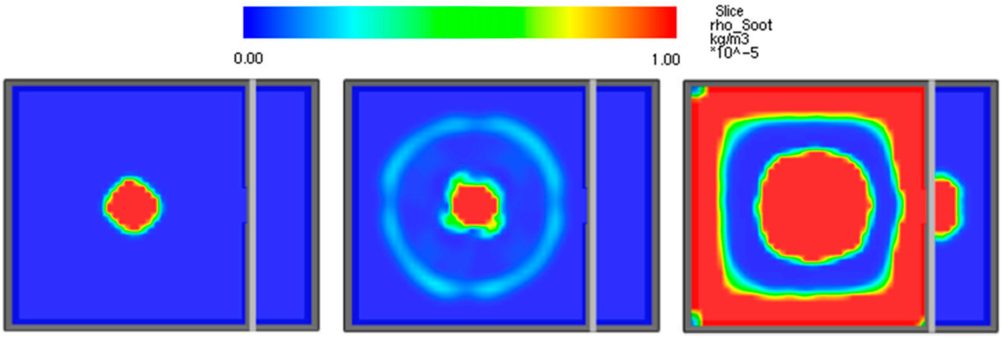

Figure 6. Profiles of soot density at z = 1.6 m without sprinkler; from left to right at t = 6.3, 10.8, 15.9 s.

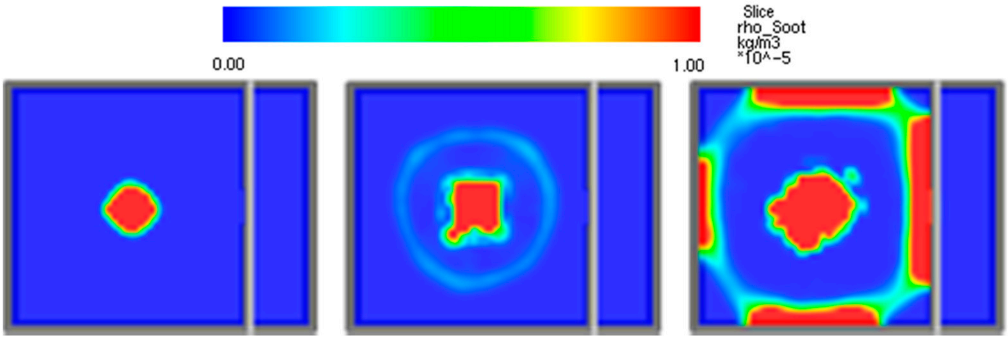

Figure 7. Profiles of soot density at z = 1.6 m with sprinkler; from left to right at t = 6.3, 10.8, 15.9 s.

Figure 8 shows the distribution of heat release rates 7.1, 10.5, 12.2, and 14.4 s after initiating the calculation. Approximately at t = 7 s, the temperature of the sprinkler reached 50 °C, so the sprinkler started water sprinkling. Since the sprinkler was installed just above the heater (center of the room), water fell on the fire-spreading region and cooled the temperature of the burning area. As a result, the fire was completely extinguished approximately at t = 14 s.

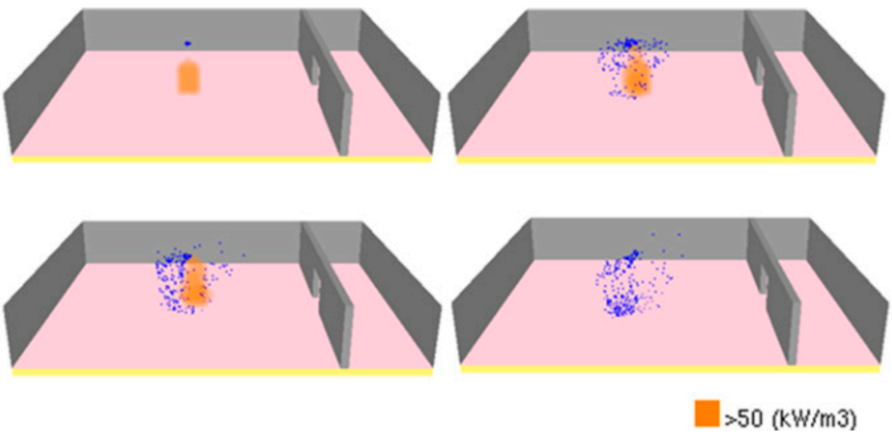

Figure 8. Profiles of heat release rate; from left to right and from top to bottom at t = 7.1, 10.5, 12.2, 14.4 s.

