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# Extinguishment of a PMMA fire by water spray with high droplet speeds

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**Abstract**

A thermal model was developed to study the extinguishment of a polymethyl methacrylate (PMMA) fire by water spray with droplet speeds high enough to travel through the plume and the flaming region. Suppression mechanisms involving fuel surface cooling, flame cooling and oxygen displacement were considered. The critical fraction of total heat released that was transferred back to the fuel surface was taken as the critical condition for solid fire extinguishment. The effects of droplet size and velocity, external radiant heat flux and specimen configuration on fire suppression were investigated. The results indicate that larger droplets would reach the fuel surface and surface cooling would play a dominating role. Smaller droplets would absorb heat from the flame and evaporate to reduce the critical fraction of total heat released at extinction as a flame extinguishing agent. This might result in a critical water application rate, above which the flame can no longer be sustained even under a high external heat flux as in real fires. Therefore, spray containing a variety of droplet sizes would perform better than a uniform spray in extinguishing PMMA fires under a high external radiant heat flux.


*Keywords:* Water spray; PMMA; Fire extinguishment; Thermal model; Critical fraction

## 1. Introduction

Extensive use of plastics in buildings has raised the concern on fire hazard [1,2]. Polymethyl methacrylate (PMMA) is one of the plastic materials widely used in buildings. A better understanding of extinguishing a real PMMA fire would help in designing suitable fire control systems. Water is widely used for fire control with fire hydrant and hose reel systems required in almost all buildings [3]. Automatic sprinkler systems are required in most of the non-residential buildings as the system is believed to be effective in controlling solid fires [4]. Also, fine water spray (water mist) has been used for suppressing solid fires in recent years [5]. Experimental and numerical investigations have been conducted on plastic fire extinguishment by water spray [6–9].

Interactions of applied water spray with a burning surface are complicated and depend on many factors including spray and surface characteristics. For larger droplets from a water spray such as those discharged by a sprinkler, temperature of the droplets will not be affected significantly by the fire plume and flame because of weak convective heat transfer. They can reach the burning surface and cooling will play a dominant role in solid fire suppression. However, for smaller droplets such as those discharged from a water mist system, some of them might be evaporated while traveling through the flame and some remaining droplets might still reach the fuel surface. Flame cooling and oxygen displacement caused by water mist will be important in fire suppression, and should be considered together with surface cooling although the latter plays the dominating role for solid fire extinguishment.

Zone models [10] and field models [11] are both widely used for fire research and each of them has its own benefits and problems. Rapid development of information technology, both hardware and software, makes it possible to carry out detailed three-dimensional simulations of coupled radiation and hydrodynamics flows. However, there is still

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**Nomenclature**

| | |
|---|---|
| $A_{di}$ | surface area of the $i$th water droplet |
| $c_p$ | specific heat of the combustion products |
| $c_{pg}$ | specific heat of the flame gas |
| $c_{pl}$ | specific heat of the liquid water |
| $c_{pv}$ | specific heat of the water vapor |
| $C_{xi}$ | drag coefficient of the $i$th water droplet |
| $D_i$ | diameter of the $i$th water droplet in the spray |
| $D_f$ | fuel surface diameter |
| $g$ | acceleration due to gravity |
| $h$ | convective heat transfer coefficient from the flame to the fuel surface |
| $h_i$ | convective heat transfer coefficient from the flame to the $i$th droplet |
| $k$ | proportional factor |
| $k_g$ | thermal conductivity of the flame gas |
| $L_f$ | flame height |
| $L_V$ | effective heat of fuel gasification |
| $L_w$ | effective cooling heat of water |
| $\dot{m}''_f$ | fuel mass flux at the fuel surface |
| $\dot{m}''_{f,cr}$ | critical fuel mass flux at extinction |
| $\dot{m}''_w$ | mass flux of water spray after traveling through the flame |
| $\dot{m}''_{wo}$ | mass flux of water spray before traveling through the flame |
| $Nu_i$ | Nusselt number of the $i$th water droplet |
| $Pr$ | Prandtl number |
| $q_e$ | latent heat of water vaporization |
| $\dot{q}''_0$ | net heat flux to the fuel surface |
| $\dot{q}''_e$ | external radiant heat flux to the fuel surface |
| $\dot{q}''_{fc}$ | convective heat flux from the flame to the fuel surface |
| $\dot{q}''_{fr}$ | radiant heat flux from the flame to the fuel surface |
| $\dot{q}''_{rr}$ | heat flux from the surface due to re-radiation |
| $\dot{Q}_c$ | heat release rate |
| $r$ | mass based stoichiometric fuel to air ratio |
| $Re_i$ | Reynolds number of the $i$th water droplet |
| $U_{di}$ | velocity of the $i$th water droplet |
| $U_g$ | flame gas velocity |
| $V_{di}$ | volume of the $i$th water droplet |
| $t$ | time |
| $T_0$ | initial temperature of the reactants prior to combustion |
| $T_{AFT}(SL)$ | adiabatic flame temperature at stoichiometric limit |
| $T_b$ | boiling temperature of liquid water |
| $T_{di}$ | temperature of the $i$th water droplet |
| $T_g$ | temperature of the flame gas |
| $Y_{O_2}$ | oxygen mass fraction in air stream |
| $Y_{O_2,\infty}$ | ambient oxygen mass fraction |
| $Y_v$ | mass fraction of the water vapor in air stream |
| $z$ | distance along the water spray axis |

*Greek symbols*

| | |
|---|---|
| $\Delta H_c$ | combustion heat of the fuel volatiles |
| $\Delta H_R(O_2)$ | heat of reaction of oxygen |
| $\phi$ | critical fraction of the total heat released that was transferred back to the fuel surface |
| $\phi_{SL}$ | fraction of the enthalpy of reaction that can be lost before extinction at stoichiometric limit |
| $\mu_g$ | dynamic viscosity of the flame gas |
| $\rho_g$ | density of the flame gas |
| $\rho_l$ | density of the liquid water |

difficulty in applying field models for predicting such complicated phenomena because turbulence, radiation, and combustion including thermal decomposition of polymers with fire extinguishing agents should be considered together [12, 13]. Further, the effects of water spray on flame radiation and decomposition process of most polymers are not clearly understood. To fill up this gap between analytical investigation and empirical criteria for fire suppression, some models have been developed and proposed to obtain the critical conditions of pyrolysis rate and water mass flux under the applied external heat flux [9,14,15].

