EFFECT OF SPRINKLER SYSTEM ON CONTROLLING FIRE AREA

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ABSTRACT

Based on the temperature and velocity equations of ceiling jet, the response time of sprinkler for various ceiling heights with different fire growth rates are calculated. Sprinkler can control fires of a smaller fire size and fire area. Integrated fire engineering system should be applied to reduce water damage and the effect of sprinkler spray could be more concentrated on the fire.

1. INTRODUCTION

Sprinkler systems are designed to control the fire spreading in a fire but most engineers would follow the rule of thumb – designing each fire service system separately and then simply putting them together as per the requirement. In this project, how sprinkler system should be designed in complementary, instead of in conflict, with other systems would be investigated.

The response time of sprinkler should be investigated at various smoke temperatures and densities in order to form a database for determining the fire growth and the corresponding consequences of a design fire. The overall performance of sprinkler in controlling the fire or limiting excessive pre-wetting area and water damage should also be considered.

Therefore, only those sprinklers close to the fire source would operate and water spray is applied to the rising plume, flame and fuel pool only.

2. FIRE GROWTH AND OPERATION SEQUENCES OF SYSTEMS

In order to study the response time, some physical conditions are assumed as the basis for calculation.

- Four different ceiling heights are considered: 2.5 m, 5 m, 10 m and 15 m.
- Unlimited flat ceiling without heat transfer on smoke flow.
- There is no specified location for the point fire source placed on ground floor with negligible height.
- Sprinklers are arranged in a 3 m by 3 m array [9,10].

Therefore, the shortest radical distance for sprinkler from the fire source is zero (right above the source), and the longest distance is 2.121 m.

Basically, t-square fire [1] is generally accepted to describe a fire growth against time as expressed in equation (1).

$$\dot{Q} = \alpha t^2 \qquad (1)$$

where α is a constant which determines the rate of growth for a particular fire as listed in Table 1 [2].

Table 1: Fire growth rate constants

Fire Growth Rate	α (W·s^{-2})
Ultra-Fast	187.6
Fast	46.9
Medium	11.7
Slow	2.9

However, only the convective heat would be transferred to the smoke plume and activate the sprinklers, and the convective heat from the fire is about 75% of the heat released by the fire [3]. So, equation (1) becomes

$$\dot{Q}_c = 0.75\dot{Q} = 0.75\alpha t^2 \qquad (2)$$

The formulae by Heskestad [3,4] to approximate the time, velocity and temperature rise for a rising plume front and ceiling jet front are shown below.

$$u_r = H^{0.2}(0.75\alpha)^{0.2}\left(\frac{g}{C_p T_\infty \rho_\infty}\right)^{0.2} 0.59\left(\frac{H}{r}\right)^{0.63} \times$$

$$\left(\frac{\left(\frac{g}{C_p T_\infty \rho_\infty}\right)^{0.2} \frac{(0.75\alpha)^{0.2}}{H^{0.8}}(t - t_o) - 0.813\left(1 + \frac{r}{H}\right)}{0.126 + \frac{0.210r}{H}}\right)^{2/3} \qquad (3)$$

$$\Delta T_r = \frac{(0.75\alpha)^{0.4}}{H^{0.6}} \left(\frac{g}{C_p T_\infty \rho_\infty} \right)^{0.4} \frac{T_\infty}{g} \times$$

$$\left(\frac{\left(\frac{g}{C_p T_\infty \rho_\infty} \right)^{0.2} \frac{(0.75\alpha)^{0.2}}{H^{0.8}} (t - t_o) - 0.813\left(1 + \frac{r}{H}\right)}{0.126 + \frac{0.210r}{H}} \right)^{4/3} \quad (4)$$

By neglecting t_o and putting the constants into the equations, equations (3) and (4) can be simplified as follows,

$$u_r = H^{0.2}\alpha^{0.2} 0.07666 \left(\frac{H}{r} \right)^{0.63} \left(\frac{0.1158(H\alpha)^{0.2} t - 0.813(H + r)}{0.126H + 0.210r} \right)^{2/3} \quad (5)$$

$$\Delta T_r = \frac{0.4005\alpha^{0.4}}{H^{0.6}} \left(\frac{0.1158(H\alpha)^{0.2} t - 0.813(H + r)}{0.126H + 0.210r} \right)^{4/3} \quad (6)$$

Then, based on β = 0.1018 [5], the calculated data are tabulated in Table 2.

