Towards Descriptive Scenario of a Burning Accident in an Obstructed Mining Passage: An Analytical Approach

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1 Introduction

Coalmining exhibits ones of the highest fatality and injury rates among industries dealing with flammable gases and combustible dust, with accidents such as that in Soma, Turkey [1] occurring on a regular basis. These accidents happen, in particular, because methane from the coal seams can be accumulated inside a mining passage during the process of coal extraction. If sufficient ventilation is not provided, a risk of sporadic methane/air/coal-dust explosion is viable. Consequently, safety measures to prevent/mitigate such hazards require understanding of the burning accident process. Predictive scenario of a coalmining fire [2] was a step in this direction. Specifically, the key characteristics of a fire such as evolution of the premixed flame front shape and velocity as well as the flame run-up distance were predicted by combining the flame acceleration mechanisms caused by a "finger" flame shape [3] and a globally-spherical flame corrugated due to the Darrieus-Landau (DL) instability [4]. However, while Ref. [2] assumed the smooth passage walls, it was subsequently recognized [5] that obstructions such as mining equipment, belt conveyor systems and pile of rubbles may block a noticeable portion of a passage, potentially providing a significant impact on a fire scenario. There is therefore a critical need to account for such obstacles in a predictive coalmining fire scenario, and in the present work we do our first step on this way. Specifically, the obstacles are imitated by a comb-shaped (Bychkov) array, Fig. 1, since it is simple to study and is known to provide extremely powerful flame acceleration [6]. This is because delayed burning in the pockets between obstacles generates a jet-flow along the centerline. Unlike finger-flame acceleration [3], obstacles-based acceleration [6] is unlimited in time and may lead, promptly, to the deflagration-to-detonation transition (DDT), constituting an extra, shock-based disaster for the personnel and equipment in underground enclosures such as a coalmine. To address this demand, in the present work we incorporate the large-scale effect of the DL instability into the originally Reynolds-independent Bychkov formulation [6], thus arriving to a theory of a burning accident in a coalmining passage. Starting with homogeneous methane-air mixture, we then extend our analysis to a gaseous-dusty environment using a modified Seshadri formulation [7]. The parametric study includes the blockage and equivalence ratios as well size and concentration of the dust.

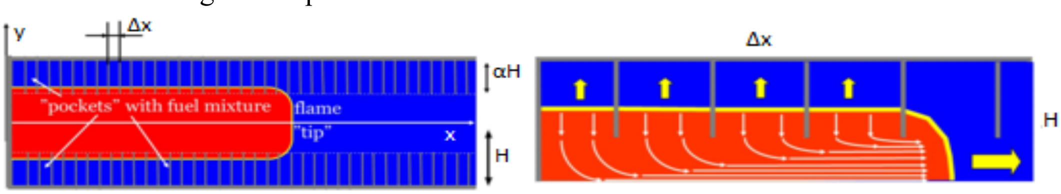

Figure 1. An illustration of the Bychkov mechanism of flame acceleration in an obstructed passage [6].

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2 Formulation

We consider a two-dimensional (2D) passage (channel) of width $2H = 2.1$ m as illustrated in Fig. 1, which is closed at one end and a premixed flame propagates towards the open end. The passage is blocked by obstacles of length αH such that channel along the central part $(1-\alpha)R$ is unobstructed. From the ignition time and until a time instant when a flame "skirt" contacts an obstacle, t_{obs}, the flame evolution is described by a predictive scenario of a burning accident in an unobstructed coalmining passage [2], which combines the mechanism of flame acceleration caused by a finger flame shape (see Ref. [3] for details), with that of a globally-spherical, expanding flame front corrugated due to the DL instability [4]. Here we recall the basics of the latter acceleration mechanism [4] and its combination with a finger flame acceleration mechanism [2]. Any large-scale premixed flame is prone to the DL instability. In particular, the radius of a globally-spherical expanding flame obeys the power law, $R_f \propto t^n$, $n = 1.3{\sim}1.5$ [4], so that instead of the unstretched laminar flame velocity U_f, the instantaneous radial flame velocity with respect to the fuel mixture is [2, 4]

