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Predictive Scenario for Premixed Methane-Air Flame Spreading and Explosion Triggering in a Mining Passage

Sri Hari Ramakrishna Chalagalla

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**Predictive Scenario for Premixed Methane-Air Flame Spreading and
Explosion Triggering in a Mining Passage**

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Thesis submitted to the

Benjamin M. Statler College of Engineering and Mineral Resources

at

West Virginia University

in Partial Fulfillment of the Requirements for the Degree of

Master of Science

in

Mechanical Engineering

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**Keywords: fire safety; mining fire scenario; combustion instability; flame
acceleration; detonation triggering; turbulent burning; dusty-gaseous
combustion.**

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ABSTRACT

To reveal the inner mechanism of gas explosion, the entire scenario of premixed flame front evolution within an accidental fire is prescribed, quantitatively, with the situation of a methane-air explosion in a mining passage as the primary application. Specifically, the key stages of flame evolution are scrutinized. First, a globally-spherical expansion of a centrally-ignited, embryonic flame, with a possibility of self-similar acceleration caused by the hydrodynamic (Darrieus-Landau) instability occurs. This stage provides an order of magnitude increase in the flame speed in realistically large mining passages. Second, a transition from a globally-spherical front to a finger-shaped one happens, when a flame starts approaching the passage walls. While this acceleration is extremely strong, it stops as soon as the flame touches the passage wall. This mechanism is Reynolds-independent; being equally relevant to micro-channels and realistically large tunnels. The flame speed increases by one more order of magnitude during this stage. Eventually, a flame may accelerate due to wall friction as well as in-built obstacles and wall roughness. While this scenario could be dominant at micro- and mesa-scales, it appears negligible in a mining passage because the influence of wall friction decreases, drastically, with the Reynolds number, and wall-attached obstacles are small in mines. Overall, we have identified the key characteristics of all stages such as the timing for each stage as well as the flame shapes, propagation speeds, acceleration rates, and flame-generated velocity profiles. The flame speed rises by orders of magnitude. Starting with laminar homogeneously-gaseous combustion, the analysis is subsequently extended to dusty-gaseous environments. For this purpose, the dependences of the thermal-chemical flame parameters, such as the planar flame speed, versus the combustible and inert dust properties, such as the dust particles size and concentration, are incorporated into the formulation.

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Nomenclature:

Symbols

c	Concentration of particles (kg/m^3)
c_o	Local sound speed (m/s)
C	Total heat capacity (kJ/kg)
C_p	Heat capacity of fresh air fuel mixture (kJ/kgK)
C_s	Heat capacity of dust particles(kJ/kgK)
H	Distance of the point of ignition from a tunnel wall (m)
K_{DL}	Darrieus-Landau cutoff wave number (m^{-1})
K_u	Thermal conductivity ($\text{K}\cdot\text{m}\cdot\text{W}^{-1}$)
Le	Lewis number
L_f	Flame thickness (m)
M_{fuel}	Total amount of fuel available per unit time per unit volume (taking into account the volatilities) ($\text{kg/m}^3\text{s}$)
M_{CH4}	Total amount of methane available for combustion per unit time per unit volume ($\text{kg/m}^3\text{s}$)
n	Number of particles per unit volume (m^{-3})
Pr	Prandtl number
Q	Heat released during combustion (kJ)
r	Distance along radial direction (m)
R	Characteristic length scale (m)
Re	Flame propagation Reynolds number

R_f	Radius of the flame skirt (m)
T	Temperature (K)
T_b	Adiabatic flame temperature (K)
T_s	Surface temperature of dust particles
T_v	Temperature at which devolatilization process is initiated
t_r	The time which the coal particles stay in the flame (sec)
t_{sph}	Time Taken for evolution from spherical flame to figure flame (sec)
t	Time (sec)
t_{wall}	Time taken for the flame skirt to contact the wall (sec)
S_L	Unstretched laminar flame speed (m/s)
U_{DL}	Instantaneous global flame speed with respect to the fuel mixture (taking into account the Darrieus-Landau instability) (m/s)
w'_v	Devolatilization rate (kg/m ³ s)
w_v	Total mass of volatilities released per unit volume
z	Distance along axial direction (m)
Ze	Zeldovich number
$Z_{r.u.d}$	Flame run up distance (m)
Z_{tip}	Flame tip position (m)

