Probabilistic assessment of off-the-shelf fire sprinkler Head activation time through laboratory experiments

M A S Tajudin¹, M Z M Tohir*¹ and M S M Said¹

¹Safety Engineering Interest Group (SEIG), Department of Chemical and Environmental Engineering, Faculty of Engineering, Universiti Putra Malaysia, Serdang, Selangor, Malaysia.

*Corresponding author : zahirasri@upm.edu.my

Abstract. The activation time of a sprinkler has a great impact on the fire growth inside a compartment. The longer time it takes for a sprinkler to activate, the higher the risk of fire to start to spread inside the compartment. In this study, the activation times of off-the-shelf half inch 68°C fire rated pendant sprinklers were assessed through experiments in laboratory settings and eventually best-fit probabilistic curve for the Response Time Index (RTI) were generated from the experimental results. The experiments were conducted in two sets; one set without smoke effect and the other set with smoke effect to determine the activation time and temperature of the sprinkler heads. The data recorded were then used to calculate the RTI and Palisade @RISK statistical analysis software was used to analyze the best-fit probabilistic curve for the RTIs. It was observed that, average time required for sprinkler to activate was 60 seconds. It was also found that the calculated RTI were within the range of the international sprinkler design guideline. However, the calculated RTI were found to be inconsistent with specified RTI from manufacturer. Based on @RISK software, the two best-fit RTI probabilistic curve for the two experiments were Gamma and BetaGeneral distribution curve. The probabilistic curves obtained from this work can be used as input for fire in enclosure simulations.

1.0 Introduction

Fire protection system is an integral component which needs to be considered in designing a building. Without fire protection system installed, the life safety of occupants inside the building are at high risk in the event of fire. Thus, having proper active and passive fire protection systems inside buildings are in principle will be able to provide a cost-savvy of risk mitigation to safety of the building occupants and also to property destruction. One of the most common active fire protection systems used inside buildings is fire sprinkler system. Fire sprinkler system is a network of pipes installed through ceiling of a floor in a building holding water under pressure. The fire sprinkler head operates by detecting heat through head sensitive element, commonly glass bulb or fusible link. Heat responsive liquid commonly in the form of glycerin solution inside frangible glass bulb of fire sprinkler head is a heat sensitive element. As the sprinkler head detects heat, the temperature of liquid in the bulb will rise and expand. As the liquid temperature reach its rated temperature, the glass bulb will be shattered. Hence, the water (sealed just below of glass bulb) start to discharge towards the deflector. Water will be distributed with certain spray pattern depending on the design of deflector use. Water spray pattern play an important role in controlling the fire. During real fire, the activation of sprinkler will provide extra time to Fire Brigade to arrive while keeping fire under control [1].

Fire sprinkler head activation time plays a major role in determining the fire growth within the compartment. The sprinkler activation time can be defined as the time at which the temperature of the
sprinkler head reaches the nominal activation temperature [2]. The sprinkler activation correlates directly to sprinkler sensitivity which depends on its thermal parameters known as Response Time Index (RTI) and Conduction Factor (C) [3]. There has been a substantial amount of research in fire sprinkler head activation in the past. Most of the research utilized plunge test and ramp test to determine sprinkler sensitivity by simulating fire conditions in a wind tunnel. The plunge test was developed in the USA at the Factory Mutual Research Corporation [4] and the principle of the test is to have air flowing past a test section at selected air velocity and temperature that higher than sprinkler’s operating temperature. Once the temperature inside test section reach equilibrium, the sprinkler head plunge into the hot air flow until it activates. Due to the fact that full-scale fires are inconvenient to perform, most of the work from literature were using computational modelling software to predict sprinkler responses.

Automatic fire sprinkler systems are designed to activate if a fire develops in the area of protection by limit or suppress the further development of the fire. The knowledge of the effectiveness of sprinkler systems in reducing the risk from fire is important evaluating a building design that incorporates sprinkler for fire safety [5]. There has been debate as to how far the sprinkler systems is effective since automatic sprinkler systems were originally invented and developed in the 1800s [6]. An early reference to estimates of sprinkler effectiveness can be found in the Preliminary Report of the New York State Factory Investigating Commission, which was released in 1912 following the Triangle Shirtwaist fire. This report stated that the efficacy of sprinkler systems is varying with sprinkler proper working limit in between 75% and 95% [7]. The effectiveness of a fire-safety system can be considered as the product of its efficacy and its reliability [8]. Effectiveness of sprinklers can be determined through statistical and other historical data. Efficacy is the degree to which a system achieves an objective given. Different objective means different efficacy of a system.

