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Are Pan Fire Tests the Right Way to Assess Sprinkler Actuation on High Ceilings?

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Abstract

As buildings with a high ceiling clearance are becoming increasingly common, making proper assessments of whether or not the ceiling sprinklers would actuate becomes very critical for such buildings. One of the commonly adopted processes for the assessments are: (1) to evaluate the potential fire load inside a facility and convert that to the maximum anticipated heat release rate, and (2) to run a pan fire test that would generate the heat release rate equivalent to the value estimated from the previous step and see if any ceiling sprinklers to actuate. If such an assessment indicates no ceiling sprinkler actuation, then a waiver of the requirement of sprinkler installation often follows---leaving the building with no active fire protection system. An analysis in this study based on a large volume of test data shows that assessing sprinkler actuations based on pan fire tests will be likely to lead to a wrong conclusion. The critical fire sizes that would actuate sprinklers on high ceilings under various conditions are also presented as a reference.

1. Introduction

The population of the buildings with a high clearance between the floor and the ceiling has been steadily increasing in recent years. Facilities with a high ceiling clearance, such as large shopping malls, atrium spaces, movie studios, theaters, sports arenas, hotel lobbies, etc., become more and more a familiar feature in our lives. These structures pose a unique challenge to fire safety engineers and building code officials alike because of their high clearances between the floors and the ceilings. A frequent concern is whether sprinklers on such high ceilings would operate and be effective. In some cases, the judgment that sprinklers would not operate may lead to a waiver of sprinkler installation.

Making a decision not to install a sprinkler system is particularly critical in view of that in most cases there are not many alternative fire protection schemes available for the buildings with high ceiling clearances. In consequence, facilities could be left without any proper means of active fire protection. On the other hand, if the sprinklers installed on the ceiling can be proven to be effective, then a highly reliable protection method becomes available.

A report[1] describing fire tests conducted at a civic center arena that had a 29.6-m high ceiling has been circulated as one of the documents supporting sprinkler waivers at high ceiling facilities. The report asserted that, “a 15.5 MW pan fire on the floor failed to activate any ceiling sprinklers.” Although the estimated fire sizes in the report were somewhat higher than what generally can be expected from the size of the pans used in the test fires, the conclusion of the report provides support that sprinklers on such a high ceiling would not activate anyway. The analysis in this work, however, indicates that under many circumstances this perception may be wrong. Thus, it is important to find out the accurate threshold fire sizes that would actuate sprinklers on high ceilings and whether the fire sizes determined by steady pan fires would be reliable to assess the actuation of sprinklers on high ceilings.

By analyzing existing data, this paper intends to show how the fire sizes that would actuate ceiling sprinklers at a certain clearance can be properly estimated. By following similar processes, engineers will be able to make a proper decision based on sound engineering principles.

Fire tests were conducted under a 18.3-m high ceiling using either 2.26-m high solid pile FM Global Class 2 commodity or 1.73-m high solid pile FM Global Standard Plastic commodity. Detailed descriptions of most of the tests were given in Ref. 2. For some facilities, such as hotel lobbies or atria, that may have a fire load that can be regarded as relatively light, the Class 2 commodity is a good representation of the fire hazard. However, if a facility is designed for occasional exhibits, such as boat shows, the potential fire load can be even heavier than what can be represented by the Standard Plastic commodity. Thus, assessing the fire load to the equivalent commodity classification must be the first job of the fire safety engineers who need to design a proper fire protection system for a facility.

In the fire tests[2], some data of which will be used in this paper, ignition was provided directly under one sprinkler which coincided with the center of the 2 by 2 center stacks. Thus, in the following analysis, it was also assumed that a sprinkler was located directly above ignition, thereby coincides with the plume centerline. One can extend the analysis by applying a proper ceiling jet formula[3] if he wants to analyze his case where a sprinkler is located at a certain radial distance from the plume centerline.

As the main objective of this study is finding the minimum fire size that would activate the first ceiling sprinkler with a given clearance, the ideal test data would be the temperature and the velocity surrounding the sprinkler generated by a free-burn fire under a ceiling with the same clearance. However, the data we have are the data from fire tests under a 18.3-m high ceiling[2]. Thus, the necessary growing fire data to determine the activation of the sprinklers installed on a ceiling higher than 18.3 m had to be estimated based on the test data. In addition, there were many operating sprinklers during the period of the fire tests[2]. That posed a problem when the test data needed to be extended beyond the time of the first sprinkler actuation. It was resolved by choosing the cases where any impact by the operating sprinklers would be minimal. In those cases, due to heavy sprinkler skipping, no sprinklers that were close enough to influence fire intensity of the burning commodity were actuated for a substantially long time, except the first actuated sprinkler that operated with a 12-mm/min discharge density over the center of the stacks. Furthermore, there were strong indications [2] that the single operating sprinkler did not impact significantly on the fire intensity of the burning commodity, although the pre-wetting of the remaining fuel stacks by the operating sprinklers successfully prevented fire from spreading to adjacent fuel stacks. Thus, the test data could be extended beyond the 18.3-m high ceiling and the data could be treated as if they were obtained from free-burn fire tests. The two fire tests chosen for the analysis are denoted as Test 1 and Test 2 for the identification purpose. Test 1 used FM Global Class 2 commodity and Test 2 used FM Global Standard Plastic commodity.