Greek Symbols

Θ	Thermal expansion coefficient
ν	kinetic viscosity (m ² /s)

ϕ	Fresh air fuel equivalence ratio
ϕ_l	Fuel lean limit equivalence ratio
ϕ_r	Fuel rich limit equivalence ratio
σ_w	Flame acceleration rate
ρ	Density (g/cm ³)
λ_{DL}	Darrieus-Landau cutoff wavelength

Subscripts
Superscripts

b	Burnt matter
f	Flame conditions
s	Dust particles
r	Radial coordinate
z	Axial coordinate
1	Fresh air fuel mixture
2	Burnt matter
$'$	Property changed due to coal particle
$''$	Property changed due to inert particle

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Chapter 1: Introduction

1.1. Fundamentals of combustion

Combustion is a chemical reaction, where oxidation of a combustible fuel takes place. It is a self-sustained chemical process in which heat is released due to overall exothermic chemical reaction. Practical applications of combustion include, in particular, power plants, chemical industries, domestic burners and automobiles. Combustion can be classified according to how the fuel and oxidizer are placed before the reaction happens: *premixed* and *non-premixed* burning. The present work is restricted to premixed combustion, i.e. the mixing of the fuel and oxidizer has completed before the ignition (for comparison, in the non-premixed combustion mode, the fuel and the oxidizer would remain separated until they enter the burning zone). In fact, premixed combustion occurs in two distinctive regimes: a *flame* (also known as a deflagration) and a *detonation*. In the case of a flame, the reaction propagates due to thermal conduction, transferring energy from the hot burnt matter to the cold fuel-air premixture. In a detonation, the reaction propagates due to shock waves, which compress the air-fuel mixture to higher temperature. A nominal, planar flame propagates slowly, of the order of 1m/s, being thereby a subsonic burning regime, whereas a detonation wave spreads with a speed of the order of ~ 1000 m/s, being a supersonic burning regime. However, a sporadic deflagration-to-detonation (DDT) transition may occur, being a powerful effect, especially in those scenarios where it has not been predicted or controlled yet (say, accidental explosions in coal mines). One of the purposes of the present study is to develop a predictive scenario of DDT due to accidental fire explosions in coal mines and provide a strategy to mitigate the process.

1.2. Mining Fire and Explosion

Mining industry has ones of the highest injury and fatality rates. Although various mining accidents are caused by many reasons, spontaneous methane explosions in dusty coal mines, followed by comprehensive methane-air-dust fires, constitute the most typical hazard. The primary outcome of the present work is a quantitative predictive scenario of such fires and explosions. One of the key characteristics of the fire spreading is the unstretched laminar flame speed S_L , which is a function of thermal-chemical properties of the fuel mixture. In particular, S_L depends on the premixture equivalence ratio ϕ . For dusty-gaseous environment, S_L also depends on the dust parameters such as the dust particle size and the dust concentration. At the same time, a fire front, as well as any practical flame front, is not planar, but strongly corrugated; thereby, it consumes more fuel per unit time and propagates faster. Typical distinctive scenarios of flame corrugation/acceleration are summarized in Table 1. In this work, we employ them to quantify the mining fire scenario and fix a relevance of any particular mechanism to the mining passage.

