Fire Extinguishing Time by Sprinkler

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ABSTRACT

Sprinkler actuation time has been calculated for various cases, but there has been little study on extinguishing time after sprinkler actuation. Therefore, we have tried to draw an equation for the prediction of extinguishing time in the compartment fires where the ceiling is not high, and burning rate and water discharge rate are comparatively low. It is considered that the fire extinguishing performance depends on the interaction of sprinkler sprays with buoyant plumes, and cooling effect on a fire source by water discharge. The ratio of the updraft gas velocity in the plume to the velocity of water drops is considered as the former factor, and the ratio of the burning rate to the water discharge rate as the latter. We have obtained a generalized equation for the extinguishing time after sprinkler actuation by dimensional analysis, using these factors. We also attempted numerical calculation of extinguishing time for an example by this equation. This is the case of a crib fire with a constant burning rate. We consider that the extinguishing time for sprinklers will become one of the important factors on extinguishing performance of sprinklers.

INTRODUCTION

Calculations of the time it takes for sprinklers to operate after their detection of fires occurring in compartments have been made for various cases [1], [2]. However, there have been published very few generalized equations for the prediction of time from actuation of sprinklers to extinguishment of the fires. In this paper we assumed fires in compartments of residential buildings and obtained an equation for the prediction of extinguishing time by dimensional analysis and determined constants by experiment for the case that the ceiling is not high, burning rate and water discharge rate are comparatively low. We also attempted numerical calculations of extinguishing time for a certain case, using the equations.

EQUATIONS FOR THE PREDICTION OF EXTINGUISHING TIME

It is considered that the fire extinguishing effectiveness of sprinklers depends on the following conditions.

1. To what extent spray water drops can penetrate through the updraft of the fire source.

2. At what discharge rate water must be delivered to the fire source in order to suppress heat generation from the fire source and to stop continued combustion.

As a dimensionless factor which governs the condition 1., the ratio of the updraft gas velocity in the plume, Up, to the velocity of water drops, Ut, is considered where the interaction between the fire plume and spray water drops is mainly governed by gravity because of comparatively low water discharge pressure [3]. As a dimensionless factor governing the condition 2., the ratio of the mass burning rate at the start of water discharge, Q, to the water discharge rate onto the upper surface of the fuel (in the case of no updraft of the gas), Qw, is considered [4]. On the other hand, as a dimensionless factor indicating the fire extinguishing effectiveness, the ratio of the time from the sprinkler actuation to the fire extinguishment, T, to the time from the outbreak of fire to the sprinkler actuation, To, is considered. Hence, the following relation is established among these dimensionless factors.

$$T/To = f(Up/Ut,\ Q/Qw) \qquad (1)$$

The maximum gas velocity of the updraft in the plume, Upm, is expressed by the following equation [2].

$$\frac{Upm}{\sqrt{gH}} = 3.16\,\frac{\dot{Q}^{1/3}}{H^{5/6}}\,[Cp\ \gamma o\ to\ g^{1/2}]^{-1/3} \qquad (2)$$

where
H : distance from upper surface of crib to ceiling
$\dot{Q}$: heat release rate from fuel
Cp: isopiestic specific heat of air
γo: density of air under standard ambient condition (20°C, 1 atm.)
to: temperature of air under standard ambient condition (20°C, 1 atm.)
g : gravitational acceleration

Since there would not be substantial change in diameter and velocity of the plume extending from the upper surface of the fuel to the ceiling, whole Up may be represented by Upm. The heat release rate from the fuel is calculated from $\dot{Q}$ = Qh, where h is the heat release rate per unit weight of the fuel and Q is the mass burning rate of the fuel. Consequently

$$Up \propto \left(\frac{Q}{H}\cdot\frac{h\ g}{Cp\ \gamma o\ to}\right)^{1/3} \qquad (3)$$

Water drops having radius of approximately 2 x 10^{-2}cm or larger and falling in the air are subjected to resistance as defined by Newton's law, and their velocity, Ut, is expressed by the following equation [5].

$$Ut = 2.11\sqrt{\frac{g(\gamma w-\gamma)}{\gamma}}\ \sqrt{\frac{d}{2}} \qquad (4)$$

where
γw: density of water
γ : density of gas in plume
d : diameter of spray drop

