

Studies of Cooling Effects of Sprinkler Spray on Smoke Layer

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ABSTRACT

An experimental study was performed to measure the cooling of a smoke layer by water sprays. This was followed by the development of a mathematical model based on the theory of Chow and Tang. The predictions of the model agree well with the experimental measurements. Water sprays investigated in the present work provided significant cooling of the smoke layer. We observed little effect of increasing the water pressure from 50 to 100 kPa on the cooling of the smoke layer.

KEYWORDS: Sprinkler spray; smoke layer; heat transfer; sprinkler cooling

NOMENCLATURE LISTING

c	sprinkler flow coefficient	$S(i)$	surface area of droplet of diameter i (m^2)
c_p	specific heat of water (kJ/kg·K)	T	temperature of smoke(K)
C_{ps}	specific heat of smoke (kJ/kg·K)	$T(i)_w$	temperature of droplet of diameter i (K)
C_{ps2}	specific heat of the smoke after sprinkler operation (kJ/kg·K)	u	velocity of hot smoke (m/s)
C_d	resistance coefficient	u_0	initial horizontal component of droplet velocity (m/s)
C_m	sprinkler diameter coefficient	U	droplet velocity (m/s)
d_m	average volume diameter of droplets (μm)	U_s	smoke velocity (m/s)
d_n	nozzle inner diameter (μm)	v	droplet vertical velocity (m/s)
h	heat transfer coefficient (W/m ² ·k)	v_0	initial vertical velocity of droplet (m/s)
$h(i)$	heat transfer coefficient of droplet of diameter i (kW/m ² ·K)	V	sprinkler flow rate (m ³ /s)
i	droplet diameter (μm)	W	width of sprinkler chamber (m)
k	coefficient of thermal conductivity (W/m·K)	h	elevation of smoke layer above ground (m)
K	resistance term	H	height of sprinkler chamber (m)
m	mass of water droplet (kg)	T_f	temperature of droplet that reaches the bottom of the smoke layer (K)
m_p	mass production rate of smoke (kg/s)	ΔT	temperature difference between smoke and ambient air (K)
$m(i)$	mass of droplet of diameter i	ΔT_2	temperature difference between smoke and ambient air after sprinkler operation (K)
$N(i)$	number of droplets of	$y(i)$	probability of droplet of diameter i in log-

	diameter i		normal distribution
$Nu(i)$	Nusselt number of droplet of diameter i		
P	sprinkler pressure (MPa)		Greek
Pr	Prandtl number of air	δ	parameter in log-normal distribution of droplet sizes
Q	experimental value of sprinkler cooling (kW)	α	empirical coefficient
Q_1	energy of smoke before sprinkler operation (kW)	ρ_s	density of smoke (kg/m ³)
Q_2	energy of smoke after sprinkler operation (kW)	ρ_w	density of water (kg/m ³)
Q_c	convective heat transfer (kW)	σ_w	surface tension of water (N/m)
Q_{cx}	actual heat removed by spray (kW)	η	fraction of droplets not removed by obstructions
$Re(i)$	Reynolds number of droplet of diameter i	ν	smoke kinematic viscosity (m ² /s)
S	smoke circulation area (m ²)		

INTRODUCTION

Automatic fire sprinkler systems are increasingly used in fire protection applications. Normally, sprinklers are installed at the ceiling. When the temperature at a sprinkler head reaches a predetermined value, the thermal element in the sprinkler activates and the water discharges from a pipe. Sprinklers control fires by four mechanisms: (1) they cool down the surface of the combustible materials; (2) they wet the surrounding material and reduce the flame spread; (3) they displace air with water vapor due to evaporation; and (4) they cool hot smoke layer and reduce its radiation [1,2].

A number of studies have been performed to investigate the effects of sprinklers on the smoke produced by a fire [3-6]. Morgan [3, 4] analyzed the heat transfer between water droplets and a hot smoke layer, using a simple model. More recent work was reported by Cooper [5, 6]. Cooper focused on the behavior of the smoke layer under sprinkler spray, and developed a physical model. Studies involving numerical modeling were later conducted by Alpert [7], Hoffmann [8], Gardiner [9] and Chow [10-12].

Chow and Tang [13] also studied the heat transfer between the sprinkler spray and hot smoke layer, both theoretically and experimentally. Temperatures at different points in smoke layer were measured, but the study was not extended to predicting the heat transfer between the smoke layer and the sprinkler spray. Their model needs further full scale validations.