$$U_{DL}(t) = U_f\left(\frac{\Theta}{n}k_{DL}\right)^{n-1} t^{n-1}, \qquad k_{DL} = L_f^{-1}\left\{1+\frac{(\Theta-1)}{(\Theta-1)^2}\Theta\ln\Theta\right\}^{-1}, \tag{1}$$

where $\Theta \equiv \rho_{fuel}/\rho_{burnt}$ is the thermal expansion ratio, $k_{DL} \equiv 2\pi/\lambda_{DL}$ is the Darrieus-Landau cut-off wavenumber, and $L_f \equiv D_{th}/U_f$ is the flame thickness, with the fuel thermal diffusivity D_{th}.

Demir *et al.* [2] combined the above analysis with the mechanisms of finger flame acceleration [3] into a unified formulation for a fire scenario in an unobstructed passage, with the evolution of the flame "skirt" position $R_f(t)$, the flame tip position $X_{tip,f}(t)$, and the flame tip velocity $U_{tip,f}(t)$ given by [2]:

$$R_f(t) = \frac{\Theta H}{\Theta-1}\left\{1-\exp\left[-\frac{\Theta-1}{\Theta H}\left(k_{DL}^{n-1}\left(\frac{\Theta U_f}{n}\right)^n\right)t^n\right]\right\}, \quad X_{tip,f} = \frac{\Theta H}{\Theta-1}\left\{\exp\left[\frac{\Theta-1}{\Theta}\frac{k_{DL}^{n-1}}{H}\left(\frac{\Theta U_f}{n}\right)^n t^n\right]-1\right\}, \tag{2}$$

$$\frac{dX_{tip,f}}{dt} = U_{tip,f} = nk_{DL}^{n-1}\left(\frac{\Theta U_f}{n}\right)^n t^{n-1}\exp\left[\frac{\Theta-1}{\Theta}\frac{k_{DL}^{n-1}}{H}\left(\frac{\Theta U_f}{n}\right)^n t^n\right]. \tag{3}$$

The readers are referred to Ref. [2] for more details of the formulation. Similar to Ref. [2], we took $n = 1.4$ and the thermal chemical parameters of the combustible mixture as tabulated in Ref. [8]. In an unobstructed passage, the formulation (2), (3) will work until the instant when the flame skirt contacts an obstacle, t_{obs}, being at the locus $X_{tip,f}(t_{obs})$, which can be calculated from a condition $R_f(t_{obs}) = (1-\alpha)H$ in Eq. (2):

$$t_{obs} = \frac{n}{\Theta U_f}\left\{\frac{\Theta H}{(\Theta-1)k_{DL}^{n-1}}\ln\left[\frac{\Theta}{1+\alpha(\Theta-1)}\right]\right\}^{1/n}, \qquad X_{tip,f}(t_{obs}) = \frac{\Theta(1-\alpha)H}{1+\alpha(\Theta-1)}. \tag{4}$$

Similarly, the respective flame tip velocity, $U_{tip,f}(t_{obs})$, can be found from Eq. (3).

The formulation (2), (3) does not work for $t > t_{obs}$ because the obstacles come to play in this case. Consequently, in order to extend the coalmining fire scenario beyond t_{obs}, the obstacles should be accounted in the formulation. Here we summarize the Bychkov mechanism of ultrafast flame acceleration in obstructed channels [6]. Adopting a limit of tightly-placed obstacles, $\Delta x \ll \alpha H$, we treat the flow between the obstacles as laminar such that the flame front therein may be taken as locally planar at all times, thus spreading in the *y*-direction with the laminar flame speed U_f. As the burnt matter expands with a thermal expansion ratio Θ, the flow is pushed out of the pockets. Coming into a central part of the passage, the flow changes its direction and pushes the flame forward in the *x*-direction towards the exit. This creates a positive feedback between the flame and pockets as the flame is pushed forward, thereby creating new pockets behind it. Considering the flow in the free part of the passage to be potential and incompressible, $\partial U/dx + \partial V/dy = 0$, and with the boundary condition $V = -(\Theta-1)U_f$ at $y = (1-\alpha)H$, we find with respect to the burnt matter