Since γ is very small compared to γw, $\gamma w/\gamma$ may be used in lieu of $(\gamma w-\gamma)/\gamma$. If sprinkler models are specified, distribution of spray drop diameters is characterized for each sprinkler model, and therefore the mean diameter of the drops, dM, may be used in lieu of d. Accordingly

$$Ut \propto \left(\frac{g\ \gamma w\ dM}{\gamma} \right)^{1/2} \qquad (5)$$

From the equations (3) and (5)

$$\frac{Up}{Ut} \propto \left(\frac{h}{Cp\ \gamma o\ to\ \gamma w^{3/2}\ g^{1/2}} \right)^{1/3} \left(\frac{Q}{H} \right)^{1/3} \left(\frac{\gamma}{dM} \right)^{1/2} \qquad (6)$$

From the equations (1) and (6)

$$\frac{T}{To} = k\left(\frac{Q}{Qw} \right)^{m} \left[A \cdot \frac{Q}{H} \cdot \left(\frac{\gamma}{dM} \right)^{3/2}\right]^{\ell/3}$$

Where

$$A = \frac{h}{Cp\ \gamma o\ to\ \gamma w^{3/2}\ g^{1/2}}$$

With $\ell/3 = n$, the above equation becomes:

$$\frac{T}{To} = k\left(\frac{Q}{Qw} \right)^{m} \left[A \cdot \frac{Q}{H} \cdot \left(\frac{\gamma}{dM} \right)^{3/2}\right]^{n} \qquad (7)$$

Then, values for k, m and n are obtained by experiment.

EXPERIMENTS AND RESULTS

As shown in FIGURE 1 three sprinkler heads were installed on the ceiling with a height of 3.5m. They were arranged with the distance from the fire source, L, varied, so that water drops may fall upon the fire source at different delivery rates. For the fire source, cribs of cedar wood sticks, each sized

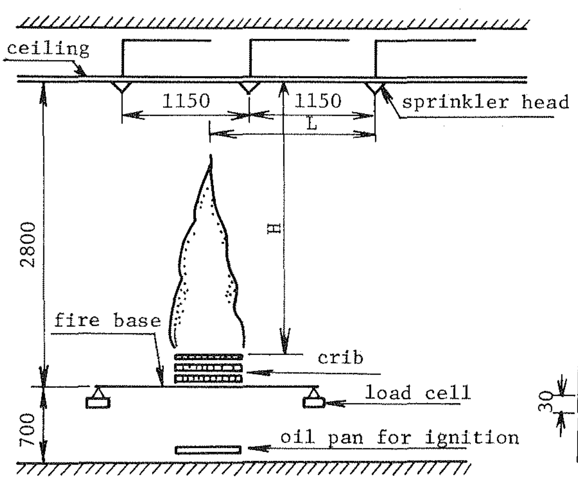


FIGURE 1 Arrangement of fire extinguishing experiment

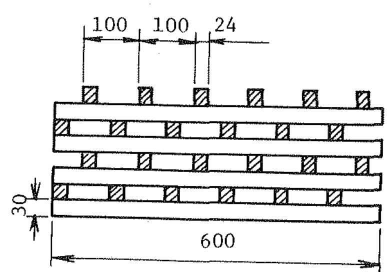


FIGURE 2 Crib (example in the case of 8 layers)

24mm x 30mm x 600mm with moisture content of 9 ∿ 12% and stacked in six, eight and ten layers as shown in FIGURE 2 were used. To ignite them an oil pan (60cm x 60cm) containing 600cc of gasoline was placed under the crib. It was removed from the position in one minute after ignition. Water discharge was started when the wood cribs showed a weight loss by 30%, but the burning rates from the ignition to water discharge (60, 90, 130 kcal/s) were considered to be almost constant because of ignition by an oil pan (heat release rate:190 kcal/s). Disappearance of flame on the crib was regarded as conclusion of extinguishment. TABLE 1 shows measured values in the experiments.