Origin of flame corrugation/acceleration	Re-dependence	Relevance to mines	Relevance to micro-scales
Flame Instability	YES, $\uparrow$ Re	YES	NO
Finger Flame	NO	YES	YES
Wall Friction	YES, $\downarrow$ Re	NO	YES
Obstacles	NO	It depends	It depends
Turbulence	YES	YES	It depends

Table 1. Various mechanisms of flame acceleration in tunnels/tubes/channels

The Reynolds number related to flame propagation is defined as

$$\text{Re} = \frac{S_L R}{\nu} = \frac{R}{\text{Pr} L_f}, \quad (1.1)$$

where Pr and L_f are the Prandtl number and the flame thickness, respectively. Also the flame

thickness is defined as D_{th} / S_L , where D_{th} is thermal diffusivity. *First* of all, obviously, the Reynolds number increases with increasing radius of the tube/channel. In this regard, the combustion instability developing on a flame front depends on the tube radius, and the effect of the instability increases with the increasing radius, whereas when confined to micro scales there is no scope for the flame instability to develop. As a result the flame instability mechanism is relevant to mining fire scenario, however it is not relevant to micro-scale combustion. Secondly, the finger flame scenario, which is independent of the Reynolds number, has the same effect in both micro and macro scales. The remaining mechanisms are described in Chapter 4.

1.3. Objectives

The major objective of this work is to develop a predictive scenario of a mining fire, aiming to provide the guidance for preventing and controlling gas explosion disasters in mines. This work primarily looks into the ways of suppressing terminating a spreading fire and/or prevention of its initiation or – if it is not possible to terminate a fire – at least mitigate its propagation and consequences. Eventually, if DDT scenario is unavoidable, then it is aimed to investigate it and find the ways to mitigate the detonation hazards. Overall, in terms of predicting the risks of fire scenarios, this work is split into three objectives:

1. To predict the timing and locus for each stage of the flame evolution such as transition from a spherical shape to a finger-like shape and that when a flame skirt contacts a passage wall.
2. To predict the speed of flame spreading and run up distance before the DDT event occur.
3. To extend the formulation to dusty-gaseous environment in coal mines.

2. Literature Review

2.1. Planar Flame Speed vs Equivalence ratio

We start with homogeneously gaseous methane-air and propane-air flames, of various equivalence ratios, ϕ , and then extend the analysis to the situation of methane-air-dust environment. The thermal expansion Θ , which changes with respect to the equivalence ratio ϕ is the fresh fuel to the burnt matter density ratio. The planar flame speed S_L is presented versus ϕ in Table 2, for propane-air premixture, and Table 3, for methane-air premixture.

ϕ	0.63	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4
Θ	6.04	6.56	7.15	7.66	8.02	8.08	8.0	7.88	7.74
$S_L(m/s)$	0.147	0.217	0.303	0.374	0.418	0.429	0.399	0.322	0.226

Table 2. Propane – Air Flame Parameters [1]

ϕ	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4
Θ	5.54	6.11	6.65	7.12	7.48	7.55	7.43	7.28	7.09
$S_L(m/s)$	0.088	0.203	0.286	0.336	0.353	0.342	0.306	0.249	0.179

Table 3. Methane – Air Flame Parameters [1]

fuel	$S_{L,max}(m/s)$	ϕ_{max}	ϕ_l	ϕ_r
methane	0.35	1.06	0.533	1.68
propane	0.41	1.08	0.536	2.50

Table 4. Fuel dependent coefficients for laminar burning velocity correlation [2]

The dependence of $S_L = S_L(\phi)$, can also be approximated as [2]

$$S_L(\phi) = S_{L,max} \left(\frac{\phi - \phi_l}{\phi_{max} - \phi_l} \right)^a \left(\frac{\phi_r - \phi}{\phi_r - \phi_{max}} \right)^b, \quad (2.1)$$

$$a = 2 \left(\frac{\phi_{max} - \phi_l}{\phi_{max} - \phi_l} \right), \quad b = 2 \left(\frac{\phi_r - \phi_{max}}{\phi_r - \phi_l} \right), \quad (2.2)$$

where ϕ_l is fuel-lean limit, ϕ_r is fuel-rich limit, and $\phi_{\max}$ corresponds to equivalence ratio for maximum laminar burning velocity $S_{L,\max}$. For the calculation of Eq. (2.1), related parameters can be seen in Table 4.