$$\left(U;V\right)=\frac{\left(\Theta-1\right)U_f}{\left(1-\alpha\right)H}\left(x,-y\right),\qquad \frac{dX_{tip,o}}{dt}=\frac{\left(\Theta-1\right)U_f}{\left(1-\alpha\right)H}X_{tip,o}+\Theta U_f. \tag{5}$$

Equation (5) summarizes the original formulation [6] yielding exponential acceleration, $X_{tip.o}\propto\exp(\sigma t)$, with $\sigma=(\Theta-1)U_f/(1-\alpha)\,H$. It is Re-independent (scale-invariant), with $U_f=const$. We next revisit it accounting for the DL instability. Namely, we consider $U_{DL}(t)$ obeying Eq. (1) until $t=t_{obs}$ such that

$$U_{DL}(t_{obs})=U_f\left\{\frac{\Theta H}{\left(\Theta-1\right)k_{DL}}\ln\left[\frac{\Theta}{1+\alpha\left(\Theta-1\right)}\right]\right\}^{(n-1)/n}. \tag{6}$$

Thereafter, we assume U_{DL} remaining at a saturated level (6), $U_{DL|obs}=U_{DL}(t_{obs})$, because a characteristic flame radius stops growing at this point. Then substituting $U_{DL|obs}$ into Eq. (5) yields an evolution equation for a flame tip propagating through an array of obstacles, for $t>t_{obs}$ (to inherit Eq. (3) valid for $t\le t_{obs}$).

$$\frac{dX_{tip,o}}{dt}=\frac{\left(\Theta-1\right)U_{DL|obs}}{\left(1-\alpha\right)H}X_{tip,o}+\Theta U_{DL|obs},\qquad t>t_{obs}. \tag{7}$$

Integrating Eq. (7) with a matching condition $X_{tip,o}|_{t=t_{obs}}=X_{tip,f}(t_{obs})$ of Eq. (3) yields the solution

$$X_{tip}=\frac{\Theta\left(1-\alpha\right)H}{1+\alpha\left(\Theta-1\right)}\left\{2\exp\left[\frac{\left(\Theta-1\right)}{\left(1-\alpha\right)}\frac{U_{DL}(t_{obs})}{H}\left(t-t_{obs}\right)\right]-1\right\}, \tag{8}$$

$$\frac{dX_{tip}}{dt}=U_{tip}=2\frac{\Theta\left(\Theta-1\right)U_{DL}(t_{obs})}{1+\alpha\left(\Theta-1\right)}\exp\left[\frac{\left(\Theta-1\right)}{\left(1-\alpha\right)}\frac{U_{DL}(t_{obs})}{H}\left(t-t_{obs}\right)\right]. \tag{9}$$

We also determine the flame run-up distance, which is conventionally defined as the distance at which the flame velocity reaches the sound speed of the reactants, c_0. Namely, Eq. (9) gives the run-up time, t_{rud}, as

$$t_{rud}=t_{obs}+\frac{\left(1-\alpha\right)}{\left(\Theta-1\right)}\frac{H}{U_{DL}\left(t_{obs}\right)}\ln\left[\frac{c_0\left(1+\alpha\left(\Theta-1\right)\right)}{2\Theta\left(\Theta-1\right)U_{DL}\left(t_{obs}\right)}\right], \tag{10}$$

and substituting t_{rud} of Eq. (10) into Eq. (8) will provide the corresponding flame run-up distance, X_{rud}.