TABLE 1. Result of extinguishing test with sprinklers

Test No.		Weight of crib	Time from ignition to water discharge	Time from water discharge to extinguishment	Water discharge rate on crib	Mass burning rate just before water discharge	Distance from upper surface of crib to ceiling	Density of air in plume
Group	No.	W (kg)	To (min.)	T (min.)	QW (kg/min. 0.36m^2)	Q=0.3W/To (kg/min.)	H (m)	(kg/m^3)
	1	5.55	1.76	8.50	0.48			
	2	5.95	1.88	7.66	"			
	3	5.57	1.76	2.12	0.85			
	4	5.70	1.80	1.75	"	0.95	2.62	0.82
A	5	5.90	1.87	1.10	1.35			
	6	5.55	1.76	1.03	"			
	7	5.45	1.72	0.55	1.77			
	8	5.55	1.76	0.50	"			
	1	7.70	1.65	7.08	0.76			
	2	7.20	1.55	6.76	0.85			
	3	7.75	1.66	4.50	1.19			
	4	7.38	1.58	3.60	1.30			
B	5	7.27	1.56	1.53	1.77	1.40	2.56	0.74
	6	7.14	1.53	1.42	"			
	7	7.88	1.69	1.12	2.48			
	8	7.95	1.71	1.02	2.97			
	9	7.53	1.61	0.87	3.17			
	10	7.30	1.57	0.83	3.29			
	1	9.55	1.39	6.63	1.77			
	2	8.79	1.28	5.75	"			
	3	9.14	1.33	4.72	2.40			
	4	9.75	1.42	3.80	"			
C	5	9.52	1.38	1.80	3.29	2.06	2.50	0.65
	6	9.85	1.43	1.58	"			
	7	9.15	1.33	1.35	4.33			
	8	9.14	1.33	1.13	"			
	9	9.27	1.35	.50	5.58			
	10	9.25	1.34	0.47	"			

DETERMINATION OF CONSTANTS FOR PREDICTION EQUATION

FIGURE 3 shows the correlation between T/To and Qw, which is plotted for each of the groups A, B and C, i.e. for each case that Q and H are same by using those figures given in TABLE 1. From the gradient of the line, m = -2 is obtained.

Values for dM, h, Cpm γo, To, γw and g in this experiment are as follows.

dM = 1mm = 1×10^{-3}m
h = 3,780 kcal/kg (cedar wood with moisture content of 9 ∿ 12%)
Cp = 0.24 kcal/kg °C
γo = 1.161 kg/m^3
to = 20°C
γw = 998.2 kg/m^3
g = 9.807m/s^2 = 35.3×10^3m/min^2

Consequently

$A = 1.172 \times 10^{-4} m^7\ min/kg^{5/2}$

Value for γ was obtained from the following equations (8), [6], and (9).

$$\Delta t = 43.9 \times \frac{(Q\ h/60)^{2/3}}{H^{5/3}} \qquad (8)$$

Where
Δt: difference between gas temperature in plume and compartment temperature °C
Q : kg/min
h : kcal/kg
H : m

$$\gamma (kg/m^3) = 1.2931 \times \frac{273}{293 + \Delta t} \qquad (9)$$

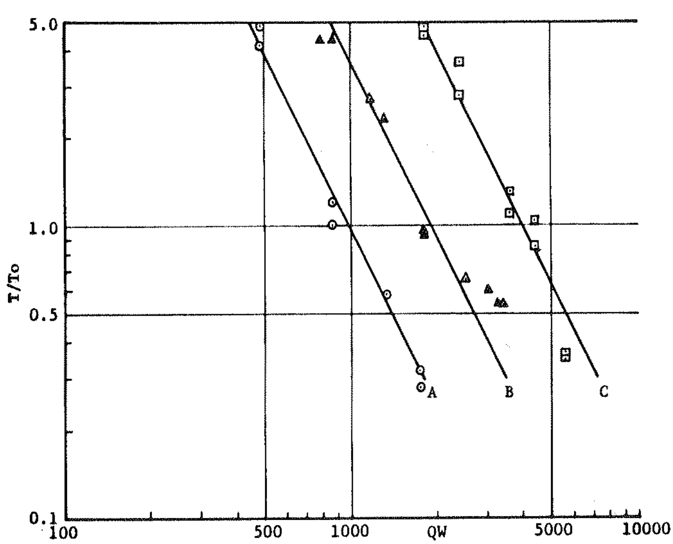


FIGURE 3 Correlation between T/To and QW

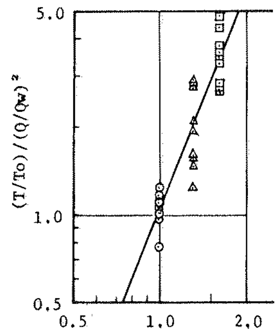


FIGURE 4 Correlation between $(T/To)/(Q/Qw)^2$ and $[A \cdot \frac{Q}{H} \cdot (\frac{\gamma}{dM})^{3/2}]$