2.2. Study on flame propagation mechanism

To prevent gas explosions, researchers used to carry out exhaustive explorations of the explosive limits and identify the characteristic detonation dynamics and influencing factors [3-5]. The studies showed that the equivalence ratio is one of primary parameter influencing the processes of combustion and explosion. Specifically, it influences, crucially, the flame propagation and acceleration mechanisms as well as the flame structure and stability limits [6]. A flame propagates as a curved front rather than maintaining a stable planar front, in particular, because of the combustion instabilities [7]. Clanet and Searby [8] first explained the acceleration mechanism at the early stages of burning in tubes, and the analytical formulation was recently developed by Bychkov et al [9]. According to [8,9], the acceleration happens due to the initial ignition geometry in the tube axis when a flame develops into a finger-shaped front, with the surface area and the flame tip velocity growing exponentially in time. It is noted that the flame accelerates quite fast, but only for a short time, until the flame skirt contacts the wall. The analytical formulas for the acceleration rate, for the flame shape and for the velocity profile in the flow pushed by the flame were developed.

A flame in a tube or channel can spontaneously accelerate until it triggers a detonation [10-15], which states one of the most important and, also, one of the complicated problems in combustion science. Various experimental studies [16,17] have shown the following steps in the DDT a flame accelerates, pushes compression waves and weak shocks, which interact, get stronger, compress

and heat the fresh fuel mixture, which finally explodes somewhere between the leading shock and the flame front and evolves into the detonation.

As the non-uniform velocity distribution makes the flame shape curved, which increases the burning rate and drives the acceleration. The quantitative theory and modeling of wall friction (Schelkin) mechanism [18] was first studied by Bychkov et al. [19]. They considered laminar premixed flames with a realistically strong density drop at the front. Subsequently, an analytical theory of accelerating flames has also been developed by Akkerman et al. [20] for a cylindrical tube geometry with one end closed and nonslip at the walls.

In Ref. [21], it was demonstrated that how initial turbulence enhances the combustion reaction rate and heat and mass transfer efficiency, thereby enlarging the range of the explosive concentration limit. Fundamental and thorough investigation of the equivalence ratios effect on the flame microstructure and propagation behavior has not been performed yet, even though some studies regarding hydrogen fires have been recently conducted [22]. Studies of premixed flames in a compartment are required to understand the effect of the equivalence ratio on the flame propagation behavior and improve the safety of the burning process.

In the present thesis we demonstrate the inner mechanism of gas explosion, and reveal the relationship between different equivalence ratios and gas explosion dynamics, which aim to provide theoretical and experimental guidance for preventing and controlling gas explosion disasters.

2.3. Analysis of Dust-Gas-Air Premixed Flames

Combustion of clouds of fuel particles in a gaseous atmosphere is having importance for understanding coal dust explosions in mines. A theory of flame propagation in a uniform cloud of

particles was developed long ago [23-25]. The flame propagation model has been developed by Refs. [26-27] depends on the number of density and initial size of fuel particles. Other important theoretical study of the structure of premixed flames, containing uniformly distributed volatile fuel particles, in an oxidizing gas mixture is analyzed by Seshadri [28]. It is presumed that the fuel particles vaporize first to yield a gaseous fuel, which is subsequently oxidized in the gas phase. This process is resulted with temperature increase in the reaction zone which promotes the equivalence ratio and thereby velocity.

Chapter 3: Gaseous Flame Formulation

We start with a premixed fire spreading in a homogenously-gaseous environment. The effect of multi-phase impurities such as combustible and/or inert dust will be considered later, in Chapters 5 and 6. To be specific, we consider an accidental ignition of a methane-air (or propane-air) premixture occurring at a distance H from a tunnel wall, as illustrated in Fig. 1. A flame propagates outwardly from the ignition point. The flame front is initially spherically-smooth, because any tendency to develop a combustion instability is suppressed by the stretch effect, which is induced by an expanding flame. The process is controlled by the interplay between the flame stretch and the mixture (non) equi-diffusion. The critical issue at an early stage of a fire is whether an embryonic flame can sustain. In this respect, the front evolution depends on the thermal to molecular diffusivity ratio, i.e. the Lewis number, Le . Indeed, the sustained flame propagation is possible for $Le > 1$ mixtures, whereas for $Le < 1$ combustibles, a flame embryo needs to attain a minimum radius, through the initial spark energy, before sustained propagation is possible [29]. Consequently, keeping $Le < 1$ in the mining environment may improve the fire safety standards.