Starting from the theoretical analysis of Chow and Tang, in this contribution, we develop a new model for heat transfer between the hot layer and water spray. We also perform full scale experiments to validate the model.

MATHEMATICAL MODEL

Characterization of the sprinkler spray droplets properties

Water is ejected from the sprinkler orifice and impacts onto the deflector to form a spray. We employ the log-normal distribution to characterize the droplet sizes [14]:

$$y(i) = \frac{1}{i\delta\sqrt{2\pi}} \exp \left\{ - \frac{\left[\ln \left(\frac{i}{d_m} \right) \right]^2}{2\delta^2} \right\} \quad (1)$$

where $y(i)$ is droplet-size distribution function, i the droplet diameter, d_m average volume diameter of droplet, δ the deviation of the function, with the value of $0.56 \leq \delta \leq 0.78$.

The volume medium diameter of the sprinkler spray droplets is taken as [15]:

$$d_m = C_m We^{-\frac{1}{3}} d_n \quad (2)$$

where d_n is inner diameter of the nozzle, We Weber number, with the coefficient C_m taken as 2.33 for ZSTP-15 sprinkler [16,17].

The Weber number is defined as:

$$We = \frac{\rho_w U^2 d_n}{\sigma_w} \quad (3)$$

where U is the drop velocity, σ_w the surface tension of water equal to 72.8 mN/m.

Droplet velocity is taken as:

$$U = \frac{V}{\pi d_n^2 / 4} \quad (4)$$

where V is the flow rate of sprinkler.

The flow rate of sprinkler can be calculated by:

$$V = \frac{c\sqrt{10P}}{60000} \quad (5)$$

where c is the sprinkler flow coefficient, with a constant value of 80 for ZSTP-15 sprinkler, and P denotes sprinkler pressure.

The number of droplets with different diameters can be calculated by the following equation [3]:

$$N(i) = \frac{V \times y(i)}{\sum_{i=1}^N \frac{y(i)}{6} \times \pi \times i^3} \quad (6)$$

where $N(i)$ is the number of droplets whose diameter is i .

For a single droplet, in accordance with Newton's second law, Bullen [18] presented an equation for the droplet vertical velocity as:

$$mg - Kv^2 = m \frac{dv}{dt} = mv \frac{dv}{dx} \quad (7)$$

where m is the mass of a water droplet, K is resistance term, and v corresponds to the droplet vertical velocity.

By solving equation (7), one obtains the droplet vertical velocity as a function of height:

$$v^2 = \frac{mg}{K} + \left(v_0^2 - \frac{mg}{K} \right) e^{-\frac{2Kx}{m}} \quad (8)$$

where v_0 is the droplet initial velocity.

Initial horizontal velocity of sprinkler droplets is:

$$u_0 = \alpha U \quad (9)$$

where u_0 is initial horizontal velocity component, α is an empirical coefficient which is taken to be 0.4.

Initial droplet vertical velocity corresponds to:

$$v_0 = \sqrt{U^2 - u_0^2} \quad (10)$$

Resistance term can be expressed by equation:

$$K = \frac{1}{8} \rho_a C_d \pi i^2 \quad (11)$$

where ρ_a is the density of air, and C_d is drag coefficient.

C_d is obtained from

$C_d = 24\text{Re}^{1/2}$	$\text{Re} < 1$
0.6	$1 \leq \text{Re} < 1 \times 10^3$
0.47	$1 \times 10^3 \leq \text{Re} < 3 \times 10^5$
0.2	$3 \times 10^5 \leq \text{Re}$

The Reynolds number of a droplet can be expressed as:

$$\text{Re}(i) = \frac{ui}{\nu} \quad (12)$$

where $Re(i)$ is Reynolds number of a droplet of diameter i , u is the velocity of hot smoke, and ν is the kinematic viscosity of the smoke.

The Nusselt number of a sprinkler droplet of diameter i is

$$Nu(i) = 2 + (0.4 Re(i)^{0.5} + 0.06 Re(i)^{2/3}) Pr^{0.4} \quad (13)$$

Pr is the Prandtl number of the air which is taken to be 0.7.

The Nusselt number can also be expressed as:

$$Nu(i) = \frac{h(i)i}{k} \quad (14)$$

where $h(i)$ is convective heat transfer coefficient of the droplet whose diameter is i , k is coefficient of thermal conductivity of the air.