We next extend our analysis to a gaseous-dusty environment by using a modified version of the Seshadri formulation [7] that expresses the laminar flame speed as a function of the local thermal-chemical properties of the gas and dust particles (inert; such as sand, combustible; i.e. coal, and combined) in the form [2]

$$U_{d,f}=U_f\sqrt{\frac{\phi_s}{\phi}}\sqrt{\frac{C_P}{C_T}\left(\frac{T_f}{T_b}\right)^2\left(\frac{T_b-T_u}{T_f-T_u}\right)}\sqrt{\exp\left(\frac{E\left(T_f-T_b\right)}{T_fT_bR_u}\right)},\quad \phi_s=\frac{\left[\left(\left(m^m_{fuel}\right)/\left(M_{CH_4}\right)\right)/\left(\left(m^m_{air}\right)/\left(M_{air}\right)\right)\right]_{act}}{\left[\left(\left(m^m_{CH_4}\right)/\left(M_{CH_4}\right)\right)/\left(\left(m^m_{air}\right)/\left(M_{air}\right)\right)\right]_{st}},$$

(11)

where ϕ_s is the modified equivalence ratio of the dusty-gaseous-air mixture in the presence of particles; M_{CH4} , M_{air} are the respective molar masses; m^m_{CH4}, m^m_{air} and m^m_{fuel} are the original masses per unit volume for a given equivalence ratio; $C_T=C_P+C_sn_sV_s\rho_s/\rho$ is the whole specific heat of the mixture, containing the components for the gas C_P and C_s; ρ_s is the density of a single dust particle while $\rho=\rho_u+c_s$ is that for the gaseous-dusty fuel-air mixture, with the density of the gas ρ_u and concentration of the dust particles c_s; $n_s=(c_s/\rho_s)/V_s$ is the number of particles per unit volume, with $V_s=4\pi r_s^3/3$ being the volume of a single particle and r_s the particle radius. For more details of the modified Seshadri formulation, see Ref. [2].

3 Results and Discussion

We start with a gaseous methane-air mixture (with no dust), with its variable thermal-chemical parameters (i.e. Θ and U_f) being the functions of the equivalence ratio ϕ as tabulated in Ref. [8]. Figure 2 presents the time evolutions of the flame tip position, X_{tip}, Fig. 2a, and its velocity, U_{tip}, Fig. 2b, for stoichiometric burning and various blockage ratios. The case of no obstacles, $\alpha = 0$, reproduces, completely, the situation of "finger + DL" flame acceleration [2]. It is noted that this acceleration is limited in time such that the flame would start decelerating when its 'skirt' contacts a sidewall at $t \sim 0.089$ s. In contrast, in obstructed channels, $\alpha > 0$, the flame tip position and velocity deviate from finger acceleration at t_{obs}, and this leads to faster acceleration until the DDT event. However, to describe the DDT accurately, we would need to account for gas compressibility in this theory; which will be done elsewhere. Besides, study of a partly-open obstructed duct as in the pioneering Taylor-Bimson model [9] will be of interest. Overall, flame acceleration observed in Fig. 2 is enormous, exceeding that of Bychkov *et al.* [6] by orders and certifying a significant impact of the DL instability on the flame/fire evolution in an obstructed coalmining passage. Figures 3 (a, b) are the counterparts of Figs. 2 (a, b) for a variety of equivalence ratios. It is seen here that a lean flame with $\phi = 0.8$ propagates/accelerates much slower than the $\phi \geq 1$ flames. This is because of a much lower U_f (and thus larger L_f and smaller k_{DL}) occurring at such a lean condition. In contrast, near-stoichiometric flames appear to accelerate extremely fast. In fact, a slightly rich flame of $\phi \sim 1.1$ (not shown in the figure) provided fastest acceleration. However, further increase in ϕ moderates acceleration as compared to $\phi = 1$.