FIGURE 4 shows the correlation between $(T/To)/(Q/Qw)^2$ and $[A \cdot \frac{Q}{H} \cdot (\frac{\gamma}{dM})^{3/2}]$ which is plotted by using the results and values obtained in the abovementioned experiment. From this figure and by regression analysis, k = 1.05, n = 2.5, and a correlation factor between the above two quantities is calculated to be 0.91. Therefore, the equation (7) becomes:

$$\frac{T}{To} = 1.05 \left(\frac{Q}{Qw}\right)^2 \left[A \cdot \frac{Q}{H} \cdot \left(\frac{\gamma}{dM}\right)^{3/2}\right]^{2.5} \qquad (10)$$

FIGURE 5 compares the equation (10) with the results of the experiment. With the weight loss of the fuel by fire until the sprinkler actuation being M = Q To, the equation (10) becomes:

$$T = 1.05 \left(\frac{Q}{Qw}\right)^2 \left[A \cdot \frac{Q}{H} \cdot \left(\frac{\gamma}{dM}\right)^{3/2}\right]^{2.5} \left(\frac{M}{Q}\right)$$

$$= 1.05\, A^{2.5} \frac{Q^{3.5}\, M}{QW^2\, H^{2.5}} \left(\frac{\gamma}{dM}\right)^{3.75} \qquad (11)$$

where

T : time from sprinkler actuation to fire extinguishment min

$A = \frac{h}{Cp\, \gamma o\ to\ \gamma w^{3/2}\, g^{1/2}}$ $m^7\ min/kg^{5/2}$

h : heat release rate per unit weight of fuel kcal/kg

Cp: isopiestic specific heat of air 0.24 kcal/kg °C

γo: density of air under standard ambient condition (20°C, 1 atm.) 1.161 kg/m^3

to: temperature of air under standard ambient condition (20°C, 1 atm.) 20°C

γw: density of water 998.2 kg/m^3

g : gravitational acceleration $35.3 \times 10^3\ m/min^2$

Q : mass burning rate before sprinkler actuation kg/min

Qw: water delivery rate onto upper surface of fuel kg/min

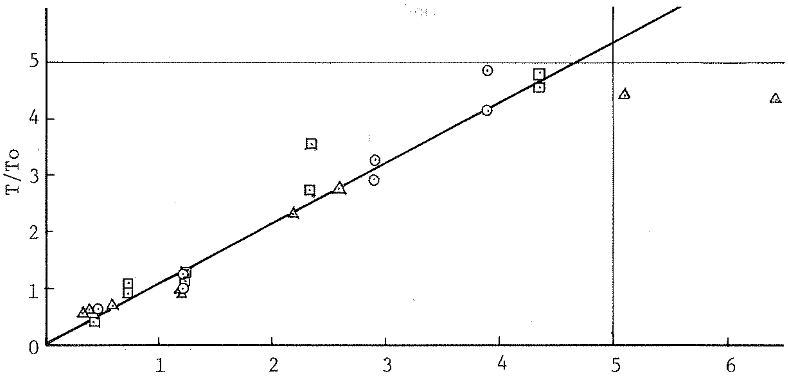
M : weight loss of fuel until sprinkler actuation kg

H : distance from upper surface of fuel to ceiling surface m

γ : density of gas in plume kg/m^3

dM: mean diameter of spray drops m

It is now possible to calculate the time from the sprinkler actuation to fire extinguishment by the equation(11).



$$\left(\frac{Q}{QW}\right)^2 \left[A \frac{Q}{H} \left(\frac{\gamma}{dM}\right)^{3/2}\right]^{2.5}$$

FIGURE 5 Correlation between T/To and $\left(\frac{\gamma}{QW}\right)^2 \left[A \frac{Q}{H} \left(\frac{\gamma}{dM}\right)^{3/2}\right]^{2.5}$

NUMERICAL CALCULATION

Here, a crib fire burning at a constant rate is used as fire model and sprinkler actuation time and fire extinguishing time are calculated. Four sprinklers are mounted on the ceiling of a very large room and on a spacing of 3.25m in a cross pattern. The crib is located in the center of the four sprinklers and with a distance of 2.5m from the ceiling to the upper surface of the crib. Therefore, the horizontal distance from the center of the crib to sprinklers is 2.3m.

