Response Time of Automatic Sprinklers below a Confined Ceiling

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ABSTRACT

In order to improve the predictability of sprinkler response time for a confined ceiling, thermal properties of sprinkler and environment of sprinklers below a confined ceiling during fire are discussed. Significance of the heat loss from the fusible link of a sprinkler by conduction and a method of estimating the response of the link to external radiation are shown. Measurements of temperature, velocity, radiation, and sprinkler response time below a ceiling are made in a confined enclosure. The measured temperature and velocity are found to be close to previous theory for an unconfined ceiling if a correction for the existence of smoke layer is applied. Finally measured sprinkler response time is compared with calculation based on measured temperature, velocity and radiation history. The result shows the significance of radiation from the fire source in the determination of sprinkler response time.
key words: sprinkler, response time, heat loss, ceiling jets, radiation.

INTRODUCTION

Sprinkler response time is one of the major elements in evaluating the effectiveness of sprinkler system, since either too early or too late actuation of sprinkler may result in a false response or the failure of fire suppression. Prediction of the response times and analysis of significant factors in the determination of sprinkler response time are becoming important as fast response sprinklers are being developed to maintain a survivable environment in residential fires and to suppress storage hazard fires[e.g.,1].

The response time of a fusible sprinkler installed below the ceiling is basically determined by its operation temperature and heat balance on its heat sensing element. In a fire situation, heating of the heat sensing element is mostly due to convective heating by fire driven ceiling-jets and radiation from the fire source, whereas heat loss from the heat sensing element may result also from the conductive heat transfer to the ceiling through the hardware of the sprinkler. Quantification of the thermal properties of sprinkler and modeling of the heating conditions, temperature and velocity history in a fire driven flow and radiative characteristics of a fire source, are two major procedures necessary for predicting at what time during the growth of a fire suppression begins.

The responsive performance of sprinkler has been often represented by the concept of Response Time Index(RTI)[2]. RTI is the major element in determining the sprinkler response time in an environment where convective heat transfer is much greater than radiation and for sprinklers whose conductive heat loss to the sprinkler fittings is insignificant. However, for a sprinkler relatively close to the fire source or for rapidly growing fires, radiation from the fire source can be a significant factor in the determination of the sprinkler response time. On the contrary, for a fast response sprinkler heated by slowly growing fires, the conductive heat loss can influence significantly on the sprinkler response time. Quantification of these processes is of primary importance to the evaluation of the responsiveness of a sprinkler system.

For the fire driven ceiling-jets there is considerable information on the flow field in which a sprinkler is submerged for conditions relatively easy to model the ceiling jets behavior; the conventional measurements and theories have generally assumed steady-state smoke layer stratification and either an unconfined ceiling or laboratory-size small enclosures[3 ~ 5] . For an unconfined ceiling, the ceiling-jets behavior can be modeled assuming a rather ideal flow system[3,4], whereas for small enclosures temperature within the smoke layer is considerably more uniform[5 ~ 8]. Although considerable information is available from full scale fire experiments on enclosures as large as a living room or an office, little is known on the flow field below the ceiling of such enclosures.

In this study, as a basis to develop a predictive method for sprinkler response times in a fire situation, an estimation method for the thermal properties of the sprinklers, responsive characteristics for external radiation and the heat loss to the sprinkler fittings by laboratory experiments are discussed. Following measurements were made in an enclosure, 8.10m x 11.10m, and 4.20m in height using 0.5m square porous propane burner as the fuel:

(a) response time of sprinklers mounted below the ceiling
(b) temperature and velocity history in the flow field in which sprinklers are submerged
(c) vertical temperature distribution in the enclosure
(d) upward total heat flux at the ceiling just above the burner

The structure of the sprinklers used for this experiment is shown in Figure 1. Measured temperature and velocity histories in the ceiling-jets within the smoke layer are compared with previous work on unbounded ceilings and on laboratory-size enclosures[3-5]. Finally, response time of the sprinklers are calculated for the temperature, velocity and total heat flux history of the experiments and compared with the measurement.

