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CFD INVESTIGATION ON THE EFFECT OF VARYING FIRE SPRINKLER ORIENTATION ON SPRINKLER ACTIVATION TIME

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ABSTRACT

Water sprinkler system is considered one of the main water-based fire suppression systems. Due to the turbulent nature of fire, prediction of water sprinklers activation time required performing numerous experiments and tests to understand the nature of the parameters involved in changing the activation time. It was noticed that the angle where the sprinkler arms are oriented towards the hot gas jet resulting from a fire had a great impact on the activation time of the sprinkler. In this research the orientation of the sprinkler's arm was changed by using Computational Fluid Dynamics (CFD) simulation. It was found that changing the sprinkler arm angle from perpendicular to the flow (90°) to 60°, 30° and parallel to the flow (0°) has resulted in increasing the sprinkler activation time by about 8%, 84%, and 163% respectively. The effect of sprinkler activation time variation was investigated on stacked wood pallets heat release rate. It was found that with a parallel orientation the fire is allowed to grow 2.5 times more in terms of Heat Release Rate (HRR) than with perpendicular orientation.

Keywords: computational fluid dynamics, fire sprinkler, activation time, response time index.

INTRODUCTION

Significant research has been conducted on controlling or suppressing fires in buildings. One popular method of fire protection that has been used for more than a century is the automatic fire sprinkler, whose efficiency has been increasing during the past century [1]. A sprinkler is a thermo-sensitive device that is designed to discharge a certain amount of water in a certain pattern, and is only activated when a fire generates a sufficient quantity of heat, and will control or suppress the fire once it has activated [2]. It contains a liquid, usually glycerol with a gas bubble in glass bulb. Once, the liquid expands due to heat from a fire it will press the gas bubble causing the glass to burst, the seal to open and the water to jets and sprayed in a spray-like pattern. There are different grades for the water sprinkler representing different activation temperatures depending on the intended kind of environment to be protected.

It was noticed during multiple experiments that the direction with which the hot gas jet faces the sprinkler had a major effect on the response time of the sprinkler (Figure-1).

Tsui and Spearpoint [3] reported that sprinkler orientation significantly affect the RTI values. Tsui and Spearpoint mentioned that when Sprinklers were tested with their yoke arms parallel to the airflow, the sprinkler Response Time Index (RTI) was higher than when the sprinkler oriented perpendicular to the airflow.

Yu [4] also tested two different sprinkler orientation frame arm orientations in a plunge testing rig (perpendicular and parallel to the air flow direction (Figure-1)). Yu reported that when the sprinkler is located with frame arm parallel to the oncoming hot gas flow (Yu called it the worst orientation), the sprinkler RTI where higher than sprinkler RTI when the frame arm were oriented perpendicular to the airflow. The sprinkler time in some cases increased to 6 times the activation time if the sprinkler position was rotated 90 degrees from facing the hot gases to being parallel to it. Which, compromises the safety and lives of occupants because predicted activation time represents the most important factor in choosing a certain type of sprinkler for building fire protection systems.

In this research, sprinkler activation time will be investigated at various orientation angles using Computational Fluid Dynamics (CFD) simulation techniques. Then the simulated sprinkler activation time is used to study its effect on wood pallets fire heat release rate growth with dimensions 1.22mX 1.22mX1.22m (h).

MODEL DEVELOPMENT

The experimental plunge test of sprinkler activation conducted by Yu [4] is modelled by using CFD simulation technique (ANSYS CFX). The detail of the modelled plunge test chamber is shown in Figure-1b.

The modelled sprinkler is pendent 68°C standard response sprinkler (Figure-2a). Based on Yu tested air velocity it was found that the hot air flow used in the test is turbulent. Yu's test was performed at sprinkler arms perpendicular to the hot air flow and parallel only (0° and 90° angles). In this research, the modelled sprinkler simulation results were validated against Yu test result (sprinkler activation time).

The reason for modelling Yu experiment is to validate the CFD model against experimental measurement. Once the model is validated, varying the sprinkler arm orientation will be carried out to investigate its effect on sprinkler activation time and RTI values.