Globally, there are several renowned manufacturers of fire sprinkler heads, namely Dyne, Tyco, Globe, Viking, and Reliable; and then there are also smaller market companies which manufacture fire sprinkler heads. The products from these companies are known to be of high quality and reliability based on previous research by Frank et al. [5]. However, nowadays there are more and more unknown manufacturers which are also producing fire sprinkler heads at a fraction of the price as compared to what has been sold by the renowned companies. Even though, the cheap sprinkler heads are claimed to be the same quality as those sold by the renowned companies, there is no guarantee that the sprinkler heads are going to activate according to the specifications. The market distribution of these cheap sprinkler heads are becoming much more extensive in Malaysia and are available off-the-shelf at many DIY stores. This has led to a growing concern in Malaysia that construction companies are opting for cheaper fire sprinkler heads while compromising the life safety of the building occupants.

Therefore, it is the aim of the study to conduct probabilistic assessment on the activation time of off-the-shelf fire sprinkler heads from repetitive experiments. The main objective is divided into sub-objectives as follows: (1) to measure activation time required for fire sprinkler head to activate with and without smoke effect; (2) to assess on variability of sprinkler head Response Time Index (RTI); (3) to identify appropriate distributions for experimental RTI values.

This research study could provide information on the reliability of the fire sprinkler heads available in the market is reliable. Besides, the research outcome will be valuable for probabilistic study of fire growth dynamics using computational modelling. In the end, the findings would be useful as a baseline study to improve current local codes and standards regarding designing, installation and inspection of fire sprinkler system, specifically in Malaysia.

2.0 Methodology

The research was performed through laboratory experiments in Combustion Laboratory at the Faculty of Engineering, Universiti Putra Malaysia. The main principle of the experiments were to have hot air flowing through a test section at a selected velocity and air temperature [9]. The specifications of the fire sprinkler head selected was a standard type sprinkler head (pendant type) with K-factor of 80.6 LPM/bar\(^{1/2}\), temperature rating of 68°C with standard coverage of 20.9 m\(^2\) (specifically for ordinary
hazard). There were a total of 68 fire sprinkler heads have been used for the two sets of experiments and the sprinkler heads were bought at a random hardware store. Both sets of experiments use a fixed value of hot air velocity (1 m/s) with thermal heat flux of 300 kW/m² except set number two had additional of smoke effect. Smoke had been generated by a fog machine (Antari) while the hot air was generated by a heat gun (AEG Powertherm 560). The sprinkler head plunged with perpendicular orientation to the hot air flow inside metal chamber with size of 0.5 m (length) x 0.5 m (wide) x 0.5 m (height). The metal chamber is a part of customized Fire Smoke Detector and Water Sprinkler System apparatus as can be seen in Figure 1. The apparatus consists of two metal chambers where one chamber installed with Fire Smoke Detector and other one metal chamber installed with fire sprinkler head. Only the chamber installed with sprinkler head used in this experiment. The air temperature inside the chamber was measured using 0.5mm diameter Type K (chrome/alumel) thermocouple.

![Figure 1. Fire Smoke Detector and Water Sprinkler System Apparatus](image)

The experiments are divided into two sets where; Experiment 1 - without smoke effect in the experimental chamber and Experiment 2 - with smoke effect in the experimental chamber. Fire sprinkler head activated time and temperature data were recorded for both of the experiments. RTI value was calculated using RTI equation before analysis using Palisade @RISK Software were conducted. The RTI equation used in this study given by:

$$RTI = \frac{-t_r \sqrt{\Delta T}}{ln \left(1 - \frac{\Delta T_{ea}}{\Delta T_h} \right)}$$ (1)

Where $t_r$ is a sprinkler head activation time, $u$ is the velocity of hot gas flow, $T_{ea}$ is a temperature surrounding of fire sprinkler head at time of activated and $T_h$ is a hot gas flow temperature.

Using the @RISK statistical analysis software, the best-fit probabilistic curves were generated for both experiments. The software used Monte Carlo simulation and includes tools to automatically fit distributions to data using different types of fitting statistics and fitted distributions are ranked according to the goodness of the fit. The fitted statistics such as the mean, the minimum value, the maximum value and the standard deviation are provided. @RISK can also apply the Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), Chi-Squared Statistics, Kolmogorov-Smirnov Statistic and Anderson-Darling Statistics for estimating distribution. The Kolmogorov-Smirnov estimation was selected for the fit statistics because it is appropriate for continuous data and it focuses on the central region of the input values. The RTI experimental data were compared with the theory and manufacturer data as to compare the extent that the data deviates and eventually assess the time effect on property loss due to failure of sprinkler to operate within time.
3.0 Results and discussion

A total of 34 experiment repetitions were performed for Experiment 1 and Experiment 2. The results and analysis of the experiments are shown in the following subsections.