Figure 9 shows the temperature distribution. To elucidate the effect of the sprinkler, the height and time in Figure 9 were the same as those in Figure 4. As the temperature of the fire source rapidly decreased due to the sprinkler, the burning area was reduced and the fire was finally extinguished.

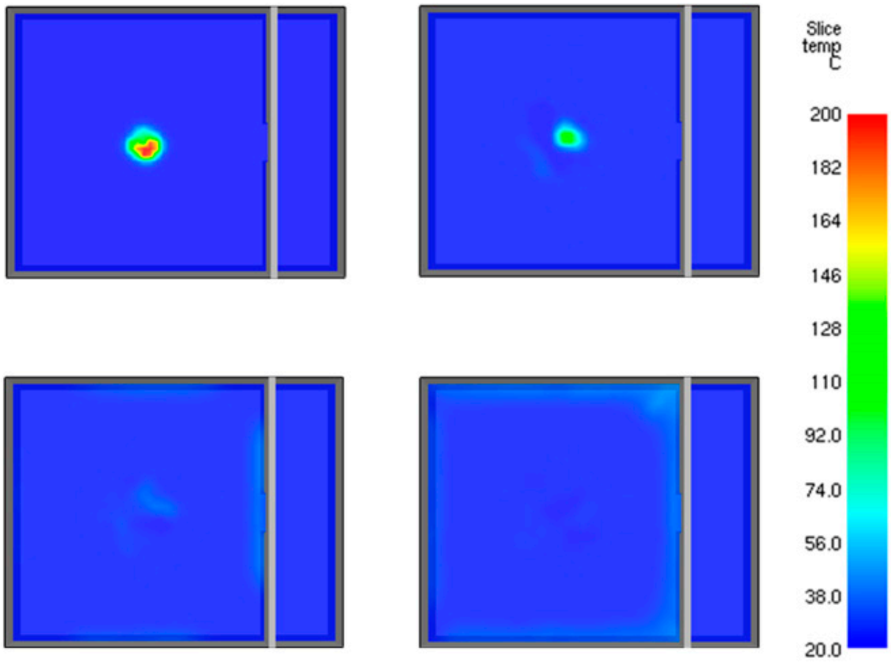

Figure 9. Profiles of temperature at z = 1.6 m; from left to right and from top to bottom at t = 6.3, 13.5, 16.2, 19.8 s.

Finally, the temporal change in the temperature field inside the room was investigated, and the difference with and without the sprinkler was examined. Since the water droplet could cool the flame region, the effect of sprinkler appears in the temperature field more clearly. Figure 10 shows the temporal changes in the temperature at the center in the room (Center) and at 5 m from the center in the room to the exit direction (5 m far). Both locations are 1.6 m above the floor. As shown in this figure, actuating the sprinkler lowered the temperature at the place near the heat source and did not change the temperature at the place far from the heat source. Thus, we confirmed that the generation of smoke was inhibited by the sprinkler.

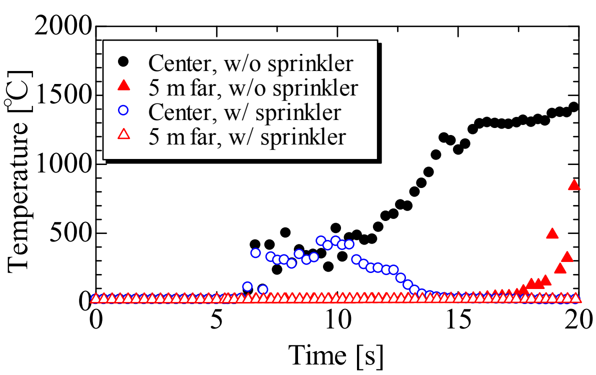

Figure 10. Time-variation of temperature.