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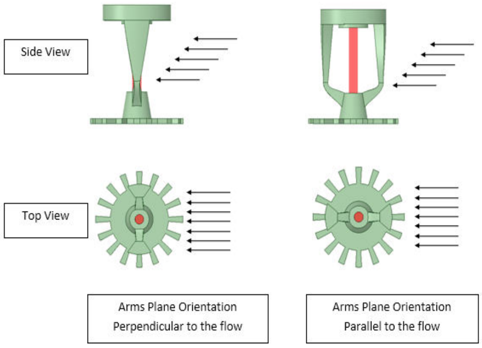
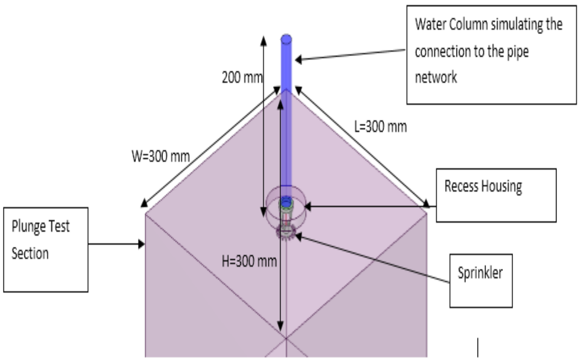


(a)

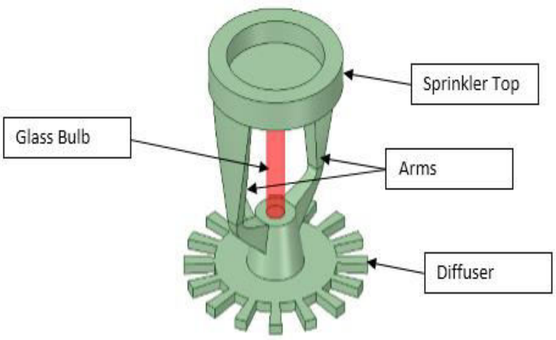


(b)

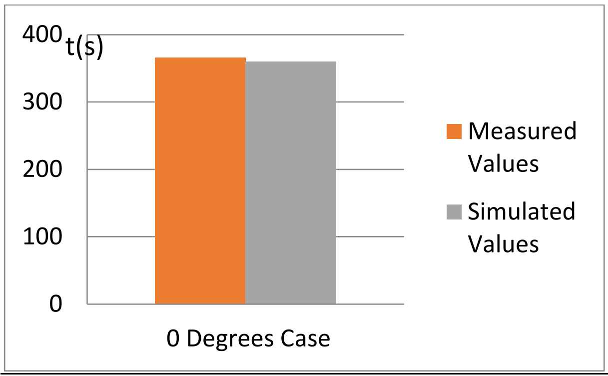
Figure-1. (a) Direction of ceiling gas jet relative to the sprinkler position, (b) Computational fluid dynamics (CFD) model.

RESULTS VALIDATION

As mentioned, Yu experimental test is modelled to validate the CFD simulation results. As seen in Figure-4, for 0° angle orientation, the simulation results are in good agreement with measurement. The deviation was 1.7% from the experimental results obtained by Yu [4].



(a)



(b)

Figure-2. (a) Sprinkler solid model, (b) Validation simulation case.

MESH INDEPENDENCE

In order to perform the verification of the CFD model, mesh independence study is performed. It was found that increasing the number of mesh from about three hundred thousand elements to four hundred fifty thousand elements will give less than 2% difference in the results. Therefore the coarser mesh is used as the optimum and most economical mesh in this simulation.

RESULTS OF DIFFERENT SPRINKLER ANGLES

Once the model was validated, CFD simulations were carried out for 30° and 60° sprinkler arms angles. Figure 3a shows that when the sprinkler arms were perpendicular to the flow, the activation time was 134s. Changing the angle to 60° caused a slight increase in the activation time (8% increase.) whereas when the angle changed to 30° the activation time was increased to about 250 seconds from 90° orientation. When the angle changed to 0° the activation time was significantly higher (2.5 times increase).

After plotting the activation time against the angle of orientation. The Response Time Index was calculated and plotted with respect to angle. Response Time Index (RTI) is defined as the thermal inertia by which the sprinkler resists the change in temperature [2]. It is calculated as follows:

$$\frac{d(\Delta T_e)}{dt} = \frac{\sqrt{u}}{RTI}\left(\Delta T_g - \Delta T_e\right) \qquad (1)$$

Where u is the velocity of hot air (m/s), ΔT_e is the difference in temperature between the sprinkler bulb element and the ambient (K), ΔT_g is the difference in temperature between the hot air gas Temperature and the ambient (K), *RTI* is the Response Time Index (m.s)½ and t is time (s). The results were then plotted in Figure-3.

