Burning Characteristics of Fuel Droplets with Addition of Nanoparticles at Dilute and Dense Particle Loading

Yanan Gan1 and Li Qiao2*

School of Aeronautics and Astronautics, Purdue University, West Lafayette, IN, 47906

The burning characteristics of fuel droplets containing aluminum nanoparticles at dense and dilute loading rates were investigated. Physical and chemical methods to disperse particles evenly in liquids and to avoid agglomeration were described. Droplets were suspended on the crossing point of two thin silicon carbide fibers and the burning process was recorded using two orthogonally located high-speed digital cameras with and without backlight respectively. Droplet temperature history was acquired using fine wire thermocouples with data acquisition systems. Particle concentration, surfactant concentration and type of base fluids were varied to study their effects on droplet burning characteristics and burning rate. The results show that at high particle loading rates without presence of a surfactant, nanoparticles tend to agglomerate easily. And the burning process has two distinctive stages - burning of the liquid fuel droplet as the first stage and burning of the large particle aggregate as the second stage. At low particle loading rates, however, most particles were transported to the flame zone shortly after ignition and were burned during the burning process of the liquid droplet. The results also show that addition of surfactant reduces droplet burning rate because of a surfactant layer formed around the primary droplet which inhibit diffusion. Similarly, addition of particles also reduces droplet burning rate, especially at high loading rate because of the solid agglomerate formed inside the droplet which also inhibit diffusion.

I. Introduction

Metal particles, such as aluminum and boron, have been employed as energetic additives in propellants and explosives due to their high combustion energy [1]. Recent advances in nanoscience and nanotechnology facilitate production, control and characterization of nanoscale energetic materials, which have shown tremendous advantages over micro-sized materials. Due to the high specific surface area, which results in high reactivity and the potential ability to store energy on the surface, metal nanoparticles offer shortened ignitions delay, decreased burn times, more complete combustion than micron-sized particles [1, 2].

Mixing nanoscale energetic materials with traditional liquid fuels to get enhanced combustion properties is gaining increasing interest. Energetic nanoparticles can increase the volumetric heat release (or energy density) of liquid fuels and thus can potentially enhance performance of current propulsion systems. Studies on ignition and combustion behavior of liquid fuels with nanoscale additives, however, are rare. Jackson et al. [3] measured the ignition delay time of slurries of n-dodecane and nano-aluminum particles in shock tube and it was demonstrated than the addition of nano-aluminum could substantially decrease the ignition delay time under temperatures above 1175K. Decreased ignition delay time was further proved by Allen et al. [4] using a rapid compression machine. They found the ignition delays of ethanol and JP-8 were reduced by 32% and 50% respectively by seeding aluminum nano-particles. Tyagi et al. [5] investigated the effects of small quantities of aluminum and aluminum oxide nanoparticles on the ignition properties of diesel fuels using a simple hot-plate experiment. It was observed that the ignition probability for the fuel mixtures that contained nanoparticles was significantly higher than that of pure diesel. Beloni et al. [6] recently studied combustion of decane-based slurries with metallic nano additives using a lifted laminar flame burner, considering pure aluminum, mechanically alloyed Al0.7Li0.3, and nanocomposite 2B+Ti as additives. Their effects on flame length, flame speed, flame emissions and temperatures were measured. These studies have shown promise of using nanoscale additives such as energetic nanoparticles to enhance combustion of liquid fuels.