Fig. 1: Quasi-spherical flame expansion: the stages of ignition, uniform propagation of a smooth front (a) as well as self-similar acceleration of a cellular front (b).

3.1 Stage 1: Quasi-Spherical, Self-Similar Accelerative Flame Expansion

Assume, nevertheless, that an embryonic flame has survived and keeps propagating. In the present study, we are interested, mostly, in large-scale fires; hence, the flame stretch can be neglected. Then, at the early stage of burning, the flame front expands with a constant speed with respect to the ignition point, $dR_f / dt = \Theta S_L$, where R_f is the flame radius. As the flame “ball” grows in size and the stretch intensity diminishes, the diffusional-thermal cells would develop over the surface of $Le < 1$ flames. Subsequently, the flame thickness relative to the global flame radius is reduced, leading to the onset of the hydrodynamic (Darrieus-Landau; DL) instability mode. The latter generates hydrodynamic cells over the flame surface, regardless of Le , and it will eventually control the surface morphology. The continuous generation of new cells leads to the continuous increase in the flame surface density and thereby an expanding flame self-accelerates in a scale-invariant (self-similar) manner; see Fig. 1b. According to numerous experimental studies, a reasonable fitting law for such acceleration is [30]

$$R_f = R_0 + Ct^n \approx Ct^n, \quad (3.1)$$

where R_0 plays the role of a critical radius related to the transition to the cellular flame structure (it can be neglected within the frame of the large-scale formulation); the exponent $n \approx 1.3-1.4$ in the most of studies; and the factor C can be evaluated as [30]

$$C = k_{DL}^{n-1} (\Theta S_L / n)^n, \quad (3.2)$$

where k_{DL}^{n-1} is a DL cutoff wavenumber that appears in the Pelce-Clavin dispersion relation [31]

$$\sigma_{DL}(k) = \Gamma(\Theta) S_L k \left(1 - \frac{k}{k_{DL}} \right), \quad \Gamma(\Theta) = \frac{\Theta}{\Theta + 1} \left[\left(\Theta + 1 - \frac{1}{\Theta} \right)^{1/2} - 1 \right]. \quad (3.3)$$

The quantity k_{DL} is coupled to the DL critical wavelength, $k_{DL} = 2\pi / \lambda_{DL}$, where λ_{DL} is the critical wavelength, which in turn depends on thermal expansion Θ and is proportional to the flame thickness, such that $\lambda_{DL} \approx (30 \sim 100)L_f$ for $\Theta = 5 \sim 8$. In this work, we employ the following formula for the DL cutoff [31]

$$\lambda_{DL} = 2\pi L_f \left(1 + \frac{(\Theta + 1)}{(\Theta - 1)^2} \Theta \ln \Theta \right). \quad (3.4)$$

With the power-law flame acceleration, Eq. (3.1), the global (radial) flame speed with respect to the ignition point is not a constant ΘS_L anymore, but a time-dependent quantity

$$dR_f / dt = nCt^{n-1} = (k_{DL} / n)^{n-1} (\Theta S_L)^n t^{n-1}. \quad (3.5)$$

To evaluate the instantaneous global flame speed with respect to the fuel mixture we divide Eq. (3.5) by Θ , with the result

$$U_{DL} = \frac{1}{\Theta} \frac{dR_f}{dt} = \frac{nC}{\Theta} t^{n-1} = S_L^n \left(\frac{\Theta}{n} k_{DL} \right)^{n-1} t^{n-1}. \quad (3.6)$$

