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Experimental studies on automatic sprinkler system

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In the present paper, an experimental method is presented for determining the response time of thermally activated sprinklers with three rates of heat, released by fire. The fraction of heat retained inside the enclosure in the form of a hot gas layer, which is available to sprinkler to raise its temperature, has been varied by changing the height of the door. The results of experiments reveal that the minimum time of sprinkler operation occurs only when the height of door is minimum. A comparison of experimental and theoretical times of sprinkler operation shows that the present method of calculating time constant, τ, is not suitable to simulate the behaviour of an automatic sprinkler in a real fire.

Early detection and control of a fire is the primary requirement of fire safety engineering. A fire releases heat which is partly fed back to the source to continue burning and the balance goes to heat other materials in the room. When combustible materials, thus heated, attain their self-ignition temperature, they ignite signalling occurrence of flashover or fully developed fire. Escape and rescue are possible only in the pre-flashover stage. The pre-flashover period is of special significance to fire protection systems such as sprinklers, which must necessarily operate early in this period to justify their provision. The absence of sprinklers or their failure may allow the fire to grow to the fully developed stage endangering the building structure to collapse.

An automatic sprinkler system is the most effective tool of fire safety system inventory in a building. They not only perform a role of fire detection, but can simultaneously and automatically carry out the equally important job of fire extinction and limitation. The sprinkler system consists of an array of automatic sprinklers, pipe layout, water gong, alarm valve and an automatic pump. Automatic sprinklers act as closures to openings in a pipe lay out system, charged with water under pressure, and are designed to open when their temperature exceeds a predetermined level. The operation of a sprinkler is controlled by the rate at which heat is transferred to the heat responsive element of the sprinker. The heat responsive element, on reaching to its operating temperature, is released, allowing water to flow through sprinkler orifice. The jet of water, on striking the deflector plate, forms a spray. The spray of water controls the spread of a fire. Fig. 1 shows constructional details of an automatic sprinkler head. The critical operational part of the sprinkler is its heat responsive element which keeps the nozzle blocked in the non-fire condition and which is removed automatically by the action of heat in case of fire occurrence.

The heat responsive element may be a glass bulb or a fusible metal link. Glass bulb sprinklers are preferred over fusible link ones due to their strength, quick response and low thermal expansion. The glass bulb, made of transparent quartz glass, is filled with highly expansible liquid and an air bubble is entrapped inside it. The increase in temperature causes the liquid to expand. The liquid expansion, initially compensated by the compression of air bubble, results in the increase in pressure inside the bulb and ultimately in the bursting of the bulb.

A detailed description of the automatic sprinkler system and the parameters useful in its design has been presented earlier[1-3]. In the present paper, results of a study carried out to determine the effect of fire heat release rate and the depth of hot gases on sprinker response have been presented.

