

Flame propagation of nano/micron-sized aluminum particles and ice (ALICE) mixtures

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Abstract

Flame propagation of aluminum–ice (ALICE) mixtures is studied theoretically and experimentally. Both a mono distribution of nano aluminum particles and a bimodal distribution of nano- and micron-sized aluminum particles are considered over a pressure range of 1–10 MPa. A multi-zone theoretical framework is established to predict the burning rate and temperature distribution by solving the energy equation in each zone and matching the temperature and heat flux at the interfacial boundaries. The burning rates are measured experimentally by burning aluminum–ice strands in a constant-volume vessel. For stoichiometric ALICE mixtures with 80 nm particles, the burning rate shows a pressure dependence of $r_b = aP^n$, with an exponent of 0.33. If a portion of 80 nm particles is replaced with 5 and 20 μm particles, the burning rate is not significantly affected for a loading density up to 15–25% and decreases significantly beyond this value. The flame thickness of a bimodal-particle mixture is greater than its counterpart of a mono-dispersed particle mixture. The theoretical and experimental results support the hypothesis that the combustion of aluminum–ice mixtures is controlled by diffusion processes across the oxide layers of particles.

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1. Introduction

Aluminum (Al) particles are used in propulsion and energy-conversion applications due to their favorable energetic properties [1]. The Al–water

mixture is promising for underwater propulsion [2], low-earth-orbit (LEO) missions, in situ propellant formulations for lunar and Mars missions [3], hydrogen generation in the high-speed air-breathing propulsion [3], and fuel-cell technology [4]. One of the main drawbacks of nano-Al/water propellant, aging caused by low-temperature reactions and evaporation of water may be overcome by freezing the water in the mixture. This prompted the consideration of nano-Al/ice (ALICE) mixtures [5].

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Nano-particles exhibit distinct thermophysical features due to the presence of a relatively large number of surface atoms [6]. As the particle size decreases from 30 to 3 nm, the percentage of surface atoms in the particle increases from 5 to 50% [7]. The melting point of Al particle decreases from 933 to 473 K when the particle diameter decreases from 10 to 2 nm [8–10]. Nano-Al particles ignite at temperatures as low as 900 K [11–13], which is substantially lower than the ignition temperature of micron-sized aluminum particles, 2350 K. They are, thus, of paramount interest for applications involving propellants, explosives, and pyrotechnics [14]. The oxide layer, however, constitutes as much as 32% of the particle mass when the particle size reaches 50 nm [15].

The combustion of Al–water mixture has been studied experimentally [15,16]. The burning rate of a 38 nm Al–H₂O mixture was found to follow a $p^{0.47}$ relation, and a d^{-1} law has been established over a size range of 38–130 nm, suggesting diffusion-controlled combustion. Theoretical analysis of Al-particle dust combustion has been performed [11,17]. The dust cloud combustion features dilute particle loading and negligible particle–particle interactions. The nano-Al/water mixture, however, is a viscous paste featuring dense particle loading and significant particle–particle interactions. Attempts to model the combustion of ALICE mixtures have been limited. In a previous study [5], a simplified model was developed assuming complete combustion, negligible heat losses, and kinetically-controlled oxidation, but there were considerable discrepancies between the predictions and experimental data. Recently, a diffusion-controlled model, incorporating additional flow physics and effects of incomplete combustion and heat losses, was established for nano-Al/water combustion [18]. The present study extends that model to predict the flame structures and burning rates of 80 nm ALICE mixtures over a pressure range of 1–10 MPa. The effects of the addition of 5 and 20 μ m Al particles on the burning rates of the baseline mixture are also analyzed. Results show favorable agreement with measured values.