3.2. Stage 2: Finger-like Flame Acceleration

Generally speaking, Eqs. (3.1) – (3.6) describe the accelerative flame expansion in an opening. However, in the practical reality, the shape of a flame front approaching (even not contacting!) the tunnel wall gets modified, forming two outwardly propagating “finger-like” fronts, as illustrated in Fig. 2. Expansion of the burning matter leads to a strong flow in the axial direction, which drifts the tip of a “finger”-shaped flame. Because of the elongated shape, the surface area of the flame front is much larger than the passage cross section. As a result, the flame accelerates. However, this, second stage of acceleration terminates as soon as the flame skirt contacts the passage sidewall. By the end of this process, the distance from the ignition point to the flame tip position

is considerably larger than the passage radius. We next combine the above analyses of an expanding flame with a finger-flame formulation [9]. Specifically, we reconcile the study [9], with a time-dependent quantity $U_{DL}(t)$, Eq. (3.6), playing the role of S_L . A rationale for this consideration is the scale- and time separation between the formulations: the tunnel width is much larger than the DL cells, and the finger-flame acceleration is much stronger than the DL one.

Fig. 2: Finger-like flame acceleration.

As the flow is separated into two regions, namely, the fresh fuel mixture and the burnt matter, the continuity equation for an incompressible flow in the axisymmetric cylindrical coordinates reads

$$\frac{1}{r} \frac{\partial(ru_r)}{\partial r} + \frac{\partial u_z}{\partial z} = 0. \quad (3.7)$$

Hereafter, we denote the axial and radial flow velocities ahead and behind the flame front (i.e. in the fresh fuel mixture and the burnt matter) by subscripts “1” and “2”, respectively. The axial flow boundary condition at walls for fresh fuel mixture is

$$u_{z,1}|_{z=0} = 0. \quad (3.8)$$

First, we are interested in the flow along the walls for $z \rightarrow 0$. In the fresh fuel mixture for the potential flow, we look for the velocity profile in the form

$$u_{z,1} = A_1(t)z, \quad (3.9)$$

where the factor A_1 is a function of time but not space, similarly to the finger flame formulation [9]. The radial velocity in the fuel mixture is calculated from the continuity equation (3.7) as

$$u_{r,1} = \frac{A_1(t)}{2} \left(\frac{H^2}{r} - r \right). \quad (3.10)$$

We next employ the radial flow boundary conditions at the centerline and sidewall of the tunnel

$$u_r|_{r=0} = u_r|_{r=H} = 0. \quad (3.11)$$

Then the velocity distribution in the burnt matter (subscript 2) takes the form

$$u_{z,2} = A_2(t)z, \quad (3.12)$$

$$u_{r,2} = -\frac{A_2(t)}{2}r. \quad (3.13)$$

To close the system, we consider the matching conditions at the front, $r = R_f$, being

$$\frac{dR_f}{dt} - u_{r,1} = U_{DL}(t), \quad (3.14)$$

$$u_{r,1} - u_{r,2} = (\Theta - 1)U_{DL}(t), \quad (3.15)$$

$$u_{z,1} = u_{z,2}. \quad (3.16)$$

Here Eq. (3.14) shows that the global radial flame speed is a time-dependent quantity, which is equal to the flow velocity plus global flame speed with respect to the fuel mixture, Eq. (3.6). Equations (3.15) and (3.16) describe the jump of the normal velocity and continuity of tangential velocity at the front. Note that Eq. (3.16) works only when the flame skirt is close to the tunnel sidewall. Substituting Eqs. (3.9) – (3.13) into Eqs. (3.14) – (3.16), we find

$$A_1(t) = A_2(t) = 2(\Theta - 1)U_{DL}(t)R_f / H^2. \quad (3.17)$$

Then the evolution equation for the flame skirt reads

$$\frac{dR_f}{dt} = \left\{ \Theta - (\Theta - 1)\frac{R_f^2}{H^2} \right\} U_{DL} = \left\{ \Theta - (\Theta - 1)\frac{R_f^2}{H^2} \right\} S_L^n \left(\frac{\Theta}{n} k_{DL} \right)^{n-1} t^{n-1}. \quad (3.18)$$