The analysis will be conducted for two sets of cases, growing fire cases and steady pan fire cases. Most of the fires we encounter in real world as accidental fires are growing fires, and the fires in Test 1 and Test 2 are growing fires. Although it is unlikely that we will encounter a steady pan fire as an accidental fire in a facility, steady pan fires are being used frequently in order to assess the effectiveness of sprinklers on high ceilings[1,4,5], mainly because of the convenience. Thus, the critical pan fire sizes that would actuate the sprinklers on high ceilings were also investigated.

2. Analysis

2.1 Growing Fires

2.1.1 Test 1: Fire with Class 2 commodity

The arrangement of the fuel stacks simulated the way fire loads are distributed in many non-storage occupancies. The material was FM Global Class 2 commodity, which consisted of a 1.07-m cube, double, triwall corrugated paper carton containing an open bottom sheet metal liner on wood pallet. The mass of the outer corrugated box was 19.5kg, the mass of the inner corrugated box was 18.6kg and the mass of metal liner was 22.2kg, and the average mass of wood pallets was 23.6kg. The height of the fuel stacks was 2.26m including 0.13-m high wood pallet. The fuel stacks were on a 0.69-m high elevated platform; thereby the ceiling clearance from the top of the fuel stacks was 15.35m and the clearance to the sprinkler was 15.20m.

Figure 1 shows the temperatures measured at 7.5 m and 15.2 m above the top of the fuel stacks directly above the ignition point. The ambient temperature during the test was 15°C. Because of the wetting of the thermocouples caused by the water droplets from the operating sprinkler, the temperature data measured at the sprinkler location are useful only up to t=180 s. For the same reason, the temperature data at z=7.5 m between 180 s and 320 s are not reliable. Figure 2 shows the fire plume velocity measured at 15.0 m above the top of the fuel loads. (The "computed" velocity in the figure will be explained shortly.)

The temperature rating of the ceiling sprinklers, which were in 3m by 3m spacing, was 74°C and the response time index (RTI) of the sprinklers was 138 $(m.s)^{1/2}$. The first open sprinkler, which was located directly above the center of the 2 by 2 stacks where the fire was ignited, actuated 178 s from ignition.

The sprinkler response time can be computed by solving the following equation.

$$\frac{dT_e}{dt} = \frac{u^{1/2}}{RTI}(T_g - T_e) \qquad (1),$$

where T_e is the sprinkler heat sensing element temperature, t is time, u is the ceiling flow velocity surrounding the sprinkler, and T_g is the surrounding hot air temperature. As the sprinkler was located along the plume centerline, the temperature and velocity in Figs. 1 and 2 were used in the computations. The velocity in Fig. 2 was the upward plume centerline velocity approximately 0.35 m below the ceiling.

The computation showed that the sprinkler actuates at 178 s, which is same as the measured time. The convective heat release rates before the sprinkler actuation was estimated based on the temperature measured at z=15.2 m, where the sprinkler was located. By using a plume correlation[6], the convective heat release rates, $\dot{Q}_c$(kW), were calculated as

$$\dot{Q}_c = C_{\Delta T_0}^{-3/2}\left(g \big/ T_\infty\right)^{1/2} C_p \rho_\infty (z-z_0)^{5/2} \Delta T_0^{3/2} \quad (2),$$

where ΔT_0 is the excess temperature at the plume centerline (K), T_∞ is the ambient temperature (K), g is the gravitational acceleration (m/s^2), C_p is the constant pressure specific heat of air (kJ/kg K), ρ_∞ is the density of ambient air (kg/m^3), z is the elevation from the source of the plume (m; here the top of the fuel stack was regarded as the zero elevation), and z_0 is the virtual origin of the plume (m).

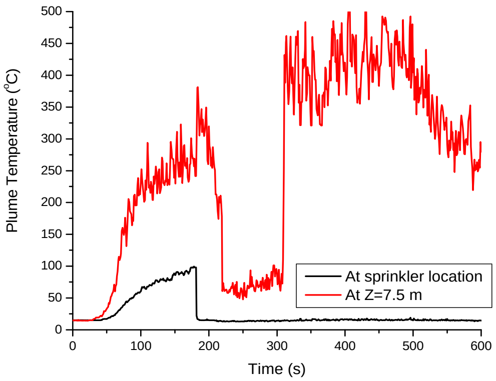

Fig 1. Fire plume temperatures at Z=15.2 m and 7.5 m in Test 1.

