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STUDY ON THE RESPONSE TIME INDEX OF SPRINKLERS

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ABSTRACT

This paper reports on the Response Time Index (RTI) of sprinkler heads. The standard plunge test has been carried out in a hot wind tunnel, which is similar to the one developed at the Fire Research Station, United Kingdom. Some of the modifications have been finished in this wind tunnel for the higher accuracy purpose. About 37 liquid-in glass sprinkler heads are studied including the pendent type and concealed type. Experimental results are reported and particularly, the time constant (τ) and the RTI have been compared under different air temperature and velocities. In this paper, the results of standard pendent type sprinkler (68 ^oC) will be discussed in detail.

1. INTRODUCTION

This paper is to study the thermal characteristics of different sprinkler heads by using a hot wind tunnel as shown in Fig. 1. The thermal responsiveness is firstly investigated by Heskestad and Smith in 1976 [1,2]. After that, many scientists also tried to test for the thermal sensitivity of sprinklers by a hot wind tunnel [1-10] or a scaled model [11-14].

Fig. 1: BSE hot wind tunnel

The study of the thermal characteristics of different sprinkler heads is particularly important in buildings with high fire load, and in areas which are unoccupied for a long period. However, the effectiveness of sprinklers and the sprinkler capacity required depends on the rapidity with which the sprinklers will operate. It is also necessary to ensure that sprinklers are unlikely to be activated by random variations in ambient temperature not associated with a fire. Thus, it is very important to have an understanding on the thermal responsiveness of sprinklers because it can greatly reduce the possibility of having uncontrolled fires, prevent a great loss in human life and property, as well as provide the information with a better design of sprinkler system. It is also the objective of this research project.

Sprinkler operation is governed primarily by the temperature of the sensing element, either in the form of a fusible link or a frangible glass bulb. However, the glass bulb sprinkler head is more commonly used in Hong Kong, which has relatively low thermal conductivity (0.16 - 0.215 W/(m.K)) [15]. In this report, the pendent type and concealed type sprinkler heads as shown in Fig. 2 have been tested. There are some differences in their operation mechanisms when they are exposed to a fire. Their thermal responsiveness are also different under a fire.

Fig. 2: The tested sprinkler heads

2. CONCEALED SPRINKLER HEAD

Concealed sprinkler systems are popular because no disturbance will be made to the appearance of the ceiling. It offers the ultimate in low profile, an esthetically pleasing appearance. According to a circular letter issued by Fire Services Department, concealed sprinkler heads are accepted in light and ordinary hazards up to (and including) OH Group III.

The glass bulb is covered by the sprinkler plate, which is soldered to the sprinkler special upper support assembly in three places. Upon the application of efficient heat, the plate falls to the floor exposing the pendent spay sprinkler as shown in Fig. 3. The glass bulb is then exposed to the hot smoke or high heat. Finally, the sprinkler operates.

Cross-section

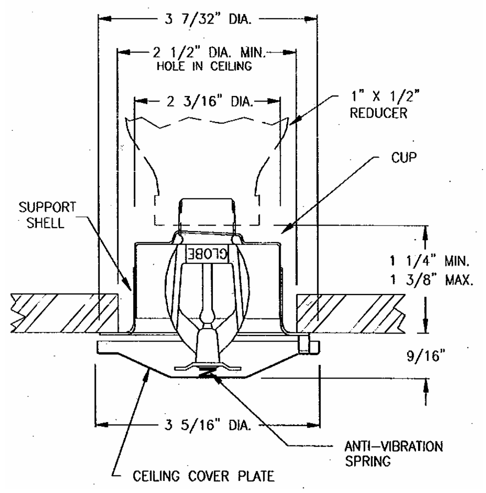


Fig. 3: The concealed sprinkler (captured from Globe Catalogue)

3. CONCEPT OF TIME CONSTANT AND RESPONSE TIME INDEX

The thermal response of a sprinkler can be described in terms of four characteristics: the nominal release temperature (θ_{nom}) and the effective operating temperature (θ_E), which are the maximum ambient temperature and the minimum activation air stream temperature of sprinklers respectively; the time constant (τ) and the response time index (RTI).