1 Graduate Assistant, School of Aeronautics and Astronautics, ygan@purdue.edu, AIAA Student Member.
2 Assistant Professor, School of Aeronautics and Astronautics, lqiao@ecn.purdue.edu, AIAA Senior Member.
Mixing solid fuels with liquid fuels dated back to a few decades ago when slurry fuels were under serious consideration as high energy fuels. Micron-sized aluminum, boron and carbon particles (5-200 µm) were added to liquid fuels as a “liquid fuel extender” in the sense that less hydrocarbon and more plentiful solid fuel (e.g., coal) can be used [7]. Burning characteristics of slurry droplets involving micron-sized boron [8-11], aluminum [12, 13], carbon or blend of aluminum and carbon [14-17] particles at high solid loadings (40-80 wt.%) were studied experimentally. A few theories or postulates were proposed based on the experimental observations [11, 18, 19]. In general, during the initial phase of droplet combustion, semiporous hollow or densely packaged shells, consisting of the particle agglomerates, may form. A key event is the micro-explosion behavior, which was first discovered by Takahashi et al. [9] for slurries of boron/JP-10 droplets. This study demonstrated that the disruption of the primary droplet results in secondary atomization, which substantially enhances the overall burning rate of the primary droplet and provides a means for dispersal and ignition of the boron. Micro-explosion behavior was also evidenced by a few other studies involving aluminum and carbon slurries [13, 17].

These previous studies have revealed some general burning characteristics of slurry fuels involving micron-sized particles at dense loadings. However, many puzzles remain. Due to the complexity of the three-phase physics, the events that can take place either individually or jointly during slurry droplet combustion have not been understood clearly [7]. In particular, there are few studies of slurry droplets involving nanoparticles, which could be different due to energy transfer and particle dynamics at different length scales (nano vs. micron). Gan and Qiao [20] recently compared the burning characteristics of fuel droplets with nano and micron-sized aluminum particles. The results show at dense loading rate five distinctive stages (preheating and ignition, classical combustion, microexplosion, surfactant flame, and aluminum droplet flame) were identified for nanosuspension, while only the first three stages occurred for micron suspension. For the same solid loading rate and surfactant concentration, the disruption and microexplosion behavior of the micron suspension occurred later with much stronger intensity. The intense droplet fragmentation was accompanied by shell rupture, which caused a massive explosion of particles, and most of them were burned during this event. On the contrary, for the nanosuspension, combustion of the large agglomerate at the later stage requires a longer time and is less complete because of formation of an oxide shell on the surface. This difference is mainly due to the different structure and characteristics of particle agglomerates formed during the early stage, which is a spherical, porous, and more-uniformly distributed aggregate for the nanosuspension, but it is a densely packed and impermeable shell for the micron suspension.

As an extension of the previous study [20], the present paper focuses on the effect of nanoparticle loading rate on droplet burning characteristics, dilute vs. dense. Additionally, particle dynamics and suspension quality under dilute and dense loading conditions are investigated. The paper starts with fuel formulation methods including particle dispersion, de-agglomeration as well as fuel characterization. The droplet combustion experiment and diagnostic methods are then described. The effects of surfactant and base fluid on suspension quality and droplet burning characteristics are discussed. Most importantly, the burning behaviors of fuel droplets with dense and dilute particle loadings were compared. Finally, the effects of surfactant and particles on droplet burning rate are discussed.

A. Fuel Preparation and Characterization

The methodology of physical and chemical methods to disperse the particles evenly in base fuels and to avoid agglomeration was described in our previous study [20]. Here, we will only briefly discuss the preparation process and characterization results. Two-step process [21] was adopted to prepare nanofluids-type fuels. Nanoparticles were firstly produced as a dry powder by physical or chemical methods such as inert gas condensation and chemical vapor deposition, which is followed by powder dispersion in liquid. The major issue of the two-step process is aggregation of particles. Sonication [22] and surfactant were used to separate particles from each other, reduce agglomeration, and promote chemical stabilization of the suspension. It is also noted that addition of surfactants can also significantly affect the combustion behavior of the fuel suspension, which will be discussed later.