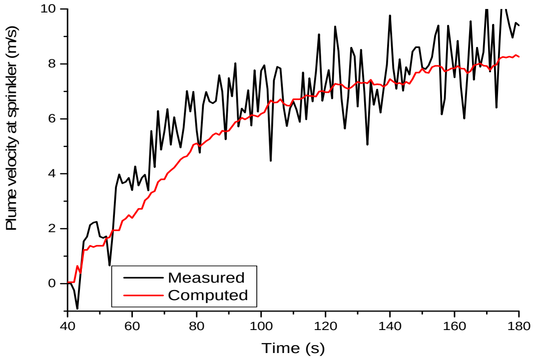

Fig 2. Fire plume velocities, measured and computed, at Z=15 m in Test 1.

Kung *et al.*[7] found that $C_{\Delta T_0}$ =11 gives the best correlation for the plume generated by either a two-tier Class 2 commodity rack-storage fire or a two-tier Standard Plastic commodity rack-storage fire; either one is quite similar to the fires used in the tests. Kung *et al.*[7] also indicated that the virtual origin for the plume from either fire correlates well with the following equation

$$z_0 = -1.6 + 0.094\dot{Q}_c^{2/5} \quad (3).$$

Thus, $C_{\Delta T_0}$ =11 and z_0 from Eq. (3) were used in solving Eq. (2). Since Eq. (3) needs $\dot{Q}_c$ that has not been found yet, a few iterations were required to solve Eq. (2). Once $\dot{Q}_c$ was calculated, plume centerline temperature at z=15.2 m and plume centerline velocity at z=15.0 m were calculated by using the convective heat release rates from Eq. (2) and the following plume correlations[6].

$$\Delta T_0 = C_{\Delta T_0}\left[(T_\infty) \big/ \left(g C_p^2 \rho_\infty^2\right)\right]^{1/3} \dot{Q}_c^{2/3} (z-z_0)^{-5/3} \quad (4),$$

$$V_{z0} = C_{V_{z0}} \left[{(g)} \Big/ {\left(C_p \rho_\infty T_\infty \right)} \right]^{1/3} \dot{Q}_c^{1/3} (z - z_0)^{-1/3} \quad (5),$$

where V_{z0} is the upward plume centerline velocity (m/s). Kung *et al*.[7] also found that the coefficient $C_{V_{z0}}$ = 4.3 provided the best correlation for the plume generated by two-tier rack-storage fires. Thus, $C_{V_{z0}}$ = 4.3 was used in all of the analysis regarding growing fires that were considered in this study.

The velocity at z=15.0 m *computed* from Eq. (5) is given in Fig 2. When the sprinkler actuation time was re-calculated by using the temperatures and the velocities computed through the above procedure, a value of 180 s was obtained, which matches well with the measured value, 178 s.

The test showed that the sprinkler on the ceiling having the clearance of 15.4 m will be actuated by a fire that can be represented by the burning of 2 by 2 solid-pile Class-2-commodity stacks height of which is 2.26 m. One of the objectives of this study is finding out the *maximum* ceiling clearance that would allow the ceiling sprinklers to be actuated by the same fuel load. That requires a continuous estimate of the heat release rate of the burning fuel that can be obtained through the measured temperature data. As the temperature measured at z=15.2 m became no longer reliable beyond the sprinkler actuation, the data at z=7.5 m was used for that purpose.

As shown in Fig 1, the temperature measured at z=7.5 m also became unreliable after the sprinkler actuation due to the wetting of the thermocouple until t is close to 320 s. Because there is no reliable way of interpolating the temperatures between the period, the temperature was assumed to have increased linearly between t=178 s and t=328 s. Such a modification would not affect the analysis significantly because:

1. The temperature was increasing before the thermocouple became wet and unreliable.
2. The temperature after t=320 s remain almost steady, which indicates that the highest HRR would not be changed by the treatment of the data described above. Since the purpose of the analysis is finding out the maximum ceiling height for sprinkler actuation, the HRRs lower than a critical value would not have made any contribution to the sprinkler actuation anyway. (As a matter of fact, when an analysis was conducted with temperature data in which the temperatures between t=180 s and t=320 s were completely deleted, there were no differences in the major findings that will be presented shortly.)

Fig 3 shows a comparison of the measured plume centerline velocity at z=15.0 m with that computed by using the plume correlation Eq. (5) with the $Q_c^{\&}$ based on the temperature data at z=7.5 m. The velocities matched well each other. The sprinkler actuation time was re-calculated by using the temperature and the velocity obtained by the above procedure. It came out as 178 s, again, matches well with the measured time, 178 s.