A unified model of fire suppression has been developed by Beyler [14] as an engineering tool to evaluate the critical conditions to sustain the piloted ignition and extinguish the existing flame. This work was based on the fire point equation developed by Rasbash [15]. The model can be applied to study the suppression effect of agents including gaseous agents and dry powder on given materials. Results are useful to select the most appropriate agent for a given scenario. Both the effects of surface cooling by water spray and the reduction of heat feedback to the burning surface by flame extinguishing agents (such as gaseous agent) were considered respectively in this model [14]. The critical fraction of total heat released that was transferred back to the fuel surface to support the critical fuel mass flux was employed as the critical condition for fire extinguishment to simplify the complicated combustion reaction. Note that in applying the model by Beyler to study a water-based fire extinguishing agent through fuel surface cooling, this critical fraction was taken as a fuel property only. However, this critical fraction would be reduced when the fire was suppressed by the flame extinguishing agents. Water spray was considered as a group of large droplets which can reach the fuel surface. Only a small amount is evaporated in flame and so evaporation effect on the reduction of the critical fraction is negligible. However, for small water droplets as discussed earlier, significant amount of water would be evaporated in the flame. The water vapor would act as a flame extinguishing agent through heat capacity and dilution effects on the determination of the critical fraction. Therefore, the model by Beyler is not applicable for studying water mist.

In studying fire suppression by water mist, the reduction of the critical fraction due to evaporation should be considered carefully. For example, evaporation effect can be linked with surface cooling to give better prediction on the minimum water application rate required for fire extinction. However, the fire point equation in Beyler's model is applicable for the flame extinguishing agents including water mist. Actually, extinguishment of gaseous and liquid hydrocarbon fire by water mist can be achieved by thermal effects in the flame. This can be analyzed by the method developed by Beyler for flame extinguishing agents on the basis of thermal and chemical effects [14]. The two suppression effects as fuel surface cooling and flame extinguishment can be considered at the same time for PMMA fire. The key point lies in how the critical fraction and the critical fuel mass flux at the burning surface at extinction can be determined.

Based on the model by Beyler and the conservation equations of momentum, mass and heat transfer between the droplet and the hot gas [16–20], a simple thermal model was developed in this paper to study the critical water application rate under applied external radiant heat flux. This model is applicable not only for sprinkler water spray with larger droplets, but also for water mist with fine droplets by combining effects due to oxygen displacement, gas phase and fuel surface cooling. To simplify the physical picture, only water spray with high droplet speeds was considered. This is consistent with practical applications where droplet speed is high to overcome the plume effect. Water discharged can then penetrate through the plume and flaming region to reach the burning surface. Evaporation effect will be simplified and the complex chemical reaction of water vapor in the flaming region can be neglected. Practically, this model is applicable for nozzles discharging water droplets with high enough droplet speeds, such as from high-pressure nozzles.

Key equations developed in the literature for studying some gaseous fire extinguishers were used in the present model to describe the similar effects of water mist on flame extinguishment. Useful design guidelines can be worked out for suppressing a polymer fire through this study. PMMA fire was selected for present paper and other types of polymers will be considered for further research.

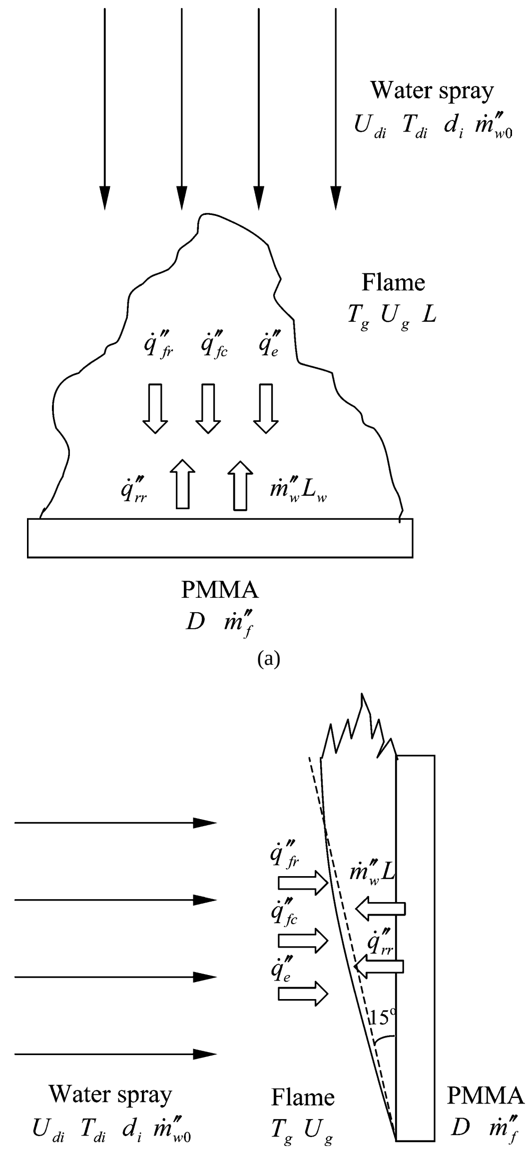


Fig. 1. Physical picture for PMMA specimen (a) horizontal orientation, (b) vertical orientation.

