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RE-IGNITION OF MULTI-SPECIES SOOT CLOUDS IN BUILDING FIRES

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Abstract

The re-ignition potential of multi-species soot clouds in building fires were investigated based on their extinction characteristics. The investigation was carried out theoretically using an adaptation of Semenov's thermal explosion theory. The critical sizes of soot particles in the cloud were found to be strongly affected by the particle temperature, shape, and reactivity, as well as the mass fraction of each species, and ambient conditions. The cloud shape, cloud particle number density, fuel mass fraction, and soot reactivity were identified as the major parameters impacting upon the cloud extinction potential. Our analysis indicate that blending of a base soot with a less reactive soot generally increases the extinction potential of the cloud (i.e. likelihood of extinction) while addition of a more reactive secondary soot to the base one minimises the probability of cloud extinction.

Keywords: *Extinction; Clouds; Re-ignition; Soot*

Introduction

The solids formed in the combustion of organic fuels include char, coke, ash and soot. The differences in these products are chemical, morphological, and relate to the combustion processes, which lead to their formation (Borman and Raglan, 1998). In building fires soot particles form during flaming combustion as a result of thermal decomposition of hydrocarbon compounds in the gas phase. These compounds, in turn, originate from either volatiles released by solid or liquid fuels due to thermal decomposition or directly from a gaseous fuel mixture. A soot particle is essentially an agglomerate of a large number of very fine carbonaceous particles. While the overall size of a typical soot particle is about 1-2 μm, the diameters of the carbon spherules making the soot particle are about 30 nm. A large number of soot particles can be generated in a building fire. In fact, about 50% of the carbon atoms present in a hydrocarbon fire end up as soot. A large number of these particles form soot clouds (a collection of soot particles), which are then transported away from the source of the fire by the airflow generated by the fire plume. These soot clouds often contain a collection of different soot types because the morphological and chemical properties of soot particles generated from various fuels are different. For this reason, soot clouds can be classified as multi-species clouds.

In the context of fire safety, soot represents a major hazard mainly because the presence of soot alters the radiative characteristics of the flame and influences the overall energetics of the system. The orange and yellow colour observed in a flame is in fact produced by light emitted from glowing soot particles, which turn black as soon as they leave the flame. The blackbody emission from soot particles is responsible for a large fraction of the radiant energy emitted from a fire.

Soot particles may also assist the spread of fire. When soot particles cool down in the post flame region, some completely extinguish but a great majority remain reactive although their reactions with oxygen significantly slow down. These latter particles still receive considerable amount of radiant energy from other burning objects or hot walls and ceiling. As a result, they might re-ignite and switch to flaming combustion again. This, in turn, may lead to the spread of fire to other parts of the building.

The evolution of soot in chemically reacting flow systems is an area of active research, and an extensive literature exists on many aspects of the topic. While many questions remain unanswered, recent studies on soot formation (Delichatsios et. al., 1992; Delichatsios, 1993 and 1994); Panagiotou and Levendis, 1994; Panagiotuo et. al., 1994, 1996a and b; Chen et. al., 1995), and soot pyrolysis kinetics (DiBlasi and Lanzetta, 1996; Hurt and Davis, 1994), have led to advances in our fundamental understanding of the soot formation and growth. In particular, Delichatsios (1993 and 1994) has shown that the sooting tendencies of solid fuels can be determined through a correlation between the smoke-point height, the smoke yield and flame radiation in turbulent diffusion flames. Delichatsios (1992, 1993, and 1994) developed a theoretical method for deducing the necessary soot formation parameters from experiments conducted inside a cylindrical quartz heater. Panagiotou and his co-workers (1994, 1996a and 1996b) employed Delichatsios's technique to extract soot tendencies of plastic materials from a

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series of particle burning experiments in a tube furnace. The main problem with these experiments was the fact that particles were subjected to the external radiative heating throughout their entire burning process. As a result, it was not possible to measure accurately the radiative properties of the flame due to interferences from the external heating source.

Unlike the mechanism of soot formation, the re-ignition of soot clouds has received little attention in the literature. While numerous studies have been conducted on ignition and combustion of mono-species char clouds (see the excellent review paper by Annamalai et al. (1994)), the extinction of such clouds under fire conditions has received less attention. Similar studies on soot clouds, to the best of author's knowledge, are non-existent. In particular, studies related to the extinction of multi-species soot clouds are generally scarce. The work presented in this paper is an attempt to address the above-mentioned shortcoming by developing an analytical model capable of analysing the extinction of multi-species soot clouds under fire conditions. The idea is to evaluate the re-ignition potential of soot clouds on the basis of their extinction characteristics.