Two liquid fuels, n-decane and ethanol, were considered as the base fluid. Nano-Al particles (mean diameter of 80nm) were considered as additives. The particles are naturally passivated with a thin layer of Al₂O₃ (2-8 nm). Particles were mixed with liquid fuels by vigorous stirring at first and then sonicated was performed in an ice bath for about 5 minutes. With sonication, suspensions of n-decane/nano-Al (10 w.t.%) typically can remain stable for about 10 minutes, beyond which particles start to settle down. All particles settle on the bottom of the test tube after about a hour. Suspensions of ethanol/nano-Al can last for 24 hours without obvious sediment, much longer than n-decane/nano-Al. To reduce particle agglomeration, we used Sorbitan Oleate (Fig. 1) as a surfactant with its physical properties, e.g., boiling point and viscosity in Table 1 compared with the base fluids n-decane and ethanol. The maximum concentration of the surfactant was 2.5 w.t.%. With even 1 w.t.% surfactant, the n-decane/nano-Al suspension can maintain homogenous for at least 3 hours, significantly longer than the suspension without surfactant. The surfactant can stabilize the suspensions because of the steric stabilization mechanism [23], shown in Fig. 2.
**Table 1 Physical property of different liquids [20]**

<table>
<thead>
<tr>
<th>Chemical Name</th>
<th>Chemical Formula</th>
<th>Molecular Weight</th>
<th>Boiling Point (K at 1 atm)</th>
<th>Viscosity (mPa·s at 20°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-Decane</td>
<td>C_{10}H_{22}</td>
<td>142</td>
<td>447</td>
<td>0.92</td>
</tr>
<tr>
<td>Ethanol</td>
<td>C_{2}H_{6}O</td>
<td>46</td>
<td>352</td>
<td>1.2</td>
</tr>
<tr>
<td>Sorbitan Oleate</td>
<td>C_{24}H_{44}O_{6}</td>
<td>428</td>
<td>852</td>
<td>1200-2000</td>
</tr>
</tbody>
</table>

**B. Experimental Setup**

Figure 3 shows a schematic diagram of the droplet combustion experiment. The experiments were performed in a closed cylindrical stainless-steel chamber, which has four quartz windows for optical access. Two silicon carbide (Si-C) fibers with a diameter of 78 μm were used to suspend the droplet. Droplet was produced using a syringe pump for accurate control of the size and then transferred to the cross point of silicon carbide fibers with a hypodermic needle. Si-C fiber was chosen because of its low conductivity compared to metal wires. Ignition was achieved using a heating wire located right beneath the droplet, which is made of Nickel and Chromium alloy with a resistance of about 1.5 Ω. A solenoid device was used to move the heating wire away right after the droplet was ignited.

The droplet burning process was recorded by two orthogonally located high-speed digital cameras, both with a framing rate up to 10,000 fps. One camera was for direct imaging of the flame, and the other was with backlight for better determination of droplet size and observation of droplet disruption/breakup. Images were analyzed by a Phantom image analyzing software. To measure droplet temperature history, we used a type K thermocouple made of platinum (Pt) and platinum-rhodium (Pt-Rh) wires of 75 μm to suspend droplet, instead of using both Si-C fibers and a thermocouple to minimize the intrusive to the droplet. A 1000 Hz data acquisition system recorded the temperature history, which was synchronized with the high speed digital camera so that the droplet size and temperature history was measured simultaneously.
II. Results and Discussion

A. Previous Studies on Droplet Combustion with Dense Particle Loading

Our previous investigation [20] compared the burning characteristics of fuel droplets containing dense nano-sized and micron-sized particles. It is noted that the same solid particle loading rate (10 w.t.%) and surfactant concentration (2.5 w.t.%) were used for comparison. Also, n-decane was chosen as the base fuel. Overall, the burning process is a multi-stage and multi-phase phenomenon, involving multiple mechanisms (liquid droplet evaporation, vapor flame, particle agglomerate, particle aggregate burning, bubble formation inside the droplet, micro-explosion, etc). As stated earlier, this paper focuses on the effect of particle loading rate on droplet burning characteristics. To facilitate the discussion, some results from our previous studies at dense particle loading are briefly summarized below:

(1) Droplet Combustion with Dense nano-Al Particles Loading

For stabilized droplet with nanoparticles (80nm), five distinct burning stages were identified:

**Pre-heating and ignition stage (Stage I):** In the pre-heating and ignition stage, evaporation occurred on the droplet surface and a vapor cloud was formed surrounding the droplet. Evaporation tended to decrease the droplet size, but the droplet swelled a little bit because of heat transfer from the heating wire. Thus, the overall droplet size decreased only slightly and the droplet temperature rose quickly after ignition.