## 2. Assumptions made on the model

The physical picture of the problem to be solved is shown in Fig. 1. The following basic assumptions are made on the developed model:

- At extinction, the critical fraction of the total heat released can be modeled by making use of an analogy between limit premixed flames and limit diffusion flames, as described in the literature [14]. Near extinction, the flame heat losses are dominated by the convection to the fuel surface [13–15].
- The combustion is considered as the stoichiometric air-fuel ratio before applying a water spray [14]. The mass based stoichiometric fuel to air ratio (the water vapor generated is included in the air stream) before and after the application are equal for a given fuel. This value can be estimated by the combustion heat of the fuel volatiles and the heat of reaction of oxygen, while the latter can be taken as constant for most organic fuels, i.e., 13.1 MJ·kg$^{-1}$ [21]. For PMMA, this value is 12.97 MJ·kg$^{-1}$.
- To simulate real fire conditions, the external radiant heat is employed to enhance the burning rate of the small-scale PMMA specimen. The specimen is thermally thick enough to give a steady burning. The burning surface

temperature remains constant before and after applying the water spray in order to estimate the heat flux from the fuel surface due to re-radiation. Experimental data suggested the value to be about 643 K [9].

- The flame is taken as a uniform hot gas zone and can be described by the ideal gas law. The maximum value of the flame thickness and temperature are employed to simulate the interaction of water droplet and hot gas to investigate the critical conditions. Water vapor evaporated in the flame is assumed to mix with hot gas immediately. The minimum droplet velocity relative to the maximum flame velocity was assumed to be 2.5 $\text{m}\cdot\text{s}^{-1}$ (from the engineering relation for fire plume due to Heskestad [22]) since this parameter was unavailable from the experimental data. In addition, how velocity will affect the critical water application rate is also investigated in this paper.
- The spray axis is perpendicular to the fuel surface. The water droplets are considered as spheres. The interaction between droplets is neglected. The radiant heat attenuation by water droplets and vapor is neglected in this model as the droplet size considered is larger than 100 µm. As reported in the literature [23], thermal radiation would only be significant for very small droplets of diameter less than 30 µm. The forced convective heat transfer from the flame to the droplet increases initially the droplet temperature because evaporation effect is negligible. Upon reaching the boiling temperature, the droplets will be evaporated. Other water droplets not yet evaporated will reach the fuel surface to reduce the fuel pyrolysis rate by cooling. The movement and evaporation processes are taken as quasi-steady.
- If the fuel specimen is vertically located, the horizontal flame thickness will affect the spray movement and heat transfer, and the thickness can be estimated by the thermal boundary layer method for wall fires. To simplify the model, the flame boundary can also be assumed with an fixed angle, say 15°, to the vertical axis (see Fig. 1(b)), by making use of an analogy to the plume angle due to buoyancy since there is no available correlation so far [22,24]. The maximum flame thickness was used to calculate the minimum water application rate required for fire extinguishment. Actually, the thickness for vertical flame is smaller than that for horizontal flame. Effect of the flame velocity on water drop movement is not so significant. The above assumptions are therefore acceptable.

Note that in the present model, the water vapor generated would act as a flame extinguishing agent through thermal and dilution effects to reduce the critical fraction at the same time. This is different from Beyler's model, where the flame and droplet characteristics were neglected. There, water spray of large droplets was considered to cool the fuel surface only. Thermal effect on flame extinguishment through reduction of the critical fraction was not included. Such effect would play an important role and cannot be neglected for water mist, due to the large amount of water vapor generated.

## 3. Key equations

Key equations are listed as flame equation, heat balance at the burning surface, critical fraction of total heat released, and equations of motion for the water droplets.

### 3.1. Flame height

For horizontally located specimen, the flame height $L_f$ can be estimated by [22]:

$$L_f = 0.23\dot{Q}_c^{2/5} - 1.02D_f \tag{1}$$

where $\dot{Q}_c$ is the total heat release rate (kW) and $D_f$ is the fuel surface diameter (m).

### 3.2. Heat balance at the burning surface

From the fire point equation [15], the heat balance at the burning surface at extinction can be described as:

$$\dot{q}''_{fr} + \dot{q}''_{fc} + \dot{q}''_e = \dot{q}''_{rr} + \dot{m}''_f L_V + \dot{m}''_w L_w \tag{2}$$

where $\dot{q}''_{fr}$ and $\dot{q}''_{fc}$ are the radiant and convective heat flux from the flame to the fuel surface, $\dot{q}''_e$ is the external heat flux to the fuel surface, $\dot{q}''_{rr}$ is the heat loss flux from the surface due to re-radiation, $\dot{m}''_f$ is the mass flux of fuel at the surface, $\dot{m}''_w$ is the mass flux of water spray at the surface, $L_V$ and $L_w$ are the effective heat of fuel gasification and of water cooling respectively. $L_w$ consists of both the latent heat of water evaporation and the heat to increase droplet temperature. For a horizontal sample, the heat to increase the water vapor from boiling temperature to flame temperature will be included in $L_w$.

As reported in the literature [6], the net heat flux to the surface (denoted as $\dot{q}''_0 = \dot{q}''_{fr} + \dot{q}''_{fc} - \dot{q}''_{rr}$) remains relatively constant and can be determined experimentally before applying the water spray. Taking $\phi$ as the critical fraction of heat loss that was transferred back to fuel surface before extinction,

$$\dot{q}''_{fr} + \dot{q}''_{fc} = \phi\Delta H_c \dot{m}''_{f,cr} \tag{3}$$

and

$$\dot{q}''_0 + \dot{q}''_e = \dot{m}''_{f,cr} L_V + \dot{m}''_w L_w \tag{4}$$

where $\dot{m}''_{f,cr}$ is the critical fuel mass flux at extinction, and $\Delta H_c$ is the combustion heat of the fuel volatiles. $\Delta H_c$ and $\Delta H_R(O_2)$ can be correlated by:

$$r = \frac{\Delta H_R(O_2) Y_{O_2,\infty}}{\Delta H_c} \tag{5}$$

where $\Delta H_R(O_2)$ is the heat of reaction of oxygen, $Y_{O_2,\infty}$ is the ambient oxygen mass fraction, and $r$ is the mass based stoichiometric fuel to air ratio.