Analytical Model

The Russian scientist Semenov (1935) developed his thermal explosion theory for gases in late 1920. The essence of Semenov's theory, as discussed in the previous chapter, is that a gaseous fuel/oxidiser mixture contained in a well-stirred vessel can be ignited if at sufficiently high temperatures the heat being generated due to chemical reactions becomes equal to that being lost at the vessel boundaries. The basics of the Semenov's theory can be employed to study the burning and extinction of solid fuel particles. Many researchers have undertaken this approach to study the ignition of mono-species dust clouds (Annamalai et al., 1994) and incomplete combustion of isolated pulverised fuel particles under conditions pertinent to PF boilers (Peters, 2002). Here, an adaptation of the Semenov's approach is employed to study the extinction of multi-species soot clouds in building fires with typical flame temperatures of 1400-1700 K (≈ 1100-1400^{o}C) and heating flux levels in the order of 50-90 kW.m^{-2}.

Let us first consider a partially burnt thermally thin (Bi < 0.2) soot particle undergoing a stable oxidation reaction (i.e. combustion). The soot particle is assumed to be originated from a virgin fuel particle that had been heated up, ignited and pyrolysed prior to the soot oxidation process. Let us also assume that the soot particle is within a mono-species cloud of similar particles and that the cloud is exposed to the hot oxidising environment in a room fire for which the ambient temperature and the convective heat transfer coefficient are T_∞ and h_∞, respectively. Because of the thermally thin assumption, the temperature distribution in the particle can be ignored and, hence, the particle can be considered to be at a uniform temperature T. If one further assumes a global first-order Arrhenius reaction for the rate of heat generation by the particle, then it can be shown that the conservation of energy for the particle takes the following form:

$$\rho V C_p \frac{dT}{dt} = Y_{O2}^{m} \rho V \Delta Ha \exp\left(\frac{-E}{R_u T}\right) - h_g A(T - T_g) - F\varepsilon\sigma A(T^4 - T_W^4) \qquad (1)$$

where ρ is the particle density, V the particle volume, C_p the particle specific heat, Y_{O2} the oxygen mass fraction in the cloud with an exponent m, ΔH the heat of reaction, a the pre-exponential factor, E the activation energy, R_u the universal gas constant, h_g the convective heat transfer coefficient of the cloud gas, A the particle surface area, T_g the cloud gas temperature, F the radiation view factor for the particle in the cloud, ε the particle emissivity, σ the Stefan-Boltzmann constant, and T_W is the furnace wall temperature.

The first term on the right hand side of eq (1) describes the heat generation by chemical reactions while the second and third terms on the right represent the heat losses by convection and radiation, respectively. Note that the gas phase conditions in the cloud (i.e. T_g and h_g) are not necessarily the same as the ambient gas phase conditions in the room. Also, the radiation exchange between the particle and the surrounding walls is strongly affected by the presence of other particles, which block the radiation (Annamalai, 1994). To account for this blockage of radiation, the view factor F has been introduced into eq (1).

According to Semenov's theory, at extinction the particle reaches a steady-state temperature where the heat generation and heat losses are equal, hence:

$$Y_{O2}^{m} \rho V \Delta Ha \exp\left(\frac{-E}{R_u T}\right) = h_g A(T - T_g) + F\varepsilon\sigma A(T^4 - T_W^4) \qquad (2)$$

The conservation of energy for the cloud gas can be obtained in a similar manner. Here, we employ Krishna's approach (1980) and assume that the cloud gas is a lumped parameter system for which the temperature and oxygen concentration have no gradients and, thus, are uniform across the cloud. Although Krishna's approach is different from Frank-Kamenetsky's treatment of particle clouds (Frank-Kamenetsky's, 1955), it allows the particle temperature (T) to be different from the cloud gas temperature (T_g) and the extinction to occur when the entire cloud reaches a certain critical temperature. It must be highlighted, however, the application of Krishna's approach is valid for relatively small cloud sizes, typically in the order of 1-5 cm in diameter

(Annamalai, 1994). But this is of no concern here because the smoke in building fires comprises of small pockets of soot particles (i.e. soot clouds) with average diameters of about 1-2 cm (DiNenno, 1995).

Following Krishna and Berlad (1980) and neglecting contributions from volatiles and radiation exchange between the cloud gas and surrounding wall, the conservation of the energy for the cloud gas phase can be expressed by:

$$\rho_g V_g C_{pg} \frac{dT_g}{dt} = Y_{O2}^m \rho V \Delta Ha \exp\left(\frac{-E}{R_u T}\right) n V_g - h_\infty A_g (T_g - T_\infty) - F\varepsilon\sigma A(T^4 - T_W^4) n V_g \quad (3)$$

where ρ_g, V_g, C_{pg}, and A_g are the density, volume, specific heat, and the surface area of the cloud gas phase, respectively. Also n is the particle number density defined as the number of particles (N) per unit volume of gas:

$$n = N / V_g \quad (4)$$

Similar to particles, the total heat generated within the cloud at extinction must be equal to the combined convective and radiative heat losses of the cloud. Therefore:

$$Y_{O2}^m \rho V \Delta Ha \exp\left(\frac{-E}{R_u T}\right) n V_g = h_\infty A_g (T_g - T_\infty) + F\varepsilon\sigma A(T^4 - T_W^4) n V_g \quad (5)$$