The temperature rise of gas at the ceiling, ΔTg, and velocity, u, are obtained from the following equation [6].

$$\Delta Tg = \frac{14\ \dot{Q}^{2/3}}{H\ r^{2/3}}\ [^\circ C] \qquad (12)$$

$$u = \frac{0.32\ \dot{Q}^{1/3}\ H^{1/2}}{r^{5/6}}\ [m/s] \qquad (13)$$

where
- r: horizontal distance from center of crib — m
- H: distance between upper surface of crib and ceiling — m
- $\dot{Q}$: heat release rate — kcal/s

Using these equations, gas temperature and velocity at the sprinklers are calculated for each of three cribs with six, eight and ten layers of wood sticks as shown in FIGURE 2. TABLE 2 shows results of the calculations. In this case the heat release rate was calculated with the heat release rate per unit weight of wood as being 3,870 kcal/kg. The sprinkler model discussed in this paper is to be the one we used for this experiment (i.e. model MHS-12B manufactured by Nohmi Bosai Kogyo Co., Ltd.). The sprinkler has a rated operating temperature of 72°C, and the relation between the time constant τ, and air velocity, u, is expressed by the following equation.

$$\tau = 2.32\ u^{-0.66}\ [\tau\text{:min, u: m/s}] \qquad (14)$$

TABLE 2. Sprinkler actuation time in fire models

Number of layers of crib	6	8	10
Mass burning rate (kg/min.)	0.95	1.40	2.06
Heat release rate [$\dot{Q}$] (kcal/s)	61.3	90.3	132.9
Distance from upper surface of crib to ceiling [H] (m)	2.5		
Horizontal distance between crib and sprinkler [r] (m)	2.3		
Rise in actuation temperature above ambient [ΔTa] (°C)	52 (72-20)		
Rise in gas temperature at sprinkler location above ambient [ΔTg] (°C)	50	65	84
Gas temperature at sprinkler location (°C)	70	85	104
Flow velocity at sprinkler location on ceiling (m/s)	1.0	1.1	1.3
Time constant of sprinkler (min.)	2.32	2.18	1.95
Actuation time of sprinkler (min.)	—	3.51	1.88

Generally the actuation time, tr, of the sprinkler exposed to air current with a constant temperature is expressed by the following equation.

$$tr = -\tau \, \ell n \, (1 - \Delta Ta/\Delta Tg) \qquad (15)$$

where
τ : time constant of sprinkler
ΔTa: difference between initial temperature (20°C) of link and actuation temperature
ΔTg: difference between initial temperature (20°C) of link and gas temperature

TABLE 2 shows sprinkler actuation time for each of the fire models obtained from the equations (14) and (15). From this table it can be seen that with the 6-layer crib fire the gas temperature at the sprinkler does not reach the operating temperature, and consequently the sprinkler is not actuated.

TABLE 3. Extinguishing time in fire models

Number of layers of crib		8	10
Mass burning rate (kg/min.)		1.40	2.06
Water discharge rate [Q] (kg/min.)	1 sprinkler	0.76	
	2 "	1.52	
	3 "	2.28	
	4 "	3.04	
Distance from upper surface of crib to ceiling [H] (m)		2.5	
Mean diameter of spray drops [dM] (m)		1×10^{-3}	
Density of air in plume [γ] (kg/m^3)		0.47	0.65
Fuel weight loss at sprinkler actuation [M] (kg)		4.91	3.87
Extinguishing time [T] (min.)	1 sprinkler	——	——
	2 "	6.27	——
	3 "	2.79	5.22
	4 "	1.57	2.93

Note: Calculated time of extinguishment more than (5 x actuation time) is not listed because there is no such time in our experiment.

With a discharge pressure of $1 kg/cm^2$ the sprinkler has a water density of 2.1 ℓ/m^2/min. (0.76 kg/min on the crib of 0.6m×0.6m) measured at the position of a vertical distance of 2.5m and a horizontal distance of 2.3m from the sprinkler, and its mean diameter of water drops is 1mm. Using these data and values given in TABLE 2, calculation of extinguishing time for each of the fire models was made by the equation (11) with respect to the both cases that only one sprinkler is actuated and two to four sprinklers are actuated simultaneously, results of which are shown in TABLE 3. In this case the weight loss of the fuel until actuation of the sprinkler, M(kg), was determined to be a product of the sprinkler actuation time and the mass burning rate (constant).

CONCLUSION

When sprinkler are used for the purpose of reducing physical damage, whether they will be capable of successfully extinguishing fires, and to what extent they will be able to suppress the burning loss until fires are extinguished are matters of our great concern. Nevertheless, it is of utmost importance that sprinklers used in houses, hotels, wards in hospitals etc., are capable of quickly responding to and extinguish fires from the viewpoint of assuring the safety of evacuation. Therefore, we consider that the extinguishing time for sprinklers will become one of the important factors as index for extinguishing effectiveness of sprinklers in the future.

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