**Classical droplet combustion stage (Stage II):** The second stage is characterized by steady evaporation of the droplet, which is similar to the classical burning behavior of a single-component droplet. A distinct flame envelop was formed surrounding the droplet. The droplet diameter decreased steadily with time, approximately following the classical $D^2$ law. During this stage, very small amount of nano-Al particles were ignited and the burning particles rose quickly and formed multiple streaks.

**Micro-explosion stage (Stage III):** In this stage, smaller droplets and particles or particle aggregates were ejected and burned during this event, which caused disturbance to the envelop flame around the primary droplet. This is called micro-explosion, which includes burning of both liquid and particle fragments. Micro-explosion repeated several times until most of the liquid fuel was consumed. At the end, nearly all the liquid fuel was consumed and a large amorphous agglomerate was left on the fiber. Magnified view of the agglomerate reveals its highly porous structure, with exploded holes and cracks on the surface resulting from micro-explosion.

**Surfactant flame stage (Stage IV):** A secondary flame was initiated around the large agglomerate after the envelope flame extinguished. It lasted for a short period of time of about 0.1 second before it was extinguished. The appearance of the flame is somewhat like an envelope diffusion flame. This stage is called “surfactant flame” as we believe it is due to combustion of the surfactant or its pyrolysis products. This flame occurred for all fuel mixtures with surfactant, in regardless of the type of the base fluid, particle size, and particle concentration. It did not occur when surfactant was not added.

**Aluminum droplet flame stage (Stage V):** The extinction of the surfactant flame was followed by ignition of the large Al agglomerate. The agglomerate was firstly melted down and then coalesced into a liquid droplet. The vapor-phase Al flame is characterized by a halo and smoke tail. The smoke tail is due to diffusion of the aluminum oxide outwardly and upwardly. The aluminum droplet flame lasted for about 0.4 second, which is comparable to the duration of the classical combustion stage. Occasionally smaller agglomerates were ejected from the primary droplet, resulting in bright streaks.

(2) Droplet Combustion with Dense micron-Al Particles Loading

For stabilized droplet with micron particles (5 µm), only three distinctive stages were identified: the pre-heating and ignition stage, the classical combustion stage, and the micro-explosion stage. Although the two suspensions share some similarities, major differences exist in terms of burning characteristics. First of all, the amount of micron-sized particles which were ignited and burned during the classic combustion stage is much less than the amount of nanoparticles burned during the classical combustion stage. This can be explained as nanoparticles are lighter and diffuse faster so that they are easier to be brought to flame zone where the temperature is much higher than the droplet inside. Secondly, both micro-explosion and fragmentation of droplets are much stronger for the micron-suspension than for the nano-suspension. In fact for micron-suspension, the particle shell/aggregate was totally exploded during micro-explosion and the majority of the particles were burning during this event. Figure 4 compares the droplet/particle aggregate fragmentation behavior using backlight for the two suspensions. For micron-suspension, many smaller droplets as well as fragmentation of particles were ejected from the primary droplet, causing massive explosion. For nanoparticles, however, only part of the aggregate was exploded away and the rest requires longer time and may not be complete due to oxide shell formed on the outer layer.
The different micro-explosion behavior between the nano-suspension and the micron-suspension is caused by differences in structure and strength of particle agglomerates formed during droplet evaporation. Droplet drying experiments were conducted to better understand the effect of particle size on shell formation and shell characteristics. The drying process was described in Ref. [20] and the results of the droplet drying experiments validate that the different micro-explosion behavior could be due to the characteristics of particle agglomerates: a porous aggregate which is more uniformly distributed in a sphere for the nano-suspension v.s. a dense-packed, impermeable shell for the micro-suspension. In addition, carbonization of the surfactant pyrolysis products result in an impermeable shell for the micron-suspension, i.e., carbon atoms bridges aluminum particles. For the nano-suspension case, the pressure accumulation inside the shell due to nucleation of n-decane and bubbles could be partly released through the porous structure before micro-explosion. This explains why only part of the agglomerate was ejected and burned, as shown in (Fig. 4(a)). However, the impermeable densely packed shell formed by micro-particles inhibits pressure release and the accumulated pressure results in much stronger shell fragmentation and micro-explosion (Fig. 4(b)).

