A NEXT GENERATION FIRE SUPPRESSION TECHNOLOGY PROGRAM SUMMARY ON THE PROPERTIES OF AEROSOLS

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INTRODUCTION

This paper is a brief review of a component of the Next Generation Program to understand the suppression performance of aerosols agents. The complete review will appear in the NGP final report. Much of the work covered was first presented at previous HOTWC meetings. The NGP aerosol program began with a review of the literature that provided both interesting and at times puzzling results. These studies brought up questions as well as pointed to areas for further study. A number of condensed phase compounds appeared to have high potential for offering good fire protection including water and powders of certain alkali and transition metal compounds. The ability to draw valid conclusions from the data in the literature was often compromised by the interdependence of the aerosol properties and the various flame conditions affecting suppression. Although it was recognized that aerosol size was an important parameter in suppression effectiveness, a quantitative understanding as to the exact role size plays was hard to determine. This was especially true for larger-scale tests where separating possible chemical effects from physical effects was difficult. NGP projects were undertaken to address the lack of quantitative information on aerosol suppression behavior, particularly targeting the effects of size, physical and chemical properties of liquid and powder aerosols, and the predictive capabilities of aerosol suppression behavior.

BACKGROUND

An aerosol is a gaseous suspension of solids or liquids or both, in a gas. Smoke, fog, mists, and sprays are all aerosols. Water mists and water sprays are liquid aerosols. Smoke and dispersed solid powders are solid aerosols. The term particle is often used to refer to the individual solid material or the individual liquid drop. Aerosols are almost never mono-disperse (all drops/particles of exactly the same size). Real aerosols can be nearly monodisperse but more typically will exhibit a range of particle sizes. A discussion of aerosol properties and techniques to monitor and quantify aerosols was presented at the 2002 HOTWC [1].

Interactions with fire and water in the form of a mist had been studied for almost four decades. However, detailed quantitative information regarding the fundamental fire suppression mechanism of water mist, useful in order to compare to model predictions and aid in model development, was lacking at the beginning of the NGP. Earlier researchers found several compounds of sodium, potassium, and copper to be effective and were able to utilize the surface area of dry powders of these compounds to explain thermal versus chemical effectiveness. Rosser et al [2] studied the effect of finely divided metal salts on the burning velocity of premixed hydrocarbon-air flames in the early 1960s. They observed that the measured inhibition correlated with the degree of particle evaporation. Successive steps were proposed for successful suppression: particle heating, particle evaporation, particle decomposition, followed by chemical flame inhibition by the added metal. Experiments by Mitani and Niioka [3] considered inhibition of premixed flames with ultra fine water drops (less than 2.4 μm mean diameter) with and without NaOH and $NaHCO_3$, indicating a flame inhibition/ extinction with addition of chemical agents. The slower $C_2H_4/O_2/N_2$ premixed flame experiments (as opposed to faster $H_2/O_2/N_2$ flames) showed distinct chemical inhibition effects. Zheng et al. [4] documented a significant enhancement in counterflow premixed flames suppression from fine drops of solutions of water/ NaCl over that of pure water.

The interactions of water mists with fires had been studied for almost four decades; prior to the 1990s our understanding was mainly based on global observations. There were few basic models that described details of drop/flame interactions. The major pathways to extinction of fires involve heat extraction, oxygen reduction, concentration changes in vapor/air mixtures and kinetic effects at the molecular level. In the late 1990s groups involved with modeling began to examine the interaction of drops with flames. In a detailed numerical study, Chen et al. [5] considered the motion of drops in a non-premixed counterflow field. They considered both n-heptane and water drops. For the drop sizes considered, Chen et al. showed that a drop can penetrate through the stagnation plane established by the gaseous streams and reverse its trajectory at some point in the opposing side of the flow. Prasad et al. [6] modeled water mist suppression of diffusion flames and investigated the dependence of the drop trajectories into the flame.

Although there was a consensus in the literature on the fundamental fire suppression mechanism of water from the earlier studies, no detailed quantitative information on the various physical, thermal, and chemical effects of water mist were available before NGP efforts. There were no detailed models describing the size reduction and evaporation of drops in flames, or their effect on surface reaction kinetics. Models that predict what size drops will reach the surface were not generally available. NGP funded efforts addressed this lack of modeling.