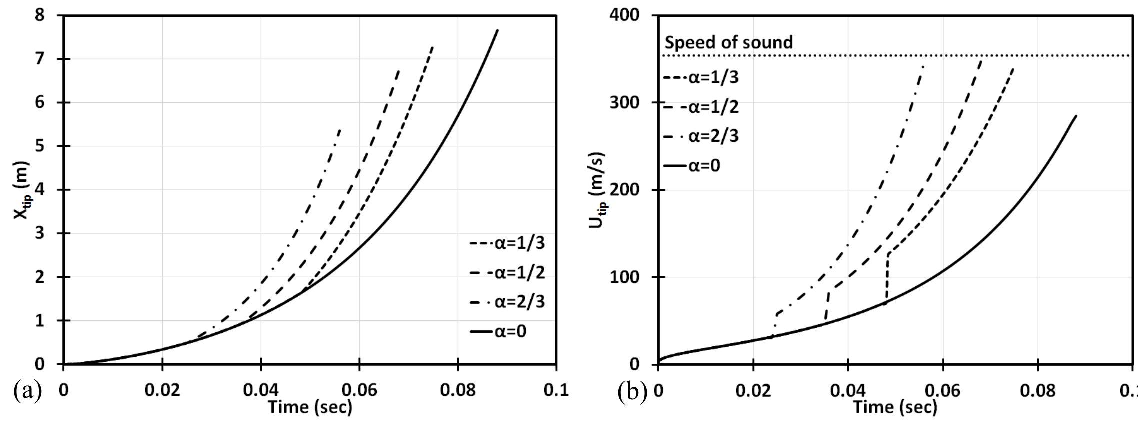

Figure 2. Time evolution of the flame tip position X_{tip} (a) and velocity U_{tip} (b) for the stoichiometric ($\phi = 1$) methane-air mixture with various blockage ratios $\alpha = 0, 1/3, 1/2, 2/3$.

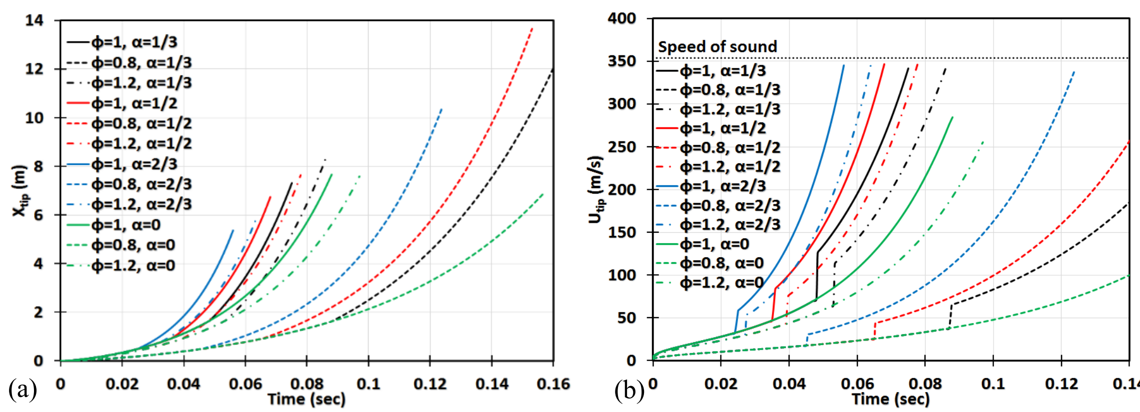

Figure 3. Time evolution of the flame tip position X_{tip} (a) and velocity U_{tip} (b) for the lean ($\phi = 0.8$), stoichiometric ($\phi = 1$) and rich ($\phi = 1.2$) methane-air mixtures with various blockage ratios: $\alpha = 0, 1/3, 1/2, 2/3$.

Anyway, in this theory flame acceleration is unlimited so that even relatively slow flames may eventually trigger a detonation provided sufficiently long passage (and time). For instance, even for $\phi = 0.8$, $\alpha = 1/3$, Eq. (11) predicts the DDT to occur at $t_{rud} \sim 0.17$ s, and this timing will drastically reduce with α and/or ϕ.