Equation(14) can also be expressed as:

$$h(i) = \frac{Nu(i) \times k}{i} \quad (15)$$

Heat transfer between droplets and smoke

For a fraction of droplets of diameter i , the energy conservation equation corresponds to [13]:

$$m(i)C_p \frac{dT(i)_w}{dt} = h(i)S(i)(T - T(i)_w) \quad (16)$$

where $m(i)$ is the mass fraction of droplets of diameter i , $T(i)_w$ the temperature of droplets of diameter i , $S(i)$ surface area of droplets of diameter i , and T the temperature of the smoke layer.

Equation 16 can be rewritten as:

$$\frac{4}{3} \pi \left(\frac{i}{2}\right)^3 \rho_w \nu C_p \frac{dT(i)_w}{dx} = \frac{kNu(i)}{i} \pi i^2 (T - T(i)_w) \quad (T(i)_w \leq 373K) \quad (17)$$

in Eq. 17, the x denotes vertically downward direction. The evolution of the temperature of a sprinkler droplet can be calculated by solving the above equation using the Runge/Kutta method.

When the temperature of a smoke layer is high, small droplets easily reach a boiling point temperature. However, in our experiments, the thickness and the temperature of the smoke layer allow only a small fraction of water droplets to reach the boiling point. For this reason, the model neglects the evaporative cooling.

The heat absorbed by a droplet of diameter i is

$$Q_c(i) = m(i)c_p(T_f - T_0)N(i) \quad (T_f \leq 373K) \quad (18)$$

where T_f corresponds to the temperature of the droplet that reach the bottom of the smoke layer. Equation 18 restricts the droplet temperature to below the boiling point. Although it is possible that very small droplets can start to boil during their passage through the smoke layer, the mass fraction of such droplets is small.

The total heat transferred from the smoke layer to spray droplets equals:

$$Q_c = \sum_{i=1}^N \frac{4}{3} \pi \left(\frac{i}{2}\right)^3 \rho_w C_p (T_f - T_0) N(i) \quad (19)$$

where Q_c is convective heat transfer, ρ_w is the density of water, C_p is the specific heat of water.

Combining Eqs. 1, 6, 8, 15, 17-19, we can calculate the heat absorbed by water droplets that pass through smoke layer characterized by given temperature and thickness.

The above calculation of the spray cooling assumes no removal of droplets by obstructions; i.e., all droplets traverse the entire smoke layer and. However, in practice, sprinklers may be located in corridors, lobbies, where substantial number of droplets are removed from the spray by collisions with walls, and do not participate in the heat exchange with the smoke layer. Therefore, the value of spray cooling calculated above needs be modified as:

$$Q_{cx} = \eta Q_c \quad (20)$$

where Q_{cx} denotes the actual heat removed by the spray, η is the fraction of droplets able to penetrate the smoke layer; i.e., the droplets that are not removed by obstructions. Since the area of the spray chamber is 8 m², and the the sprinkler coverage corresponds to 20 m² [19], we estimate the value of the parameter η to be 0.4.

EXPERIMENTS

The experimental apparatus is shown in Fig. 1. It consists of the connected combustion and sprinkler chambers. As shown in Fig. 1, pool fires were burned in the combustion chamber to generate an initial stable smoke layer in the upper region of the sprinkler chamber. The combustion chamber was 2.5 m in length, 1.22 m in width and 2.2 m in height. The opening between the combustion and sprinkler chamber was 1.22 m in width and 1.8 m in height. The dimensions of the sprinkler chamber corresponded to 4 (length) \times 2 (width) \times 2.6 (height) m. In order to ensure adequate air supply, the combustion and sprinkler chambers were equipped with vents at the bottom and side walls, as illustrated in Fig. 1. A smoke curtain with height of 2.2 m was installed below the ceiling of the sprinkler chamber to form a smoke layer of 1 m in initial thickness.

A single sprinkler was installed at the center point of the ceiling of the sprinkler chamber. Two thermocouples trees, each with 12 thermocouples, were located symmetrically 1 m away from the sprinkler. We used K-type thermocouples, 0.3 mm in diameter, and accurate to $\pm 1^\circ\text{C}$. The vertical interval between the thermocouples was 0.15 m. In order to minimize the cooling of the thermocouple by the water spray, a

thin reverse “U” shaped metal shield was installed above the thermocouples. These metal shields prevented water from the sprinkler reaching the thermocouples directly. The dimensions of the thermocouples trees are shown in Fig. 1.