2. Experiment

The burning rates of ALICE mixtures were obtained using a constant-volume pressure vessel in an argon environment, as shown schematically in Fig. 1 [15]. The 61 cm long chamber, constructed from stainless steel, is equipped with four optical viewing ports, each having a 15.2×2.54 cm field of view. It has an inner diameter of 22 cm and a total free volume of 23 L to minimize the pressure variation caused by the generation of gaseous combustion products. The nano- and micron-sized Al particles are mixed using a

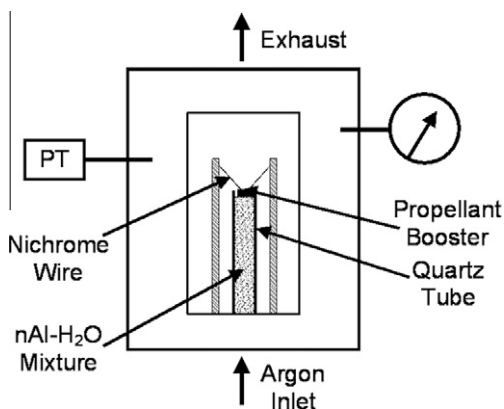


Fig. 1. Schematic of optical constant-volume vessel [15].

Resodyn LabRAM acoustic mixer to breakup agglomerates and produce a homogeneous blend of particles. The required amount of water is determined based on the active Al content of the particle blend. It is then hand-mixed with the particles. The amount of water in the mixture is varied to maintain constancy of equivalence ratio under varying loading density of micron-sized particles. The mixture is packed into a quartz glass tube (1 cm OD, 0.8 cm ID, 6.35 cm long), which is sealed at one end. The propellant strands are then frozen at approximately -30 °C. A small ignition booster made of a homogenous double-base gun propellant (NOSOL 363) is placed atop the strand. Ignition is initiated by a resistance-heated nichrome wire threaded through the booster. The temporal evolution of the regressing luminous front, which is recorded using video equipment, is used to determine the burning rate of the strand.

3. Theoretical framework

The present study deals with pressures representative of those in solid rocket motors. Free-molecular effects could, thus, be neglected without major loss in the accuracy. For example, the mean free path of a water molecule is ~ 7 nm at a chamber pressure of 7 MPa and combustion temperature of 2000 K. The Knudsen number is 0.0875, which is significantly lower than unity. This is more so at lower temperatures. To facilitate analysis, the coordinate system is attached to the flame front. The ALICE mixture approaches the stationary flame and the combustion products travel away from it. A differential form of the conservation laws for the fluid (including ice) and particulate phases is employed. Steady-state, one-dimensional flame propagation is considered at isobaric conditions. The experimental data indicates that the flame propagates at a constant

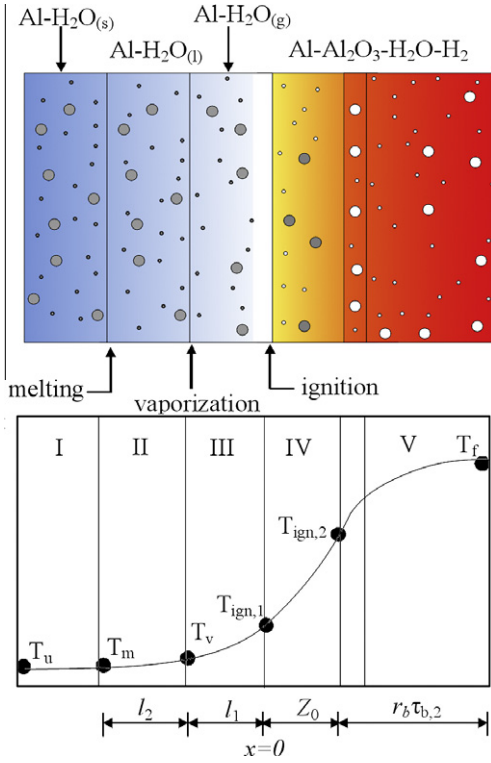


Fig. 2. Physical model and multi-zone frame structure (●, nano-Al; ○, Al_2O_3 ; ●, micron-Al).

speed [15]. There is a noticeable variation of pressure in the experiments. For example, an average pressure of 7.24 ± 0.08 MPa is observed when the initial pressure is 7 MPa. The initial pressure is used, since this corresponds to less than 5% change. The particles are assumed to be uniformly sized at the mean diameter and are in thermal equilibrium with the surrounding fluid, as proposed in Ref. [11]. Phase changes, which are inherently isothermal, occur at the interfacial boundaries.