Elimination of the cloud gas phases temperature (T_g) between eqs (8.2) and (8.5) results in:

$$\left(Y_{O2}^m \rho V \Delta Ha \exp\left(\frac{-E}{R_u T}\right) - F\varepsilon\sigma A(T^4 - T_W^4)\right) \cdot \left(nV_g h_g A + h_\infty A_g\right) = h_g h_\infty A_g A (T - T_\infty) \quad (6)$$

Dividing both sides of eq (8.6) by (AA_g), one obtains:

$$\left(\left(\frac{V}{A}\right) Y_{O2}^m \rho \Delta Ha \exp\left(\frac{-E}{R_u T}\right) - F\varepsilon\sigma A(T^4 - T_W^4)\right) \left(\left(\frac{V_g}{A_g}\right) n h_g A + h_\infty\right) = h_g h_\infty (T - T_\infty) \quad (7)$$

The ratio V/A defines a critical particle characteristic length at extinction, L_{cr}. For a spherical soot particle:

$$L_{cr} = \frac{V}{A} = \frac{(4/3)\pi R_{cr}^3}{4\pi R_{cr}^2} = \frac{R_{cr}}{3} \quad (8)$$

where R_{cr} is the critical radius of the particle. The critical characteristic length, L_{cr}, for non-spherical soot particles can be related to R_{cr} using the following equation:

$$L_{cr} = \frac{R_{cr}\phi}{3} \quad (9)$$

in which ϕ is a particle shape factor representing the surface area of a sphere equivalent to the volume of the actual particle divided by the surface area of the actual particle. The ratio V_g / A_g similarly represents a characteristic length for the cloud, L_g. For typical cloud shapes L_g can be calculated from the following expressions:

$$\begin{cases} L_g = R_g / 3 & (Spherical\ Cloud) \\ L_g = R_g / 2 & (Cylindrical\ Cloud) \\ L_g = 2R_g & (Planar\ Cloud) \end{cases} \quad (10)$$

where R_g denotes a physical dimension, for instance, the radius for the spherical and cylindrical clouds or the half thickness for planar shape clouds.

If the volume to surface area ratios for both particle and cloud in eq (7) are replaced with relevant expressions, one can reduce eq (7) to the following cubic equation for the critical particle size at extinction:

$$R_{cr}^3 - I_1 R_{cr}^2 + I_2 R_{cr} - I_3 = 0 \quad (11)$$

in which:

$$I_1 = \frac{F\varepsilon\sigma A(T^4 - T_W^4)}{\frac{\phi}{3} Y_{O2}^m \rho \Delta Ha \exp\left(\frac{-E}{R_u T}\right)} \quad (12)$$

$$I_2 = \frac{h_\infty \phi}{4\pi n L_g h_g} \quad (13)$$

$$I_3 = \frac{F\varepsilon\sigma A(T^4 - T_W^4) h_\infty + h_g h_\infty (T - T_\infty)}{\frac{4}{3}\pi n L_g h_g Y_{O2}^m \rho \Delta Ha \exp\left(\frac{-E}{R_u T}\right)} \quad (14)$$

For a given cloud gas temperature (T_g), the particle temperature (T) can be calculated from eq (5) and substituted into eqs (11-14). Analytical solution of eq (11) will then yield the critical size of the particle at extinction (see Appendix F). Once R_{cr} is calculated the cloud extinction can be evaluated by working out the percentage of soot particles that have to shrink to sizes below the critical size in order to extinguish the cloud. This, in turn, will allow us to estimate the minimum cloud mass loss necessary for cloud extinction. The higher the value of the minimum cloud mass loss, the lower the extinction potential of the cloud (i.e. the higher the probability of cloud re-ignition) and vice versa. In the case of multi-species clouds the critical size and the number of sub-critical particles must be calculated for each soot species present in the cloud. The probability of the cloud extinction can be then examined by summing up the number of sub-critical particles for each fuel and, subsequently, estimating the combined mass loss of the cloud. See the next section for details.

The analysis of the cloud essentially comprises the estimations of the convective heat transfer coefficient of the cloud (h_g), F, particle numbers for each species and the percentage of the cloud mass loss required for attaining extinction (%*CML*). The value of h_g can be estimated by reducing the value of h in the room with the factor: $1/((G/3)+1)$ to account for interaction among the particles in the cloud (Annamalai, 1994):

$$h_g = \frac{h}{\left(\frac{G}{3}\right)+1} \tag{15}$$

The parameter G is a dimensionless group combustion number defined as (Annamalai, 1994):

$$G = 3\gamma^{1/3} N_t^{2/3} \tag{16}$$

where N_t is the total number of particles (i.e. $N_t = N_1 + N_2 + \ldots.$) and γ is the total fuel volume fraction. The value of G for dense clouds (e.g. near the flame) is typically between 100-130 while for dilute clouds formed deep in the room and away from the flame $G \approx 1$. The group combustion number G can be also employed to estimate the view factor F using the following expression (Annamalai, 1994):

$$F = \exp\left(\frac{-G\, r_{avg}}{L_g}\right) \tag{17}$$

where r_{avg} denotes the radius of an equivalent average particle representing all particles in the cloud. The value of r_{avg} is extracted by combining the mean particle radiuses (r_j) of all fuel species.