The critical mass flux of fuel at extinction is determined by the convective heat feedback to the surface and can be given by [14]:

$$\dot{m}''_{f,cr} = \frac{h}{c_p} \ln\left[1 + \frac{Y_{O_2} \Delta H_R(O_2)}{\phi \Delta H_c}\right] \tag{6}$$

In the above equation, $c_p$ is the specific heat of the combustion products, $Y_{O_2}$ is the oxygen mass fraction in the air stream, and $h$ is the convective heat transfer coefficient from the flame to the fuel surface. $h$ might be taken as a constant for a particular material and fuel surface configuration [14]. This value can be estimated from correlations derived from free convection of external flow geometries [24]. Two methods were used to estimate $h$ in this paper:

*Method A:* Correlations [24] for external flow geometries and Grashof number from free convection are used.
*Method B:* Empirical values are used directly by taking $h$ to be independent of the fuel surface diameter $D$ for turbulent conditions, and proportional to $D^{-1/4}$ for laminar conditions [8].

Introducing Eq. (6) to Eq. (4) would give

$$\dot{q}''_e - \dot{m}''_w L_w = \frac{L_V h}{c_p} \ln\left[1 + \frac{Y_{O_2} \Delta H_R(O_2)}{\phi \Delta H_c}\right] - \dot{q}''_0 \tag{7}$$

Note that lower critical fraction of heat loss would result in larger critical mass flux of fuel at extinction. Therefore, less water application rate is required for fire extinguishment under a fixed external radiant heat flux.

### 3.3. Critical fraction of total heat released due to water spray application

Before applying a fire extinguishing agent, as discussed in the literature [14], using the analogy between limit premixed flames and diffusion flames as assumed would give an expression for the critical fraction of heat loss before extinction $\phi_0$:

$$\phi_0 = k\phi_{SL} = k\left[1 - \frac{(1+r)c_p(T_{AFT}(SL) - T_0)}{\Delta H_R(O_2) Y_{O_2,\infty}}\right] \tag{8}$$

where $\phi_{SL}$ is the fraction under stoichiometric limit, $k$ is a coefficient and normally taken as 0.6, $T_0$ is the initial temperature of the reactants prior to combustion, $T_{AFT}(SL)$ is the adiabatic flame temperature (for most fuels, this is about 1700 K).

Under the action of water spray, water vapor generated from the water droplets heated up by convection would act as a flame extinguishing agent through thermal effect to reduce the critical fraction. If effect of water vapor is not yet significant, the critical fraction would not change as considered in Beyler's model. But when more water vapors were generated, most heat would be absorbed from the flame to reduce the oxygen fraction and increase the heat capacity of the combustion products. Therefore, the critical fraction $\phi$ would be affected as:

$$\begin{aligned}\phi &= k\big[1 - \big\{(1+r)c_p\big(T_{AFT}(SL) - T_0\big) + q_e Y_v \\ &\quad + (c_{pv} - c_p)\big(T_{AFT}(SL) - T_b\big)Y_v\big\} \\ &\quad \times \big\{\Delta H_R(O_2) Y_{O_2,\infty}(1 - Y_v)\big\}^{-1}\big] \\ &= \left\{\phi_0 - kY_v\left[1 + \frac{q_e + (c_{pv} - c_p)(T_{AFT}(SL) - T_b)}{\Delta H_R(O_2) Y_{O_2,\infty}}\right]\right\} \\ &\quad \times (1 - Y_v)^{-1}\end{aligned} \tag{9}$$

where $c_{pv}$ is the specific heat of water vapor, $q_e$ is the latent heat of water vaporization, and $Y_v$ is the mass fraction of water vapor in air stream. $Y_v$ can be expressed as:

$$Y_v = \frac{\dot{m}''_{wo} - \dot{m}''_w}{\dot{m}''_{f,cr}/r} \tag{10}$$

where $\dot{m}''_{wo}$ and $\dot{m}''_w$ are the mass flux of water spray before and after traveling through the flame. Note that the smaller drop size and velocity, the larger the mass fraction of water vapor and the smaller critical fraction of heat loss.

Introducing Eq. (9) into Eq. (7) would give the heat balance equation at extinction under water spray application

$$\begin{aligned}&\dot{q}''_e - \dot{m}''_w L_w \\ &\quad = \frac{L_V h}{c_p} \ln\Big[1 + \big\{Y_{O_2} \Delta H_R(O_2)(1 - Y_v)/\Delta H_c\big\}\Big\{\phi_0 \\ &\quad\quad - kY_v\left[1 + \frac{q_e + (c_{pv} - c_p)(T_{AFT}(SL) - T_b)}{\Delta H_R(O_2) Y_{O_2,\infty}}\right]\Big\}^{-1}\Big] \\ &\quad\quad - \dot{q}''_0\end{aligned} \tag{11}$$

It can be seen from Eq. (9) that the critical fraction would be decreased by the water spray before extinction by producing water vapor. As shown in Eq. (7) or (11), if $\phi$ reaches 0 when large amount of water is applied, the right-hand side of the equation will tend to infinity. That means the flame will not be sustained any more, even under a high external heat flux. This point is quite important for extinguishing a solid fire with fine water spray to prevent combustible fuel gas from ignition.

### 3.4. Equations for description of water droplets

The droplet size distribution can be described by a finite number, say 4 or 5, of size classes. The droplet number for each class size can be determined by integrating droplet distribution function in a quasi-steady condition as discussed in the literature [20]. The production of water vapor can be calculated by comparing the mass flux of water spray before and after traveling through the flame. The mass flux of water spray can be calculated by drop size and velocity.