(3) Effect of Surfactant

In our previous studies [20], we determined the effect of surfactant on combustion behavior through studying burning process of n-decane/surfactant (2.5 w.t.% for comparison) without adding any particles. The burning process was as follows: After ignition, relatively small bubbles were observed rising inside the droplet and the number of bubbles and volume they occupied increased as the droplet size decreased. At a certain point, all these bubbles were observed to merge into one big bubble. The micro-explosion occurred immediately after that, featured by rupture of the big bubble and ejection of many smaller droplets. The swelling and micro-explosion repeated several times until all the liquid fuel was consumed. Burning behavior is consistent with previous studies [24] of two or multi-component liquid mixtures. The more-volatile component, which is n-decane in this study, will be vaporized first when exposed to heat. The droplet surface is more concentrated with surfactant as more n-decane is consumed, and a thin surfactant layer will be formed around the droplet surface. Since droplet temperature is controlled by its less volatile component, the droplet core temperature could be higher than the boiling point of n-decane. The superheat accumulated after the droplet is heated beyond the boiling point of n-decane will result in the nucleation of n-decane, which explains the formation of bubbles inside the droplet described in the previous section. Pressure build-up inside the bubbles will ultimately break the surface tension by surfactant layer, which will result in disruption of the primary droplet.

(4) Effect of Base Fuel Type

The effects of the base fuel on the droplet combustion characteristics of the suspensions were also investigated [20]. For the purpose of comparison, nanoparticle loading (10 w.t.%) and surfactant addition (2.5 w.t.%) were kept the same with nano-suspension in n-decane. The burning characteristics for the two suspensions are similar, however, some differences exist. First of all, the ethanol/nano-Al droplet experienced the swell-and-contract process with smaller droplets ejected from the primary droplet even before the primary droplet was ignited. This behavior can be explained by the lower boiling point of ethanol (352 K) compared to n-decane (447 K). Because of its high volatility, the ethanol near the droplet surface was quickly vaporized and a surfactant layer was formed around the droplet. The ethanol inside the surfactant layer was rapidly heated beyond its boiling point, even before ignition took place, and nucleation and pressure buildup inside the droplet resulted in droplet fragmentation. Another difference is that more particles were burned during the classic droplet burning stage and the micro-explosion stage for the ethanol/Al droplet than for the n-decane/Al droplet. This can also be explained by the higher volatility of ethanol compared with n-decane. Fragmentation of the primary droplet is much more intense for the ethanol/Al droplet than for the n-decane/Al droplet. Moreover, the frequency is higher. As a result, more sub-droplets were emitted and consequently more particles and particle agglomerates were ignited and burned.
B. Droplet Combustion with Dilute Particles Loading

The above results show that at dense particle loading rates, most particles are burned in the later stage as a large agglomerate for nanosuspension and most particles are burning during the micro-explosion event for micron suspension. This indicates nanoparticles may be less efficient than micron-sized particles because burning of the large particle aggregate requires longer time and may not be complete because of the oxide shell formed on the surface. However, on the other side, nanoparticles are more desirable than micron-sized particles because they are a lot easier to suspend in liquid. Nanosuspension can last much longer than micron-suspension because of the random Brownian motion and significantly increased surface area for surface reaction to take place when a chemical agent is used to promote suspension stability. For practical application, it is desired that particles could be burned completely, rather in the form of a large agglomerate. Ideally, the burning of particles should take place simultaneously with the burning of liquid fuel so that the overall burning time will not be increased.