Integrating Eq. (3.18) with the initial condition $R_f|_{t=0} = 0$, we obtain

$$t(R_f) = \left\{ \frac{\Theta H}{2\alpha C} \ln \left(\frac{\Theta + \alpha(R_f / H)}{\Theta - \alpha(R_f / H)} \right) \right\}^{1/n} = \frac{n}{\Theta S_L} \left\{ \frac{\Theta H}{2\alpha k_{DL}^{n-1}} \ln \left(\frac{\Theta + \alpha(R_f / H)}{\Theta - \alpha(R_f / H)} \right) \right\}^{1/n} \quad (3.19)$$

or

$$\frac{R_f(t)}{H} = \frac{\Theta}{\alpha} \tanh\left(\frac{\alpha}{\Theta} \frac{Ct^n}{H}\right) = \frac{\Theta}{\alpha} \tanh\left(\frac{\alpha}{\Theta H} k_{DL}^{n-1} \left(\frac{\Theta S_L}{n}\right)^n t^n\right), \quad (3.20)$$

where $\alpha = \sqrt{\Theta(\Theta-1)}$. A characteristic time instant devoted to the transition from a globally-spherical to a finger-like flame shape, t_{sph} , can be evaluated as

$$t_{sph} \approx \left(\frac{\Theta H}{2\alpha C}\right)^{1/n} = \frac{n}{\Theta S_L} \left(\frac{\Theta H}{2\alpha k_{DL}^{n-1}}\right)^{1/n}, \quad (3.21)$$

with the respective flame skirt location being

$$R_f(t_{sph}) = \frac{\Theta H}{\alpha} \tanh(0.5) \approx 0.46 \sqrt{\frac{\Theta}{\Theta-1}} H. \quad (3.22)$$

Substitution Eq. (3.22) into Eq. (3.6) provides the instantaneous radial flame propagation speed in the laboratory reference frame

$$U_{DL}(t_{sph}) = \frac{nC}{\Theta} t_{sph}^{n-1} = n \left(\frac{C}{\Theta}\right)^{1/n} \left(\frac{H}{2\alpha}\right)^{(n-1)/n}. \quad (3.23)$$

Similar to Eq. (3.14), the evolution equation for the flame tip position Z_{tip} (located at a centerline, $r = 0$) takes the form

$$\frac{dZ_{tip}}{dt} - u_{z,2} = \Theta U_{DL}(t). \quad (3.24)$$

Together with Eqs. (3.12) and (3.17), Eq. (3.24) becomes

$$\frac{dZ_{tip}}{dt} = 2(\Theta-1)U_{DL}(t) \frac{R_f(t)Z_{tip}}{H^2} + \Theta U_{DL}(t), \quad (3.25)$$

with the solution

$$Z_{tip} = \frac{\Theta H}{2\alpha} \sinh\left(2 \frac{\alpha}{\Theta} \frac{Ct^n}{H}\right) = \frac{H}{2} \sqrt{\frac{\Theta}{\Theta-1}} \sinh\left(2 \sqrt{\frac{\Theta-1}{\Theta}} \frac{k_{DL}^{n-1}}{H} \left(\frac{\Theta S_L}{n}\right)^n t^n\right). \quad (3.26)$$

Differentiating Eq. (3.26), we find the flame tip velocity and acceleration in the form

$$\frac{dZ_{tip}}{dt} = nCt^{n-1} \cosh\left(2 \frac{\alpha Ct^n}{\Theta H}\right), \quad (3.27)$$

$$\frac{d^2 Z_{tip}}{dt^2} = nCt^{n-2} \left(2 \frac{\alpha C}{\Theta H} nt^n \sinh \left(2 \frac{\alpha C t^n}{\Theta H} \right) + (n-1) \cosh \left(2 \frac{\alpha C t^n}{\Theta H} \right) \right). \quad (3.28)$$

The characteristic timing when the flame skirt touches the wall (and thereby terminates the finger flame scenario) can be obtained from Eq. (3.20) with the boundary condition $R_f = H$, namely

$$t_{wall,1} = \left\{ \frac{\Theta H}{2\alpha C} \ln \left(\frac{\Theta + \alpha}{\Theta - \alpha} \right) \right\}^{1/n} = \frac{n}{\Theta S_L} \left\{ \frac{\Theta H}{2\alpha k_{DL}^{n-1}} \ln \left(\frac{\Theta + \alpha}{\Theta - \alpha} \right) \right\}^{1/n}. \quad (3.29)$$