The equation of motion for the $i$th water droplet in the flame can be described as:

$$\frac{dU_{di}}{dt} = \left[\frac{\rho_l - \rho_g}{\rho_l} g - \frac{3}{4}\frac{\rho_g}{\rho_l}\frac{C_{xi}}{D_i}|U_{di} - U_g|(U_{di} - U_g)\right] \tag{12}$$

where $U_{di}$ and $U_g$ are the velocity of the $i$th droplet and the flame gas velocity respectively; $t$ is the time; $D_i$ is the diameter of the $i$th droplet; $\rho_l$ and $\rho_g$ are the density of the liquid water and the flame gas respectively; $C_{xi}$ is the drag coefficient and $g$ is the acceleration due to gravity. For horizontal water spray, the item for gravity can be taken as 0 since only these spray reaching fuel surface are concerned.

The drag coefficient can be correlated by Reynolds number [25]:

$$C_{xi} = \begin{cases} \frac{24}{Re_i} & 0 \leqslant Re_i \leqslant 0.2 \\ \frac{24}{Re_i} + 5.48Re_i^{-0.573} + 0.36 & 0.2 < Re_i \leqslant 1000 \\ 0.44 & 1000 < Re_i \leqslant 1 \times 10^5 \end{cases} \tag{13}$$

The Reynolds number $Re_i$ is defined from the relative velocity between the $i$th droplet and the hot gas:

$$Re_i = \frac{D_i|U_{di} - U_g|\rho_g}{\mu_g} \tag{14}$$

where $\mu_g$ is the dynamic viscosity of the flame gas.

As assumed, the convective heat transfer between the $i$th droplet and the flame can be expressed as [13]:

$$\begin{aligned} &\rho_l V_{di} c_{pl} \frac{dT_{di}}{dt} = h_i A_{di}(T_g - T_{di}), \quad T_{di} < T_b \\ &D_i \frac{dD_i}{dt} = -\frac{2k_g}{c_{pg}\rho_l} Nu_i \ln\left[c_{pg}(T_g - T_{di})/q_e + 1\right] \\ &\quad T_{di} = T_b \end{aligned} \tag{15}$$

where $V_{di}$ and $A_{di}$ are the volume and surface area of the $i$th water droplet respectively; $T_{di}$ and $T_g$ are the temperature of the $i$th water droplet and the flame gas respectively; $T_b$ is the boiling temperature of water; $c_{pl}$ and $c_{pg}$ are the specific heat of the liquid water and the flame gas respectively; $k_g$ is the thermal conductivity of flame gas; $h_i$ is the convective heat transfer coefficient from the flame to the $i$th droplet, which can be evaluated using:

$$Nu_i = \frac{h_i D_i}{k_g} = 2.0 + Re_i^{1/2} Pr^{1/3} \tag{16}$$

where $Nu_i$ and $Pr$ are the Nusselt number and Prandtl number of the gas.

As the evaporation process is assumed to be quasi-steady, the variables of water droplet are only dependent on the distance $z$ traveling through the flame. Eqs. (12)–(15) can be further rewritten as:

$$U_{di} \frac{dU_{di}}{dz} = \left[\frac{\rho_l - \rho_g}{\rho_l} g - \frac{3}{4} \frac{\rho_g}{\rho_l} \frac{C_{xi}}{D_i} |U_{di} - U_g|(U_{di} - U_g)\right] \tag{17}$$

and

$$\begin{aligned} &\rho_l c_{pl} D_i^2 U_{di} \frac{dT_{di}}{dz} = 6k_g Nu_i (T_g - T_{di}), \quad T_{di} < T_b \\ &c_{pg}\rho_l D_i U_{di} \frac{dD_i}{dz} \\ &\quad = -2k_g Nu_i \ln\left[c_{pg}(T_g - T_{di})/q_e + 1\right], \quad T_{di} = T_b \end{aligned} \tag{18}$$

The above set of equations is a complete system of coupled first order ordinary differential equations. It can be solved numerically using a $z$ marching Runge–Kutta scheme of the fourth order to give the water spray characteristics reaching the burning surface. Computed droplet temperature, diameter and velocity can be used to calculate the production rate of water vapor. With those results, the critical fraction of heat loss and the surface cooling effect can be estimated.

## 4. Simulation conditions

Numerical simulations using the present model were carried out with the available experimental data of PMMA fire extinguishment by water sprays. The calculation procedure flowchart is shown in Fig. 2. Two fuel configurations as described in the literature [6] were studied in this paper: the turbulent burning of a vertical wall and a pool fire. The specimens for burning vertically were 17.8 cm wide × 35.6 cm high × 5 cm thick, and those for burning horizontally were 17.8 cm × 17.8 cm × 5 cm. The specimens were thermally thick enough to keep quasi-steady burning. Radiant heaters were employed to enhance the burning rate to simulate the

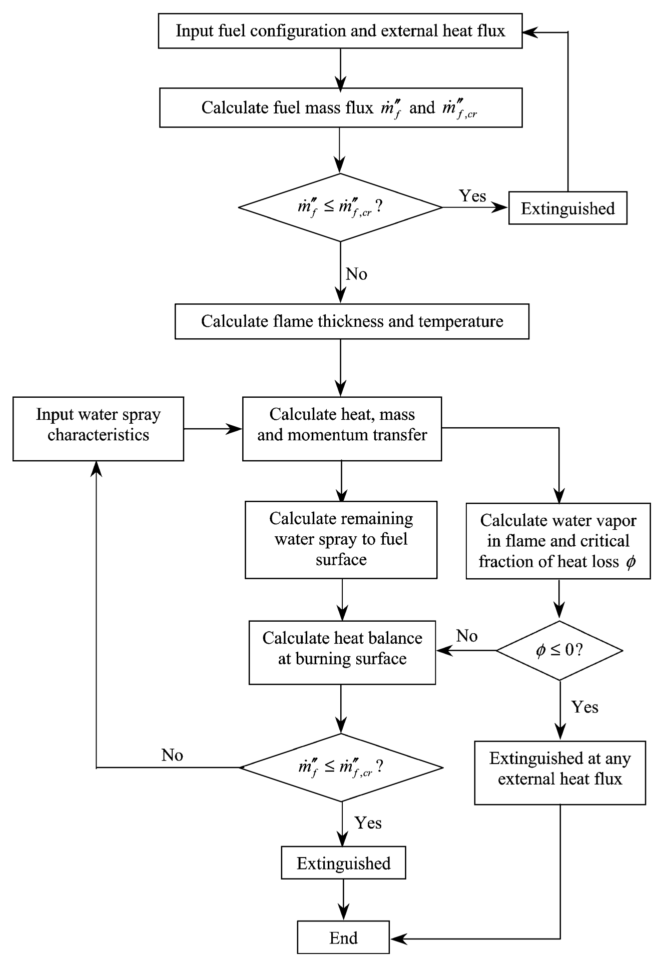


Fig. 2. Calculation procedure flowchart for studying PMMA fire extinguishment by water spray.