Figure 2 shows the physical model of concern and a multi-zone flame structure. The entire region is divided into five different zones based on the thermodynamic states of water and Al-particle reactions. Water is initially at its solid state, and then melts and evaporates when the local temperature reaches its phase transition values, T_m and T_v , respectively. A bimodal distribution of particle sizes at nano- and micron scales is considered here; each group starts to burn at its corresponding ignition temperature, $T_{\text{ign},1}$ or $T_{\text{ign},2}$. No chemical reactions are assumed to occur in the preheat zones. Thermal energy is transferred to the unburned mixture by conduction.

Thermo-physical properties are of paramount importance in predicting the flame characteristics. For oxide coated particles, the thermal conductivity, λ_p , is calculated as follows [19]:

$$\lambda_p = \frac{\lambda_{Al}^2 R}{(r-R)[2\lambda_{Al} \ln a - 2\lambda_{ox} \ln a - (\lambda_{Al}^2/\lambda_{ox})] + r\lambda_{Al}}, \quad (1)$$

where

$$a \equiv \frac{b - \lambda_{Al} R}{b - \lambda_{Al}(R-r)}; \quad b \equiv 2(R-r)\lambda_{ox} + 2r\lambda_{Al}. \quad (2)$$

Here λ stands for the thermal conductivity, r the radius of the Al core, R the outer radius of the particle. The subscripts Al , ox , and p refer to aluminum, oxide, and particle, respectively. The following correlation for the mixture thermal conductivity, λ_m , provides the best fit to the experimental data for a wide range of particle volume fractions [20]:

$$\lambda_m = \lambda_p \exp[-1.5\Phi_f/(1-\Phi_f)]. \quad (3)$$

Here Φ is the volume fraction. The subscripts m and f refer to mixture and fluid, respectively. The thermophysical properties are evaluated at an average temperature in each zone.

3.1. Al-ice zone (I)

The energy conservation in this region takes the form:

$$(\rho_{Al}C_{p,Al}\Phi_{Al} + \rho_{ox}C_{p,ox}\Phi_{ox} + \rho_I C_{p,I}\Phi_I)r_b dT/dx = \lambda_{m,1} d^2 T/dx^2, \quad (4)$$

subject to the interfacial conditions:

$$T_{x \rightarrow -\infty} = T_u; \quad T_x = (l_1 + l_2) = T_m; \quad (5)$$

where ρ is the density, C_p the specific heat, r_b the burning rate, T the temperature, l_1 and l_2 the thickness of the vapor and water zones, respectively, and x the space coordinate. The subscripts u and I refer to the unburned state, and ice, respectively. An analytical solution is obtained for the temperature profile:

$$T = T_u + (T_m - T_u) \exp\{k_1(x + l_1 + l_2)\}, \quad (6)$$

where k_1 is the ratio of the burning rate to the thermal diffusivity of the ALICE mixture, defined as:

$$k_1 = r_b(\rho C_p)_I / \lambda_{m,1}, \quad (7)$$

where $(\rho C_p)_I$ denotes the volume-averaged product of density and specific heat for the mixture. The temperature varies exponentially with the spatial coordinate, x .

3.2. Al-water zone (II)

The melting of ice does not affect the particle volume fraction. The mass conservation of water is used to derive the following energy equation:

$$(\rho_{Al}C_{p,Al}\Phi_{Al} + \rho_{ox}C_{p,ox}\Phi_{ox} + \rho_I C_{p,w}\Phi_I)r_b dT/dx = \lambda_{m,2} d^2 T/dx^2, \quad (8)$$

subject to the interfacial conditions:

$$\begin{cases} x = -l_1 : T = T_v, \\ x = -l_1 - l_2 : \lambda_{m,2} dT/dx = \lambda_{m,1} dT/dx + h_{sl} \Phi_I \rho_I r_b, \end{cases} \quad (9)$$

where h_{sl} is the enthalpy of melting of ice. The subscripts v and w refer to vaporization and water, respectively. The thickness of this liquid zone is calculated by performing the heat-flux balance at the melting front, $x = -(l_1 + l_2)$:

$$l_2 = \frac{1}{k_2} \ln \left(1 + \frac{\lambda_{m,1} k_2 (T_v - T_m)}{\lambda_{m,1} k_1 (T_m - T_u) + h_{sl} \rho_I \Phi_I r_b} \right). \quad (10)$$