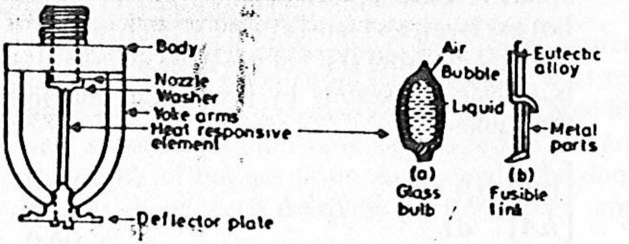


Fig. 1 — Automatic sprinkler head

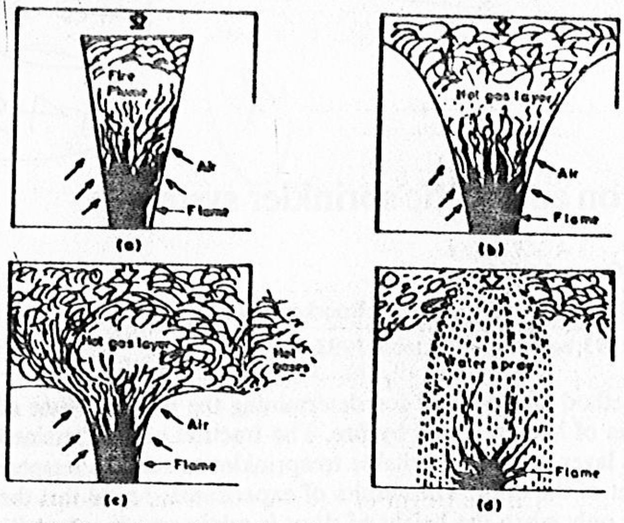


Fig. 2—Schematic of a fire phenomena in a compartment

Theoretical Model

On burning, a combustible releases hot gases. The column of hot gases moves upwards due to its temperature generated buoyancy. The 'fire plume', as this column of hot gases is called, acts to lift a large volume of cold air from the lower level to the higher elevations setting up the flow pattern. When the pume reaches the ceiling, it spreads out and forms a hot gas layer which descends with time. The temperature of the hot gas layer increases by absorbing heat, released by a fire, through convective and radiative modes. As the heated gas layer reaches an opening, such as a window/door provided in the wall, hot gases tend to flow out of the opening. The maximum thickness of hot layer depends upon the size of the opening. Fig. 2 shows a schematic representation of fire in a compartment.

A sprinkler has two functions to perform. First, it should detect a fire, and then provide adequate quantity of water to prevent the spread of fire. Each function is performed separately and one is related to the other in so far as early detection makes extinction easy. Sprinkler, being a "constant temperature" device, activates only when its heat-sensitive element achieves a specific operating temperature. The operation of sprinkler mainly depends upon operating temperature of sprinkler, thermal and physical properties of heat responsive element, temperature and depth of the hot gas layer, and rate of heat out put from fire.

The heat from the hot gas layer to the sprinkler is transferred mainly by convection, and follows the equation,

$$\left[\frac{mc}{hA}\right]\frac{\mathrm{d}(\Delta T_s)}{\mathrm{d}t}=(\Delta T_g-\Delta T_s) \qquad \ldots (1)$$

Where ΔT_s and ΔT_g are the excess temperatures of the heat responsive element and the hot gas layer above the initial ambient temperature respectively. m is the mass, c is the specific heat and A is the area of heat responsive element, h is the average convective heat transfer coefficient. The quantity (mc/hA) has the units of time and is known as time constant.

Thus, $mc/hA=\tau$

$$\ldots (2)$$

The time constant, τ, of the heat responsive element is a measure of the sensitivity of the sprinkler and is not really a constant because the value of heat transfer coefficient, h, depends upon the velocity and temperature of gas flow. The greater is the gas velocity, larger is the heat transfer coefficient and smaller is the time constant. Eq. (1) can now be rewritten as follows:

$$\frac{\mathrm{d}(\Delta T_s)}{\mathrm{d}t}=\tau^{-1}(\Delta T_g-\Delta T_s) \qquad \ldots (3)$$

Eq. (3) is an ordinary differential equation (ODE) which is integrated to obtain,

$$t=-\tau\ln(1-\Delta T_s/\Delta T_g) \qquad \ldots (4)$$

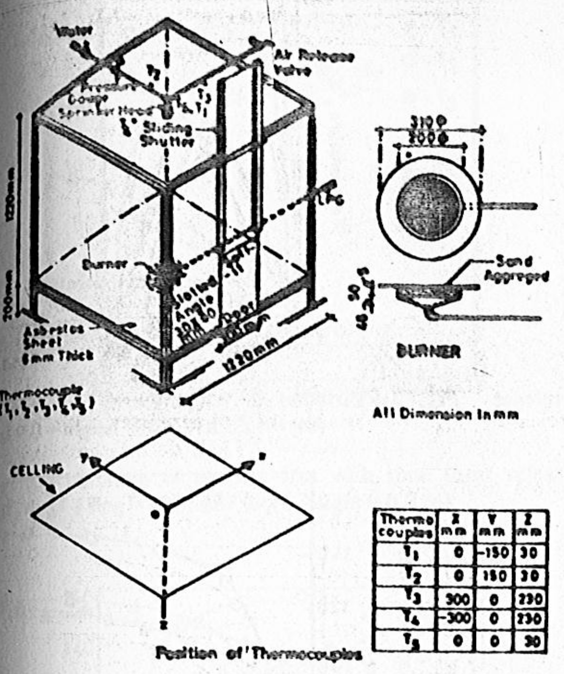
where t is the time of sprinkler operation.