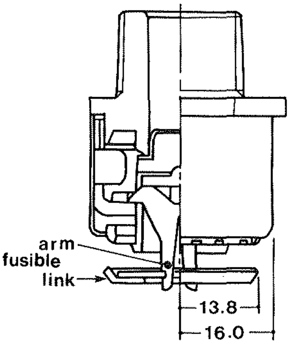


Figure 1 Structure of the tested sprinkler

THERMAL PROPERTIES OF SPRINKLERS

Heat balance on the heat sensing element is described as

$$dT_s/dt = (T_a-T_s)/\tau + C_r(\dot{q}''_e-\sigma T_s^4) - f_L(t) \qquad (1)$$

Time constant for convective heat transfer, τ, parameter representing the responsiveness for radiation, C_r, and heat loss, f_L, are the parameters to be quantified for the prediction of the response time. Among these properties, time constant for convective heat transfer, or RTI, has been studied for its primary importance to the heat balance of a heat sensing element[1,2]. Although the heat loss has been conventionally expressed by a conductance model, $f_L=C(T_s-T_o)$, there is still a question whether this expression would be always correct, since the part connecting the heat sensing element with the sprinkler fittings is heated by the ceiling jets and there must be its some influence on the heat loss. Especially for fast response sprinklers, the arm of a sprinkler, the major part conducting heat from the heat sensing element tends to be made of materials of large heat capacity; therefore the heat loss is expected to be transient until the sprinkler is operated.

Significance of the heat loss from a heat sensing element can be assessed by the comparison of the temperature history of the heat sensing element of a sprinkler altered such that the heat loss becomes negligible and that of a "normal" sprinkler in a wind tuunel. Representing excess temperature of the heat sensing element of the normal sprinkler and that of the altered one as θ_s and θ'_s respectively, then change of θ_s and θ'_s can be represented as

$$d\theta_s/dt = (\theta_a - \theta_s)/\tau - f_L(t) \qquad (2)$$

$$d\theta'_s/dt = (\theta_a - \theta'_s)/\tau \qquad (3)$$

where radiative heat transfer is ignored for its insignificance in a wind tunnel test. Figure 2 shows the time history of $\Delta\Theta_s = \theta'_s - \theta_s$ for some

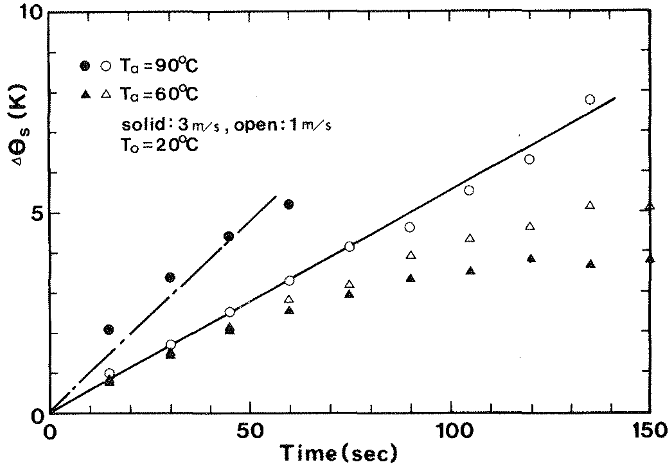


Figure 2 History of $\Delta\Theta_s(t)$.

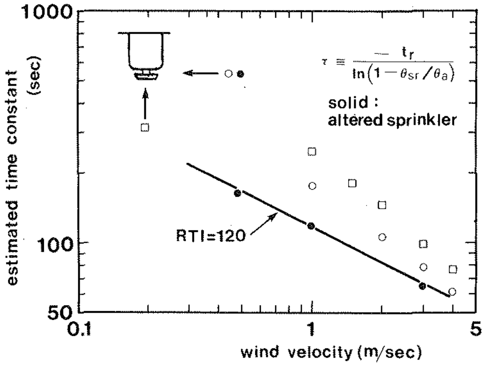


Figure 3 Estimated time constant of the tested sprinkler
For solid symbols, the arm was replaced by insulative fabrics.

velocity and temperature conditions. The relatively rapid growth of θ_s at the beginning of the test seems to show the failure of the conductance model for the present sprinkler, since the conductance model must lead to such pattern of $\Delta\Theta_s$ history that $\Delta\Theta_s$ grows quite slowly at the beginning, then turns to be rapid and finally approaches to a steady state. Figure 3 shows the time constant for convective heat transfer estimated from $\tau=-t_r/\ln(1-\theta_s/\theta_a)$, an expression originally effective for the altered sprinklers, using the response time data for T_a=90°C. RTI for the altered sprinklers is estimated as RTI= $\tau \cdot u^{1/2} \simeq 120$, while time constant thus calculated for the "normal" sprinklers is somewhat more sensitive to wind velocity. $\tau \propto u^{-0.8}$ may be appropriate for the normal sprinklers, and becomes almost twice the value for the altered sprinklers. This implies that the influence of the heat loss to the sprinkler fitting on the determination of the sprinkler response time is significant if wind velocity is relatively low.