3.1 Sprinkler Activation Temperature and Activation Time

Experiment 1 was conducted under constant hot air flow without smoke effect. Sprinkler activation times were established visually by seeing the activation through the window and identified by the noise of glass bulb breaking. In other words, the activation time of the sprinkler head is the time at which the temperature of the sprinkler link reaches the nominal activation temperature. At this stage, the data logging and video recording is halted. On average, it takes around 60 seconds time for the sprinkler to activate. It was observed that sprinkler head with a unique number 1-27 gave fastest activation time at 31.82 seconds at 78.8°C. While, sprinkler head with a unique number 1-25 gave the longest activation time at 89.13 seconds at 94.1°C. The difference in activation time was 57.31 seconds. Further details on the distribution of frequency for sprinkler head activation time is shown in Figure 2(a). Also from the figure, out of the 34 sprinkler heads, seven sprinkler heads required 55 seconds time average to activate, while five sprinkler heads activated within time range of 37.5 seconds until 65 seconds. From here, it can be concluded that average of sprinkler will achieve activation time less than 60 seconds.

Experiment 2 was conducted under constant hot air flow with additional smoke effect. It was observed that the average time required for sprinkler head to activate is around 60 seconds. Sprinkler head with a unique number 2-1 gave fastest activation time (35.3 seconds at 87.3°C). While, sprinkler head with a unique number 2-11 gave the longest activation time (85.14 seconds at 96.2°C). The difference in activation time was 49.84 seconds. Further details on the distribution of frequency for sprinkler head activation time is shown in Figure 2(b).

![Figure 2](image_url)

**Figure 2.** (a) Frequency distribution of the activation time of sprinkler head for Experiment 1 (b) Frequency distribution of the activation time of sprinkler head for Experiment 2

Based on the results from Experiment 1 and Experiment 2, additional smoke effect, has a slight impact on the activation time of fire sprinkler. From the results, it was observed that without the additional smoke effect, the maximum temperature achieved at glass bulb break was 102.8°C while with additional smoke effect, the maximum temperature achieved was 109.6°C. From the average, it is found that about 6.6% temperature increase due to additional smoke effect while the activation time between both experiments decrease by 8%. From these experiments, it can be concluded that additional smoke effect contributes to quicker fire sprinkler activation time. This is in agreement with the work by Beyler [10] where it was found that the presence of smoke increased the gas temperature at ceiling level which contributes directly to quicker activation time for fire sprinkler heads.

From the observation of both experiments, the temperature recorded at time when glass bulb is broken were on average higher than temperature rating given by manufacturer (68°C). The temperature...
recorded is also known as glass bulb surface temperature. However, this phenomenon is considered normal as Sze [11] mentions that the glass bulb surface temperature is technically a bit higher than 68°C because it still needs more time for the hot gas to enter through the glass bulb surface into the liquid inside. Therefore, there is a thermal lag of bulb mass [12].

3.2 Response Time Index (RTI) analysis

Figure 3 shows the plotted RTI for each of the sample experiment repetition from Experiment 1. The RTI values are scattered across the test condition for a given bulb diameter and orientation. Sprinkler head with the unique number of 1-23 gave highest RTI value with 72.13 m$^{1/2}$·s$^{1/2}$, while sprinkler head with the unique number of 1-27 gave lowest RTI value with 16.01 m$^{1/2}$·s$^{1/2}$. Figure 4 shows the plotted RTI for each of the sample experiment repetition from Experiment 2. Sprinkler head with the unique number of 2-16 gave highest RTI value with 82.20 m$^{1/2}$·s$^{1/2}$, while sprinkler head with the unique number of 2-4 gave lowest RTI value with 15.37 m$^{1/2}$·s$^{1/2}$.

![Figure 3](image1)

**Figure 3.** The plotted RTI for each of the sample experiment from Experiment 1

![Figure 4](image2)

**Figure 4.** The plotted RTI for each of the sample experiment from Experiment 2

RTI values observed were almost similar across different set of experiments for a given bulb diameter and orientation. Based on Figure 3 and Figure 4, both experiments have shown almost the
same pattern of distribution except for Experiment 1 which had the widest scatter in the data. Also from both experiments, it was observed that as the activation times were reduced, RTI value also reduced. The similar analysis was also carried by Sze [11] to investigate the relationship between RTI and activation time. It was found from the work that, if the activation time is getting smaller, the RTI also will be getting smaller.