Table 2: Initiation time ranges for sprinkler at 2.121 m from fire source for various ceiling heights with different fire growth rates

$t_{ini,spr}$ (s)		H (m)			
β	α (W·s^{-2})	2.5	5	10	15
0.1018	187.6	9.49	12.73	18.86	24.56
	46.9	12.51	16.78	24.87	32.39
	11.7	16.52	22.16	32.83	42.76
	2.9	21.83	29.29	43.40	56.52

3. ACTIVATION OF SPRINKLE AND FIRE AREA

By the following ODE [6], equations (5) and (6), the response time for sprinklers with different RTI can be calculated numerically by 4-order R-K Method based on the data given in Table 2 and then tabulated in Table 3.

$$\frac{dT_d}{dt} = \frac{u^{0.5}(T_g - T_d)}{RTI} \quad (7)$$

Table 3: Response time ranges for sprinkler at 2.121 m from fire source for various ceiling heights with different fire growth rates

$t_{act,spr}$ (s)		H (m)			
RTI	α (W·s^{-2})	2.5	5	10	15
100	187.6	66.03	83.92	120.05	157.90
	46.9	102.97	133.54	199.16	272.03
	11.7	163.91	219.68	347.46	493.16
	2.9	269.15	378.89	638.21	931.02
200	187.6	84.91	103.73	142.88	178.02
	46.9	125.46	158.97	226.93	298.06
	11.7	197.36	255.56	381.28	522.01
	2.9	317.25	425.28	674.57	960.45
300	187.6	91.71	113.82	155.91	196.79
	46.9	141.89	177.95	249.12	321.81
	11.7	222.15	283.36	410.89	549.55
	2.9	353.98	464.00	709.47	989.55

Assuming that the fire is controlled by sprinkler spray, the heat release rates are frozen at those moments and summarized in Table 4.

Table 4: Frozen heat release rates by sprinkler at 2.121 m from fire source for various ceiling heights with different fire growth rates

$\dot{Q}_f$ (MW)		H (m)			
RTI	α (W·s^{-2})	2.5	5	10	15
100	187.6	0.8179	1.3212	2.7037	4.6773
	46.9	0.4973	0.8364	1.8603	3.4706
	11.7	0.3143	0.5646	1.4125	2.8455
	2.9	0.2101	0.4163	1.1812	2.5137
200	187.6	1.3525	2.0186	3.8298	5.9453
	46.9	0.7382	1.1852	2.4152	4.1666
	11.7	0.4557	0.7641	1.7009	3.1882
	2.9	0.2919	0.5245	1.3196	2.6751
300	187.6	1.5779	2.4304	4.5602	7.2651
	46.9	0.9442	1.4851	2.9107	4.8570
	11.7	0.5774	0.9394	1.9753	3.5335
	2.9	0.3634	0.6244	1.4597	2.8397

Since the fire is assumed frozen by the sprinkler spray, the minimum area on fire with maximum fire load 1135MJm^{-2} [7] can be approximated by integrating equation (1),

$$A_{fire} = \frac{\alpha t^3}{3 \times 1135 \times 10^6} \quad (8)$$

Hence, the results are tabulated in Table 5.

Table 5: Area of fire controlled by sprinkler at 2.121 m from fire source for various ceiling heights with different fire growth rates

A_{fire} (m^2)		H (m)			
RTI	α (W·s^{-2})	2.5	5	10	15
100	187.6	0.01586	0.03256	0.09532	0.21690
	46.9	0.01504	0.03280	0.10881	0.27727
	11.7	0.01513	0.03643	0.14414	0.41213
	2.9	0.01661	0.04633	0.22140	0.68732
200	187.6	0.03373	0.06149	0.16071	0.31083
	46.9	0.02720	0.05534	0.16097	0.36473
	11.7	0.02642	0.05735	0.19046	0.48877
	2.9	0.02720	0.06551	0.26143	0.75458
300	187.6	0.04250	0.08124	0.20880	0.41988
	46.9	0.03935	0.07762	0.21295	0.45904
	11.7	0.03767	0.07818	0.23837	0.57028
	2.9	0.03778	0.08508	0.30415	0.82527

On top of the data in the above tables, some more figures are listed in Table 6 as reference.