The parameter related to the responsiveness for radiation can be estimated by measuring the response time of the sprinkler irradiated by strong constant radiation, $\dot{q}''_e$, within a room temperature. Since $(T_a-T_s)/\tau$, σT_s^4 and $f_L(t)$ must be much less significant than $\dot{q}''_e$ in this system, C_r can be estimated as $C_r=(T_{sr}-T_o)/\dot{q}''_e t_r$. For estimating C_r, the sprinkler heads were exposed to strong radiation, 5-20kW/m^2, generated by a premixed propane ceramic furnace. The C_r value for the present sprinkler was estimated as $C_r \simeq 0.19$Km^2/kJ.

CEILING-JETS IN A CONFINED ENCLOSURE AND SPRINKLER RESPONSE TIME

Experiment

The experiments were conducted in an enclosure shown in Figure 4. The burner was located at the center of the floor, and the height of its exit was changeable, 1.0m or 2.0m above the floor. The fuel supply rate was kept constant during each experiment for the simplicity of the analysis. Temperature was monitored with 0.5mm diameter chromel-alumel thermocouples with approximately 5mm diameter half-spherical aluminum foil shade for the protection from radiation. Velocity was measured with bidirectional pressure tubes. Heat flux was monitored just above the burner by a Gardon type heat flux meter; the heat flux data are believed to be close to

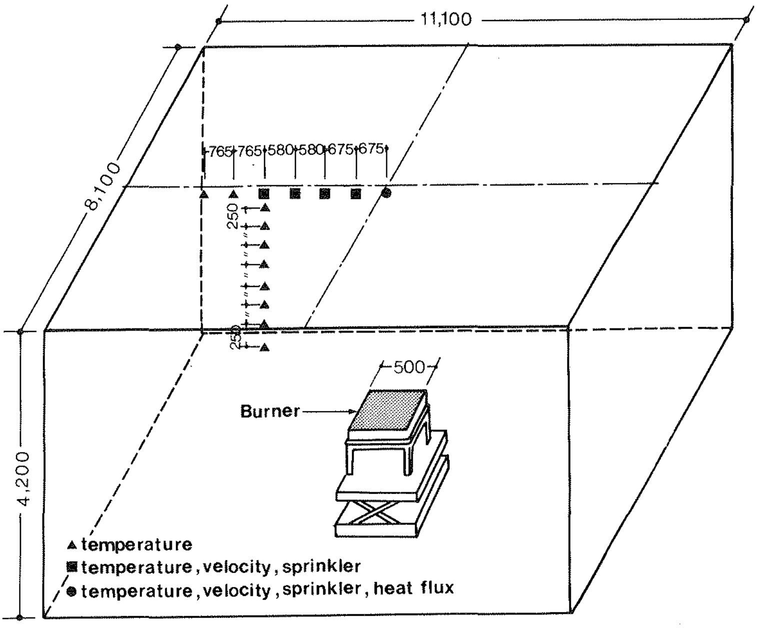
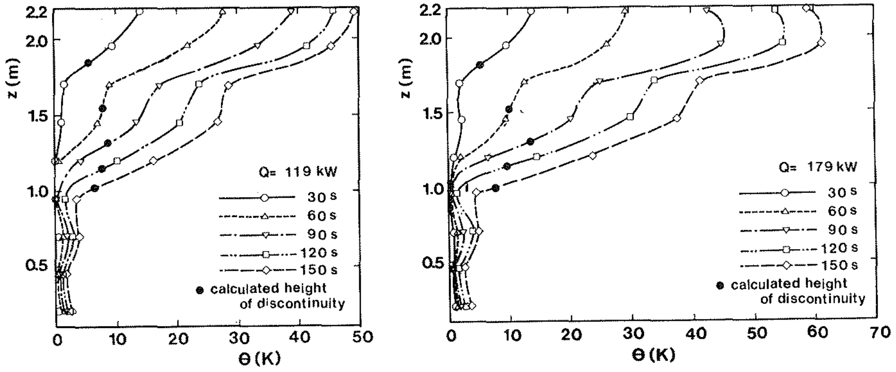