Time constant (τ) can be defined from the heat balance equation:

$$mc\frac{d\theta_e}{dt} = h_c A(\Delta\theta_g - \Delta\theta_e) \qquad (1)$$

$$\tau = \frac{mc}{h_c A} \qquad (2)$$

where m, c, h_c, A are the mass, specific heat capacity, temperature, convective heat transfer coefficient, and surface area of the sensing element respectively. The time constant (τ) depends on the convective heat transfer coefficient and the air velocity. In the plunge test, it can be simplified as:

$$\frac{d\theta_e}{dt} = \frac{\Delta\theta_g - \Delta\theta_e}{\tau}$$

$$\Rightarrow \int \frac{d(\Delta\theta_e)}{(\Delta\theta_g - \Delta\theta_e)} = \int \frac{dt}{\tau}$$

$$\Rightarrow \tau = \frac{-t}{\ln\left(1 - \frac{\Delta\theta_e}{\Delta\theta_g}\right)} \qquad (3)$$

where

$$\Delta\theta_e = \theta_{nom} - \theta_e(0)$$

with $\theta_e(0)$ being the initial temperature of the sensing element and $\Delta\theta_g$ the gas temperature above initial temperature of the sensing element. However, the time constant (τ) is not a good quantity since the convective heat transfer coefficient (h_c) depends on the hot air speed (u).

$$h_c \propto u^{1/2} \text{ and } \tau \propto u^{-1/2}$$

Thus, the response time index (RTI), which is independent on the air velocity and temperature, is defined as:

$$RTI = \tau u^{\frac{1}{2}}$$

However, it has not included the conductive heat transfer between the element, the frame and the associated pipework.

4. WIND TUNNEL FOR TESTING THERMAL SENSITIVITY

The components and functions of the hot wind tunnel used to carry out the plunge test are summarized in Table 1 and Fig. 4. The hot wind tunnel is 3 m long, 1.6 m high and 0.7 m wide. It is made from 1.2 mm mild steel sheet and its low thermal mass enables the tunnel air temperature to respond rapidly to any programmed changes.

The following were modified.

- PID controller

  The air temperature is controlled by the manual On/Off of the number of heaters previously. In order to have a higher accuracy when carrying out the experiment, a PID controller has been installed to control the air temperature in the hot wind tunnel as shown in Figs. 6 and 7. Besides the advantage of higher accuracy, it can reach the set point of the temperature faster. It can save more time and effort in controlling the stable air temperature manually. The simplified control logic diagram of hot wind tunnel after modification is shown in Fig. 5.

- Stainless steel K-type thermocouple

Thermocouples are used to measure the temperature of different parts of sprinklers and air in this research. Previously, a standard K-type thermocouple is used to measure the air temperature as the control point. However, it has been replaced by a stainless steel K-type thermocouple after modification, which is shown in Fig. 8. Thus, results of higher accuracy can be obtained.

Table 1: A summary of the location, components and their functions of the BSE hot wind tunnel

Components of heated wind tunnel	Functions
A belt driven centrifugal fan	To produce the circulation of air
A frequency inverter	To control the air speed within the tunnel
Finned air heaters (total rating = 15 kW)	To produce the hot air
PID temperature controller	To control the air temperature within the tunnel
An air straightener	To direct the air flow to the working section
An insulated water-circulating working section	To ensure that the heat transfer to the sprinkler is mainly from convection rather than radiation from the working section
A sprinkler test plate	To fit the test sprinkler