As outlined before, the extinction potential of the cloud can be judged based on $\%CML$ necessary for attaining extinction that is:

$$\%CML = \left(\frac{m_{t,ini} - m_{t,ext}}{m_{t,ini}}\right) \times 100 \tag{18}$$

where $m_{t,ini}$ and $m_{t,ext}$ are the values of the total particle mass of the cloud (all fuel types) at the beginning of the soot conversion process and at the onset of extinction, respectively. The initial total cloud mass can be calculated from:

$$m_{t,ini} = \sum_{j=1}^{Itotal} N_j\, \rho_j\, V_j \tag{19}$$

where the subscript j refers to jth fuel type in the cloud and the integer I_{total} represents the total number of fuel types in the cloud. In a binary soot cloud for instance, $I_{total} = 2$. Initially the particle numbers for individual soot species are not known and, hence, their values must be calculated from the mass fractions of each soot species (Y_j) and N_t using the following equations (see Appendix F for relevant derivation):

$$N_j = \left(\frac{Y_j}{Y_1}\right)\left(\frac{\rho_1}{\rho_j}\right)\left(\frac{V_1}{V_j}\right) N_1 \tag{20}$$

$$N_1 = \left(\frac{Y_1 N_t}{\rho_1 V_1}\right)\left(\sum_{j=1}^{Itotal} \frac{Y_j}{\rho_j V_j}\right)^{-1}. \tag{21}$$

Assuming particle numbers for each soot type to remain unchanged throughout the soot conversion process, the total cloud mass at extinction ($m_{t,ext}$) can be calculated from:

$$m_{t,ext} = \sum_{j=1}^{Itotal} N_j\, \rho_j\, V_{j,ext} \tag{22}$$

where for the jth soot species, $V_{j,ext}$ represents the volume of a soot particle. The value of $V_{j,ext}$ should be calculated from the mean particle size at extinction $(r_{j,ext})$ determined, in turn, from the particle size distribution. In this study, particles of each soot species are assumed to follow Rossin-Rammler type size distributions, expressed by:

$$f_{ext} = 1 - \exp\left(-\left(\frac{R_{j,cr}}{r_{j,ext}}\right)^{k_j}\right) \tag{23}$$

where f_{ext} denotes the fraction of particles smaller than the critical size $(R_{j,ext})$ and k_j is the distribution coefficient of the Rossin-Rammler size distribution for the jth soot species. For spherical soot particles at extinction for example, one can conclude that:

$$V_{j,ext} = \frac{4\pi}{3}\left(R_{j,cr}\, \ln\left(\frac{1}{1-f_{ext}}\right)^{\frac{-1}{k_j}}\right)^3 \tag{24}$$

It must be highlighted that the parameter f_{ext} can be used as a criterion for cloud extinction. In our base-case studies, for example, f_{ext} was assumed to be 50% although the sensitivity of the results with respect to f_{ext} was investigated by varying f_{ext} between 20%-80%. The set of algebraic eqs (11-24) fully describe the extinction of multi-species clouds. These equations have been used to identify the major characteristics of soot cloud extinction in building fires and the results are presented in the next section.

Results and Discussion

A number of case studies were conducted to investigate the effects of particle shape, cloud geometry, particle loading (i.e. cloud particle number density), mixing ratio, fuel type, wall temperature, and ambient conditions (i.e. $Y_{O2,}\, T_{g,}\, h_{g,}\, T_\infty$ and h_∞) on the extinction of soot clouds typically encountered in room fires. Calculations were carried out for soot particles of PMMA and several wood species. Also, in a number of case studies coal soots were considered for comparison. While the global chemical kinetic properties (i.e. a and E) of PMMA and coal soot species used in the analysis were measured using conventional techniques, for wood-based soot species a technique specifically developed for biomass fuels (Meesri and Moghtaderi, 2003) was employed to obtain the kinetic parameters.

The base-case calculations were performed on a binary soot cloud of Radiata pine and PMMA, and the surrounding wall and room temperatures as well as the convective heat transfer coefficient in the room (T_W, T_∞ and h_∞) were set to nominal values of 650°C, 675°C, and 30 W.m^{-2}K^{-1}, respectively, suggested in the literature (DiNenno, 1995) for typical room fires. The soot particles of each fuel type were assumed to follow their own Rossin-Rammler type size distributions. In the base-case calculations the mean radii of the Rossin-Rammler size distribution for all fuel types were assumed to be 130 nm to ensure that 50% of particles were smaller than the average size of 90 nm typically encountered in building fires (DiNenno, 1995). The values of f_{ext} and k were assumed to be 50% and 1, respectively for all fuel types in the base-case calculations although they were varied in other case studies.