AEROSOL STUDIES

NGP scientists studied several flame configurations in the various NGP related aerosol projects including both premixed (the fuel and oxidizer are combined or premixed before hand) and non-premixed (fuel and oxidizer kept separate until entering the reaction region). In general, the greater the complexity of the flow field, the more computationally challenging it is to include the details of the flow and the details of the chemistry in the modeling treatment of the flame process. This makes for an even greater challenge in understanding multiphase flow problems with the interaction of liquid drops or solid particles with gaseous flames. In order to understand the extinction mechanism of aerosols and approach a quantitative understanding of the aerosol/flame interaction, NGP researchers studied several flame configurations over a range of flow conditions. This sometimes required a re-examination of key experiments in the literature with the focus on minimizing the number of parameter that might vary and exploring the dependence of several of these parameters on the overall suppression performance. Researchers paid close attention to the control of experimental parameters that could possible influence the results. In this way, the new data could be used more directly to validate the predictions of multi-phase flame suppression codes as well as aid in their development.

In addition to the interactions with the gas phase flames, a suppression mechanism possibility for aerosol agents is the potential to cool any burning surfaces or hot surrounding surfaces. NGP projects explored this area. For surface cooling, the greatest benefit will arise from the use of agents that are efficient thermal agents, particularly aerosols that have large heats of vaporization per gram of agent. There are a number of scenarios possible that could help to limit or eliminate fire spread and effect cooling of the immediate area and/or surroundings such as interaction of the aerosol with horizontal or vertical burning surfaces or cooling of surrounding surfaces which could in turn cool the air and combustion product gases.

Premixed Flames

NRL scientists examined the flame suppression properties of very small water drops in reducing the burning velocity of methane/air flames. Modeling was done in collaboration with Prof. Robert Kee at the Colorado School of Mines. Details of the experiment and results are reported in Ref [7]. Examination of the thermodynamic properties of water compared to thermal gaseous agents and halon 1301 are consistent with the experimental observations; small water drops acting thermally exhibit a comparable effectiveness on a mass basis in premixed flames as CF_3Br with its chemical effect. For small drops, the burning velocity decreases monotonically as a function of water loading. For sufficiently small drops, the burning velocity becomes independent of drop size but still depends on water loading. For stoichiometric, methane-air, premixed flames, this small-drop limit is achieved for a drop diameter of approximately ten micrometers. Sub-micrometer diameter drop inhibition results are in excellent agreement with modeling predictions of Yang and Kee, requiring no adjustable parameters [8]. Water vapor is both observed and predicted to be less effective than water aerosols of drop sizes less than ~ 15 µm. There is an increase in effectiveness of liquid water as the drop diameter is reduced to ~ 10 µm. Below this size limit, there is no increase in suppression effectiveness with decreasing drop size. This limiting drop size correlates with those drops that completely evaporate in this flow field. Complete evaporation of the sub-micrometer mist drops by the time they enter the luminous flame zone was confirmed by monitoring light scattered from the drops in the flame using laser sheet illumination. Drop size measurements using PDPA for larger drops as a function of position in the flame indicate that the drop size for onset of complete evaporation in this flame is between 6 and 27 µm. The sub-micrometer diameter drop measurements are consistent with a predicted ~ 10 µm limiting drop size of the multi-phase model.

The Yang and Kee model predicts a turning-point behavior for the effect of moderate and larger sized drops (above 25 µm for stoichiometric, premixed, methane flames) on burning velocity. At the turning point the derivative of burning velocity with respect to the water mass loading is infinite. Turning points are caused by the drop dynamics within the flame. Specifically, longer drop residence time in a suppressed flame causes further increase of efficiency in flame suppression. Mathematically, at a turning point, an infinitesimally small increase of water mass loading causes the burning velocity to fall to the lower branch of the suppression curve. Such very-low-burning-velocity branches are experimentally not achievable due to the various heatloss mechanisms that would prevent these flames from stabilizing. Therefore, it may be safe to interpret such turning points as flame extinction points.

Experiments that focus on the inhibition effects of larger drops in premixed flames are needed. Unfortunately, both creating the flame and developing the required diagnostics are significant challenges. For the studies reported above, flame structure, burning velocity, and extinction characteristics are modeled as an ideal flat flame. The experiment is a Bunsen-like configuration that allows drops to be introduced through the open tube. The burning velocity in these flames is inferred from analysis of the flame area. In addition, flame profile data can be measured, for example on the centerline. This configuration and modeling approach are valid for sub-micron drops that fully evaporate prior to entering the flame. However, for larger drops or particles, data from such experiments cannot be compared directly to one-dimensional flat-flame models. The gas and particle/drop velocities, for example, are much greater in the Bunsen-like flame. It appears that there are two choices for modeling the inhibition effect of larger particles/drops in premixed flames: configure a “flat” premixed, burner stabilized flame that can be seeded with large water particles/drops, or directly model the three dimensional Bunsen-like flame. The success of uniformly seeding particles/drops into a flat flame is highly unlikely considering the particle/drop sizes to be studied. Success seems more likely for alternative modeling approaches. This area is one that still requires further development.