Eq. (4) can be used to determine the time of sprinkler operation provided the value of time constant, τ, and the hot layer temperature, ΔT_g, are known.

Time constant—In order to determine the time of sprinkler operation, one should know the value of time constant, τ. The time constant, as the name suggests, is not really a constant, but it varies with the velocity and temperature of gases flowing across the sprinkler. Ideally, the time constant represents the minimum time of sprinkler operation.

Nash and Young[4,5] have suggested that the value of τ should lie between 1.5 to 2.5 min. They have also suggested a closed circuit wind tunnel apparatus to determine the value of τ. Bureau of Indian Standards[6] has adopted the same apparatus and method of determination of τ. The closed circuit wind tunnel, provided at CBRI, has been used to determine the value of τ of a particular brand of sprinkler used in the present studies. It is found equal to 132 s.

The conditions proposed in the standard[6] are rarely met. For example, IS: 9972-1981 suggests that the air shall be circulated at the rate of 80 cm/s and is heated at the rate of 2-30°C/min. In a closed environment, such as an enclosure,



Thermo couples	X mm	Y mm	Z mm
T_1	0	-150	30
T_2	0	150	30
T_3	300	0	230
T_4	-300	0	230
T_5	0	0	30

Fig. 3—Experimental set-up

the movement of air is restricted by the boundaries resulting in the formation of a hot gas layer. The variation in temperature of the hot layer is not linear. Thus the rate of heat transfer and hence the heat transfer coefficient, *h*, in case of a closed circuit wind tunnel test is ought to be higher than in a real situation. In an enclosure the heat is transferred to the sprinkler by the hot layer, which is almost stagnant. The degree of stagnation, however, depends upon the depth of the hot layer. It is, therefore, the purpose of the present study to highlight the effect of the depth of hot layer and also the effect of heat release rate on the performance of a sprinkler.

Experimental Procedure

An experimental set-up, as shown in Fig. 3, has been fabricated to study the time of sprinkler operation under different rates of heat release and depth of the hot gas layer. The depth of hot layer has been regulated by changing the soffit height of the door. Although the depth of the hot layer is defined as the distance between the ceiling of the enclosure and the neutral plane, which lies somewhere in the middle of the door (Fig. 2), in the present case the distance of the soffit from the ceiling has been taken as to represent the depth of hot layer. This has been done to avoid the calculations of the neutral plane. Moreover, a practitioner is concerned only with the geomertrical dimensions of the enclosure. It is, therefore, be appropriate, at this stage, to clear that the effect of the depth of hot layer, in the present study, is manifested by changing the distance of soffit from the ceiling, referred to as depth of soffit.

The enclosure, measuring 1.22 × 1.22 m is a cubical structure made of asbestos sheet supported on an angle iron frame. The thickness of the asbestos sheet is 4 mm. A door, width 300 mm, has been provided on one face of the enclosure. The height of the door is varied by changing the height of the soffit with the help of a sliding shutter. This has been done to study the effect of the depth of hot gas layer on the response of the sprinkler.

The fire has been created by burning of liquified petroleum gas (LPG) in a specially designed diffusion flame burner. The burner has been placed at the centre of the floor of the enclosure. It is then connected to a LPG bottle through a dry gas flow meter. A number of control values are provided to regulate the supply of the fuel gas, i.e., LPG. The burner, to produce a diffusion flame, is a cylindrical vessel joined to a conical vessel at its lower side. At the junction of the two vessels a grate has been fixed to support a bed of bloated clay aggregates, size 10 to 15 mm diameter, to distribute the gas uniformly.

A number of thermocouples have been fixed at different locations, as shown in the figure, to monitor temperatures. The thermocouples, that have been used in the present study, are Chromel-Alumel type made of 0.5 mm diameter wire. The cold junctions of these thermocouples are connected to a data logger for printing temperatures at a number of time intervals.

An automatic sprinkler, glass bulb type, is fixed at the centre of the ceiling. Connection has been provided to pressurise the sprinkler with water, to simulate the real fire scenario. For the purpose of measuring the change in the temperature of the glass bulb, a thermocouple is fixed on it with the help of an adhesive (m-seal).

With the arrangement, described above, a set of nine experiments have been conducted with three sizes of heat release rate and three door openings. The results are presented in Figs 4-12.