An analytical solution to Eq. (8) is derived by matching the temperature at the interfacial boundaries:

$$T = \frac{T_v (e^{k_2(x+l_1)} - e^{-k_2 l_2}) + T_m (1 - e^{k_2(x+l_1)})}{1 - e^{-k_2 l_2}}. \quad (11)$$

3.3. Al–water vapor zone (III)

The vaporization of water causes water vapor to emerge at a higher velocity at the vaporization front, $x = -l_1$. Its velocity is calculated by considering the mass conservation of water:

$$\rho_I r_b = \rho_v v_g, \quad (12)$$

where v_g is the gas velocity and ρ_v the density of water vapor. Note that the particle velocity and density are unchanged during vaporization. The energy conservation equation is derived as follows:

$$(\rho_{Al} C_{p,Al} \Phi_{Al} + \rho_{ox} C_{p,ox} \Phi_{ox} + \rho_I C_{p,v} \Phi_I) r_b dT/dx = \lambda_{m,3} d^2 T/dx^2, \quad (13)$$

subject to the interfacial conditions:

$$\begin{cases} x = -l_1 : \lambda_{m,3} dT/dx = \lambda_{m,2} dT/dx + h_{fg} \Phi_I \rho_I r_b, \\ x = 0 : T = T_{ign,1}, \end{cases} \quad (14)$$

where h_{fg} is the enthalpy of water vaporization and $T_{ign,1}$ the ignition temperature of nano-Al particles. The thickness of the vapor zone is obtained by considering the heat-flux balance at $x = -l_1$:

$$l_1 = \frac{1}{k_3} \ln \left(1 + \frac{\lambda_{m,3} k_3 (T_{ign,1} - T_v)}{\frac{\lambda_{m,2} k_2 (T_v - T_m)}{(1 - e^{-k_2 l_2})} + h_{fg} \rho_I \Phi_I r_b} \right). \quad (15)$$

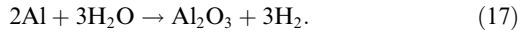
The temperatures at the interfacial boundaries are matched to provide a closed-form solution to the energy equation:

$$T = \frac{[T_v (1 - e^{k_3 x}) - T_{ign,1} (e^{-k_3 l_1} - e^{k_3 x})]}{1 - e^{-k_3 l_1}} \quad (16)$$

The temperature profiles in the water and vapor zones depend on their respective thicknesses, which are not known a priori and must be solved for simultaneously with the burning rate and flame thickness.

3.4. Reaction zone (IV,V)

The water vapor reacts with Al particles to form aluminum oxide and hydrogen:



The mixture properties are obtained by averaging their respective quantities of the reactant and product species. The reaction zone is divided into three regions: (1) nano-Al reaction region in which nano-Al particles ignite and burn; (2) over-lapping reaction zone in which both nano- and micron-sized Al particles burn; and (3) micro-Al reaction zone in which only micron-sized particles continue to burn. The energy conservation can be written in the following general form:

$$\left(\sum_i \rho_i C_{p,i} \Phi_i \right) r_b dT/dx = \lambda_{m,4} d^2 T/dx^2 + \sum_{j=1}^2 \eta_j \rho_{u,m} Q/\tau_{b,j}, \quad (18)$$

where $\rho_{u,m}$ is the unburned mixture density, η the fraction of nano/micron-sized particles in the particle blend, and τ_b the particle burning time scale. The subscripts i, j refer to species i and particle class j , respectively. The heat of reaction, Q , is calculated as:

$$Q - Q_v - Q_m = C_p (T_f - T_u), \quad (19)$$

where Q_v and Q_m are the enthalpies of water vaporization and ice melting per unit mass of the mixture, respectively. The actual flame temperature, T_f , is lower than its adiabatic counterpart, due to radiation and conduction heat losses and incomplete combustion. Diakov et al. [21] burned 100 nm Al–water strands at 1 atm pressure and measured the flame temperature as 1800 K for 87% combustion efficiency. In the present study, chemical equilibrium calculations [22] are employed to extrapolate this flame temperatures to higher pressures and bimodal particle distributions by assuming the same combustion efficiency.