Figure 4 Experimental set-up , probes; 20mm below ceiling.

radiation, since the data were generally greater than the estimation of convective heat transfer and almost constant with time irrespective of considerable change in the ceiling jet temperature. The sprinklers used for this experiment were the product whose thermal properties are discussed in the previous chapter. Since some interference between the bidirectional tubes and sprinkler heads was anticipated, measurement was conducted twice for each environmental and heat release conditions, one using thermocouples, bidirectional tubes and a heat flux meter, and the other using sprinklers and thermocouples. The excess temperatures from these two measurements were consistent within the error of 2% at the reported conditions. The measured sprinkler response time will be compared with calculation based on the quantified thermal properties of the sprinklers.

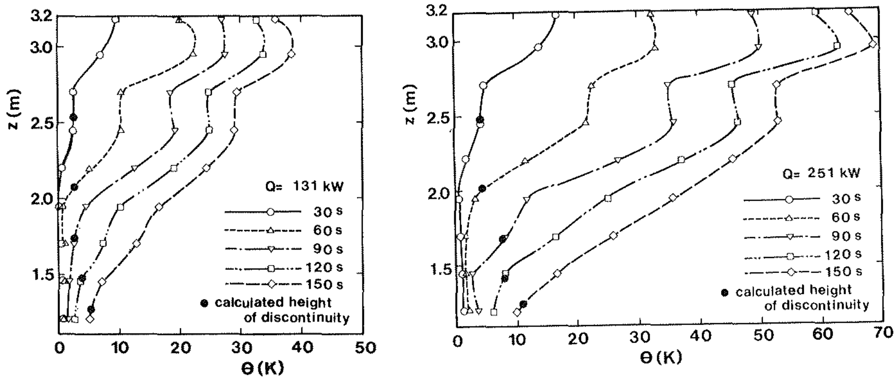
Ceiling Jets Behavior

Development of the temperature profile for four conditions is shown in Figures 5(a) ~ (d). While the discontinuity in the temperature profile is evident in laboratory-size small enclosure [6,7,8] , clear boundary between smoke layer and lower layer was not observed in the temperature profile of the present experiment. Height of the bottom of smoke layer calculated from Zukoski' et al's result on entrainment[10] is superimposed on the figure for reference; both the calculation and the smoke layer thickness suggested by the temperature distribution show that the smoke layer is generally deeper for the higher ceiling than for the lower one. It is attributed to greater entrainment for higher ceiling, and as its result, temperature within the smoke layer is generally higher for the lower ceiling than for the higher ceiling.



(a) H=2.2m, Q=119kW

(b) H=2.2m, Q=179kW



(c) H=3.2m, Q=131kW

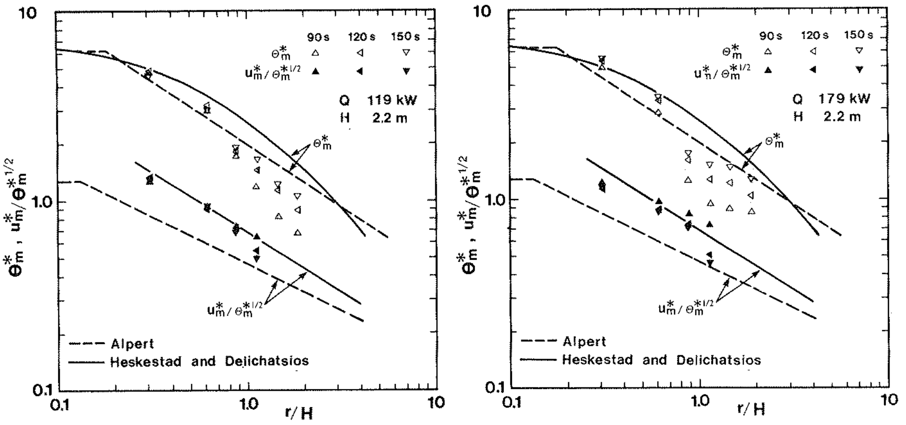
(d) H=3.2m, Q=251kW

Figure 5 Development of vertical temperature profile

For steady ceiling-jets driven by a fire plume ,distribution of temperature and velocity beneath an unconfined ceiling has been modeled by Alpert[3], and Heskestad and Delichatsios[4]. Expansion of these models for confined ceiling has been proposed by Evans[5] by correcting the location and intensity of the heat source. In his correction, ambient temperature is replaced by the smoke layer temperature, and the following dimensionless temperature and velocity are defined.