ZSTP-15 sprinkler with the nozzle diameter of 12.7 mm was used for all experiments. A pressure reducing valve and a pressure transmitter were installed on the water pipe to control the operating pressure of the sprinkler with an accuracy of 0.002 MPa.

In total 16 tests were conducted with the smoke layer generated by diesel (heat of combustion of 42 MJ/kg) pool fires of four sizes. The transient mass of the fuel was measured by a weighting system with six strain gauges, capable of measuring mass of up to 60 kg. The heat release rates of the pool fires were calculated from the mass loss rates of the fuel with the combustion efficiency assumed to be 75% of that calculated from the heat of combustion. Table 1 summarized the heat release rates for all experiments. The sprinkler spray was discharged at the same time after the ignition. The total burning time of each test was about 600 s. The operating pressure of the sprinkler was set to 0.05, 0.075 or 0.1 MPa.

The heat release rate of the pool fire was measured by six fulcrum piezoelectric weighing platforms. These platforms measure the pressure changes, with the signal digitized by the data acquisition system and stored on a PC, providing records of fuel consumption as a function of time. By differentiating this signal, we calculated the instantaneous fuel mass consumption rate, and then the heat release rate of the pool fire.

Hot wire anemometer with temperature compensation was used in experiments to measure the smoke flow velocity. Scale gauge was used to measure the thickness of the smoke layer. Measurements were performed right at the opening of the sprinkler chamber. During each experiment, the smoke flow velocity and thickness were measured every 30 s. The average values during the steady-state stage of each experiment were then deduced.

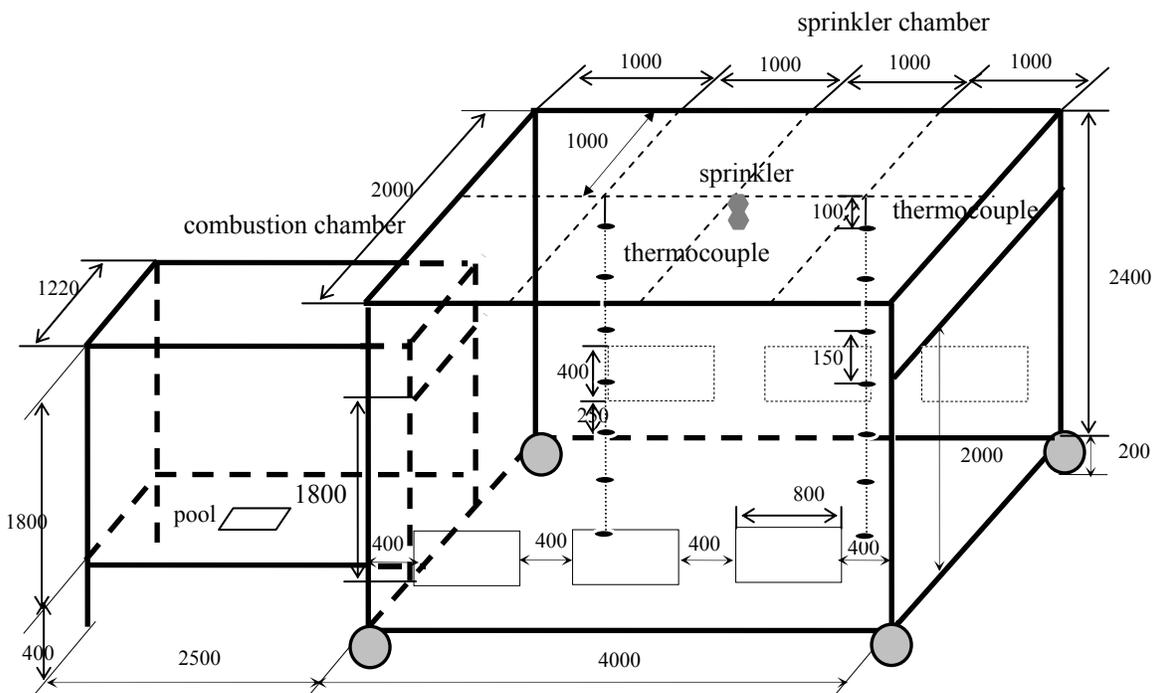


Fig. 1. Schematic diagram of the experimental rig; all dimensions are in mm.