The RTI distribution for both experiments were fitted using @RISK to get the best fit probabilistic curve. For Experiment 1, using the Kolmogorov-Smirnov (K-S) technique, the goodness-of-fit comparison ranks Gamma, Log normal, and Weibull distribution as the top 3 fittest distribution curve. Figure 5 illustrates the RTI data distribution comparison between 3 types of distribution for Experiment 1. It was observed that Gamma distribution curve is the fittest when compared to the experimental data while Lognorm and Weibull distribution little bit skewed to the left and skewed to the right. Hence, Gamma distribution was ranked first as the fittest distribution curve for Experiment 1. Gamma distribution is a two-parameter family of continuous probability distributions with a shape factor (also known as α value) and rate factor (also known as β value). As can be seen in Figure 6, the shape factor and rate factor were 11.207 and 4.1762. Therefore, these values can be applied into Gamma distribution equation to predict the time of activation for no smoke effect.

![Figure 5. RTI Comparison between 3 types of distribution for Experiment 1](image1)

![Figure 6. RTI Gamma Distribution for Experiment 1](image2)

While for Experiment 2, using the Kolmogorov-Smirnov (K-S) technique, the goodness-of-fit comparison ranks Weibull, Gamma, and BetaGeneral distribution as the top 3 fittest distribution curve. Figure 7 illustrates the RTI data distribution comparison between 3 types of distribution for Experiment 2. It was found that BetaGeneral distribution is the fittest distribution for Experiment 2 data while
Weibull and Gamma distribution little bit skewed to the left and skewed to the right respectively. Hence, BetaGeneral distribution was ranked first as the fittest statistics for Experiment 2. BetaGeneral distribution are characterized by two continuous shape parameter, $\alpha_1$ and $\alpha_2$, and two continuous boundary parameter i.e. min and max. As can be seen in Figure 8, the $\alpha_1$ value, $\alpha_2$ value and max value were 5.02, 7.13 and 112.5. Therefore, these values can be applied into BetaGeneral distribution equation to predict the time of activation with smoke effect.

![Figure 7. RTI Comparison between 3 types of distribution for Experiment 2](image)

![Figure 8. RTI Gamma Distribution (with smoke effect)](image)

Table 1 shows the summary of best fit distribution curve for Experiment 1 (without smoke effect) and 2 (with smoke effect). The information provided is sufficient and ready for use into any fire simulation software as input for RTI or even can be converted into sprinkler activation time. Technically, in the fire simulation, when the ceiling jet reaches the advertised activation time of the sprinkler, the distribution comes into place where it will randomly select a time of activation of the sprinkler using the information from the best fit distribution.
Table 1. The summary of best fit distribution curve for Experiment 1 and 2

| Attributes                        | Experiment 1 (Without smoke effect) | Experiment 2 (With smoke effect) |
|-----------------------------------|-------------------------------------|----------------------------------|
| Best Fit (Ranked by K-S)          | Gamma distribution                  | BetaGeneral distribution         |
| K-S value                         | 0.0897                              | 0.0856                           |
| α value (Gamma)                   | 11.207                              | -                                |
| β value (Gamma)                   | 4.1762                              | -                                |
| \(α_1\) value (BetaGeneral)       | -                                   | 5.0193                           |
| \(α_2\) value (BetaGeneral)       | -                                   | 7.1307                           |
| Max value (BetaGeneral)           | -                                   | 112.50                           |

4.0 Conclusion
The data collected from both experiments were recorded and analyzed through Microsoft Excel and @RISK statistical analysis software. The study assesses sprinkler activation time through two experiments; 1) Without smoke effect and 2) With smoke effect. Based on both experiments, on average, the sprinkler heads activated at around 60 seconds after the ceiling jet inside the experimental chamber reached the advertised operating temperature of the sprinkler heads. Overall, it was found that the sprinkler activation time recorded for Experiment 2 was slightly faster compared to Experiment 1. It is clearly shown that, there is a possibility of sprinkler performance being impaired by the existence of smoke. Experimental Response Time Index (RTI) of sprinkler was calculated based on activation time recorded and compared with manufacturer RTI sprinkler. It shows inconsistency of RTI value between experimental RTI and manufacturer RTI. Experimental RTI value were used to generate probabilistic curve by using @RISK software. The summary of the best fit probabilistic curves for both conditions is shown in Table 1.

5.0 References
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