Figure 1 illustrates the plots of particle temperature versus cloud gas temperature for Radiata pine and PMMA soot particles (base-case). As shown, at any given T_g the particle temperature for Radiata pine is generally higher than that of PMMA. This can be attributed to the fact that wood-based soot species are generally less reactive than PMMA soot as depicted in Figure 2 for Radiata pine and PMMA in terms of the volumetric heat generation.

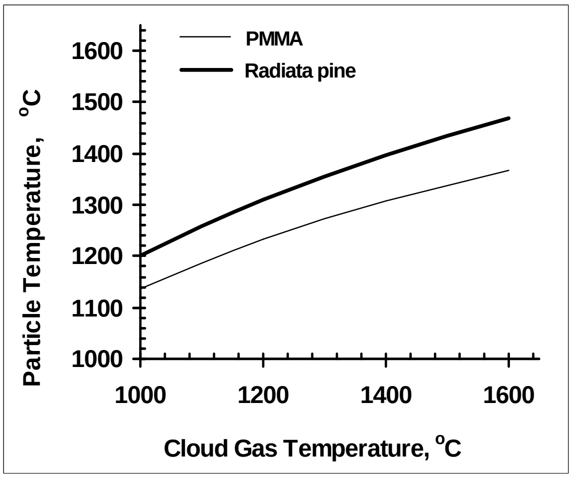

Figure 1. Particle temperatures of Radiata pine and PMMA soots within a binary-species cloud (base-case calculations) as a function of the cloud gas temperature.

As a result, wood-based soot particles in a cloud must reach higher temperatures in order to maintain their thermal equilibrium with the cloud gas phase. This will allow wood-based soot particles to attain heat release rates similar to those of PMMA soot particles despite the fact that wood-based soot species tend to have relatively low densities and, thereby, larger volumes. The dynamic between the cloud gas and particle temperatures (e.g. Figure 1) is the underlying mechanism for many of the cloud extinction characteristics, which are discussed in this section.

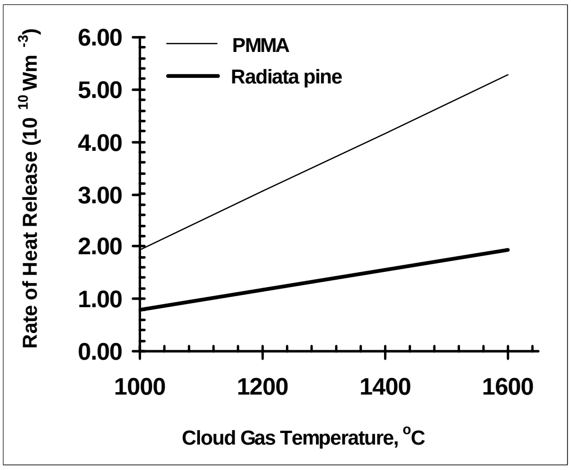

Figure 2. Heat release plots for Radiata pine and PMMA soots within a binary-species cloud (base-case calculations).

One such characteristic is the critical diameter of the soot particle at extinction. The critical diameters of wood-based and PMMA soot species under several different settings have been plotted in Figure 3 against the cloud gas temperature. Similar data were used for the mono-species cloud calculations with the exception of *Itotal* and *Y,* which were both set to unity. The single particle results were obtained from a simple energy balance for an isolated soot particle.

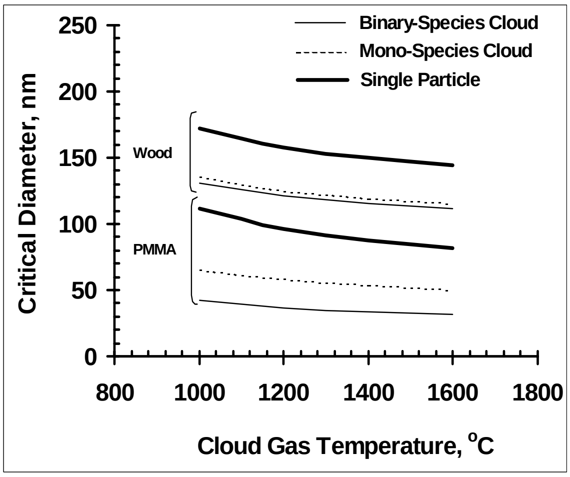

Figure 3. Critical dimensions of mono- and binary-species spherical clouds of Radiata pine and PMMA soots as a function of the cloud gas temperature.