To address this question in detail, Fig. 4 depicts the flame run-up distance X_{rud} versus ϕ for various $\alpha = 1/3, 1/2$ and $2/3$. The case of no obstacles, $\alpha = 0$, is not relevant here since a flame skirt contacts a sidewall and stops accelerating before the DDT event for all ϕ studied, which is in line with the findings of Ref. [2]. Figure 4 agrees with the analysis above in that the fastest DDT (the shortest X_{rud}) occurs for slightly rich burning of $\phi \sim 1.1$, with $X_{rud} \sim 7.34$ m, 6.68 m, and 5.37 m for $\alpha = 1/3, 1/2$ and $2/3$, respectively. For the lean or rich mixtures, the run-up distances are much higher: up to 80 m for $\phi = 0.6$ and up to ~35 m for $\phi = 1.4$.

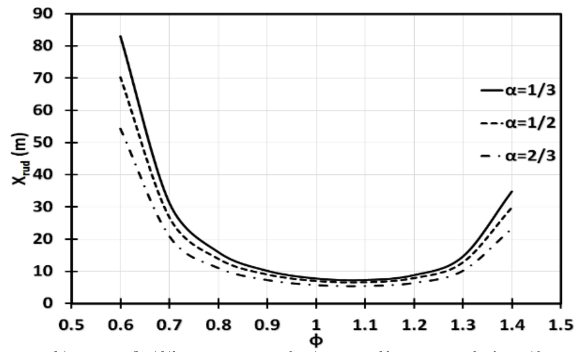

Figure 4. The run-up distance X_{rud} vs ϕ for the CH_4-air mixtures and various $\alpha = 1/3, 1/2, 2/3$.

Finally, we extend the analysis from a purely gaseous to a gaseous-dusty environment by a modified Seshadri formulation as explained in the previous section. The combustible (e.g. coal) and inert (e.g. sand) particles as well as their combinations are considered. Figure 5 is devoted to the cases of dust particles of radius $r_s = 75\ \mu m$ and concentration $c_s = 120\ g/m^3$, as well as to that without particles. We employed $\phi = 0.7$ and various α, including the case of no obstacles. We see that the combustible dust promotes flame acceleration, while the inert dust and its combination with the combustible one moderate the acceleration process, at least in the case of $r_s = 75\ \mu m$. Figures 6 (a, b) are the counterparts of Fig. 5 (a, b) for a smaller dust particle radius, $r_s = 10\ \mu m$. It is seen that smaller particles provide a stronger impact and, while the flame velocities did not exceed 35 m/s for the particles of size $r_s = 75\ \mu m$, in the case of $r_s = 10\ \mu m$, the sound threshold of 352 m/s for $\phi = 0.7$ methane-air mixture has been reached in the combustible coal gaseous-dusty environment during the time interval of approximately 0.118 s. In contrast to $r_s = 75\ \mu m$ in Fig. 5, the combined combustible-inert particles promoted flame acceleration in the case of $r_s = 10\ \mu m$, Fig. 6. This shows that the heat sink effect of inert particles is dominated by the heat release effect of combustible particles when the size of the particles is smaller. As for the inert particles, similarly to the case of $r_s = 75\ \mu m$, flame acceleration is also suppressed for $r_s = 10\ \mu m$. The particles effects grow with α.

