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Measuring modified glass bulb sprinkler thermal response in plunge and compartment fire experiments

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ABSTRACT

Automatic fire sprinklers use a heat sensitive element such as a glass bulb or fusible link to respond to the heat from a fire. The response of commercial fire sprinkler glass bulbs has been extensively characterised in convection-dominated dry gas flows but in real fires there may be more factors that influence the heat transfer to the bulbs such as radiation from the fire or cooling from adjacent sprinkler sprays. The time of activation is the only indication of the thermal response of typical commercial fire sprinklers using glass bulbs to a fire, but direct temperature measurement using a modified proxy may provide a better understanding of how sprinklers respond in a complex environment. Modified glass bulbs have been created that allow a thermocouple to be inserted in the bulb for direct temperature measurement. In this paper, the thermal response of sprinklers with these modified bulbs has been observed in hot-air wind tunnel plunge experiments and full scale room fire experiments. At the time of activation the measured temperature of the modified sprinklers was found to be higher than the nominal activation temperature specification for the unmodified sprinklers. For the compartment fires, a thermal response model generally predicted longer sprinkler activation times based on ceiling jet temperature and velocity measurements than was observed experimentally.

1. Introduction

Automatic fire sprinklers operate as heat detectors in a fire environment but they only provide one data point in their response to heating: the time of activation, when they have been heated to their activation temperature and either a glass bulb element breaks or a solder link melts. The thermal response of automatic fire sprinklers is typically evaluated by plunging them into an air flow of known temperature and velocity, but there may be other factors impacting their response in actual fires such as direct radiation from the fire [1] or interactions with water from other activated sprinklers [2]. A nominal value for activation temperature is available from the manufacturer, but there has been shown to be uncertainty in the actual activation temperature of glass bulb sprinklers when heated slowly in a stirred liquid bath [3]. In order to simulate the temperature response of a sprinkler during the time leading up to activation, a sprinkler proxy using a typical commercial sprinkler frame with a modified glass bulb that allows a thermocouple to be inserted has been developed. This paper describes the characterisation of the thermal response of the modified thermocouple-equipped sprinklers. The response was evaluated experimentally using both wind tunnel plunge experiments [4] and fires in an ISO 9705 compartment. The results are compared to the thermal detector response model by Heskestad and Bill [5] and activation times for unmodified sprinklers.

2. Theory

The thermal response of automatic sprinklers in a hot environment can be estimated by using the law of conservation of energy:

$$\Delta E_{sys} = E_{in} - E_{out} \tag{1}$$

such that the change of energy of the system (in this case the sprinkler activation element) is equal to the energy leaving the system subtracted from the energy entering the system. Assuming that the energy change in the element is entirely sensible and the properties are uniform, Eq. (1) can be re-written as follows:

$$m_d c_{p,d} \Delta T_d = (\dot{Q}_{in} - \dot{Q}_{out}) \Delta t \tag{2}$$

This equation assumes a lumped system; ie., the detector temperature is uniform throughout. From this equation, Heskestad and Bill [5] developed a two parameter model for temperature response which accounts for convective heat transfer from a hot gas stream to the

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Nomenclature

c_p	heat capacity (kJ/kg/K)
C	conduction factor ($(m/s)^{1/2}$)
h	heat transfer coefficient ($W/m^2/K$)
E	energy (kJ)
m	mass (kg)
$\dot{Q}$	heat transfer (kW)
RTI	response time index ($(m \cdot s)^{1/2}$)
T	temperature (K)
t	time (s)
u	gas velocity (m/s)

subscripts

act	activation
amb	ambient
d	detector
gas	gas stream properties
pred	predicted
sys	system

sprinkler and conductive losses through the sprinkler fixture. Heskestad and Bill's model is as follows:

$$\frac{d\Delta T_d}{dt} = \frac{\sqrt{u}}{RTI}\left[\Delta T_{gas} - \left(1 + \frac{C}{\sqrt{u}}\right)\Delta T_d\right] \tag{3}$$

where ΔT_d is $T_d - T_{amb}$ and ΔT_{gas} is $T_{gas} - T_{amb}$, respectively. The RTI accounts for the convective heat transfer from the gas stream to the element and the C-factor accounts for conduction losses to the sprinkler pipe, water, and other components of the assembly. For a situation in which a detector is plunged into a hot gas stream where the gas velocity and temperature are constant, this equation can be rearranged as follows:

$$\Delta T_d = \frac{\Delta T_{gas}}{1 + \frac{C}{\sqrt{u}}}\left[1 - e^{\frac{-t\sqrt{u}\left(1+\frac{C}{\sqrt{u}}\right)}{RTI}}\right] \tag{4}$$

to obtain the sprinkler element temperature as a function of time. This equation can be rearranged to estimate the RTI from an plunge experiment where the time of activation, nominal activation temperature, and gas stream temperature and velocity are known:

$$RTI = \frac{-t_{act}\sqrt{u}}{\left(1 + \frac{C}{\sqrt{u}}\right)^{-1} \cdot ln\left[1 - \frac{\Delta T_{d,act}}{\Delta T_{gas}\left(1 + \frac{C}{\sqrt{u}}\right)^{-1}}\right]} \tag{5}$$

3. Literature review

In previous work Ruffino [6] attempted to represent the thermal response of a sprinkler head using brass or aluminium cylinders with thermocouples inserted. The cylinders were not mounted in a sprinkler frame so the effects of the frame on the response were not investigated. The thermal response of the simulated sprinklers was not directly compared to activation times for commercially available sprinklers. Similarly, the Society of Fire Protection Engineers (SFPE) evaluation of the DETACT-QS fire model [7] for estimating sprinkler activation times describes the use of brass disc thermocouples to approximate thermal detector elements in a ceiling jet. However as with Ruffino, the response of the brass disc thermocouples was not compared to the response of actual sprinklers.

Ingason [8] measured the temperature of a glass bulb when it was cooled after removal from a furnace and also placed in a free state and heated in a plunge experiment. The purpose of these experiments were to evaluate the assumptions of pure heat conduction in the liquid and liquid thermal properties. The bulb was not mounted in a sprinkler frame or exposed to actual fire conditions. The experimentally measured temperatures were reported in close agreement with calculated temperatures, validating the assumptions. Ingason found higher RTI values with a preconditioning temperature close to the activation temperature, and hypothesised that this effect could be a result of temperature gradients in the glass bulb during heating.

The primary source of heat transfer to sprinklers in fires is usually considered to be convective heat transfer from the ceiling jet flow and this mechanism can be affected by the orientation of the yoke arms to the flow. A numerical simulation on heat transfer to sprinkler glass bulbs conducted by Ingason and Persson [9] estimated that heat transfer to a sprinkler bulb was decreased by a factor of two when changing the sprinkler arm orientation to the flow from perpendicular to parallel. Tsui [10,11] carried out plunge experiments using commercially available unmodified sprinklers with similar frame and bulb geometry to the modified sprinklers used in this study. He calculated the RTI based on the activation time and nominal reported activation temperature. Summary statistics for his results are shown in Table 1. Tsui found that RTI in the parallel orientation was greater than the perpendicular orientation by a factor of approximately 1.7, which is comparable to Ingason and Persson's observations that the convective heat transfer was reduced by a factor of two.

4. Apparatus setup

4.1. Sprinkler modification

Standard response 5 mm diameter bulbs were chosen for comparison in this study because they were easier to manipulate and to construct representative modified bulbs when compared to fast response 3 mm diameter bulbs. The modified bulbs were used in commercially available pendent, 1/2″ national pipe thread (NPT) spray sprinkler frames with a nominal K-factor of $8\,\frac{l/min}{\sqrt{kPa}}$. Fig. Fig. 1(a) shows the modified sprinkler bulb, along with an unmodified commercially available sprinkler bulb and the remaining components of a commercial sprinkler head. In a frangible bulb sprinkler such as the one pictured, the glass bulb is held against a brass plug and belleville spring by a set screw. The plug and spring form the seal to retain the water until activation. The modified sprinkler bulbs had one open end which was placed towards the plug to allow for the insertion of a thermocouple. The brass sprinkler seal was drilled to allow the thermocouple to pass through. The modified sprinkler bulbs could not break like an unmodified commercial sprinkler bulb because they were not sealed.

Type K AWG 24 (nominally 0.5 mm diameter wire) thermocouples were used in the modified sprinklers. The thermocouple was extended approximately half way into the glass bulb as shown in Fig. 1(b). The

Table 1
Tsui's [11] RTI summary statistics for unmodified sprinklers similar to the modified sprinklers used in this research.

Orientation	**RTI ($(m\ s)^{1/2}$)**	
	Mean	**St. Dev.**
Perpendicular	97	2.7
Parallel	162	9.8