As is evident in Figure 3, over the range of temperatures of interest in building fires (1100°C < T_g < 1400°C) the critical dimension of the fuel decreases as the cloud gas temperature and, hence, the particle temperature is increased. The individual particles in the cloud are, therefore, less likely to extinguish at higher temperatures because they ought to shrink to much smaller critical diameters (i.e. an increase in re-ignition potential). The reason behind this phenomenon is that the heat release varies exponentially with the particle temperature whereas the convective and radiative heat losses vary with the first and fourth power of the particle temperature, respectively. Consequently, the gain in the heat release due to the rise in particle temperature would be higher than the corresponding increase in the heat loss.

The discrepancy between the mono- and binary-species results in Figure 3 is primarily due to the differences in their respective particle volume fractions which, in turn, impact upon *G* and, thereby, h_g and *F* (see eqs 15-17). Bear in mind that in the present analysis we used identical particle number densities for both clouds. As a result, the actual particle numbers of wood-based and PMMA soot species in the binary cloud were different from their mono-species counterparts.

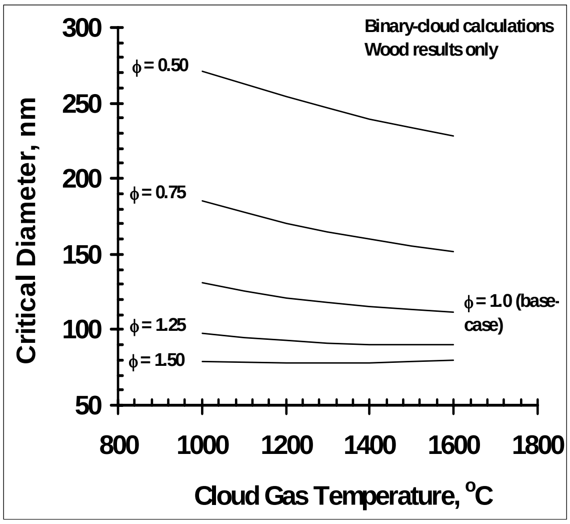

Figure 4. Critical diameter versus cloud gas temperature for irregular shape Radiata pine soot particles in the base-case binary-species cloud of PMMA and Radiata pine soots.

Effects of the cloud and particle shapes on the critical dimension of soot particles at extinction have been summarised in Figures 4 and 5. As indicated in Figure 4 for wood, the more irregular shape the soot particle (i.e. smaller ϕ) the higher its critical diameter and, therefore, the higher its extinction potential (i.e. lower re-ignition potential). Also, it appears that the spherical clouds in general lead to smaller critical particle diameters and, as such, are less susceptible to extinction.

Figures 6 and 7 respectively illustrate plots of the critical particle diameter and %*CML* against T_g at various mixing ratios. Here, the mixing ratio refers to the mass fraction of a secondary soot species (e.g. wood-based soot) in a binary-species cloud. As shown in Figure 6, mixing generally reduces the critical diameter of soot particles and, thus, their extinction potential. However, for the particular binary-species cloud under investigation, Figure 7 indicates that mixing also lowers the %*CML* and, hence, dramatically increases the cloud extinction potential because it is easier and certainly faster to achieve a relatively low cloud mass loss in the range of 55%-70%. However, the particular behaviour exhibited by Radiata pine in Figure 7 is an artefact of its low reactivity.

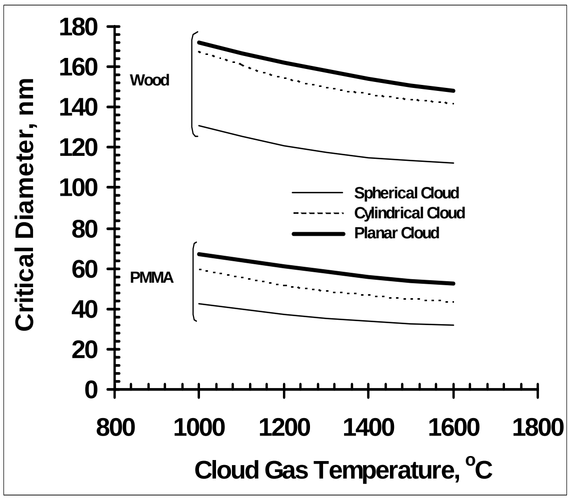

Figure 5. Effect of the cloud shape on the critical diameter of soot particles for the base-case binary-species cloud of PMMA and Radiata pine soots.

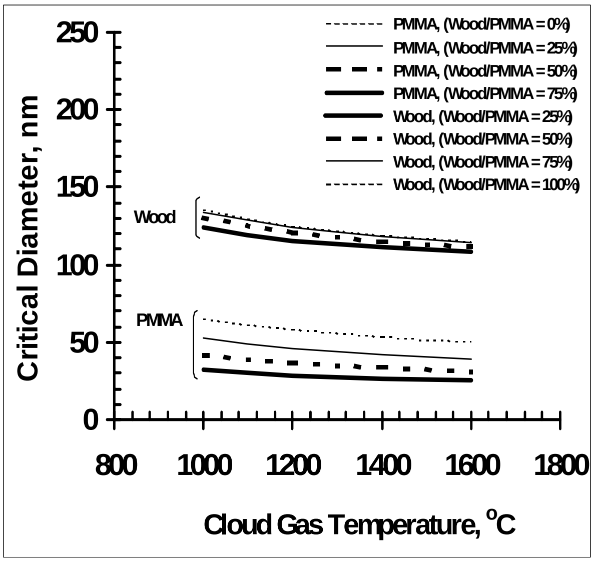

Figure 6. Effect of the mixing ratio on the critical diameter of soot particles for the base-case binary-species cloud of PMMA and Radiata pine soots.