Counterflow Non-Premixed Flames

To understand the behavior of water drops in counter flowing fields, Lentati and Chelliah at the University of Virgina (UVa) developed a two-phase hybrid Eulerian–Lagrangian formulation for gas-drop flow for treating drop dynamics as well as extinction behavior in counterflow flames. Complete details of the model can be found in Ref. [9]. Using the model they analyzed the effectiveness of monodisperse condensed-phase fire suppressants in extinguishing counterflow flames. An important feature of the UVa model is its ability to treat the singularities associated with solving the drop number density equation in the counterflow field accurately and in a very robust manner. This was achieved by using a hybrid Eulerian–Lagrangian formulation for the gas–drop flow, with the introduction of drop flux fraction to describe the drop number density equation. The model was applied to a case where monodisperse water drops are introduced with the air stream to a non-premixed counterflow flame of methane and air. Several cases with different drop sizes, diameters ranging from 5 μm to 50 μm, were considered. The model predicts that small drops (< 20 μm) tend to follow the gas closely and go through rapid evaporation in the hot mixing layer; it was shown that the < 20 μm drops never cross the stagnation plane. The 50-μm drop considered was shown to cross the stagnation plane several times, before being completely vaporized. The flame extinction strain rate shows non-monotonic behavior for different monodisperse drop sizes considered for several water mass loadings (1–3% in condensed phase). Assuming that the drops leave the air stream at the same velocity as the gas, 15-μm drops were predicted to be the most effective. For example, addition of 3% of water by mass in condensed phase (in addition to 2.22% as saturated vapor) was shown to reduce the extinction rate to 134 s^{-1}, from about 400 s^{-1} for the dry case. The non-monotonic effect of drop size, especially the superior flame extinction phenomenon associated with 15-μm drops, is attributed to the drop dynamics in the counterflow field and to the large mass evaporation and heat sink observed near the oxygen consumption layer.

NRL NGP scientists measured the extinction strain rates of non-premixed propane/air counterflow flames at various water mass fractions (up to 3%) of drop sizes of 14 μm, 30 μm, and 44 μm. Details of the experiments are reported in [10]. Using piezoelectric generation of aerosol drops, NRL investigated the evolution of velocity and size distributions of initially monodisperse, 30 μm and 18 μm water mists in non-premixed propane/air counterflow flames. For both size mists, the peak in the drop size distribution does not change until the flame zone is reached. The peak then shifts to smaller diameters due to evaporation. Variations in number density with axial position are strongly correlated with variations in drop axial velocity. The fluxes of both 30 μm and 18 μm drops decrease between the air tube exit and the stagnation plane, due to the effects of the diverging flow and evaporation. For both 30 μm 18 μm mists, very few 30 μm drops survive the flame, none of the 18 μm drops survive, suggesting that for this size drop in a counterflow flame at moderate strain rate, most of the suppression potential of the mist is being used. On a mass basis, both 14 μm and 30 μm diameter mists were found to be more effective than Halon 1301 at suppressing non-premixed propane/air counterflow flames. The flame inhibition properties of the 44 μm diameter mist were considerably poorer than those of the 14 μm or 30 micron mists. The lower suppression efficiency of the 44 μm mist parallels previous predictions of numerical modeling, and appears to be caused by incomplete drop vaporization during passage through the reaction zone. Comparison of the computational extinction strain rates with the reported experimental measurements show good agreement in consideration of the degree of mist evaporation in the experimental air stream entering the flame. These results explain the observed drop dependent suppression behavior in the range of 14 μm to 42 μm in suppressing counterflow propane air flames. The agreement between the UVa model predictions and NRL experiment results are remarkable, considering the high effectiveness of the small amount of water mass introduced to the flame with the air stream. The hybrid Eulerian-Lagrangian multi-phase flame suppression model and chemical kinetic propane combustion mechanism well predict the measured local propane-air extinction strain rate. Water drop suppression modeling of the flames and consideration of the amount of humidification of the air stream for the reported experimental mists quantitatively account for the observed response of the flames to the added liquid water mass as well as the effect of water drops in this size range. Because of the higher strain rate at extinction, the optimum size water drop is $\leq$ 15 μm, somewhat smaller than for methane air flames. This smaller optimum size may be anticipated for other fuels considering the similarity of the extinction properties of propane to that of many other higher hydrocarbon “typical” fuels. The findings indicate that, if the delivery issues inherent to a condensed phase fire suppressant can be successfully addressed, aerosols of water composed of fairly small drops have the potential to be comparable to that of CF_3Br.