To facilitate the analysis, the temperature and the spatial coordinate are normalized as follows:

$$\theta = T/T_u, \quad y = x/(r_b \tau_0), \quad (20)$$

where τ_0 is taken as the nano-particle burning time scale at a reference temperature. The location $y = 0$ is the ignition point of nano particles. Substituting the normalized variables defined in Eq. (20), Eq. (18) is written as:

$$d^2 \theta / dy^2 - \kappa^2 d\theta / dy = - \sum_{j=1}^2 \mu_j \kappa^2 (\theta_{ign,j} - 1), \quad (21)$$

where $\kappa = r_b \sqrt{\tau_0 / \alpha_{m,4}}$ is the normalized burning rate, with α being the thermal diffusivity. The normalized heat-release rate, μ_j , is written as:

$$\mu_j = -\alpha_{m,4} \rho_{u,m} Q \eta_j / [\lambda_{m,4} P_j (T_{ign,j} - T_u)]. \quad (22)$$

Here, P_1 is set to unity, and P_2 is the particle burning-time scale ratio, $\tau_{b,2}/\tau_{b,1}$. Equation (21) is solved to give the temperature profile in the reaction zone:

$$\theta = \sum_{j=1}^2 \mu_j (\theta_{ign,j} - 1) y + C_1 e^{\kappa^2 y} + C_2. \quad (23)$$

The normalized heat-release rates, μ_1 and μ_2 , are set to zero in the micro- and nano-Al reaction zones, respectively. The burning rate is determined iteratively by matching the temperature distribution and heat flux at the interfacial boundaries.

The present model requires input of the ignition temperature and burning time scale of Al particles. Parr et al. [23] ignited and burned Al particles in post-combustion gases from a hydrogen–oxygen–argon burner flame. The ignition temperatures of 24–192 nm Al particles are in the range of 1325–1360 K, while that of 3 μm particles is 1400 K. Gurevich et al. [24] observed ignition of 20 μm particles in a water vapor medium at 1300 K. Low-temperature ignition of micron-sized Al particles in water vapor has also been observed in a recent study by Schoenitz et al. [25]. For convenience, the ignition temperature is taken to be 1360 K. The combustion of nano-Al particle involves diffusion through the gas-phase mixture and oxide layer and chemical reactions at the particle surface. A $d^{0.3}$ law for the single particle burning time is established for sub-micron particles at 1 atm pressure [11]. The resulting burning rates of the ALICE mixture follow $d^{-0.13}$ law [18]. This contradicts the experimental data, which indicates d^{-1} law at higher pressures. It is important to note that the continuum hypothesis breaks down for sub-micron particles at 1 atm pressure. The experimental burning rate trend is obtained only if the burning time scale follows the d^2 law [18]. This motivated us to opt for the d^2 law for nano-sized Al particles burning in ALICE mixture at pressures representative of those in solid rocket motors. The baseline time scale is approximated as the burning time of a 24 nm particle at 1 atm pressure; it is 0.22 ms at 1600 K [23]. For nano-aluminum, the burning time decreases with increasing pressure exponent in the burning time relationship varies between -0.3 and -1 , depending on the ambient temperature [26]. Although Ref. [26] deals with oxygen, it is the only published work discussing the effect of the pressure on burning time of nano-aluminum and is, thus, used in the present study. For example, the calculated burning time scale for an 80 nm Al particle at a pressure of 7 MPa and tempera-

ture of 1600 K is 0.21 ms. The burning time scale of micron-sized Al particle at 1 atm pressure is taken to be 1.189 ms [11], and its variation with pressure is given in Refs. [11,27]. As a further example, the calculated burning time scale for a 5 μm Al particle at 7 MPa and 1600 K is 2.78 ms, which is obviously higher than the corresponding value for nano-aluminum. Recently, Park et al. [28] studied the oxidation rates of 50–150 nm Al particles in air using a single particle mass spectrometer. The experimental data and model results indicate that combustion is indeed controlled by the diffusion processes across the oxide layer. In Refs. [29,30], the calculated burning time follows the $d^{1.6}$ or d^2 law and is inversely proportional to pressure. The present model for ALICE combustion, thus, represents a diffusion-controlled combustion mechanism. Note that the model does not consider the species transport properties in the oxide layer, since they are poorly known.