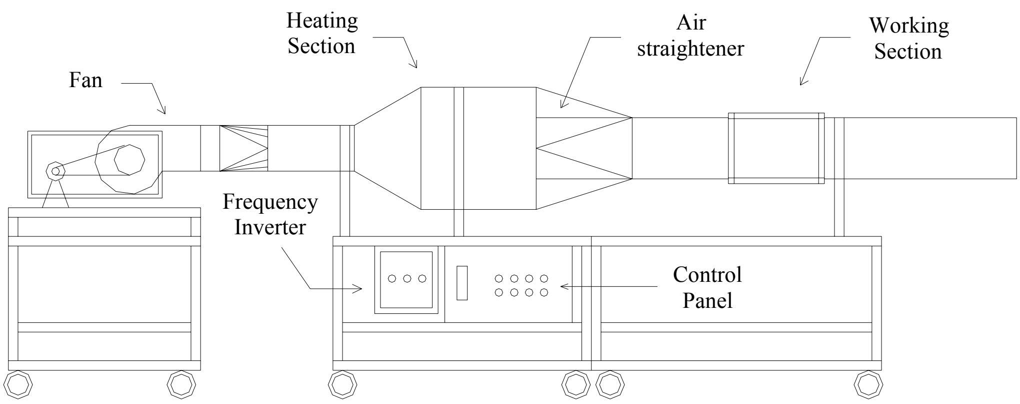


Fig. 4: The BSE hot wind tunnel

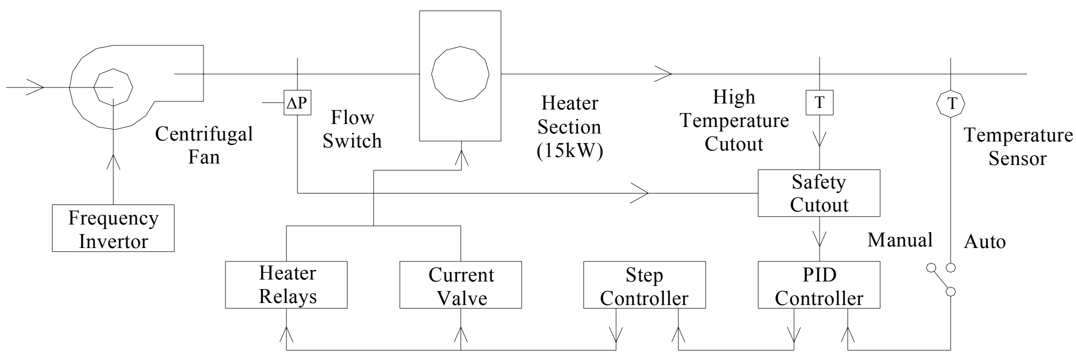


Fig. 5: The simplified control logic diagram of the tunnel after modification

Fig. 6: The PID controller

Fig. 7: The PID controller after installation

Fig. 8: Stainless steel K-type thermocouple

- Replacement of wire joints

  As the hot wind tunnel has been used for about 10 years, some of the connections of electric wires and its joint have been damaged or even melted. Therefore, the wire joints have been replaced for safety purpose.

- Calibrations of thermocouple

  The K-type thermocouple has been used for measuring the temperature of different points of sprinklers or air, the useful temperature range is within -200 ^{o}C to 1100 ^{o}C. To do the calibrations, thermocouples and thermometers are immersed into ice and boiling water. The results are shown in Table 2.

  It is shown that the percentage errors of both are very low, and it revealed that both thermocouple and thermometer are acceptable in measuring temperature. Although they are both very reliable, thermocouples will be used to measure the temperature. The temperature change can be noticed more easily by using thermocouples.

- Hot wind tunnel

  The hot wind tunnel performance test has been carried out for checking. The rates of rise of temperature under different wind speed have been measured. Since air velocity between 1 and 4 ms^{-1} has only been found in the ceiling jet during the early stages of a fire [8], higher values of air speed are not recommended because they are unrealistic in real fires. Air velocities of 2 ms^{-1}, 3 ms^{-1} and 4 ms^{-1} have been used. The results showed that the temperature increasing rate is almost linear within the first 5 to 8 minutes. When doing the performance test, it is found that the air velocity increases when the temperature increases. It is because the volume of the air expands during heating, but the mass flow rate remains unchanged, so the velocity will increase. Hence, when carrying out the experiment, the air speed should be observed and always kept constant by adjusting the frequency of the centrifugal fan.