Aerosols with Chemical Suppression Properties

Fire suppression by chemically active particulates such as the alkali metal bicarbonates had been investigated for a number of years prior to the NGP. Fine $NaHCO_3$ powder (<10 μm) was known to be far more effective than any other gaseous chemical agent being considered to replace halon 1301, but the exact physical and chemical mechanism had yet to be quantified. Explicit understanding of the suppression behavior was also lacking. NGP projects explored the suppression behavior of these powders in counterflow flames. Details and results are reported in Refs. [11] and [12]. These projects provided quantitative information that contributed to the development of suitable chemical and physical models describing the behavior of these aerosols.

NGP scientist at NRL studies the fire suppression particle size effects of potassium and sodium bicarbonate powders in propane/air counterflow non-premixed flames. $KHCO_3$ was shown to be more effective on a mass basis than $NaHCO_3$ for all particle sizes tested. It was also shown that the effectiveness of the powder agent varies inversely with the particle size for the size range tested: smaller particles are more effective in suppressing the flames than the larger ones. Models addressing the behavior of particles in counter flowing fields were consistent with an asymptotic behavior for the suppression effectiveness when fuel is introduced from the bottom tube. An explanation of the high effectiveness observed for the alkali bicarbonate particles requires a significant contribution from a chemical suppression mechanism.

NGP researchers at the University of Virginia examined the behavior of sodium bicarbonate particles with the explicit attention to the modeling the aerosol/flame interaction. The work appeared in Ref. [11]. The numerical predictions took into account the detailed homogeneous chemistry and global particle decomposition model of the alkali compounds considered. Modeling results indicated a trend in particle effectiveness very similar to that obtained from the experiments. By varying the temperature at which the particles decompose rapidly to gaseous products, the predictions showed that the smallest particles are more effective because of the rapid heating, leading to complete decomposition of the particles. By manipulating various source terms in the model, the superior effectiveness of sodium bicarbonate particles was attributed to the homogeneous catalytic radical scavenging by NaOH formed, while thermal effects associated with particle heating play a minor role.

Cup Burner Flames

The effectiveness of aerosol agents in a cup burner apparatus was not explicitly investigated under the NGP. Gaseous agents that produced particles in the flames were investigated [13]. Such particle *formation* in the flame after agent introduction limits the effectiveness of chemical agents. It is a fundamental thermodynamic limitation regardless of whether the agent enters the flame as a gaseous species or a condensed liquid or solid. The cup burner flame is a challenging yet relevant flame configuration for understanding aerosol effectiveness in general. Work continues in a number of labs including the NRL to understand the behavior of aerosols agents in a cup burner apparatus and other co-flow flame configurations.

Burning Surfaces

Key physical phenomena involved in the interaction of aerosols with burning surfaces include: buoyancy effect on the trajectory of the aerosol particles, evaporation/decomposition effect on the trajectory of the particles, cessation of reaction and reduction in flame spread caused by the aerosol on flaming surface combustion, and reduction in surface temperature. NGP studies examined the key water drop properties, such as surface loading and drop diameter that affect flame spread rate, through numerical and experimental comparison to determine the effect of drop size and velocity on drop buoyancy and evaporation as the drops approach a hot surface or fire. The work is covered in Refs. [14], [15], [16], [17] and [18]. Experiments were conducted with non-evaporating and evaporating particles of controlled density injected at controlled velocities towards a variably heated surface. Particle velocity as a function of the impressed buoyancy forces were measured to determine the likelihood of a particle reaching a burning surface. Evaporation effects were also examined. Both mono-disperse and poly-disperse drops were injected over PMMA flames or over heated polyurethane foam, using drop loading, delay time after ignition, and location of the spray from the leading edge as parameters. In the presence of water mist, the flame spread rate was observed to rapidly decrease with water loading on the fuel surface. The effect was more pronounced at low values of opposing wind speeds. The effect of mean drop size of the spray on flame spread rate was small for the range of drop sizes used in the experiments. An empirical correlation of the water loading required to retard the spread of unwanted fires and to extinguish them was developed. At ambient oxygen concentration, the heat transfer controlling fuel vapor evolution rate is the dominant factor controlling the flame spread rate. The correlation in water loading and reduction in flame spread rate could be modeled empirically. The influence of drop diameter was found to be minimal. A non-evaporating spray (Dow Thermal Fluid 510) was used to assess the effects of buoyancy induced air velocity on drop size and trajectory; an evaporating spray (water) was used to study the combined effects of buoyancy induced flow. Results show that drop coalescence is the dominant mechanism by which drops change size during their flight to the hot surface. Two coalescence and evaporation models evaluated during the first two years of the project were not successful in predicting drop size histories. The implication is that a well designed and directed spray nozzle can be used to extinguish the fire with water as effectively as a flooding nozzle working with a more efficient suppressant, since the optimal local liquid loading required can be calculated a priori. In addition, secondary collisions and coalescence can cause small mist sprays to reach the fire as large drops.