Results and Discussion

A total of nine experiments have been carried out on a 68°C rated sprinkler with three heat release rates, viz., 8.0, 12.5 and 16.36 kW. Three levels of soffit location have been selected to vary the depth of hot gas layer. Accordingly, the door heights have been selected as 0.90, 0.75 and 0.60 m.

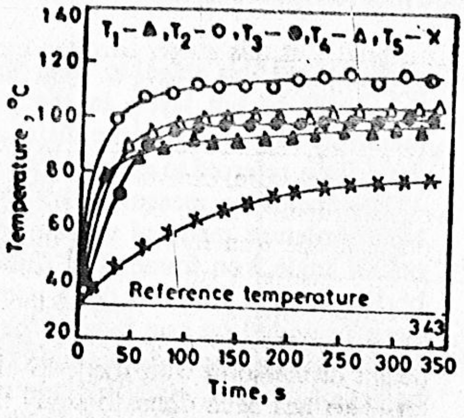


Fig. 4—Variation of temperatures with time (heat release rate = 8.0 kW, door height = 0.9 m)

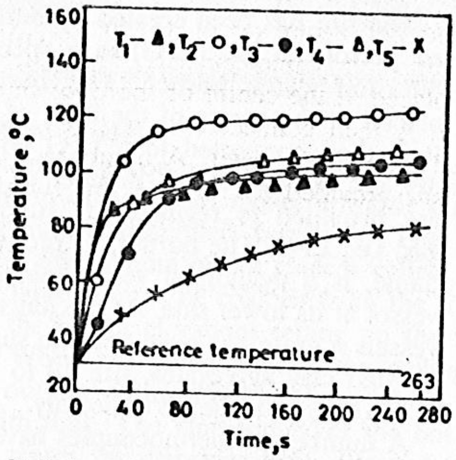


Fig. 5—Variation of temperatures with time (heat release rate = 8.0 kW, door height = 0.75 m)

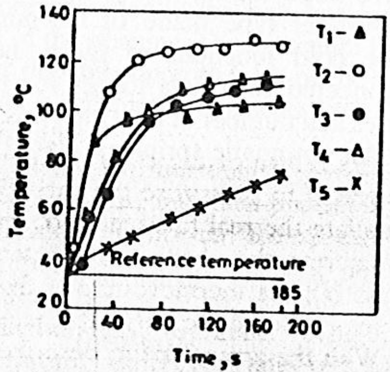


Fig. 6—Variation of temperatures with time (heat release rate = 8.0 kW, door height = 0.6 m)

Temperatures of the hot gas layer have been monitored at four locations around the sprinkler. Two thermocouples have been placed 30 mm below the ceiling and 150 mm away from the sprinkler, and another two have been placed 230 mm below the ceiling and 300 mm away from the sprinkler. This has been done to check the uniformity of temperature of hot gas layer[7].

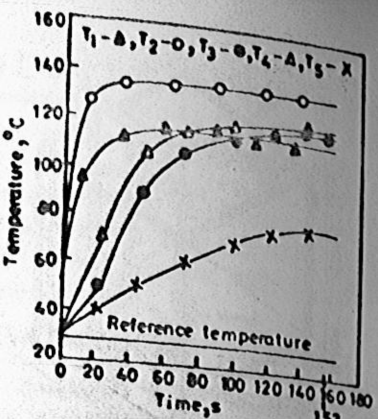


Fig. 7—Variation of temperatures with time (heat relea rate = 12.5 kW, door height = 0.9 m)

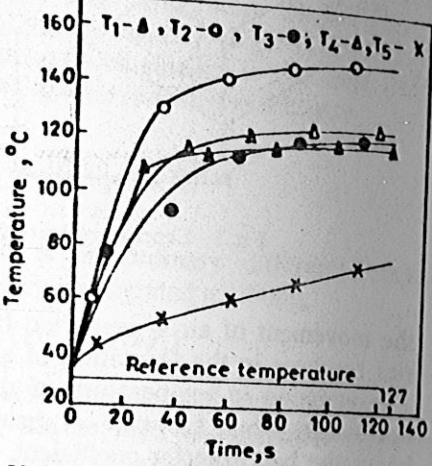


Fig. 8—Variation of temperatures with time (heat releas rate = 12.5 kW, door height = 0.75 m)