4. Results and discussion

The analysis described in Section 3 is employed to study the flame propagation of stoichiometric ALICE mixtures over a broad range of pressures and particle sizes. An analytical model for the burning rate, derived in Ref. [18], is shown below:

$$r_b = \sqrt{\frac{\lambda}{\rho C_p} \cdot \frac{2Q}{2C_p(T_{ign} - T_u) + h_{fg}} \cdot \frac{1}{\tau_b}}. \quad (24)$$

The burning rate is most sensitive to variations in the mixture thermal diffusivity, heat of reaction, and particle burning time scale. The thermophysical properties, including the packing density of the mixture, are well known, while the heat of reaction is tailored to the experimental combustion temperature. The particle burning time scale is chosen based on experimental data and results, as discussed in Section 3. Figure 3 shows the

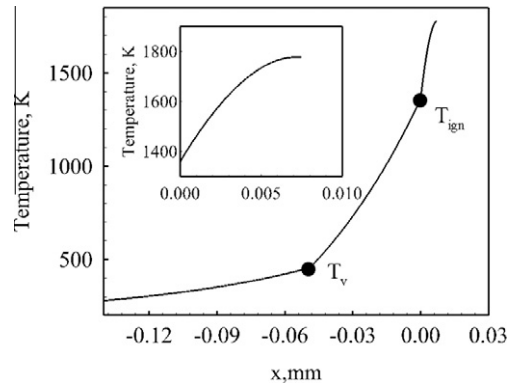


Fig. 3. Temperature distribution for stoichiometric 80 nm ALICE mixture at 1 MPa.

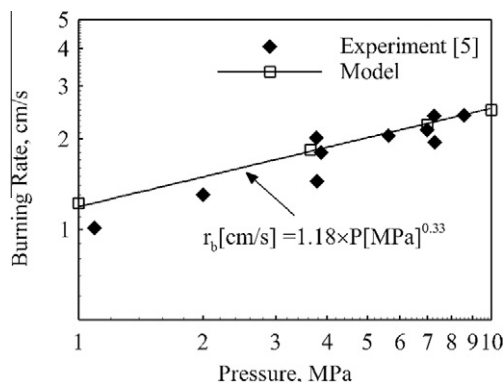


Fig. 4. Effect of pressure on the burning rate of stoichiometric 80 nm ALICE mixture.

temperature distribution for an ALICE mixture with mono-dispersed 80 nm particles at a pressure of 1 MPa. The active Al content is 75% and the oxide layer thickness is 2.7 nm. The calculated flame temperature is ~ 1800 K. The thickness of the reaction zone is ~ 7 μm , which agrees well with the estimate, $r_b \cdot \tau_b = 6.5$ μm . The vapor zone is approximately 0.05 mm thick. Chemical equilibrium calculations indicate that the flame temperature increases with increasing pressure [22]. One major factor contributing to this phenomenon is the lesser energy expended for phase transitions of water at higher pressures. Figure 4 shows the variation of the burning rate of ALICE mixture with pressure. It increases from 1.22 to 2.5 cm/s, as the pressure increases from 1 to 10 MPa. This is because the burning time scale of nano-aluminum decreases with increasing pressure. The burning-rate pressure exponent of 0.33 agrees well with experimental data [5].