Table 1
The ratio of droplet number and water application rate for each class of droplet size based on droplet distribution

| | Ratio | Class 1 size 1000 μm | Class 2 size 600 μm | Class 3 size 200 μm | Class 4 size 100 μm |
|---|---|---|---|---|---|
| Spray 1 VMD 800 μm | Number ratio | 0.3679 | 0.5146 | 0.1109 | 0.0066 |
| | Volume ratio | 0.7665 | 0.2316 | 0.0018 | 0.0000 |
| Spray 2 VMD 250 μm | Number ratio | 0.0000 | 0.0166 | 0.7891 | 0.1943 |
| | Volume ratio | 0.0000 | 0.3558 | 0.6249 | 0.0192 |
| Spray 3 VMD 150 μm | Number ratio | 0.0000 | 0.0000 | 0.3679 | 0.6321 |
| | Volume ratio | 0.0000 | 0.0000 | 0.8232 | 0.1768 |

real fire scenarios. The experimental data of heat of fuel gasification from the literature [6] were 1508 kJ·kg$^{-1}$ for burning vertically and 1773 kJ·kg$^{-1}$ for burning horizontally. The external radiant heat flux was up to 30 kW·m$^{-2}$. The burning rates without external heat flux were 5.6 g·m$^{-2}$·s$^{-1}$ for burning vertically and 7.7 g·m$^{-2}$·s$^{-1}$ for burning horizontally. Other main physical properties of PMMA specimens used in the numerical experiments were: combustion heat of fuel volatiles 24900 kJ·kg$^{-1}$; mass based stoichiometric fuel to air ratio 0.12; and flame temperature 1260 K.

The diameter of the uniform spray ranged from 100 to 2000 μm. An investigation on the effects of relative droplet velocity was also conducted and the value ranged from 2.5 to 12.5 m·s$^{-1}$. In practical application, the water spray may contain a variety of droplet sizes, and the comparisons between a practical spray and a uniform spray were conducted in this paper. For a practical spray, 4 classes of typical droplet sizes were selected to represent the whole spray, i.e., 1000, 600, 200 and 100 μm. The volume mean diameter (VMD) was used to describe the size characteristics and number of each class of droplet size was predicted by the droplet distribution function. The sprays with VMD of 800, 250 and 150 μm were selected, and the droplet number and water application rate for each class of typical droplet size are shown in Table 1. Note that the values have been normalized by the total droplet number and water application rate respectively.

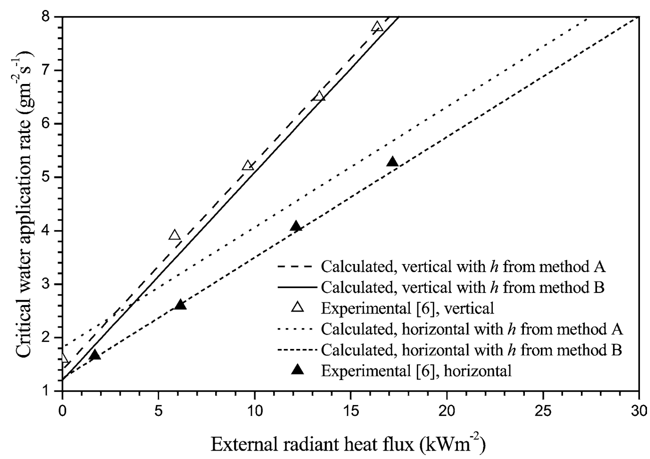


Fig. 3. Critical water application rate versus external radiant heat flux for PMMA (Droplet size: 1300 μm).

## 5. Results and discussion

Since the external radiant heat was applied to enhance the burning rate of the small-scale PMMA specimens to simulate a real fire, water application rate required for fire extinguishment would increase with the external radiant heat flux. The predicted and experimental critical water application rates for both vertical and horizontal configurations at different external radiant heat fluxes are plotted in Fig. 3. The experimental data was taken from literature [6] and the droplet diameter is 1300 μm. Without external radiant heat flux, the critical water application rates for both horizontal and vertical configurations are from 1.2 to 1.8 g·m$^{-2}$·s$^{-1}$.

For the vertical specimen, the estimated convective heat transfer coefficient using Grashof number is about 9.1 W·m$^{-2}$·K$^{-1}$, while the empirical value is about 10 W·m$^{-2}$·K$^{-1}$ for wall fires. Both the calculated results are in good agreement with the experimental data. For horizontal specimen, the estimated value using Grashof number is about 8.9 W·m$^{-2}$·K$^{-1}$, while the empirical value is about 13 W·m$^{-2}$·K$^{-1}$. The calculated result using the empirical value is in good agreement with the experimental data, while the result using the estimated value is not good, and over-estimation of critical water application rate is about 0.4 g·m$^{-2}$·s$^{-1}$. The actual heat transfer coefficient at extinction might be larger than the value calculated by using Grashof number. These suggested empirical values appeared to be more suitable for use in this present model, and so selected for the following calculations.