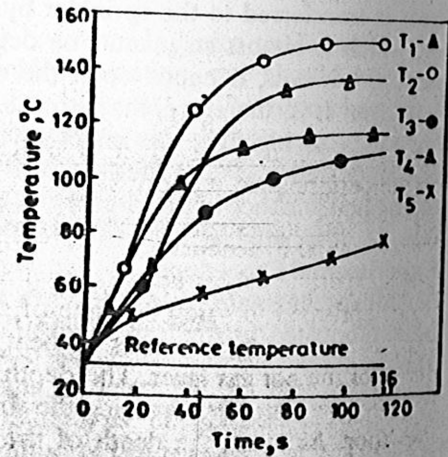


Fig. 9—Variation of temperatures with time (heat release rate = 12.5 kW, door height = 0.6 m)

The sprinkler has been fixed in such a way that the middle point at the glass bulb lies 30 mm below the ceiling. A thermocouple is fixed at this point to monitor the rise in temperature of the glass bulb. The glass bulb thermocouple has been

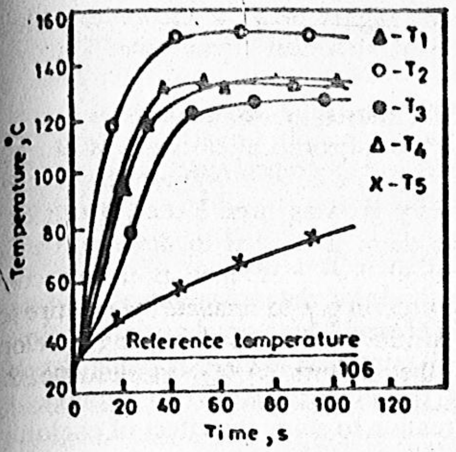


Fig. 10—Variation of temperatures with time (heat release rate = 16.36 kW, door height = 0.9 m)

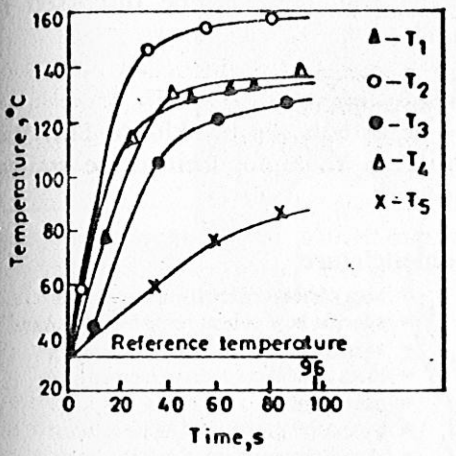


Fig. 11—Variation of temperatures with time (heat release rate = 16.36 kW, door height = 0.75 m)

shielded with the help of an insulating material to prevent the exposure of hot gas layer temperature to it. Figs 4-12 show the variation of temperature with time with three heat release rates and three door heights.

Figs 4-6 show the temperature vs time history, with 8.0 kW fire source, for three heights of a door of fixed width, respectively. It is evident from these figures that higher temperatures are obtained with lower door heights. This is perhaps, due to larger amount of gas retained in the upper layer. The amount of gas leaving a compartment is proportional to the 3/2 power of the door height[8], thus, any reduction in the door height results in the lower door-jet flow out of the compartment. Hence, the amount of heat lost with the gases leaving the enclosure is reduced, resulting in an increase in the enclosure temperature.

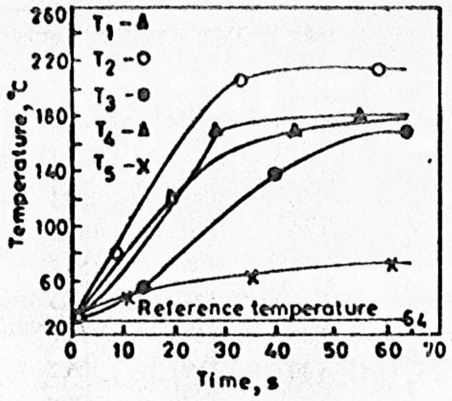


Fig. 12—Variation of temperatures with time (heat release rate = 16.36 kW, door height = 0.6 m)

The temperatures recorded at different ceiling locations are nearly identical, except for one location, which is on the opposite side of door face (T_2). This is due to the leaning of flame due to the entrainment of air through the lower portion of the door. The effect of flame leaning becomes predominant because the size of experimental room is small. Temperatures at all the points increase linearly upto 60 s, and thereafter become nearly constant. The trend suggests that, for most of the time of exposure to the sprinkler, the temperature of the hot gas layer is constant and uniform, as it the sprinkler has been submerged in a constant temperature environment.

