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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 ith 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 ith water droplet
D_i	diameter of the ith 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 ith 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 ith 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 ith water droplet
U_{di}	velocity of the ith water droplet
U_g	flame gas velocity
V_{di}	volume of the ith water droplet
t	time
T_0	initial temperature of the reactants prior to combustion
$T_{\mathrm{AFT}}(SL)$	adiabatic flame temperature at stoichiometric limit
T_b	boiling temperature of liquid water
T_{di}	temperature of the ith 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

ΔH_c	combustion heat of the fuel volatiles
$\Delta H_R(O_2)$	heat of reaction of oxygen
ϕ	critical fraction of the total heat released that was transferred back to the fuel surface
ϕ_{SL}	fraction of the enthalpy of reaction that can be lost before extinction at stoichiometric limit
μ_g	dynamic viscosity of the flame gas
ρ_g	density of the flame gas
ρ_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