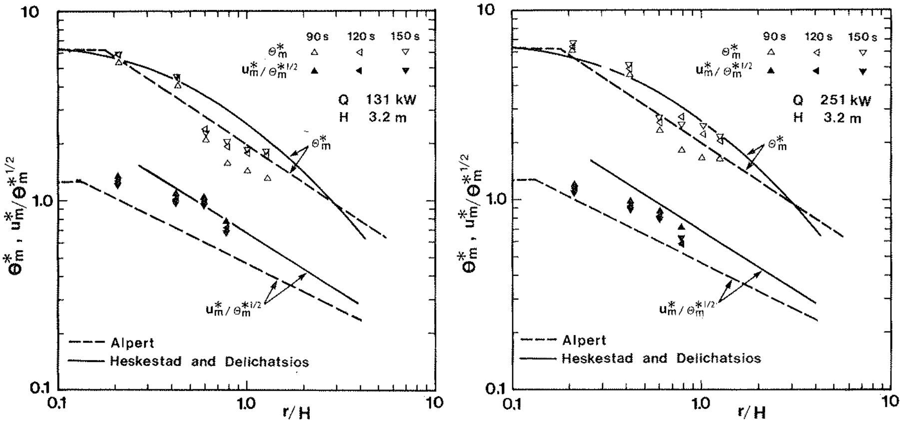
$$\theta_m^* = \theta_m (C_{po}^2 \rho_o^2 g H^5 / T_o Q_c^2)^{1/3} \quad (4)$$

$$u_m^* = u_m (C_{po} T_o \rho_o H / g Q_c)^{1/3} \quad (5)$$



(a) H=2.2m, Q=119kW

(b) H=2.2m, Q=179kW



(c) H=3.2m, Q=131kW

(d) H=3.2m, Q=251kW

Figure 6 θ_m^* and $u_m^*/\theta_m^{*1/2}$ distributions

Figures 6(a) ~ (d) show the horizontal distribution of θ_m^* and $u_m^*/\theta_m^{*1/2}$ for the present experiments. While there is considerable vertical distribution of temperature within the smoke layer, the temperature of the smoke layer is represented by its average for the ease of prediction of characteristic smoke layer temperature by a two-layer zone model[11]. The resulting correlations seem to be close to both models of Alpert, and Heskestad and Delichatsios, while temperature decreases slightly earlier with r than expected from these models. It may be noteworthy that the Evans' correction method has resulted in only a minor change of location and intensity of the heat source, less than 5% of the actual ceiling height and heat release rate. Therefore, the model of Alpert or Heskestad and Delichatsios will give a practical estimate of the environment in which a sprinkler is submerged only by using the average of smoke layer temperature instead of ambient temperature.