Figs 7-9 and Figs 10-12 show the variation of hot gas layer temperature with time, with a 12.5 and 16.36 kW fire source, respectively, for three sizes of door. The nature of time-temperature curves, in the present cases, is similar to those shown in Figs 4-6, drawn with a fire source of 8.0 kW strength. The only difference between the three cases, is that higher temperatures are obtained with high strength fire source, for a particular door height.

The temperatures of the sprinkler's glass bulb have also been recorded simultaneously in all the experiments and have been shown on the respective figures. It could be noticed from these figures that the temperature of the glass bulb increases linearly with time. The sprinkler operates as soon as the temperature of the glass bulb equals to its operating temperature. The time of sprinkler operation is minimum with a fire source of 16.36 kW and a door of height 0.6 m. It is maximum with 8.0 kW fire source and a door of height 0.9 m. The times of sprinkler operation with the three fire sources and three door heights are shown in the Table 1. Table 1 also shows the

Table 1—Time of sprinkler operation

Test No.	Heat release rate, kW	Door height, m	Time of sprinkler operation, s	
			Experimental	Theoretical
1	08.00	0.90	343.1	139.8
2	08.00	0.75	263.1	133.9
3	08.00	0.60	185.0	096.2
4	12.50	0.90	153.2	102.7
5	12.50	0.75	127.3	088.9
6	12.50	0.60	116.1	084.9
7	16.36	0.90	106.2	079.4
8	16.36	0.75	096.0	091.5
9	16.36	0.60	064.0	070.8

time of sprinkler operation as calculated by using Eq. (4). In Eq. (4) the value of the time constant, τ, has been supplied by experiments carried out in a closed circuit wind tunnel as dictated by IS: 9972-1981. In all the cases, except in case of highest heat release rate, the theoretical value of the time of sprinkler operation is less than the corresponding experimental value. It is simply because we have taken a constant value of the time constant, τ, which is, infact, not a constant. However, it could be concluded that the value of τ, as determined in accordance with IS: 9972 is suitable for situation where the rate of heat release is rapid.

Conclusions

A set of nine experiments have been carried out in a cubical enclosure of each side equal to 1.22 m. Three rates of heat release 8.0, 12.5 and 16.36 kW and doors of height 0.9, 0.75 and 0.6 m have been taken to study the effect of heat release rate and the depth of hot gas layer on the operating performance of the automatic sprinkler. The times of sprinkler operation have been calculated both experimentally and theoretically and are presented in Table 1. It could be concluded from Table 1 that minimum time of sprinkler's operation is obtained with lower door heights for the same amount of heat release rate. Also, the experimental value of operating time is significantly higher than the theoretical value except in case of high heat release rate. Thus, the value of time constant, τ, as determined in a closed circuit wind tunnel in accordance with IS: 9972 and used for theoretical calculations of sprinklers operating time is, possibly, applicable only in case of rapidly growing fires. Hence, it can be concluded that there is a need to develop a more realistic method, for determination of time constant, than the present one to simulate the real fire scenarios.

A numerical method is being developed by one of the authors (AKG) to simulate the real fire situation to study the effect of enclosure, and door size on the sprinkler's performance. The mathematical model, under development, will also be helpful in the determination of an appropriate value of the time constant, τ. The results of the model will, however, be discussed in a future publication.

Acknowledgement

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Nomenclature

A = area of heat responsive element, m^2
c = specific heat of heat responsive element, kJ/kgK
h = average heat transfer coefficient, kW/m^2K
m = mass of heat responsive element, kg
t = time, s
ΔT_s = excess temperature of heat responsive element, K
ΔT_g = excess temperature of hot gas layer, K
τ = time constant, s

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