RESULTS AND DISCUSSION

Variations of the smoke temperature

Based on the experimental observation, the upper eight thermocouples were located in the smoke layer, and the average temperature of the smoke layer was deduced from the readings of these thermocouples. Figures 2(a) - (d) present typical temperature histories of tests 1-16.

The average smoke temperature was estimated from the steady state portions of the temperature histories. For Figs. 2 (a), (b), (d), we estimated the smoke temperature from the measurements between 200 and 400 s, for Fig. 2 (c), between 100 and 300 s. For all conditions, the average smoke temperatures are listed in Fig. 3.

As shown in Fig. 3, smoke temperature decreased significantly after sprinkler operation. For 0.6×0.6 m pool fire, the average temperature rise of the smoke is 107 K without sprinkler; whereas the sprinkler spray, generated at 0.05 MPa, decreases this temperature rise to 35.2 K.

When the sprinkler pressure increases, the volume medium diameter of the sprinkler spray droplets decreases and the proportion of smaller droplets increases[15], enhancing the cooling effect of the sprinkler. For 0.5×0.5 m pool fire, and spray generated at 0.05 MPa, the average temperature rise of the smoke is 29.7 K. Likewise the average temperature rise of the smoke layer is only 20.1 K for the 0.1 MPa spray.

It can be also seen from Fig. 3 that the effect of water pressure is small. For example, for 0.3×0.3 m pool fire, and the spray pressure of 0.05 MPa, the average temperature rise of the smoke is 9.4 K, whereas for 0.1 MPa spray, the average temperature rise of the smoke is 4.9 K.

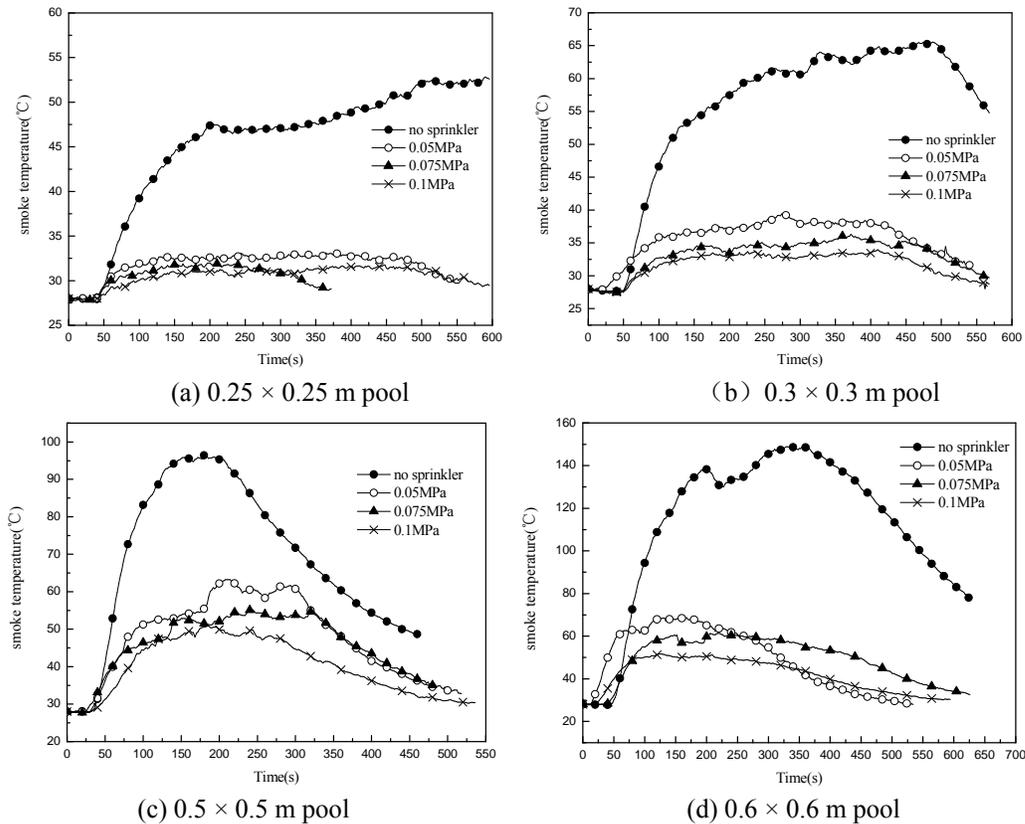


Fig. 2. Temperature variation for different pool fires

Calculating heat loss from the smoke layer to the sprinkler spray

The energy of the hot smoke layer before sprinkler operation can be expressed as:

$$Q_1 = m_p c_{ps} \Delta T = \rho_s V_s c_{ps} \Delta T = \rho_s U_s S c_{ps} \Delta T = \rho_s U_s (H - h) W c_{ps} \Delta T \quad (21)$$

where Q_1 is the energy of smoke before sprinkler operation, m_p mass production rate of smoke, c_{ps} is specific heat of smoke, ρ_s is density of smoke, ΔT is temperature difference between smoke and ambient air, U_s is smoke velocity that pass through the sprinkler chamber, S is smoke circulation area that pass through the sprinkler chamber, W is width of the sprinkler chamber, H is height of the sprinkler chamber, h is the height between smoke layer to the ground.

The energy of the hot smoke layer after sprinkler operation is:

$$Q_2 = m_p c_{ps2} \Delta T_2 = \rho_s U_s (H - h) W c_{ps2} \Delta T_2 \quad (22)$$

where Q_2 is the energy of smoke after sprinkler operation, c_{ps2} is the specific heat of the smoke after sprinkler operation, ΔT_2 is temperature difference between smoke and ambient air after sprinkler operation.

The heat loss from the smoke layer to the sprinkler spray can then be deduced from the experimentally measured temperature of the smoke layer according to:

$$Q = Q_1 - Q_2 \quad (23)$$

where Q is the experimental value for heat loss from the smoke layer to the sprinkler spray.

Comparison of analytical and experimental results

The main experimental results are summarized in Table 1, demonstrating good agreement between the measurements and the calculations, which use the values of the parameters listed in Table 2.

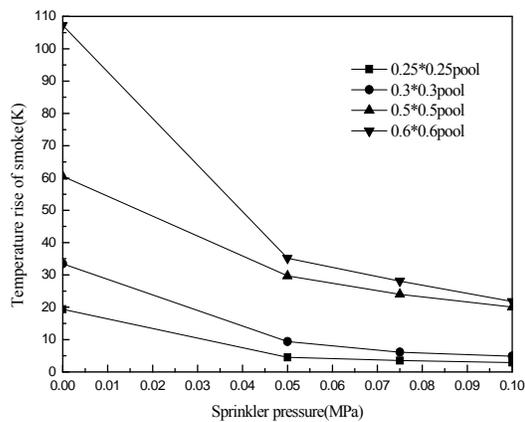


Fig. 3. Temperature rise of smoke layer versus sprinkler pressure

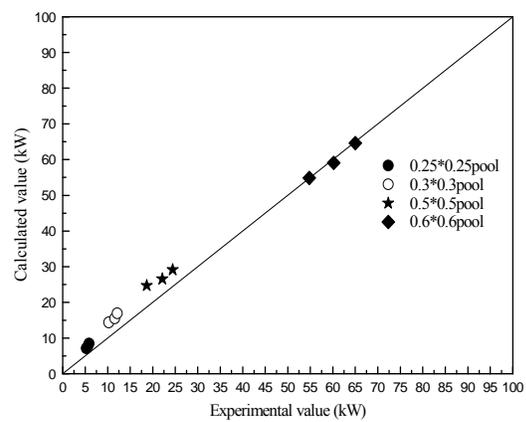


Fig. 4. Comparison of experimental and calculated smoke layer cooling

Figure 4 compares the cooling of the smoke layer calculated by Eq. 1-20 with that measured experimentally. It can be seen that the sprinkler cooling increases to some extent with the operating pressure of the sprinkler. For smaller fires, the heat losses of the smoke layer predicted by the mathematical model slightly exceed the experimental measurements. The biggest error is 46% for test 8, but for larger fires, the value obtained by the mathematical model agrees fairly well with the experimental data. For the 0.6×0.6 m pool fire, for the spray generated at 0.05 MPa, experimental value of the heat extracted by the spray is 54.8 kW and the model value is 54.9 kW.

CONCLUSIONS

We have developed a new model to calculate the heat loss from a smoke layer to a sprinkler spray. Our model is based on the theoretical analysis of Chow and Tang, applies a log-normal droplet-size distribution, function and neglects droplet boiling. A series of experiments was also conducted to verify the model. Results show that experimental measurements and calculated predictions are in good agreement. Sprinkler operation has a great effect on the smoke temperature. For the range of pressure studied in the present investigation, we found only a small effect of pressure on the cooling of the hot layer, consistent with the square root dependence of droplet diameter on pressure.