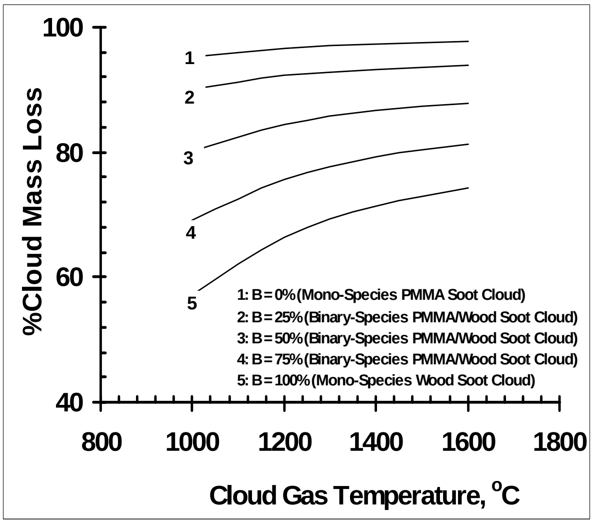

Figure 7. Effect of the mixing ratio on (%CML) for the base-case binary-species cloud of PMMA and Radiata pine soots.

As illustrated in Figure 8, reactive soots like those of PMMA tend to have smaller critical dimensions, which translate to low extinction potentials (i.e. high re-ignition potentials) whereas less reactive wood-based soot species typically possess larger critical dimensions. Therefore, one expects that if PMMA soot particles mentioned above were mixed with a more reactive fuel like that reported by Annamalai et al. (1994) (see Figure 8), then the extinction potential of the cloud would have been significantly lower than that of a mono-species cloud.

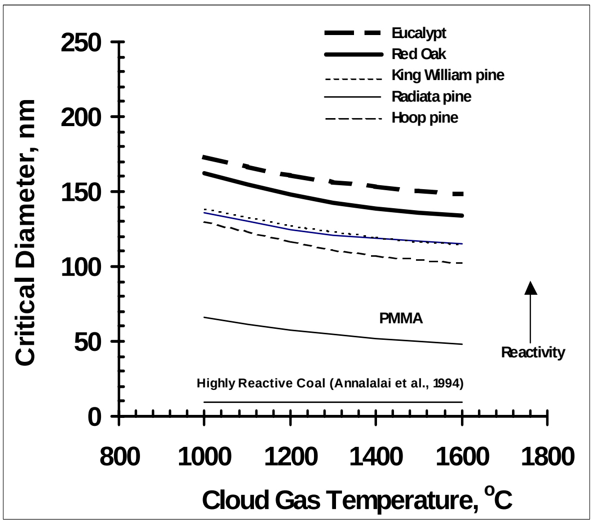

Figure 8. Effect of the fuel type (reactivity) on the critical diameter of soots particles in mono-species soot clouds of various fuels.

This has been demonstrated in Figure 9 where the %*CML* of several PMMA/coal soot blends have been plotted against the mixing ratio for a cloud gas temperature of 1600°C. As can be seen, the blend of PMMA and HR coal has the highest %*CML* and, thus, the lowest extinction potential (i.e. the highest re-ignition potential).

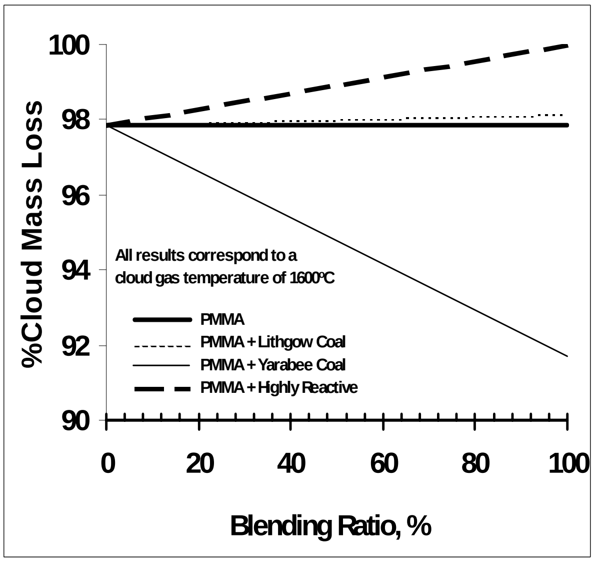

Figure 9. Effect of the mixing ratio on %CML for binary-species clouds of PMMA and several coals soot species.