We know that micro-explosion happens for stabilized fuel droplets because of the existence of surfactant. To understand the effect of particle loading rate, surfactant was not used for the experiments in this section. Our experience shows that nanoparticles and micron particles, especially the latter, tends to settle down rather quickly in n-decane if no surfactant is added. On the contrary, using ethanol as base fluid can provide a good quality suspension even without the help of a surfactant. This is because of ethanol’s higher viscosity and its ability to the formation of weak gel structures around the particles. The results shown in the following are based on ethanol as base fluid. The burning characteristics of ethanol droplets with dense (10 wt.%) and diluted (0.1 wt.%) nanoparticles were compared in Fig. 5 and Fig. 6.

![Figure 5. A burning sequence of a non-stabilized ethanol/nano-Al droplet.](image)

The nano-Al (80 nm) concentration is 10 wt.%.

![Figure 6. A burning sequence of a non-stabilized ethanol/nano-Al droplet.](image)

The nano-Al (80 nm) concentration is 0.1 wt.%.

For the droplet with dense (10 wt.%) particle loading, two combustion stages were identified. The droplet was ignited in Fig. 5 (a). The first stage was characterized by steady combustion of the droplet, similar to combustion of
A pure ethanol droplet. Very few nanoparticles were ignited during this stage, as shown in Fig. 5 (b). The second stage started when a large agglomerate was formed on the cross point of the fibers as shown in Fig. 5 (c). After the droplet flame was extinguished, the Al agglomerate was melted into Al droplet and then an Al vapor flame was established (Fig. 5 (d)). Finally, a solid residue was left on the cross point of the fibers after Al vapor flame extinguished, as shown in Fig. 5 (e).

The burning characteristics of droplet with dilute nanoparticle loading (0.1%) are shown in Fig. 6. The burning behavior is completely different from that with dense particle loading. The droplet was burned steadily in a similar manner as a single-component droplet. However, particles were continuously transported to the hot flame zone, and then ignited and burned. We observed that nanoparticles escaped from the surface of droplet, reached the flame zone where the temperature is high and there are more oxygen. The particles were then ignited and burned, rising up due to natural convection. Thus, the ignited nanoparticles were heavily populated in the top tail of the envelope ethanol flame. Almost all nanoparticles were burned simultaneously with burning of base fuel, without forming an aggregate or leaving burned residue on the fiber, as shown in Fig. 6 (e). Additionally, as droplet size decreases, more particles were ignited and burned, comparing Fig. 6 (a), (b) & (c). This may be because shrinking of the droplet increases particle concentrations and thus more particles can escape from the droplet and reach the hot flame zone. It is noted that ethanol flame in Fig. 6 was very weak and can hardly be seen because we used short exposure time (200µs) for better imaging the burning of nanoparticles. The flame shape of a pure ethanol droplet with longer exposure time (999 µs) was shown in Fig. 7, which was compared to that of a non-stabilized ethanol/nano-Al droplet.

The different burning behavior of nanoparticles in fuel droplets under dense and dilute loading can be explained by particle transport and dynamics inside the droplet. Under dense loading (10 w.t.%), the number density of nanoparticles is higher and the collision rate for each particle is higher. Thus, particles are much easier to collide with others to form an aggregate. As the droplet surface regresses, nanoparticles and nano-agglomerate tend to move inward and form a large agglomerate on the cross point of the fibers. Because of the strong tendency of aggregation, individual particles have little chance to transport to the droplet surface and then escape from the surface. Under dilute loading rate (0.1 w.t.%), particle number density is much lower and the collision rate for each particle is much lower. The random Brownian motion is the dominant mechanism for particle transport. Following the outward diffusion of the liquid fuel, particles could have the chance to escape from the droplet surface as the droplet was continuously vaporized. This resulted in the observed continuous ignition and burning of particles in the area above the flame zone.

![Pure Ethanol](image1) ![Ethanol with nano-Al](image2)

**Figure 7.** Comparison of flames of a pure ethanol and a non-stabilized ethanol/nano-Al droplet.

The nano-Al (80 nm) concentration is 0.1 wt %.