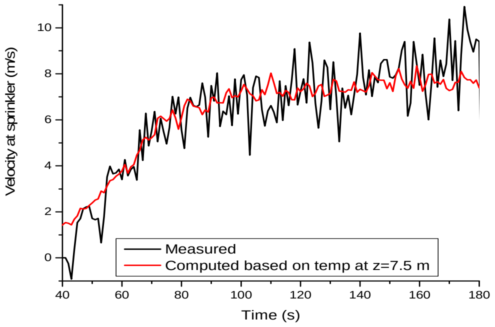

Fig 3. The measured and computed plume centerline velocity at Z=15 m in Test 1.

The maximum ceiling clearance that would allow the actuation of the ceiling sprinklers by the fire discussed above came out as 21.5 m, which corresponds to a 23.7 m high ceiling, and the sprinkler was expected to actuate at 460 s. If the sprinklers were the quick response ones with the RTI=28 $(m.s)^{1/2}$, then the actuation time was expected to be 310 s. The maximum ceiling height with the use of the quick response sprinklers (RTI=28 $[m.s]^{1/2}$) can be extended to 24.4 m, which provides a difference of about 0.7 m. The sprinklers are expected to actuate at 462 s. With the given fuel load as in Test 1, which was an *isolated* 2.26-m high, two-by-two stacks of solid-pile Class 2 commodity, the estimated peak convective heat release rate is approximately 5.4 MW. If a ceiling is higher than 24.5 m, then the analysis indicates that the fuel load will eventually burn itself out without actuating any sprinklers on the ceiling.

2.1.2 Test 2: Fire with Standard Plastic commodity

A similar analysis was conducted with the data obtained through a fire test that used FM Global Standard Plastic commodity as a fuel. The Standard Plastic commodity consisted of polystyrene tubs in compartmented, single-wall, corrugated paper cartons; eight cartons were placed on a wood pallet (2 by 2 by 2 high). The dimensions of each carton were 0.53m×0.53m×0.51m high and it had 125 compartments; there were five levels of compartments with 25 (5×5) compartments on each level. Vertical and horizontal cardboard dividers (about 4-mm thick) were used to form the compartments. A 473 ml polystyrene tub was placed in each compartment. The total mass of the polystyrene tubs per carton was 3.66 kg. The mass of an empty carton with dividers was 2.73 kg.

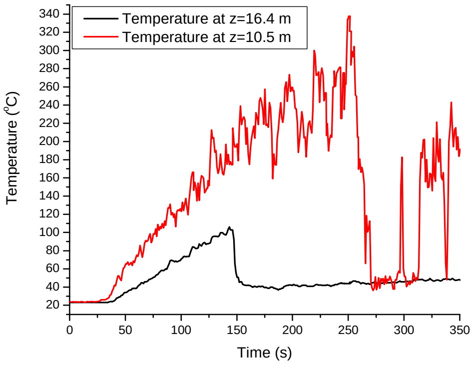

Fig 4. The plume temperature measured at Z=16.4 m and 10.5 m in Test 2.

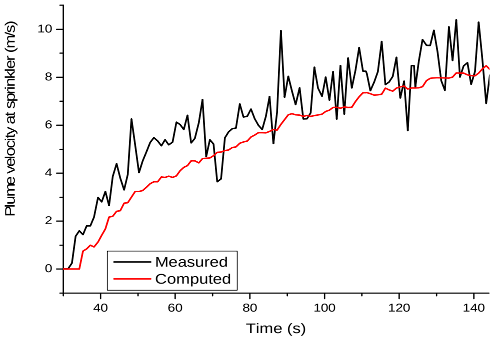

Fig 5. The upward plume velocity at the sprinkler compared with that from a computation based on the temperature at Z=16.4 m in Test 2.

The fuel stack arrangement simulated a distribution of fire loads in many non-storage occupancies practicing aisle separations. As the ceiling height was 18.3m and the fuel stack height was 1.73m, the ceiling clearance during the test was 16.6m. The temperature measured at z=16.4m and at z=10.46m (above the top of the fuel stacks) are given in Fig 4. The ambient temperature during the test was 23°C. The plume centerline velocity at z=16.15m is given in Fig 5. In the test, the sprinkler actuated at 141s. When the program that numerically integrates Eq. (1) was used in conjunction with the measured temperatures and the velocities, the sprinkler actuation time came out as 146 s.

As in the previous section, the convective heat release rates were estimated based on the measured temperatures at the sprinkler location. The velocity that was obtained through the plume correlation, Eq. (5), is given in Fig 5 for a comparison with the measured one. The calculated sprinkler actuation time, in conjunction with the temperatures and the velocities obtained through Eqs. (4) and (5) using the estimated heat release rates based on the temperature data at z=16.4 m, was 151 s.

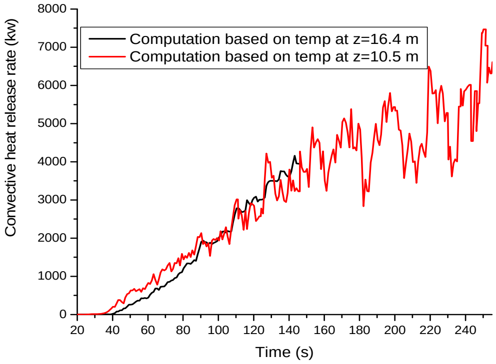

Fig 6. Convective HRR in Test 2.