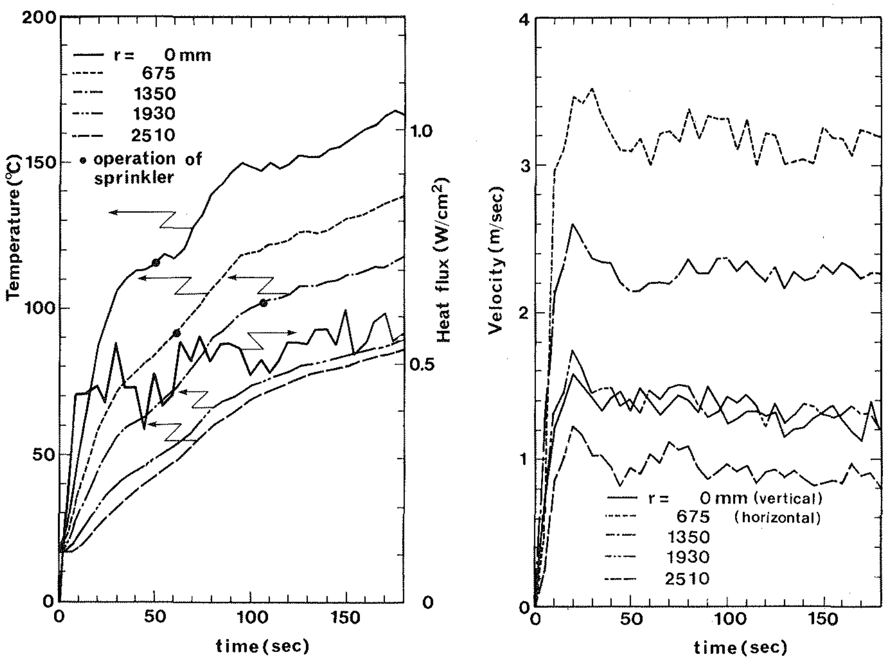


Figure 7(a) History of temperature at the location of sprinklers

(b) History of velocity at the location of sprinklers

Table 1 Measured and calculated sprinkler response time

distance from the centre	measured sprinkler response time	calculation	
		with radiation	without radiation
0 mm	51 sec	48 sec	133 sec
675 mm	60 sec	52 sec	91 sec
1,350 mm	105 sec	101 sec	129 sec
1,930 mm	186 sec	183 sec	233 sec
2,510 mm	-	-	-

Calculation of Sprinkler Response Time

Since response time of a sprinkler and environmental conditions determining the sprinkler response time are measured in the enclosure experiment for various heat release conditions, it is useful for examining the precision of the calculation method of sprinkler response time to compare the measured sprinkler response time with calculation using the quantified properties on the experimental environmental conditions. For this purpose, the data for H=3.2m and Q=251kW are chosen; however since the radiation is measured only just above the heat source($\dot{q}''_e \simeq 4.6kW/m^2$), the radiative heat flux on the other sprinklers are assumed to follow the relation obtained from previous experiments[12]. Figures 7(a),(b) shows the history of temperature and velocity at the location of each sprinkler. The convective heat transfer is calculated using these data along with the responsiveness for the normal sprinklers shown in Figure 3.

Table 1 shows the calculated temperature history of the heat sensing element. The measured time of operation for each location is compared with the calculation. In this calculation, temperature history of the heat sensing element is calculated also for the assumption that radiation is ignored. The measured sprinkler response time is much closer to the calculation with radiation than to the one without radiation.

CONCLUSIONS

In this paper, significant quantities in the determination of sprinkler response time including thermal properties of sprinkler and environmental conditions have been discussed. Although the investigation was limited to only one product of sprinkler of relatively low RTI value, the following conclusions can be drawn.

1. The influence of the conductive heat loss from the heat sensing element of a sprinkler on the determination of sprinkler response time is significant unless wind velocity around the sprinkler head is considerable high.
2. Characteristic temperature and velocity of ceiling-jets can be estimated by the conventional models of steady-state ceiling-jets below an unconfined ceiling by using temperature above the average of smoke-layer temperature instead of temperature above ambient.
3. Radiative heat transfer from fire source to the link may have a significant influence on the determination of response time of a sprinkler installed at appropriate distance suggested by usual code requirements.

ACKNOWLEDGEMENTS

The authors wish to acknowledge Mr. J. Izumi, research associate of Building Research Institute from Mitsui Homes Co., Messrs. E. Nakamura, N. Ruichi, and Y. Shimizu of Nohmi Bosai Co. for their assistance in the experiments. The authors are indebted to Messrs. K. Endo and A. Kunikawa of Nohmi Bosai Co for the arrangement for the experiment. Also the authors wish to thank Dr. T. Yamada of Fire Research Institute for technical suggestions on the measurements. This study is partly supported by the Research Program for the Development of Fire Safety Design Method for Buildings sponsored by The Ministry of Construction.

TERMINOLOGY

C : conductance
C_p : specific heat of air
C_r : parameter representing the responsiveness of sprinkler to radiation

H : ceiling height above fuel surface
Q : heat release rate
Q_c : convective fraction of heat release(assumed as 2/3Q)
RTI : response time index($\tau \cdot u^{1/2}$)
T : absolute temperature
$f_L(t)$: function representing time history of heat loss from the link of sprinkler
g : gravitational acceleration
$\dot{q}''_e$: external radiation
t : time
t_r : response time
u : radial velocity
u^*_m : normalized maximum radial velocity
θ : excess temperature
θ_{s*} : link temperature of "altered sprinkler" above ambient
θ_m : normalized maximum excess temperature at given radius
ρ : density
τ : time constant for the operation of sprinkler
$\Delta\Theta$: $\theta'_s - \theta_s$

suffix

a : air
m : maximum at given radius
o : ambient, or initial condition
s : sprinkler link
sr : sprinkler link at the operation of sprinkler

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