At near extinction, flame radiation becomes insignificant while convective heat transfer would play an important role. As discussed in the literature [8], fuel mass flux would decrease when mass pyrolysis rate decreases, and surface blowing effect would then decrease to increase the convective heat transfer. Therefore, maximum convective heat flux from the flame to the fuel surface is found at extinction. With larger convective heat transfer, the critical fuel mass flux increased and the extinction condition will be easier to achieve.

The slope of the curve represents the cooling effects of water. The value for the vertical specimen curve is smaller than that for the horizontal one. This phenomenon, e.g., [14]

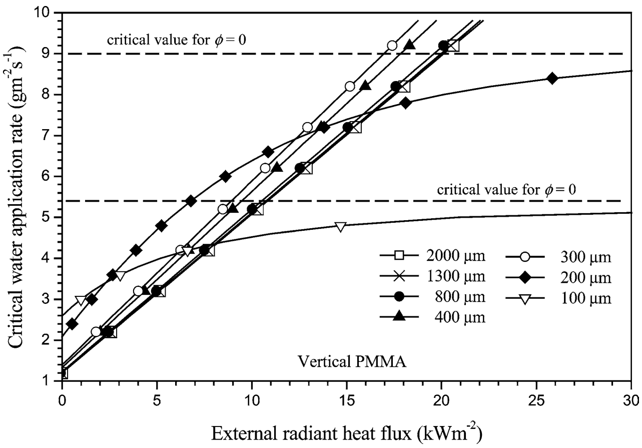


Fig. 4. Critical water application rate versus external radiant heat flux with various droplet diameters for vertical PMMA (Droplet velocity: 2.5 m·s$^{-1}$).

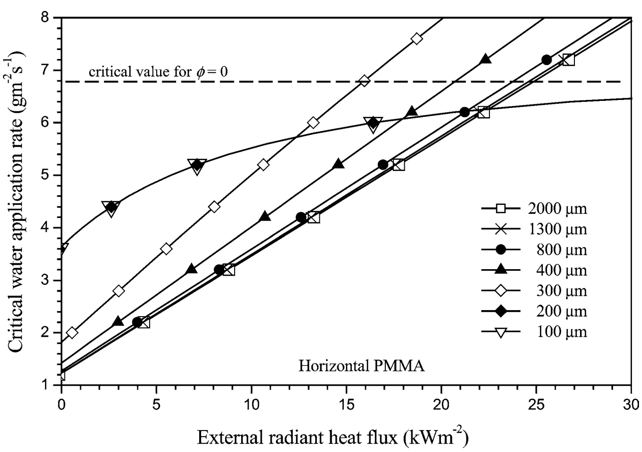


Fig. 5. Critical water application rate versus external radiant heat flux with various droplet diameters for horizontal PMMA (Droplet velocity: 2.5 m·s$^{-1}$).

is due to the additional water vapor cooling effect, which is significant for horizontal specimen but not for vertical specimen.

The predicted results for critical water application rates are plotted against external radiant fluxes with various droplet diameters for vertical and horizontal PMMA in Figs. 4 and 5, respectively. For larger droplets, the surface cooling effect played the absolutely dominating role, so the curves are almost linear. With the decrease in droplet diameter, the convective heat transfer from hot gas to droplets increased, resulting in the increase in droplet temperature. Therefore, the effective surface cooling effect of liquid water decreased. For the horizontal specimen, the critical fraction and the critical mass burning rate are plotted against the critical water application rate in Figs. 6 and 7, respectively. For larger droplets, little water vapor was produced; while for smaller droplets, with decreasing droplet diameter, the water vapor fraction increased, the critical fraction decreased and the critical mass burning rate increased, resulting in easier extinction.

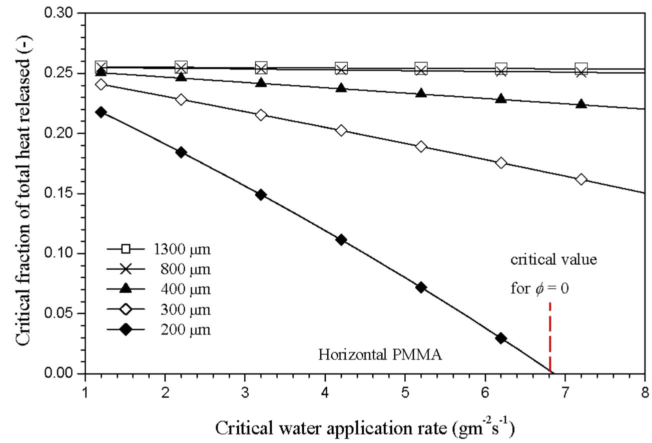


Fig. 6. Critical fraction of total heat released versus critical water application rate for horizontal PMMA.

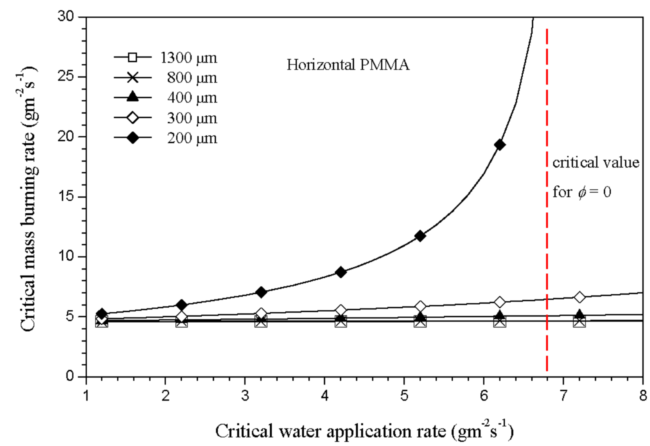


Fig. 7. Critical mass burning rate versus critical water application rate for horizontal PMMA.