As the data used in the previous test, the data in Test 2 also can be treated as free-burn data because, except the one operated directly above the ignition location, all other sprinklers operated farther away from the center ignition stacks due to skipping; thus, no additional sprinkler water was delivered to the burning fuel stacks. When the actuation time was calculated by using the temperature and velocity obtained through the plume correlations in which the convective heat release rates were estimated based on the temperature measured at z=10.46 m, it was 149 s, a good match with the measured one, 141 s. The convective heat release rates estimated by the temperatures at z=16.4 m and that by the temperatures at z=10.46 m are given in Fig 6. The estimated convective heat release rates based on the temperature at z=10.46 m was used to estimate the maximum ceiling clearance that would allow the actuation of the ceiling sprinklers by the given fuel package---equivalent to 2 by 2 stacks of 1.73 m high solid-pile FM Global Standard Plastic commodity. The maximum ceiling clearance came out as 24.2 m and the sprinkler would actuate at 254 s. If the quick response sprinklers with RTI=28 $(m.s)^{1/2}$are used, they would actuate at 241 s. The estimated temperature and the velocity at z=24.0 m, where the sprinklers are to be located, obtained through the processes described above are given in Fig 7.

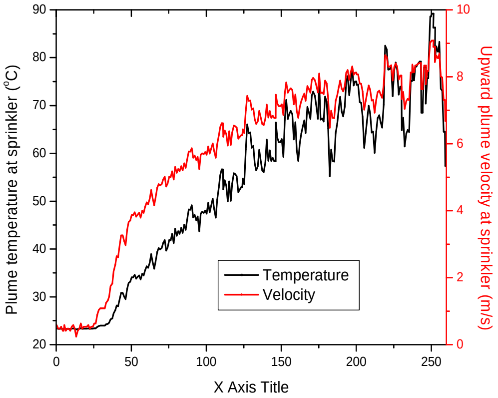

Fig 7. The estimated plume temperature and velocity at Z=24 m in Test 2.

The maximum ceiling clearance can be increased to 26.6m if quick response sprinklers $(RTI=28[m.s]^{1/2})$ are installed. The first sprinkler would actuate at 252 s. Thus, the computation indicates that with the given fuel load used in Test 2, the ordinary response sprinklers on a 25.9-m (85-ft) high ceiling or the quick response sprinklers on a 28.3-m (93-ft) high ceiling would actuate.

2.2 Steady fires (spray and pan fires)

2.2.1 Heptane spray fires

Table 1 shows sprinkler actuation times in tests that used fires generated by steady spray of heptane. Tests 3, 4, and 5 used 0.85 *l/min*, 0.88 *l/min*, and 1.20 *l/min* heptane spray nozzles, respectively. The spray nozzles were located 1.52 m above the floor under a 5.79 m ceiling; thus the clearance was 4.27 m. A ceiling sprinkler was located 2.16 m radial distance away from the spray nozzles in each test. Figs. 8 and 9 show the temperatures and the velocities, respectively, measured during the tests at the sprinkler location. The temperature rating of the sprinkler was 57^{o}C and the RTI was 143 (m.s)$^{1/2}$ in all the tests.

The sprinkler actuation times in the table were calculated by Eq. (1) with the temperatures and the velocities given in Figs. 8 and 9. If a fire is in a true steady state thus the temperature and the velocity are steady, the sprinkler actuation time can be obtained by the following closed form solution, which is an integration of Eq. (1) with fixed T_g and u.

$$\tau_s = \frac{RTI}{\sqrt{\bar{u}}}\ln\left(\frac{\bar{T}-T_\infty}{\bar{T}-T_r}\right)+t_c \qquad (6),$$

where τ_s is the sprinkler actuation time from ignition, $\bar{u}$ is the average ceiling jet velocity at the sprinkler, $\bar{T}$ is the average ceiling jet temperature at the sprinkler location, T_∞ is the ambient temperature, T_r is the temperature rating of the sprinkler, and t_c is a ramp-up time from ignition associated with the transport of hot air from fire to the sprinkler. In the computations shown in Table 1, t_c was taken as 8 s for Test 3, 13 s for Test 4, and 22 s for Test 5, based on the temperature curves in Fig 8.

The average temperatures (^{o}C) and the velocities (m/s) at the sprinkler in Table 1 were obtained from the measured values as the data were available. However, in other cases where the temperatures and the velocities are not measured, the values can be estimated through plume correlations and ceiling jet formulas in conjunction with the estimated heat release rate of a pan fire.