Generally, an increase in h_∞ translates to a reduced extinction potential (i.e. an increase in re-ignition potential) because it leads to a decrease in D_{cr} and a respective rise in %*CML*. An increase in ambient temperature, on the other hand, leads to an increase in the extinction potential of the cloud (i.e. a decrease in re-ignition potential). The effect of ambient temperature can be easily explained by noting that T-T_∞ and, thereby, convective heat losses decrease when the T_∞ is increased. But lowering the ambient temperature (at a given T_g) also lowers the particle temperature, which in turn, causes an even greater decrease in the heat released by the particle. Consequently, particles exhibit larger critical dimensions (i.e. smaller %*CML*) since the critical dimension is proportional to the ratio of heat losses to heat gains. The opposite of this phenomenon occurs when h_∞ is increased.

Conclusions

An analytical model was developed to investigate the extinction characteristics of multi-species soot clouds. The model was developed from the conservation of energy for the cloud and soot particles in conjunction with an adaptation of the Semenov's thermal explosion theory. The model was applied to examine the extinction of mono- binary- and multi-species soot clouds of PMMA and several types of wood-based soot species. Parameters such as, the cloud and particle shapes, the ambient temperature, the ambient convective heat transfer coefficient, the wall temperature, the cloud oxygen mass fraction, the initial particle size, the mass fraction of fuel species in the cloud (i.e. mixing ratio), the cloud particle number density and fuel reactivity were identified as the major parameters impacting upon the extinction of multi-species clouds. While some of the parameters listed above (e.g. T_W) had notable impacts on the extinction potential and, thereby, re-ignition of the clouds, others were found to have less prominent effects.

The results of the present study clearly demonstrate that the extinction characteristics of soot clouds are distinctively different from those exhibited by isolated soot particles. As such, the extinction behaviour of multi-species soot clouds cannot be accurately predicted by single soot particle models. From a practical viewpoint the implication of this finding for building fires is that the extinction of soot particles in the regions near the flame where dense clouds are typically formed cannot be adequately analysed by single particle models. Such models, however, may be applied to dilute regions deep inside the room and away from the fire source.

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References

Annamalai, K., Ryan, W., and Dhanapalan, S.V., (1994), *Prog. in En. and Comb. Sci*., 20: 487.

Borman, G.L. and Raglan, K.W.. (1998). "*Combustion Engineering*", Mc. Graw-Hill International Edition.

Chen, Y., Motevalli, V., and Delichatsios, M.A., (1995). *Comb. Sci. and Technol.*, 104, p. 401, 1995.

Delichatsios, M.A., (1994), *Comb. Sci. and Technol.,* 100, p. 283.

Delichatsios, M.A., (1993), *Fire Safety Journal.*, 20, p. 299.

Delichatsios, M.A., Orloff, L., and Delichatsios, M.M., (1992), *Comb. Sci. and Technol.,* 84, p. 199.

DiBlasi, C., and Lanzetta, A., (1996), *Journal of An.l and App. Pyrolysis*.

DiNenno, P., (1995), "*SFPE Handbook of Fire Protection Engineering*", National Fire Protection Association, Second Edition.

Frank-Kamenetsky, D.A. (1955). *Diff. and Heat Exc. in Chem.l Kinetics*, Princeton University Press.

Hurt, R.H. and Davis, K.A., (1994), *Proc. Twenty-fifth symp. (Int.) on comb*., 561.

Krishna, C.R. and Berlad, A.L., (1980), *Comb. and Flame*, 37, p. 207.

Meesri, C., (2003), "A Fundamental Study on Combustion Characteristics of Pulverised Coal/Softwood Blends", *PhD Thesis*, The University of Newcastle.

Meesri, C. and Moghtaderi, B., (2003), "Experimental and Numerical Analysis of Sawdust Char Combustion Reactivity in a Drop Tube Reactor", *Comb. Sci. and Technol.*, 175 (4), p. 793-823.

Panagiotou, T., and Levendis, Y.A., (1994), *Comb. and Flame*, 99, No. 1, p. 53.

Panagiotou, T, Levendis, Y.A., and Delichatsios, M.A., (1994), *Comb. Sci. and Technol.*, 103, No. (1-6), p. 63.

Panagiotou, T., Levendis, Y.A., and Delichatsios, M.A., (1996a), *Comb. and Flame*, 104, No. 3, p. 272.

Panagiotou, T, Levendis, Y.A., and Delichatsios, M.A. (1996b), *Comb. Sci. and Technol.*, 112, p. 117.

Peters, B., (2002), "Extinction of Burning Particles Due to Unstable Combustion Modes", *Fuel*, 81, p. 391-396.

Semenov, N.N., (1935), "*Chemical Kinetics and Chain Reactions",* Oxford University Press, London.