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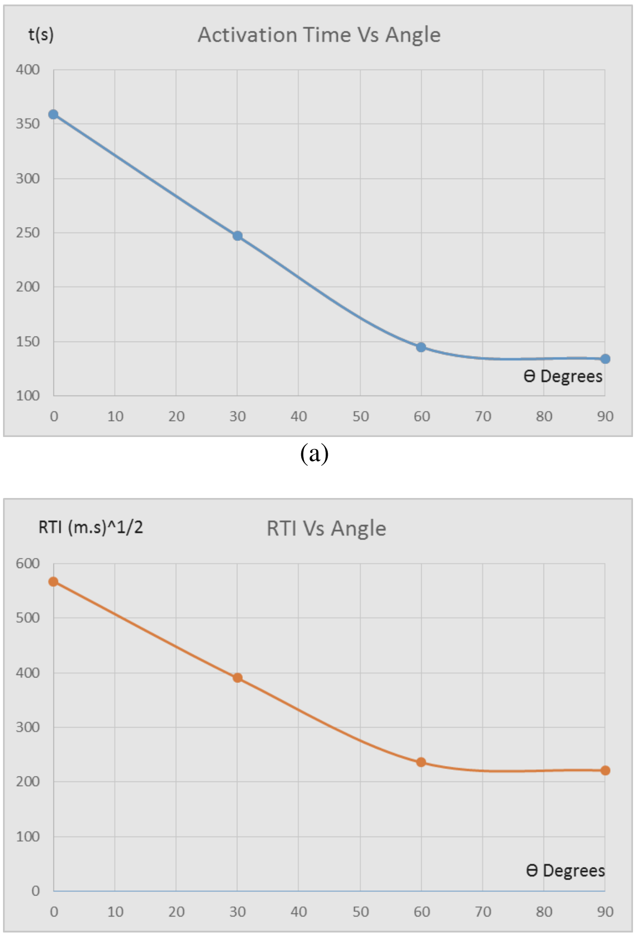

(a)

(b)

Figure-3. (a) Activation time vs angle of orientation, (b) Response time index vs angle.

As mentioned, the modelled sprinkler is pendent 68° standard response. In Figure-4, based on the calculated RTI (Figure-5), for 90 and 60° angles, the sprinkler performed as standard response (as specified by the manufacturer. However, at 30 and 0° angles, the sprinkler performance deteriorated and positioned outside the standard response region. This is may not be considered by the sprinkler manufacturer and it may affect the expected sprinkler activation in building fire safety design.

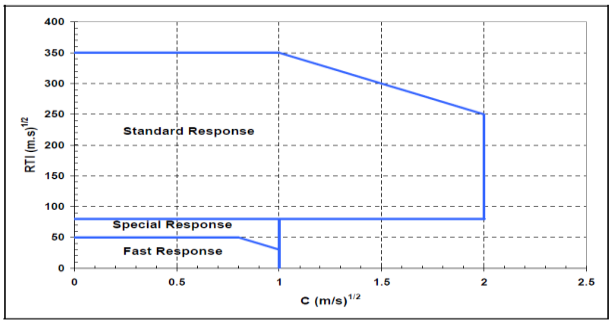

Figure-4. Response type index and conductivity factor for different sprinkler categories [4].

EFFECT OF DELAY IN SPRINKLER ACTIVATION ON DESIGN FIRES

The effect of sprinkler activation time variation at different sprinkler arms angles is investigated on a fire generated by burning wood pallets with dimensions of 1.22mX1.22mX1.22m (h). The heat release rate is shown in Figure 5 which was developed by using the t squared growth rate method, the heat release rate is calculated from [5]

$$Q = 2 \times \alpha \times t^2 \qquad (2)$$

Where Q is Heat release rate (MW), α is the fire intensity coefficient (MW/s^2) and t is time (s)

For the stacked wood pallets α is taken as 4.66×10^{-5} MW/s^2 [5].

The sprinkler temperature is calculated by using the following equation developed by Schifiliti *et al.* [6].

$$T_{spn} = \left[\frac{u^{\frac{1}{2}} \left(T_{g\,n} - T_{Spn-1} \right)}{RTI} \right] + T_{Spn-1} \qquad (3)$$

Where *Tsp n* is the sprinkler temperature at time step *n*, *Tsp n-1* is the sprinkler temperature at time step previous time step *(n-1)*, *u* is the ceiling jet gas velocity, *Tg n* is the ceiling jet gas temperature at the current time step and *RTI* is the Response Time Index of the Sprinkler. The *RTI* is obtained from the calculated *RTI* in Figure-3 which includes the sprinkler activation time obtained from the CFD simulation.