3.2. Evacuation Dynamics

Secondly, we simulated evacuation dynamics when the sprinkler was and was not actuated, and the differences in the evacuation behavior due to the sprinkler were examined. Figure 11 shows the evacuation dynamics at t = 0, 4, 6, and 20 s when a sprinkler was not installed; 100 evacuees were initially allocated. In this figure, the dot and arrow represent the location and movement direction, respectively, of each evacuee. The color of an evacuee when being overwhelmed by smoke was changed. Evacuees were found to perform avoidance behavior when the burning area expanded. At t = 4 s, the evacuees were congested near the exit, causing a bottleneck. Because congestion occurred at the exit, many evacuees were overwhelmed by smoke.

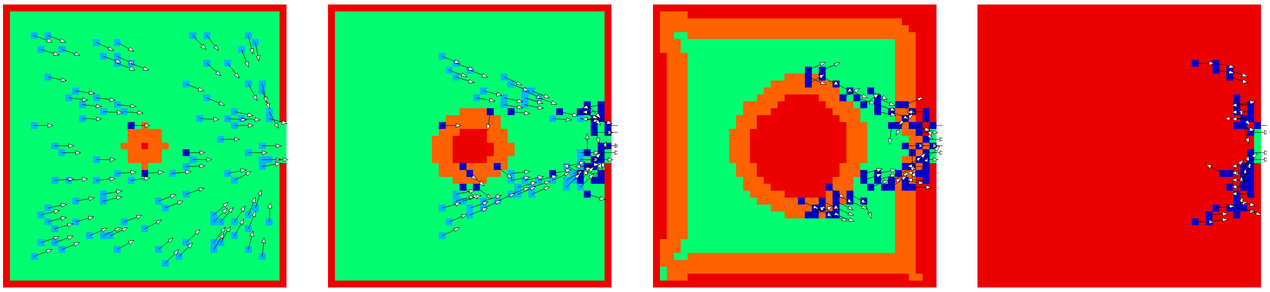

Figure 11. Evacuation dynamics without sprinkler; from left to right at t = 0, 4, 6, 20 s.

Figure 12 shows the evacuation dynamics at t = 0, 5.3, 6, and 20 s when a sprinkler was installed; 100 evacuees were initially allocated. Since the burning area was reduced and the fire was extinguished due to the sprinkler, the evacuees did not perform avoidance behavior, and they could move toward the exit along the shortest distance at t = 5.3 s.

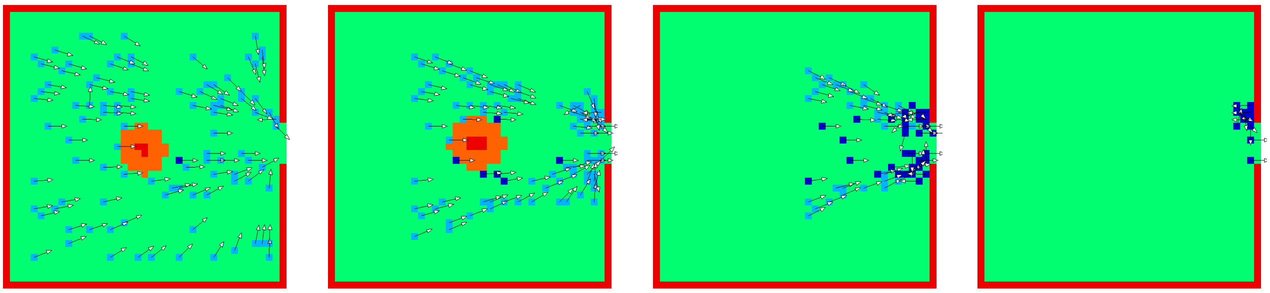

Figure 12. Evacuation dynamics with sprinkler; from left to right at t = 0, 5.3, 6, 14 s.