The effect of the addition of micron-sized particles to the ALICE mixture is studied with a loading density in the range of 0–80%. Figure 5 shows the temperature profiles of ALICE mixtures with 80 nm and 5 μm particles at a pressure of 1 MPa. The active Al content of the 5 μm particle is 100%. The bimodal ALICE mixtures have a unique flame structure, which is characterized by two distinct particle burning regimes corresponding to nano- and micron-sized particles. When the loading density is 15% (80 nm/5 μm : 85/15 by mass), the majority of the heat release stems from the combustion of nano-Al particles. At a higher loading density, both nano- and micron-sized particles contribute significantly to the overall heat release. The addition of 5 μm particles also results in thicker liquid and vapor zones. The flame thickness of the bimodal particle mixture is higher than its counterpart of a mono-dispersed particle mixture. Figure 6 shows the effect of addition of 5 μm Al particles on the burning rates of ALICE mixtures with 80 nm particles at

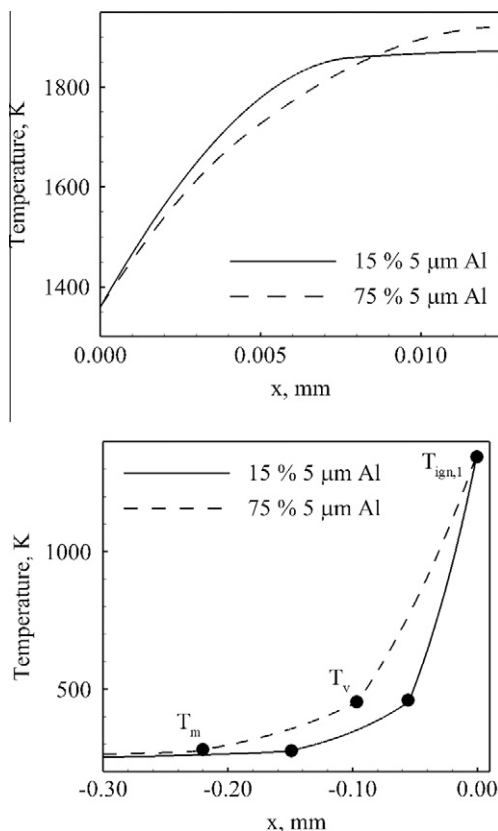


Fig. 5. Effect of addition of 5 μm Al particles on the flame structure of stoichiometric 80 nm ALICE mixture in the reaction (top) and preheat (bottom) zones; $P = 1$ MPa.

a pressure of 7 MPa. The experimental data is taken from Ref. [31]. In spite of the longer burning time scale of 5 μm Al particles, the burning rate does not significantly change for a loading density less than 15%. The addition of 5 μm Al particles increases the flame temperature, while decreasing the overall heat-release rate. These two effects try to counteract each other for loading densities less than 15%. The burning rate, however, decreases to an asymptotic value of 0.6 cm/s when the loading density reaches 80%. Figure 7 shows a similar trend at a lower pressure of 1 MPa. Figure 8 shows the effect of pressure on the burning rates for two different 5 μm particle loading densities of 0% and 15%. The pressure exponent decreases from 0.33 to 0.23 when the loading density of 5 μm particles increases from 0 to 15%.

Figure 9 shows the effect of the addition of 20 μm Al particles on the burning rates of 80 nm ALICE mixtures over a pressure range of 1–10 MPa. The pressure exponent decreases with the addition of 20 μm Al particles, since the parti-

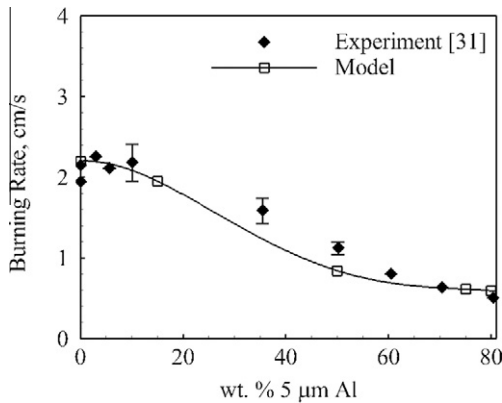


Fig. 6. Effect of addition of 5 μm Al particles on the burning rate of stoichiometric 80 nm ALICE mixture at $P = 7$ MPa.

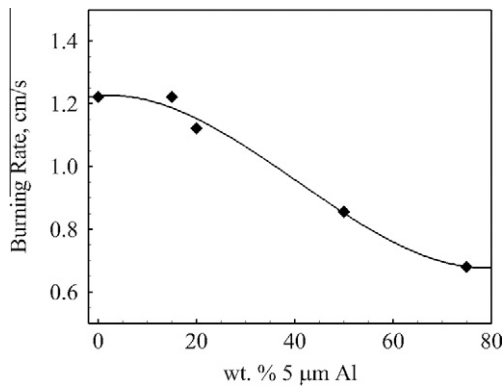


Fig. 7. Effect of addition of 5 μm Al particles on the burning rate of stoichiometric 80 nm ALICE mixture at $P = 1$ MPa.