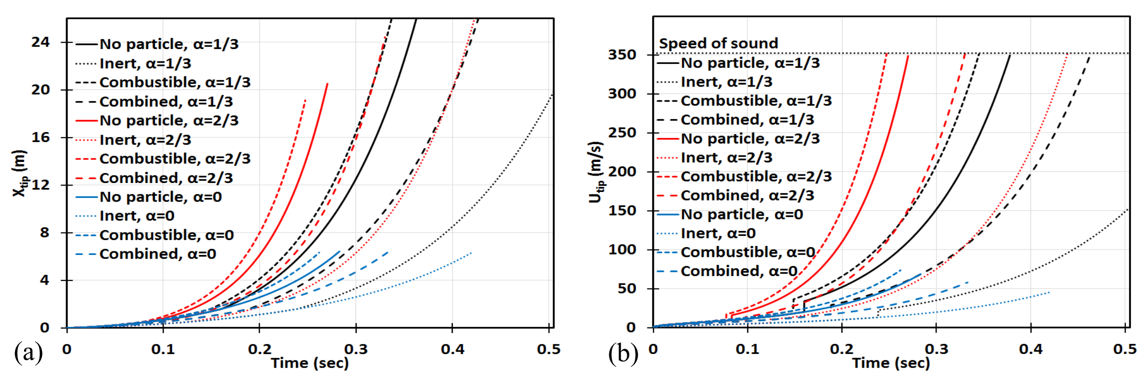

Figure 5. Time evolution of the flame tip X_{tip} (a) and velocity U_{tip} (b) for a lean methane air-mixture of $\phi = 0.7$ with and without dust particles (inert, combustible, and combined) of radius $r_s = 75$ μm and concentration $c_s = 120$ g/m^3, for various blockage ratios: $\alpha = 0, 1/3, 1/2, 2/3$.

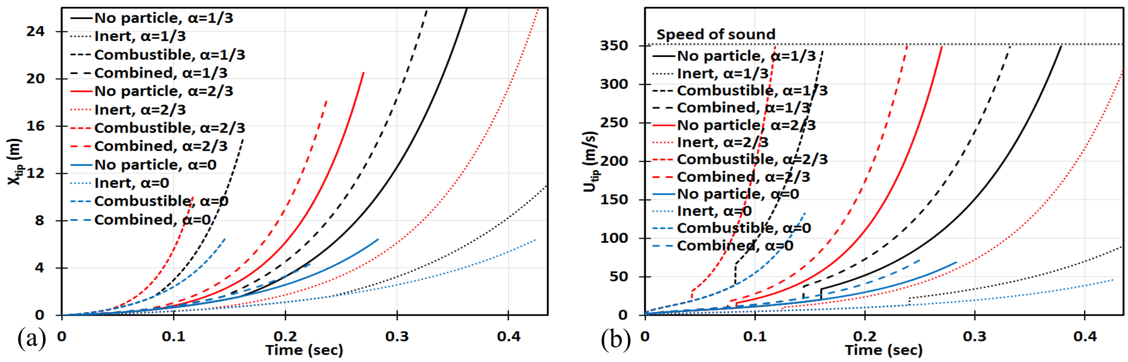

Figure 6. Time evolution of the flame tip X_{tip} (a) and velocity U_{tip} (b) for a lean methane air-mixture of $\phi = 0.7$ with and without dust particles (inert, combustible, and combined) of radius $r_s = 10$ μm and concentration $c_s = 120\ \mathrm{g/m^3}$, for various blockage ratios: $\alpha = 0, 1/3, 1/2, 2/3$.

4 Conclusion

This theoretical formulation, combining the Bychkov mechanism of flame acceleration in obstructed pipes [6] with that due to finger flame acceleration [2, 3] and the DL instability [4] is a step towards a predictive scenario of a burning accident in obstructed coalmining passage. The newly-identified flame propagation has been studied in terms of the flame tip position, X_{tip}, and its velocity, U_{tip}. The role of the DL instability is found to be significant. Near-stoichiometric flames accelerate faster and the same happen with the increase in the blockage ratio. Starting with homogeneous gaseous combustion, the analysis is subsequently extended to the uniformly-distributed dust particles. It is found that the combustible particles of radii 10-75 μm promote flame acceleration, whereas the inert particles of same size mitigate the acceleration process. The effect of particle size is significant in the sense that small coal particles provide faster flame acceleration.

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