Table 6: Temperature rise of fire controlled by sprinkler at 2.121 m from fire source for various ceiling heights with different fire growth rates

ΔT_r (K)		H (m)			
RTI	α (W·s^{-2})	2.5	5	10	15
100	187.6	170.69	116.03	79.59	66.05
	46.9	126.73	89.05	65.20	57.26
	11.7	96.29	71.13	56.79	52.64
	2.9	75.76	60.09	52.39	50.31
200	187.6	250.63	160.97	104.39	79.66
	46.9	170.40	115.80	79.41	65.70
	11.7	126.48	88.86	65.08	57.18
	2.9	96.01	70.95	56.70	52.58
300	187.6	281.20	185.19	119.26	92.90
	46.9	204.22	136.86	91.24	73.65
	11.7	150.11	103.25	72.55	61.60
	2.9	112.26	80.35	60.92	54.85

4. DISCUSSION

The data listed in Tables 3 to Table 6 would not apply if there is any obstruction which could affect the ceiling flow. In other words, the equations describing velocity and temperature distributions versus time should not be affected around the sprinklers considered. Therefore, the convection heat transfer to the sprinkler would become conduction.

Thus, the sprinkler response time can be approximated by the time for the confined smoke temperature to increase to the sensitive temperature of the sprinkler. These response time ranges can be calculated by integrating the cumulative heat stored in the confined smoke or smoke reservoir with infinite depth. Therefore, the temperature in the smoke layer is subjected to the area of smoke reservoir such that the larger the area of a smoke zone, the longer the time for the temperature of the smoke layer to rise up to the required temperature.

However, it is impossible and impractical. The effect on the temperature of the smoke reservoir by the impingement of the rising plume, the mixing of the hot gas from time to time and the energy lost should be considered.

Moreover, the confined smoke flow around the sprinkler may not be totally shifted from convection to conduction and the problem becomes much more complicated. First of all, what smoke velocity ranges around the sprinkler are regarded as undergoing convection and conduction should be defined. Also, further study should be carried out on the velocity and temperature profile near a sprinkler for various conditions in confined smoke flow. Therefore, the sprinkler response time in these environments would be determined at the moment.

On the other hand, the fire sizes controlled by sprinkler spray are smaller. Also, the areas of the fires are not so large as expected. Therefore, a fire can be ‘frozen’ effectively by sprinkler system with four sprinklers only in general conditions if the premises are being used properly according to the initial design parameters. Then, further sprinkler operation should be avoided in order to minimize water damage by integrated fire engineering design such as smoke extraction systems. In addition, more water and higher pressure should be concentrated at those operating sprinklers only so that the efficiency of sprinkler is higher in fighting against the fire.

The response time for sprinkler decreased for smaller RTI but the effect reduced for taller ceiling height. On top of that, good building management is far more important in upholding the efficiency of fire services systems.

5. CONCLUSION

In usual cases, sprinkler system can control a growing fire effectively with a smaller fire size and fire area for slow, medium, fast and even ultra-fast growth rate. Shorter ceiling height with smaller RTI has prompt action in responding to the outbreak of a fire. Water damage could be limited with performance-based design.

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NOMENCLATURE

A_{fire}	Area of fire (m^2)
C_p	Specific heat capacity of air at constant pressure ($Jkg^{-1}K^{-1}$) = 1005
g	Acceleration of gravity (ms^{-2}) = 9.81
H	Ceiling height above fire source (m)
$\dot{Q}$	Heat release rate of fire (W)
$\dot{Q}_c$	Convective heat release rate of fire (W)
$\dot{Q}_f$	Heat release rate of frozen fire (W)
r	Radial distance from the centre of fire source (m)
T_d	Temperature of sensitive element for sprinkler (K)
T_g	Temperature of smoke (K)
T_L	Response temperature of sprinkler (K)
T_∞	Ambient temperature (K) = 293
ΔT	Temperature rise for above ambient (K)
ΔT_r	Temperature rise for ceiling jet at r above ambient (K)
t	Time (s)
$t_{act,spr}$	Activation time for sprinkler
t_{ceil}	Time for the ceiling jet temperature to rise to desired temperature (s)
$t_{ini,spr}$	Initiation time for sprinkler (s)
t_o	Virtual time origin (s)
t_{rise}	Time for the rising plume to reach the ceiling after the ignition of a fire (s)
t_r	Time for the ceiling jet to reach r (s)
u_{max}	Maximum ceiling jet flow speed (ms^{-1})
u_r	Average ceiling jet flow speed at r (ms^{-1})
u_H	Rising plume speed at H (ms^{-1})
u_z	Rising plume speed at z (ms^{-1})
α	Fire growth coefficient (Ws^{-2})
β	Constant ratio of b_z to z
ρ_∞	Ambient air density (kgm^{-3}) = 1.2