Combined Chemical/Physical Aerosol Suppression Agents

Chelliah and coworkers at UVa using both experimental and modeling approaches, examined the interactions of small drops of water and water/NaOH solutions with steady, laminar counterflow methane/air non-premixed flames. The combined work is reported in Ref. [19]. The work brought a critical experimental component to earlier modeling predictions and agreed with earlier NRL measurements [7,10] that on a mass basis, small water drops (~20 μm diameter) can be as effective as the gaseous halon 1301. Inclusion of NaOH in water (up to 17.5 % by mass) was observed to significantly enhance the fire suppression ability of water by complementing its thermal effects with chemical catalytic radical recombination effects of NaOH. When the air stream is saturated with water vapor only, it was shown that the counterflow non-pre-mixed flame extinction condition measurements agreed well with the corresponding numerical predictions. With addition of condensed phase water drops, the trends agreed well; however, considerable differences existed between the experiments and modeling which could not be accounted for by the affected by the polydispersivity of the atomizer employed. Other submodels in the numerical model, including radiative heat losses, need to be evaluated.

In the UVa studies, addition of NaOH to water complemented the thermal fire suppression mechanism of water. At the low end of the strain rates investigated (~ 125 s^{-1}), 17.5% by mass of NaOH in the solution was shown to reduce the flame extinction strain rate by almost a factor of five. Chelliah and co-workers also examined the effectiveness of other water additives in both premixed and non-premixed opposed flow flames. This work was reported in Ref. [19]. Non-premixed and premixed methane/air flames were studied. Efforts to combine the thermal fire suppression ability of fine water drops with the chemical inhibition of alkali metals have indicated the existence of an upper limit for agent effectiveness perhaps due to condensation of some intermediate alkali metal species. When the mass fraction of alkali hydroxide in water is below this condensation limit, comparison of the chemical effectiveness clearly indicates that KOH is about 2 times more effective than NaOH on a molar basis for a wide range of flow strain rates. Comparison of the effectiveness of water/NaOH with water/NaCl on a molar basis indicates a superior effectiveness of NaCl over NaOH. The relationship between drop size and flow residence time is found to be important both for comparing the behavior of condensed-phase agents between flame types, as well as for evaluating the efficacy of chemically active additives. Comparison of the effects of water/NaOH drops on the extinction of non-premixed and inhibition of premixed flames implies that if the drops are not completely evaporated before reaching the chemical reaction layer (because of non-optimal drop size or short drop residence time), then the full chemical effectiveness of the agent is not realized. Similarly, when equally sized fine water drops are introduced to non-premixed and premixed flames, with no velocity lag between the drops and the gas phase, the characteristic flame extinction/inhibition conditions of the two flames differ. Flame structure analysis reveals distinct flow residence time of drops (with a median diameter of 13 μm) through each flame structure: 14 ms for the non-premixed flame, 4 ms for the premixed flame. These results point out the importance of understanding the specific reacting flow field and temperature conditions in order to validly assess the intricate coupling between drop size and drop residence time through the flame structure.