TABLE 1: HEPTANE SPRAY FIRES

Test No.	HRR (kW)	T_∞	Avg. Flow Temp.	Avg. Flow Vel.
3	270	28	83	3.2
4	280	27	84	3.3
5	380	24	88	3.7
Sprinkler Actuation Time (s)				
Test No.	Measured		Solving Eq. (1)	Solving Eq. (6)
3	72		66	68
4	68		66	72
5	71		66	76

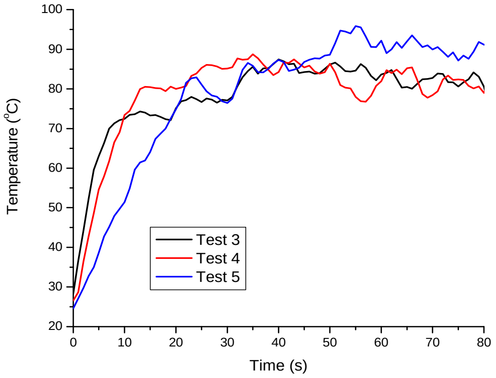

Fig 8. Ceiling jet flow temperatures at the sprinkler in Tests 3, 4, and 5.

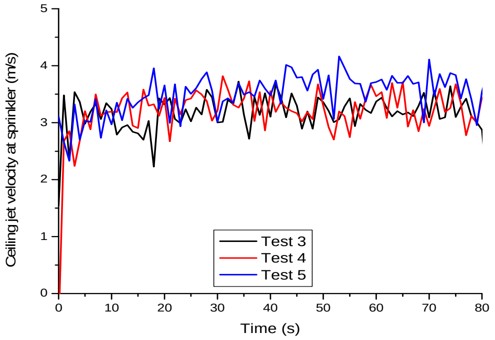

Fig 9. Ceiling jet flow velocities at the sprinkler in Tests 3, 4, and 5.

2.2.2. Pan fires under a 15-m ceiling

Gott *et al.*[4] conducted a few pan fire tests measuring sprinkler response times under a 15-m high ceiling. In Test 7 of Ref. 4, a 2-m diameter pan filled with JP-5 fuel was used. The estimated steady heat release rate from the pan fire was reported as 5.6 MW[4]. The ceiling sprinkler located directly above the center of the pan actuated 313s after ignition. The temperature rating of the sprinkler was 79°C and the RTI was $35(\mathrm{m.s})^{1/2}$ while the ambient temperature was 30°C. The temperature data given in the report[4] indicate that t_c is around 55 s.

The temperatures were measured at the geometric plume center 0.31 m below the ceiling. The average temperature, $\overline{T}$, between t=55 s and t=310 s was about 91 °C, which was computed based on the temperature curve shown in the report. The average plume velocity, $\overline{u}$, between the same time period was estimated as 6.0 m/s, which was estimated by using the plume correlations[7] with the plume centerline temperature being fixed at 91 °C.

Inserting the above data into Eq. (6) resulted in τ_s =78 s, which is far shorter than the measured sprinkler actuation time, 313 s. The most likely explanation for the discrepancy is that the sprinkler was not exposed *continuously* to the hot plume that was originated from the fire source. In large pan fires under a high ceiling clearance, it is often observed that: (1) plume centerline does not necessarily coincide with the geometric centerline of the pan, and (2) the plume centerline keeps drifting during a test. Thus, if the sprinkler that was located along the geometric plume center line was exposed to a hot temperature only *intermittently* during the test thereby allowing the heat sensing element to be cooled down frequently, it would take a much longer time to actuate than the predicted time.

When the same test (Test 5 in Ref. 4) was conducted with a draft curtain, the dimensions of which were 24.4 m by 18.3 m by 3.7 m deep and the center of which coincided with the center of the pan, the first sprinkler actuated at 138 s, which was much closer to the time computed through Eq. (6), compared with the time measured in Test 7 (of Ref. 4). The draft curtain contained the hot gas from the fire plume inside the curtain so that the sprinkler could be exposed to the high temperature *continuously*. The first actuated sprinkler, however, was not the one directly above the center of the pan. Rather, it was the one located 3.1 m east of the center one, which is an indication of the leaning of the flame to that direction during the test. Also note that the fire size in Test 5 estimated by the authors was 6.7MW, which was substantially higher than that in Test 7, although identical test conditions, except the existence of the draft curtain, were maintained. This difference in the reported fire size makes a one to one comparison between the two tests somewhat less justifiable.