### C. Effect of Surfactant and Particles Loading on Droplet Burning Rate

In order to study the effect of surfactant and particles on burning rate, burning rates of different fuels were derived and compared here. It is noted that only classical combustion stage was considered for burning rates comparison regardless of preheating, transition and micro-explosion stages. Scaling of variables suggested by the classical theory of droplet burning was used. Taking n-decane for example, the evolution of droplet $D$ (D$^2$ v.s. t) with different initial size was shown in Fig. 8 (a) and the scaled results ($D^2/D_0^2$ v.s. $t/D_0^2$) were shown in Fig. 8 (b).

It is demonstrated that the burning rate is a unique property for a given fuel and is independent of initial droplet size.

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The unification of droplet burning history \((D^2/D_0^2 \text{ v.s. } t/D_0^2)\) allows the comparison of burning rate of different fuels with arbitrary size.

![Fig. 8 Droplet size history of pure n-decane droplets](image)

Using the methodology discussed above, the burning rates of three different fuels were examined to study the effect of surfactant and particles loading, and their scaled droplet size histories were shown in Fig. 9 (a). The burning rate \((K)\) for each fuel corresponds to the slope of each straight line. Surfactant’s influence on the burning characteristics has been discussed in the previous sections. Since the surfactant tends to form a thin layer around the droplet surface, the diffusion of liquid fuel inside will be somewhat inhibited. As a result, the burning rate for n-decane/surfactant \((K_2=0.550)\) will be smaller than that for pure n-decane \((K_1=0.644)\). For nanoparticles interior, they tend to agglomerate and a agglomerate structure will be formed inside the fuel droplet as more liquid fuel is vaporized and burned. The liquid fuel needs to diffuse out of the agglomerate structure and then the surfactant layer. The diffusion barrier due to the existence of agglomerate structure will further reduce the burning rate, which was proven by the even lower burning rate for n-decane/nano Al/surfactant \((K_3=0.474)\) compared with that for n-decane/surfactant \((K_2=0.550)\). The effects of particles on burning rate were further validated in Fig. 9 (b), where burning rates of stabilized droplets with varied particle loading rate (with 1%, 10% and 20% nanoparticles respectively) were compared. The inhibiting effect of particles was further confirmed by the fact that high loading rate will lead to lower burning rate. The effect of diluted nanoparticles on droplet burning rates was also investigated without the interference of surfactant, as shown in Fig. 10. It can be observed that the burning rate was decreased even with 0.1% addition of nanoparticles.

![Fig. 9 Burning rates comparison of different fuels with dense particles loading](image)
III. Conclusion

The burning characteristics of fuel droplets containing dense and dilute nanoscale aluminum particles were compared. Additionally, the effect of surfactant and particles loading on droplet burning rate were determined. It is found that ethanol/nano-Al suspension can last much longer than n-decane/nano-Al suspension. This is mainly due to the fact that ethanol tends to form a gel structure surrounding the particles making the suspension more stable. Also, ethanol has a higher viscosity than n-decane so that the particles move slower in ethanol. The results show that at high particle loading rates, nanoparticles tend to agglomerate easily. Without the presence of a surfactant, the burning process has two distinctive stages - burning of the liquid fuel droplet as the first stage and burning of the large particle aggregate as the second stage. Burning of the large particle agglomeration increases the overall burning time and may not be complete because of the oxide shell formed on the surface. At low particle loading rates, however, most particles were continuously transported to the flame zone shortly after the droplet was ignited. Most particles are burned during the burning process of the liquid droplet. Thus low particle loading rate may be more attractive in practical applications as it can still increase the energy density of the fuel without increasing the overall burning time. Moreover, particles can be burned more completely without forming a large agglomerate. Additionally, the suspension quality is much better as low loading rate because of much lower inter-particle collision rate. Finally, addition of surfactant and solid particles slightly reduces droplet burning rate at dense loading rates. The former is because of the surfactant layer formed around the droplet which inhibits diffusion. The latter is because of a solid agglomerate formed inside the droplet which also inhibit diffusion.

Acknowledgments

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References