IMPORTANCE OF SCALE

The NGP studies covered here have involved the injection of aerosol particles directly into laboratory flames. In real fires with turbulent flow fields, the flow residence times of drops can be very different from those in the premixed and non-premixed flames investigated here, and the optimum drop sizes can be much larger than 10–20 μm. Therefore, design of optimal fire-suppression systems using fine drops of water solutions must consider the flow residence times and flame structures of each application carefully. For real-scale fires, the aerosol must get to the fire to begin the suppression process. Key issues are delivery of the aerosol to the general location, generation of a sufficient quantity of the desired aerosol, and spatial distribution of the agent in the region of the fire. Since in general, the fire location is not known, distribution throughout the area requiring protection must be planned. In addition to answering what aerosol properties are optimum at the fire, engineers must also address what aerosol properties should be generated at the source to achieve this optimum at the fire. These optimum properties will likely change as the fire involves the surrounding areas. The quantitative understanding developed in this program on drop size effectiveness and evaporation/transport issues are critical for successful predictions of aerosols behavior in real-scale fires.

SUMMARY

At the end of the NGP program on the suppression effectiveness of aerosols, we now know that the speculation as to the mechanism of the effectiveness of metal salts on premixed hydrocarbon-air flames proposed by Rosser et al in 1963 is no longer just speculation. As the NGP aerosol data bears out, the earlier proposed mechanism is also more general than for just powders; it also applies to liquid aerosols including primarily physical acting aerosol agents with and without chemical acting additives. This statement can be made now after the collection and analysis of a large body of quantitative data from a number of experiments for a range of experimental flame configurations, several different fuels, a range of aerosol properties including particle size and chemical makeup, as well as a number of modeling predictions.

The interrelated dependencies of particle size and flame conditions explain why seemingly contradictory suppression results appeared in the earlier literature exploring the effectiveness of aerosols in differing flame systems. Suppression results employing an aerosol with a large size distribution or one with many very small particles that dominate the overall effectiveness will likely skew a mass based conclusion. It was key to experimentally quantify the aerosol particle size and number density actually delivered to the flames. Monitoring sizes and velocity as the particles passed through the flame were also key to establishing valid correlations with observed suppression effectiveness. Two-phase model predictions of the interaction of the aerosol and the flame aided in our understanding of the experimental observations. Comparison of the experimental data in combination with the modeling predictions permitted explorations of aerosol parameter space that would have been much more difficult with only experimental approaches.

While flame and aerosol specifics must dominate, some mechanism generalizations can be made. In order to achieve maximum suppression effectiveness, the individual components of an aerosol must pass through a succession of steps: I - heating, II – evaporation/decomposition, followed by III - flame inhibition. Step III for chemical agents must also include the generation of the chemical inhibitor specie(s). In general, inhibition can be in the form of diluting the amount of oxygen available and lowering the temperature which alter the flame chemistry indirectly or by direct participation of the aerosol (or more likely its decomposition products) in the flame radical chemistry. Suppression effectiveness will be controlled by how quickly the aerosol particles progress through these steps. Obviously small particles are favored.

The transition diameter from very effective, small particles to larger, less effective ones depends on the time to complete steps I and II (i.e., the evaporation rate of the aerosol material). Evaporation times are shorter at higher temperatures. For premixed flames, higher flame temperatures mean higher burning velocities and shorter residence times. In counterflow flames, the residence time for small particles is related to the strain rate. The same flame conditions can present a longer residence time to a larger particle which can often oscillate around the stagnation plane several times due to their inability to follow the gas streamlines. For co-flow flames (e.g. in a cup burner) residence times can be long quite long. Entrainment of the aerosol is another factor in the overall suppression effectiveness for co-flow flames. However, thermodynamic limitations can impose restrictions on the concentration of chemical radical scavenger and a longer residence time may offer no advantage.

Due to the time constraints on the individual steps, the residence time presented by the various flame configurations yielded different results. For the same fuel, aerosols are generally less effective in premixed flames than in non-premixed flames. Residence time requirements are greater for water aerosols with a chemical acting additive. These aerosols must complete steps I and II for the liquid water followed by steps I and II again for the additive residue. Thus, there is a tradeoff between flame temperature, flow field, residence time and the particles' physical and chemical properties. Non-monotonic behavior should not be ruled out.

For real-scale fires, the suppression mechanism outlined above must include a critical first step; to be effective the aerosol must *first* get to the fire to begin the process. The type of delivery and what happens in transport often control the ultimate suppression performance. Thus, in addition to answering what aerosol properties are optimum at the fire, one must also address what aerosol properties should be generated to achieve the optimum properties at the fire. The choice will likely change as the fire grows, involving the surrounding areas. As a result of the NGP, such considerations and other engineering issues can now be better addressed.

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