Table 2: Calibration results of thermometer and thermocouple

	Boiled water bath	Ice bath	Percentage error (%)
Thermometer	0.1	100.2	-0.002
Thermocouple	0.1	99.9	0.001

5. METHODOLOGY

The plunge test will be mainly investigated in this research project. In this test, several assumptions have been made. First, it is assumed that there is no radiative heat transfer from the sprinkler frame and the pipework system to the sensing element. Second, the sensitive element is heated purely by forced convection. Third, all heat transferred to the sensitive element is stored in the element. In addition, there are no conduction losses to those connecting elements. Also, the heat sensing element is heated isothermally.

In this experiment, a pitot static tube will be connected to a pressure transducer and set vertically to measure the air velocity. A number of K-type thermocouples will be used to measure the air temperature, the temperature of sprinkler frames and glass bulb, which will be linked up with the data logger and computer. After that, the whole wind tunnel will be left to operate for about 15 minutes for the operation to become stable when all the setting is satisfied. The average velocity and the average temperature will be measured by taking a number of points, which can be referred to Fig. 9. Finally, the tested sprinkler with the thermocouple will be immersed into the wind tunnel immediately. A data logger and a computer have been used to take the data per second. A stop switch will be used to record the activation time. Then, by using equations (3) and (4), the time constant and the RTI of the tested sprinkler can be found.

6. EXPERIMENTAL RESULTS

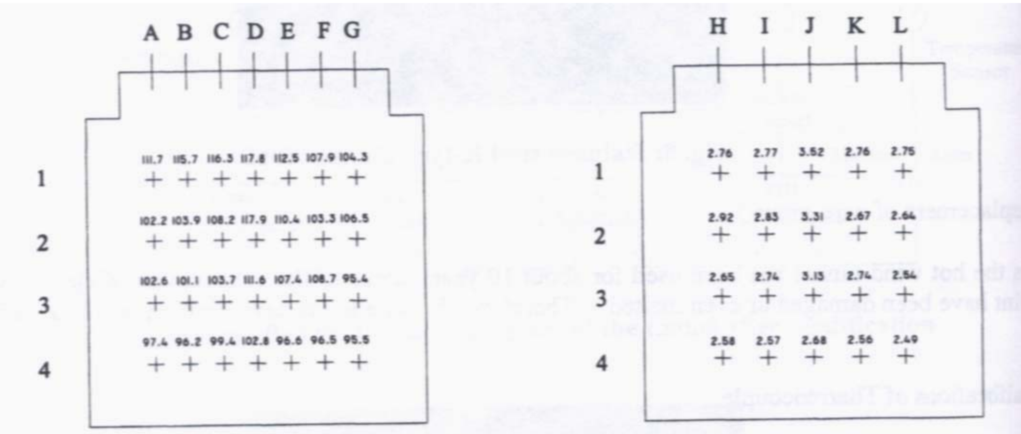
Experiments were carried out for two types of sprinkler: a pendant type and a concealed type, 68 ^{o}C, glass bulb with normal response. The activation time of both of the sprinkler heads are shown in Tables 3 and 4. Each of the result is the average of three sets of trial experiment. In addition, typical results on the temperature-time curve are shown in Fig. 10.