When the critical fraction approached 0 under a critical water application rate as shown in these figures by a dash line, the critical mass burning rate approached infinity, and the water spray of droplet diameter 200 or 100 μm in the present paper would cause flame extinguishment even under a high external heat flux in real fires, say up to 100 kW·m$^{-2}$. This critical nonlinear phenomenon is quite different from that of surface cooling. Note that the fuel surface under applied external radiant heat flux would release toxic and combustible gases to the environment, which might cause danger to human and lead to re-ignition [23,26]. The surface cooling would reduce pyrolysis, while the flame extinguishment due to the decreasing of the critical fraction by water vapor would prevent the combustible gases from re-ignition under the high external heat flux.

For the vertical configuration, the thickness of the flame was small, so the droplet of diameter 200 μm would not be evaporated entirely in a short traveling time, but the droplet of diameter 100 μm would. This critical water application rate for droplet of 100 μm is about 5.4 g·m$^{-2}$·s$^{-1}$; while for the droplet of 200 μm, this value is larger than 9.0 g·m$^{-2}$·s$^{-1}$. For the horizontal configuration, both

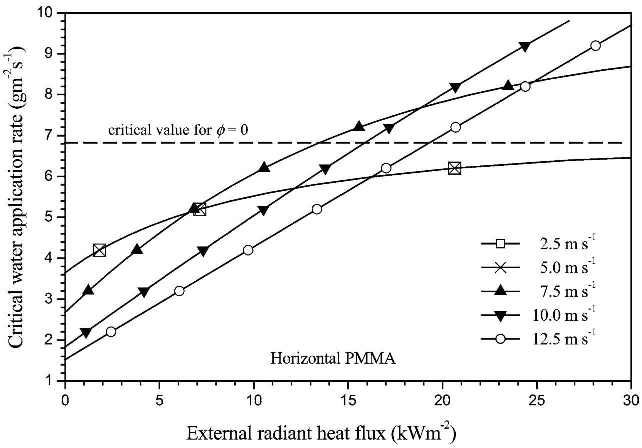


Fig. 8. Critical water application rate versus external radiant heat flux with various droplet velocities for horizontal PMMA (Droplet diameter: 200 µm).

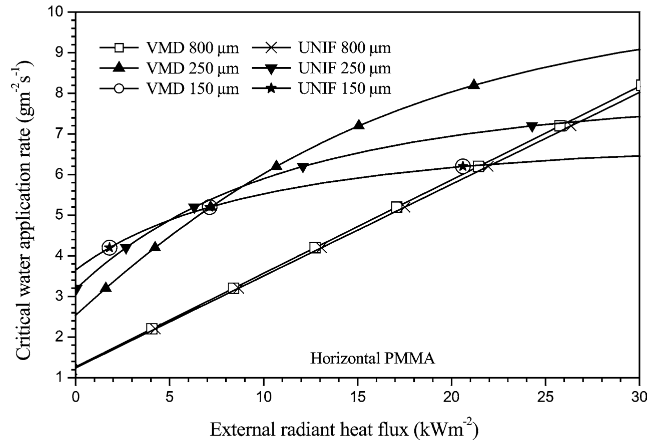


Fig. 9. Critical water application rate versus external radiant heat flux with water spray of various VMD and uniform water spray.

droplets of 100 and 200 µm would be evaporated entirely, so the critical values are 6.8 $g \cdot m^{-2} \cdot s^{-1}$ as shown in Fig. 6. However, the assumption of rapid mixing of oxygen and water vapor has been made for the present model, and actually the fluid dynamics would affect this process significantly. In practical applications, the preferred water application rate should be several times larger than the critical value [4]. Experimental data indicated that water mists of diameter about 200 µm and mass flux about several tens $g \cdot m^{-2} \cdot s^{-1}$ could extinguish small-scale PMMA fires under external radiant heat flux of 14 and 25 $kW \cdot m^{-2}$ in a short time [7].

The predicted results for the droplets of diameter 200 µm with various velocities are shown in Fig. 8. With increasing droplet velocity, the traveling time in hot gas decreased and the surface cooling effect would contribute more to extinction than the flame extinguishing effect. The curves would change from nonlinear to linear types.

As discussed earlier, smaller droplets would contribute more to reduce the critical fraction for flame extinguishment, while larger droplets would contribute more to surface cooling. Therefore, it is reasonable to employ a water spray containing a variety of suitable droplet sizes to extinguish PMMA fires. As shown in Fig. 9, for practical spray of larger VMD, say 800 µm, a little higher water application rate was required for fire extinguishment than that for the uniform spray of the same droplet size. This is because the temperature of some smaller droplets in the practical spray increased, resulting in the decreasing of cooling potential. There is no difference between the practical spray of smaller VMD, say 150 µm, and the uniform spray of the same droplet size since all of them were evaporated in the hot gas. There is significant difference between the practical spray of medium VMD, say 250 µm, and the uniform spray. Note that the volume ratio of 600, 200 and 100 µm in the practical spray of VMD 250 µm are 0.3558, 0.6249 and 0.0192, respectively. The combined effect of surface cooling (mainly due to larger droplet) and flame extinguishment (mainly due to smaller droplet) resulted in such better performance with less water application rate under high external radiant heat flux.

## 6. Conclusions

The extinguishment of PMMA fire by both larger droplets from sprinkler water sprays and smaller droplets from water mist system can be simulated by using a thermal model described in this paper. Suppression mechanisms include oxygen displacement, gas phase and surface cooling. Similar approach can be extended to model how water spray would interact with other plastic fires. Obviously, assumptions made should be verified by experiments such as determining the convective heat transfer coefficient under critical conditions. This model will be further developed for studying fire extinguishment of other solid fuels. Modification and comparison with experimental studies will be conducted and reported later.

With lower water application rate, the larger droplets would perform better than the smaller ones. With higher water application rate, the smaller droplets might perform better than the larger ones. A possible explanation is because the reduced critical fraction of total heat released back to fuel surface might result in a critical water application rate with which the flame cannot be sustained even under a high external heat flux in real fires. The spray containing a wider range of droplet sizes would perform better than a uniform spray when extinguishing PMMA fires under high external radiant heat flux. Less critical water application rate might be required for fire extinction under high external radiant heat flux.

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