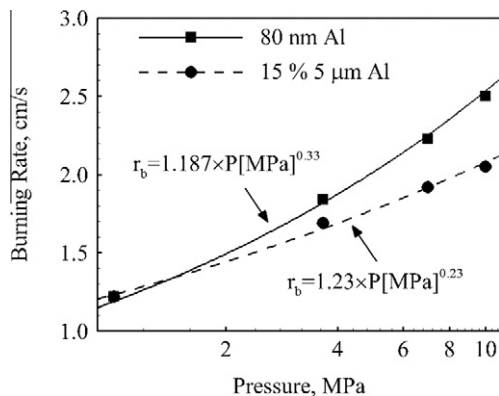


Fig. 8. Effect of pressure on the burning rates of stoichiometric ALICE mixtures with mono-dispersed and bimodal size distribution of particles.

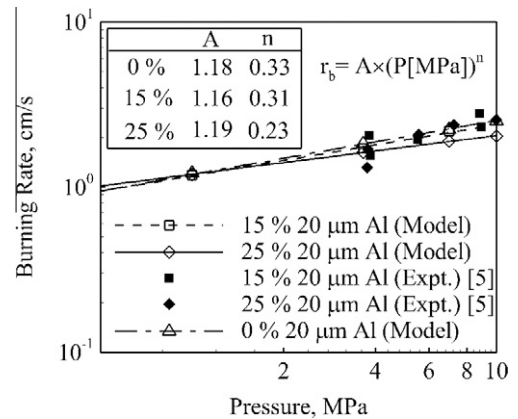


Fig. 9. Effect of pressure on the burning rates of stoichiometric ALICE mixtures with 80 nm and 20 μm particles.

cle burning is controlled by species diffusion through the gaseous mixture ($\sim \tau_b \propto p^{-0.1}$) [11]. The burning rate, however, is not significantly affected within the range of the loading density considered here. Thus, a portion of nano-Al particles could be replaced by micron-sized Al particles to increase the combustion efficiency and hydrogen generation without significantly altering the burning behaviors. Note that particle entrainment is neglected in the present analysis. All the particles are not carried away by the flow, due to the inertial and gravitational forces, high loading density, and quartz tube wall effects. A significant amount of particles remains in the tube for 80 nm Al-water mixtures [32]. It is important to note that the particle motion is likely to be important in the post combustion zone, since they are under the continuous influence of the flow of the combustion gas (H_2) and could be carried away. To avoid excessive complexity, we have focused our attention only up to the reaction zone and neglected the entrainment effect. This can be incorporated into the model by considering the effects of gravity, particle-particle interactions/collisions, and wall-effects in a more advanced model in the future. The current model, however, captures the main features of Al-water combustion, with reasonably good agreement between experimental data and model predictions.

5. Conclusions

A theoretical framework has been established to analyze the combustion of stoichiometric aluminum-ice (ALICE) mixtures. Both nano and micron-sized particles were considered over a pressure range of 1–10 MPa. Combustion experiments of ALICE strands in a constant-volume vessel were also performed to measure the burning

rates. For an ALICE mixture with 80 nm particles, the burning rate showed a pressure dependence of $r_b = aP^n$, with an exponent of 0.33. The burning rate was not significantly affected by the addition of 5 and 20 μm Al particles for a loading density less than 15–25%, and decreased significantly beyond this value. The ALICE mixtures with bimodal particle distributions exhibited a two-stage flame structure, characterized by the presence of two distinct particle burning regimes corresponding to nano- and micron-sized particles. The flame thickness of a bimodal particle mixture was greater than its counterpart of a mono-dispersed particle mixture. The model results and experimental data indicate that the combustion of ALICE mixtures is controlled by mass diffusion across the oxide layers of the particles.

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