Table 3: Activation time (s) of the pendant type sprinkler in plunge test

Air velocity (ms^{-1})	Gas temperature (^{o}C)			
	100	110	120	130
2	34	---	22	22
3	38	27	23	---
4	38	33	25	---

Table 4: Activation time (s) of the concealed type sprinkler in plunge test

Air velocity (ms^{-1})	Gas temperature (^{o}C)		
	100	110	150
2	81	63	93
3	---	75	---
4	---	96	---



Mean Temperature = 105.5^{o}C *Mean Velocity = 2.78 ms^{-1}*

Temperature distribution Velocity distribution

Fig. 9: Temperature and velocity distribution in the working section of the hot wind tunnel

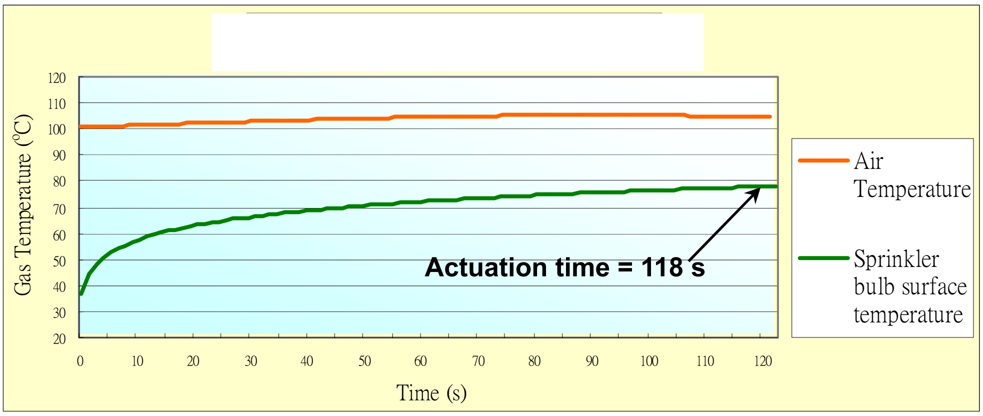


Fig. 10: Typical results of concealed type sprinkler on the temperature-time curve (110 °C, 3 ms^{-1})

7. ANALYSIS

From Tables 3 and 4, it is obvious that the higher the velocity, the slower the activation time. On the contrary, the higher the air temperature, the faster the activation time. Both standard pendent and concealed type sprinkler heads were installed under the suspended ceiling. Therefore, the convection is based on the ceiling jet effect. It can also be found that the activation time of pendent type sprinklers are generally faster than that of the concealed type. It is because the sensing element of the concealed type sprinkler is covered by a metal cap and metal plate. Hot air cannot directly reach the sensing element of the concealed sprinkler after immersing it into the hot wind tunnel. Thus, the sensing element of this sprinkler will not reach the activation temperature before the drop of the sprinkler plate. Therefore, it has a time lag in the activation time. By using equations (3) and (5) as well as Table 3, the time constant and the RTI can be found as shown in Table 5.

Values of the RTI as a function of the set temperature for the tested standard pendent type sprinkler head at each of the three air velocities: 2 ms^{-1}, 3 ms^{-1} and 4 ms^{-1} are presented in Fig. 11. It is seen that the RTI varies with the air temperature and air velocity, which is not too consistent with the theory [1]. However, it is still quite reasonable. The main reason of this error may be due to the measurement of activation time is not so accurate. In addition, the inconsistent initial temperature of the sensing element may also be a reason.

The time constant and the RTI of concealed sprinkler heads in the plunge test cannot be calculated by equation (3). It is because there exists a time lag in the activation of the concealed type sprinkler. The time delay of the drop of sprinkler plate will affect the activation time of the concealed type sprinkler. Thus, it cannot simply use equation (3) for calculating the time constant and the RTI of concealed sprinkler heads in the plunge test.