The model requires further improvement. Especially, one needs to incorporate the evaporation effect. Should this effect be included, the cooling would be more than that predicted in this study. Also, the droplet size distribution function and some parameters, derived from previous studies, need to be refined. A follow-up investigation is in progress and further results will be reported in a subsequent publication.

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Table 1. Summary of the tests

Test No.	Ambient temperature (K)	Pool size (m ²)	Heat release rate (kW)	Sprinkler operating pressure (MPa)	Height of smoke layer (m)	Smoke velocity (m/s)	Average temperature rise of the smoke layer (K)	Mass rate of smoke (kg/s)	Experimental value of sprinkler cooling (kW)
Test1	301	0.25*0.25	52.5	—	1.6	0.36	19.4	0.35	—
Test2	301	0.25*0.25	52.5	0.05	1.6	0.36	4.5	0.35	5.25
Test3	301	0.25*0.25	52.5	0.075	1.6	0.36	3.5	0.35	5.6
Test4	301	0.25*0.25	52.5	0.1	1.6	0.36	2.9	0.35	5.83
Test5	301	0.3*0.3	72	—	1.55	0.45	33.5	0.42	—
Test6	301	0.3*0.3	72	0.05	1.55	0.45	9.4	0.42	10.22
Test7	301	0.3*0.3	72	0.075	1.55	0.45	6.1	0.42	11.59
Test8	301	0.3*0.3	72	0.1	1.55	0.45	4.9	0.42	12.13
Test9	301	0.5*0.5	145	—	1.5	0.67	60.5	0.6	—
Test10	301	0.5*0.5	145	0.05	1.5	0.67	29.7	0.6	18.67
Test11	301	0.5*0.5	145	0.075	1.5	0.67	24.0	0.6	22.15
Test12	301	0.5*0.5	145	0.1	1.5	0.67	20.1	0.6	24.46
Test13	301	0.6*0.6	228	—	1.4	0.75	107	0.75	—
Test14	301	0.6*0.6	228	0.05	1.4	0.75	35.2	0.75	54.8
Test15	301	0.6*0.6	228	0.075	1.4	0.75	28.1	0.75	60.2
Test16	301	0.6*0.6	228	0.1	1.4	0.75	21.8	0.75	65.02

Table 2. Input parameters of the model and results of the calculation

Test No.	Density of smoke (kg/m ³)	Coefficient of thermal conductivity of the smoke (W/m·K)	Specific heat of smoke (kJ/kg·K)	Prandtl number of the air	Kinematical viscosity coefficient of smoke (m ² /s)	Flow rate of the sprinkler (L/s)	Volume medium diameter of the droplets (μm)	Model value of the sprinkler cooling (kW)	Error (kW / %)
Test1	1.095	0.0000278	1.008	0.7	0.000018	—	—	—	—
Test2	1.095	0.0000278	1.007	0.7	0.000018	0.94	1390	7.12	1.87/36
Test3	1.095	0.0000278	1.007	0.7	0.000018	1.15	1220	7.72	2.12/38
Test4	1.095	0.0000278	1.007	0.7	0.000018	1.33	1100	8.48	2.65/46
Test5	1.045	0.0000289	1.008	0.7	0.000019	—	—	—	—
Test6	1.045	0.0000289	1.007	0.7	0.000019	0.94	1390	14.36	4.14/41
Test7	1.045	0.0000289	1.007	0.7	0.000019	1.15	1220	15.48	3.89/34
Test8	1.045	0.0000289	1.007	0.7	0.000019	1.33	1100	16.96	4.83/40
Test9	0.9702	0.000031	1.01	0.7	0.000022	—	—	—	—
Test10	0.9702	0.000031	1.008	0.7	0.000022	0.94	1390	24.68	6.01/32
Test11	0.9702	0.000031	1.008	0.7	0.000022	1.15	1220	26.56	4.41/20
Test12	0.9702	0.000031	1.008	0.7	0.000022	1.33	1100	29.12	4.66/19
Test13	0.8556	0.0000352	1.0154	0.69	0.000029	—	—	—	—
Test14	0.8556	0.0000352	1.008	0.69	0.000029	0.94	1390	54.88	0.08/0.1
Test15	0.8556	0.0000352	1.008	0.69	0.000029	1.15	1220	59.04	-1.16/-2
Test16	0.8556	0.0000352	1.008	0.69	0.000029	1.33	1100	64.64	-0.38/-0.6

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