$T_{g\,n}$ was calculated from ceiling jet correlations as follows [8]

$$U_g = \frac{[0.2(Q)]}{r^{5/6}} \qquad (4)$$

$$T_g = \frac{\left[0.2 \left(\frac{\dot{Q}}{r} \right)^{2/3} \right]}{H} - T_a \qquad (5)$$

Where H represent the difference between the room ceiling height and wood pallets height (ceiling height was taken as 4.2 m), r represents the distance between the sprinkler and the fire pallet location, *Ta* is the ambient temperature, *Tg* is the ceiling jet gas temperature and $\dot{Q}$ is the Heat Release Rate of the fire.

When the temperature in equation 3 reached 68°C, the sprinkler is considered activated. For the respective sprinkler, the following formula was used to calculate the sprinkler activation and water spray effect on heat release rate of the fire [7].

$$\dot{Q}_{(t-t_{act})} = \dot{Q}_{(t_{act})} \exp\left[\frac{-(t-t_{act})}{3\dot{w}^{-1.85}}\right] \quad (6)$$

Where $\dot{w}$: Sprinkler density (mm/s), the water spry density used as 0.025mm/second for one sprinkler which was obtained from real measurements. $\dot{Q}_{(t_{act})}$: Heat release rate at the sprinkler activation time (MW), $\dot{Q}_{(t-t_{act})}$: Heat release rate at the time following the sprinkler activation time (MW) and t is any time following the activation time of the sprinkler (t_{act}) of the sprinklers (s). For fire calculations and simulation in buildings, the fire is considered unsteady and hence the calculations were performed at 20 seconds time step.

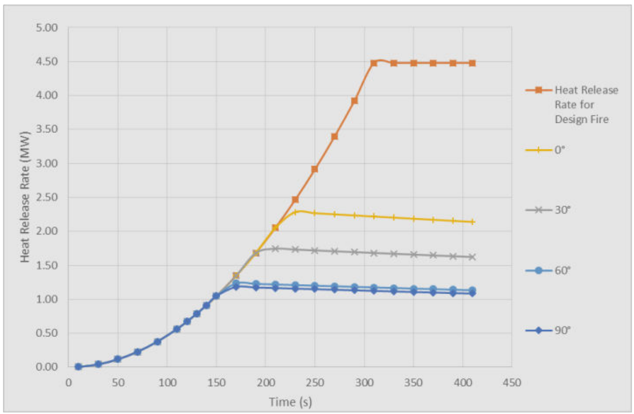

Figure-5. Heat release rate for fire at different sprinkler activation times.

As see in Figure-5, it is clear that the longer time it takes for the sprinkler to activate, the more the fire grows and it would be difficult to control. From Figure-5, changing the angle to 60° resulted in minor change in sprinkler activation time and consequently fire heat release rate was controlled similar to 90° orientation. However, changing the angle to 30° has resulted in controlling the fire at heat release rate of 1.8 times as compared to 90°. The worst case which is identified as the sprinkler angle being parallel to the hot ceiling jet (0°) has resulted in delaying the activation time of the sprinkler which caused the design fire to grow to about 2.5 times its potential at the perpendicular orientation (90°) and thus made it more difficult that the fire will be controlled by the sprinkler activation. The above mentioned results showed the significant effect of sprinkler orientation on sprinkler activation time. These results should be considered by building designers in order to design fire safe building.

CONCLUSIONS

Sprinkler arms orientation angle with respect to the direction of the hot air/hot gases flow represents a very significant factor in the activation of the water sprinkler. It was found that when the sprinkler arms orientation was perpendicular (90°) to the hot gas flow, the activation time was 134s. It was also found that changing the arms angle to 60 and 30° resulted in 8% and 84% increase respectively. However, when the sprinkler arms was positioned parallel to the flow (0°) the activation time was drastically increased by 163%.

The above variation of sprinkler activation time was investigated on heat release rate of wood pallets fire. Where at 0°, the fire grows to 2.5 times the heat release rate of 90° orientation which could be a catastrophic delay that may affect the fire safety design of a building.

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