Table 5: A summary of time constant and RTI of pendent type sprinklers in plunge test

Air velocity (ms^{-1})	Gas temperature (°C)							
	100		110		120		130	
	τ	RTI	τ	RTI	τ	RTI	τ	RTI
2	47	66	---	---	44	62	50	71
3	52	91	46	79	46	79	---	---
4	52	105	56	111	50	99	---	---

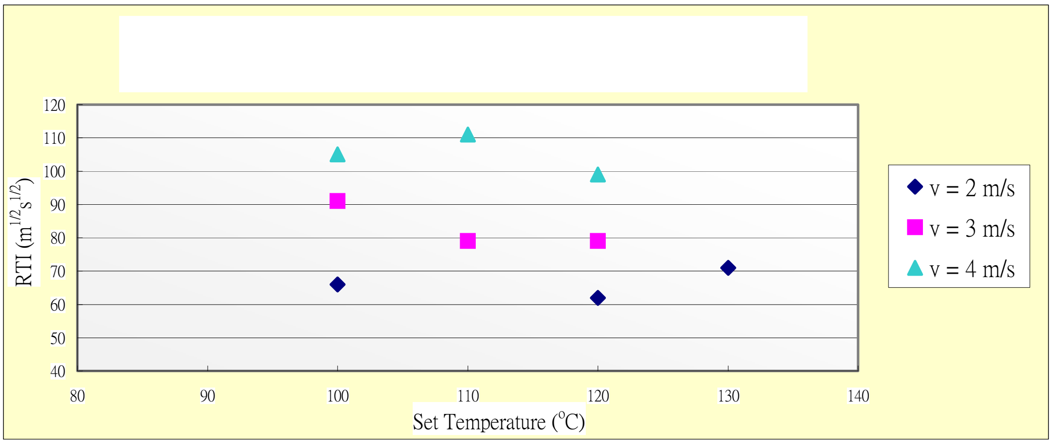


Fig. 11: RTI of pendent type sprinkler head against set temperature

8. CONCLUSION

Thermal response of sprinkler heads is introduced and expressed in terms of θ_{nom}, θ_E, time constant and their associated RTI. The standard pendent type and concealed type sprinkler heads have been tested at this stage. A heated wind tunnel is developed to simulate different fire conditions in order to measure those thermal properties of the sprinkler heads. Measurements on the thermal response of sprinkler head followed the plunge test. The time constants and RTI are obtained accordingly. From the result of the plunge test of standard sprinkler head, the RTI can be obtained, the value is quite reasonable and it revealed that the standard sprinkler is reliable and it can fulfil the function of automatic sprinkler system. It means that it can detect the fire and be actuated to suppress the fire at the early stage. However, the RTI of the concealed sprinkler head cannot be successfully found at this stage. This is because the time constant cannot be simply found from equation (3) for this type of sprinkler. Besides, the time constant of the glass bulb must also include the time constant of the sprinkler plate of the concealed type sprinkler. Then, the RTI of the concealed type sprinkler can be found. Concealed sprinkler heads are usually used in premises that aesthetic appearance is most concerned. However, its poor thermal response will pose danger in case of fire, because it cannot detect and be actuated to control the fire at the early stage.

9. FUTURE PLANNING

At this stage, the standard pendent sprinkler head has been discussed in detail. Some preliminary testing on the concealed type sprinkler has been carried out. However, equation (3) of the plunge test cannot be applied to the concealed type sprinkler. Thus, a new equation should be defined to find the time constant of the concealed type sprinkler in the next stage. The concealed type sprinkler head with the brass sprinkler plate, which was used in the first stage, will be further studied. In addition, different types of concealed sprinkler heads such as the fast response type concealed sprinkler head and the concealed sprinkler head with white-painted sprinkler plate will be investigated. The results will then be compared among these three types of concealed sprinkler. The data of those concealed type sprinklers will also be compared with the standard sprinkler head. Thus, the time constant and the RTI of the standard sprinkler head and three types of concealed sprinkler head can be compared.

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Q & A

Q1: Since the measurement error of RTI mainly came from velocity measurement, I suggest you can fix the air velocity and investigate the effect of gas temperature on RTI measurement.

Tsang: Yes, I have conducted several case studies and will calibrate the velocity measurement.

Q2: Does one kind of sprinkler head have only one RTI value?

Tsang: Yes, but there are some measurement errors in our experiments and various values appeared.