3.3. Effect of Sprinkler

We then examined the effect of the sprinkler on the evacuation time. The number of initially allocated evacuees N was changed, and the time when all the evacuees were completely evacuated was expressed as the evacuation time T_E. Results are shown in Figure 13. As shown in this figure, the evacuation time increased as the number of initially allocated evacuees increased, regardless of the sprinkler. However, the evacuation time was less when the sprinkler was actuated. We consider the reason for this to be that when the sprinkler was actuated, the burning area disappeared and evacuees could move toward the exit along the shortest distance.

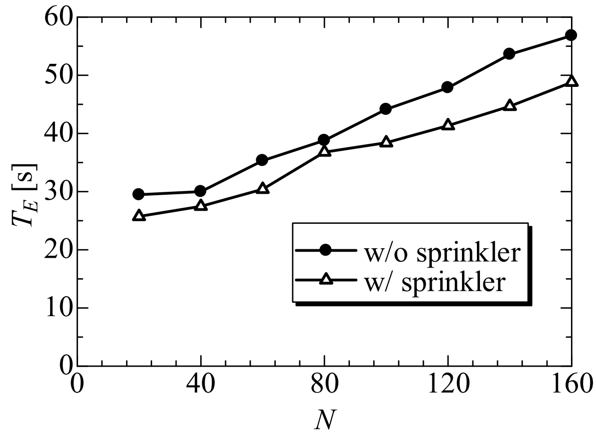

Figure 13. Variation of evacuation time with *N*.

Finally, the duration of evacuees being overwhelmed by smoke was estimated, and the effect of the sprinkler was evaluated. When $n = 100$, the duration of evacuees being overwhelmed by smoke T_s was used as class, the number of evacuees being overwhelmed by smoke was counted, and a histogram was created (Figure 14). Evacuees overwhelmed by smoke for more than 12 s were aggregated as one class. Although the sprinkler was activated, smoke generated at the beginning of the fire diffused in the room. However, since the amount of smoke generated was largely inhibited due to the sprinkler, the duration of evacuees being overwhelmed by smoke greatly decreased. In particular, when the sprinkler was not installed, many evacuees were overwhelmed by smoke for more than 10 s. When the sprinkler was actuated, the duration of evacuees being overwhelmed by smoke decreased. Therefore, the improvement in fire safety during evacuation due to a sprinkler was confirmed based on the smoke emission and the evacuation time.

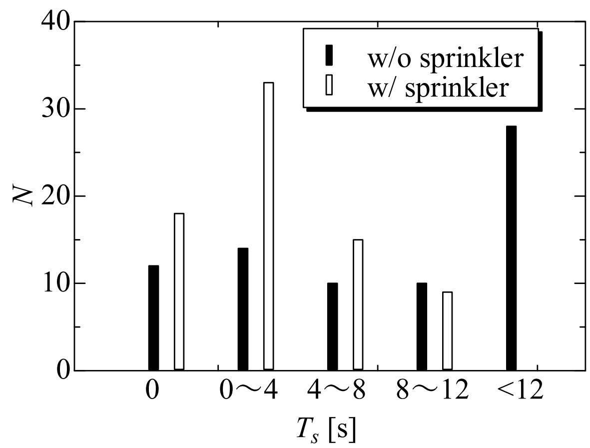

Figure 14. Number of people involved in smoke; $n = 100$.

4. Conclusions

The room fire was simulated using the FDS. The temperature in the burning area greatly decreased due to the sprinkler and the smoke emission was inhibited. Using time-series data reproduced by the FDS, the evacuation dynamics in the compartment fire was evaluated. Since the burning area disappeared when the sprinkler was actuated, the evacuation route changed; consequently, the evacuation time decreased. Although the sprinkler was actuated, smoke generated at the beginning of the fire diffused in the room. However, the amount of smoke generated could be largely inhibited, so the duration of evacuees being overwhelmed by smoke was less when the sprinkler was installed compared to when it was not installed.

Author Contributions

Kazuhiro Yamamoto had the original idea for the study, and drafted the manuscript. Yuki Takeuchi was responsible for data analyses. Shinnosuke Nishiki developed and consulted on analyses. All authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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