When the plume correlations were used to estimate the first sprinkler actuation time, the equations were applied with

$$z_0 = -1.02D + 0.083\dot{Q}^{2/5} \qquad (7),$$

$$\dot{Q}_c = \chi_c \dot{Q} \qquad (8),$$

where D is the pan diameter in *m*, $\dot{Q}$ is the total heat release rate in *kW*, and χ_c is the convective fraction of the total heat transfer. The equation for the computation of the virtual origin in the pan fires, Eq. (7), came from Ref. 9. Also note that $C_{\Delta T_0}$ =9.1 and $C_{V_{z0}}$ =4.3 were used for pan fires[6]. Applying χ_c =0.65 to above Test 7 yields $\overline{T}$ =104 °C and $\overline{u}$ =6.5 m/s at the ceiling. By using the same t_c =55 s, we can get τ_s =70 s, which is not very far from the one obtained by using the measured temperatures and the velocities, 78 s. The maximum ceiling height that would allow the sprinkler actuation with the given 5.6 MW pan fire was estimated through the plume correlations. It was 17.8 m and the actuation time τ_s =121 s, provided that t_c =55 s. A similar trend was found for the tests using a 2.5-m diameter pan filled with JP-5 fuel. In Test 8 of Ref. 4, the estimated steady heat release rate from the pan fire was 7.7MW. The sprinkler located directly above the center of the pan actuated at 311 s. The temperature rating of the sprinkler was 79^{o}C and the RTI was 35 (m.s)$^{1/2}$ while the ambient temperature was 29^{o}C. The temperature curve 0.31m below the ceiling at the geometric plume center given in the report indicates that t_c can be 72 s. The average ceiling temperature calculated through the temperature curve in the report between t=72 s and t=310 s was about 128^{o}C. The average plume velocity at the sprinkler location that was estimated by using Eqs. (4) and (5), with the plume centerline temperature being fixed at 128^{o}C, was 7.6 m/s. Inserting these values to Eq. (6) yields τ_s =81 s, which is far shorter than the one measured, 311s. Again, the most reasonable explanation for the discrepancy is the likelihood of continuous drifting of the plume centerline positions.

When the identical test (Test 6b of Ref. 4) was conducted with the sprinklers that were surrounded by the same draft curtain described earlier, the center sprinkler actuated at 78s, which is very close to the computed one, 81s. Note that Ref. 4 reported the same fire size in Tests 8 and 6b.

When the plume correlations, Eqs. (4) and (5), were used to compute $\overline{T}$ and $\overline{u}$ with χ_c =0.65, they yielded $\overline{T}$ =118^{o}C and $\overline{u}$ =7.3 m/s at z=14.9 m. Application of Eq. (6) with the above values resulted in τ_s =83 s, provided that t_c =72 s. The maximum ceiling height that would allow the actuation of the same type of the ceiling sprinklers with the given pan fire ($\dot{Q}$ = 7.7MW) was estimated by using the plume correlations. It came out as z=20.5 m and τ_s =130s, provided that t_c =72 s.

2.2.3 Pan fire tests under a 22-m high ceiling

Gott *et al.* [4] conducted several pan fire tests under a 22-m high ceiling and measured sprinkler actuation times. They found that the smallest fire size among the tested was 7.9 MW that actuated the ceiling sprinklers, the temperature rating and the RTI of which was 79^{o}C and 35 (m.s)$^{1/2}$, respectively.

A 2.5-m diameter pan filled with JP-5 under a 22-m high ceiling was used in Test 14 of Ref. 4. The ambient temperature was 12^{o}C. The estimated fire size in the repot was 7.9 MW[4]. The ceiling sprinklers were surrounded by a draft curtain, the dimensions of which were 45.7 m by 14.8 m by 6.1 m deep. The average plume temperature at the geometric plume center 0.31m below the ceiling was reported as 91^{o}C[4]. The first actuated sprinkler was the one located 3.1 m south of the center sprinkler and it actuated at 262 s, which is an indication of the leaning of the plume to the south from the geometric center line. The average plume temperature measured in the test far exceeded the average temperature that can be obtained through the plume correlation of Eq. (4): 91^{o}C vs. 55^{o}C with $\chi_c = 0.65$. (Note that the ambient temperature was substantially lower than that in the earlier pan fire cases.) The higher temperature measured in the test was likely to have been caused by the existence of the relatively deep (6.1m) draft curtain that covered a large area. The ceiling was concave so that the clearance at the boundary of the draft curtain was significantly lower than the center height (22m), and that would have allowed the plume with substantially higher temperature to be contained inside the curtain than the temperature anticipated at the center location.

3. Discussion

The results of Test 1 indicated that the maximum ceiling clearance that would allow the actuation of the ceiling sprinklers would be 22.2m. When the plume correlations were applied to calculate the size of a heptane pan fire that would actuate the ceiling sprinklers at the same height, it came out as 11.7 MW (z=22.2 m, $T_r = 74$ ^{o}C, RTI =28 (m.s)$^{1/2}$, χ_c =0.65, T_∞ =15^{o}C). That is considerably higher than the maximum heat release rate in the test, which would be close to 8.9 MW if we can assume that χ_c =0.65.

The results of Test 2 indicated that the maximum ceiling clearance that would allow the actuation of the ceiling sprinklers would be 26.6m. When the plume correlations were applied to calculate the size of a heptane pan fire that would actuate the ceiling sprinklers at the same height, it came out as 14.5MW (z=26.6m, $T_r = 74$ ^{o}C, RTI=28(m.s)$^{1/2}$, χ_c = 0.65, T_∞ =23^{o}C). That is, again, considerably higher than the maximum heat release rate from the fire in the test, which would be close to 11.5 MW assuming that χ_c =0.65.

These two comparisons clearly show that assessing sprinkler actuations on high ceilings by estimating maximum heat release rate of real fire load in a facility, and then validating that with pan fire tests, which appears to be a common practice, will be highly likely to lead to a wrong conclusion.

While the steady pan fire sources are plane two dimensional, the growing fires generally involve three dimensional fire sources. The flames in the growing fires grow horizontally as well as vertically. Thus, at the position of z=0, the plume from the growing fires already possess a sizable amount of momentum that the counter part from the steady pan fires lacks. That difference seems to attribute the differences in the coefficients (e.g., $C_{\Delta T_0}$ and $C_{V_{z0}}$) and the virtual origins (z_0) between the plume correlations relevant to the growing fires and that to the steady pan fires.

In cases pertinent to high ceiling clearances, it can be assumed as $z_0 \big/ z << 1$. Then Eq. (4) can be simplified as

$$\Delta T_0 = C_{\Delta T_0}\left[\left(T_\infty\right) \Big/ \left(g C_p^2 \rho_\infty^2\right)\right]^{1/3} \dot{Q}_c^{2/3} z^{-5/3}\left(1+\frac{5}{3}\varepsilon\right) \qquad (9)$$

where $\varepsilon << 1$. When the critical fire size from a pan fire is compared with that from a growing fire that would actuate a sprinkler at the same ceiling height, the comparison of the fire size can be expressed as

$$\frac{\left(\dot{Q}_c\right)_S}{\left(\dot{Q}_c\right)_G} \approx \left[\frac{\left(C_{\Delta T_0}\right)_G}{\left(C_{\Delta T_0}\right)_S}\right]^{3/2} = \left(\frac{11.0}{9.1}\right)^{3/2} \qquad (10)$$

because ΔT_0 in both cases should be comparable each other and $\left[\left[\left(T_\infty\right) \Big/ \left(g C_p^2 \rho_\infty^2\right)\right]^{1/3} z^{-5/3}\left(1+\frac{5}{3}\varepsilon\right)\right]$ in both cases would be almost same each other. Here the subscripts $_S$ and $_G$ stand for steady pan fire and growing fire, respectively.

Eq. (10) shows that it would require an approximately 30% larger fire if a test was conducted with a steady pan fire compared with that from a growing fire, in order to activate a ceiling sprinkler on the same ceiling height. The two example cases introduced above related to Tests 1 and 2 match well with this prediction.

4. Conclusions

1. A fire load equivalent to 2.26-m high 2 by 2 stacks of solid-pile FM Global Class 2 commodity is likely to actuate sprinklers installed on a 24.5-m high ceiling, provided that the sprinkler temperature rating is 74°C or lower, the RTI of the sprinklers is 28 $(m.s)^{1/2}$ or smaller, and the ambient temperature is 15°C or higher. The maximum convective heat release rate from the fire load is estimated as 5.4 MW.

2. A fire load equivalent to 1.73-m high 2 by 2 stacks of solid-pile FM Global Standard Plastic commodity is likely to actuate sprinklers installed on a 28.3-m high ceiling, provided that the sprinkler temperature rating is 74°C or lower, the RTI of the sprinklers is 28 $(m.s)^{1/2}$ or smaller, and the ambient temperature is 23°C or higher. The maximum convective heat release rate from the fire load is estimated as 6.5 MW.

3. A steady pan fire generating the total heat release rate of 5.6 MW is likely to actuate sprinklers installed on a 17.8-m high ceiling, provided that the sprinkler temperature rating is 79°C or lower, the RTI of the sprinklers is 35 $(m.s)^{1/2}$ or smaller, the ambient temperature is 30°C or higher, and χ_c is 0.65 or higher.

4. A steady pan fire generating the total heat release rate of 7.7 MW is likely to actuate sprinklers installed on a 20.5-m high ceiling, provided that the sprinkler temperature rating is 79°C or lower, the RTI of the sprinklers is $35(m.s)^{1/2}$ or smaller, the ambient temperature is 30°C or higher, and χ_c is 0.65 or higher.

5. When the ability of sprinkler actuation is assessed by using a pan fire test, the test fire size should be at minimum 30% larger than the expected size from a growing fire in order to make a proper assessment.

6. The comparison between the growing fire cases and the pan fire cases shows that deciding the threshold fire size that would actuate sprinklers on high ceilings based on pan fire tests will be likely to lead to a wrong conclusion. The critical maximum heat release rate obtained through pan fire tests is likely to be much higher than the fire size that can and will actuate sprinklers on a high ceiling from growing fires, which are the most likely fires that we will encounter in any accidental fire scenarios.

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