The second flame wing contacts the opposite wall a little latter, when $R_f = 2R - H$,

$$t_{wall,2} = \left\{ \frac{\Theta(2R-H)}{2\alpha C} \ln \left(\frac{\Theta + \alpha}{\Theta - \alpha} \right) \right\}^{1/n} = \frac{n}{\Theta S_L} \left\{ \frac{\Theta(2R-H)}{2\alpha k_{DL}^{n-1}} \ln \left(\frac{\Theta + \alpha}{\Theta - \alpha} \right) \right\}^{1/n}. \quad (3.30)$$

Further simplification of Eq. (3.29) by substituting Eq. (3.31) yields

$$Z_{tip}|_{wall} = \Theta H. \quad (3.31)$$

For simplicity, hereafter it is assumed $H \approx R$, where R is the channel radius. Then $t_{wall,1} = t_{wall,2}$,

$$t_{wall} = t_{wall,1,2} = \frac{n}{\Theta S_L} \left\{ \frac{\Theta H}{2\alpha k_{DL}^{n-1}} \ln \left(\frac{\Theta + \alpha}{\Theta - \alpha} \right) \right\}^{1/n} = \frac{n}{\Theta S_L} \left\{ \frac{\Theta R}{2\alpha k_{DL}^{n-1}} \ln \left(\frac{\Theta + \alpha}{\Theta - \alpha} \right) \right\}^{1/n}. \quad (3.32)$$

3.3. Potential Effect of Wall Friction and In-built Obstacles

When the flame skirt contacts the tunnel sidewall, the finger-like acceleration terminates, and the flame propagation will be controlled by the so-called Schelkin mechanism [18], associated with wall friction at non-slip walls. The idea behind the Schelkin acceleration scenario is the following. A combustion process results in the expansion of the burning matter, which drives the flow of fresh fuel mixture. But due to the friction at a tube/tunnel walls, the flow becomes non uniform such that the burning matter bends the flame front, which increases the flame velocity. Therefore, the flame front accelerates. The total burning rate is given by

$$U_w \propto \exp(\sigma_w S_L t / R), \quad (3.33)$$

with the following acceleration rate

$$\sigma_W = \sigma_W(\text{Re}) \rightarrow \Theta^2 / \text{Re} . \quad (3.34)$$

Since the time required for the flame to double its speed with the acceleration (3.34) is around 1000 seconds and also the acceleration generated by wall friction weakens with the increase in the tunnel width, as in the mines, where the diameter of a tunnel is of more than a human height, $\sim 2\text{m}$, the Schelkin flame acceleration rate appears several orders of magnitude lower than that for Reynolds-independent finger flame acceleration. Consequently, being a key phenomenon in micro- and mesa-scale pipes, the wall friction acceleration mechanism appears not relevant in the configuration of a mining tunnel.

Overall, the expansion of hot burnt gases behind the flame front push the flow of fresh mixture according to various scenarios clarified above such as corrugation/acceleration of spherically-expanding flames, the finger-like flame acceleration and the wall friction mechanism. All these scenarios contribute to the enhancement of the flame propagation speed in a significant manner. One more mechanism is that associated with obstacles that a flame front meets on the way of its spreading. Obviously, the outcome of flame-obstacle interactions depends on a particular configuration and shape of such obstructions. Specifically, a “tooth-brush” array of obstacles should be mentioned as a geometry providing extremely fast acceleration and deflagration-to-detonation transition [33-34]. This tooth-brush acceleration mechanism is Re-independent, being thereby applicable to both micro- and macro-scales. However, this mechanism is relevant when obstacles occupy, say, 10-90% of the flow path, which is not the case for a mining passage. Consequently, neither wall friction nor obstacles play a substantial role in a coal mine, and thereby can be omitted in this work.

4. Gaseous Flames: Results and Discussion

In this Chapter we adopt the analytical formulation of Chapter 3 for a set of parameters from the practical reality, such as those from a realistic accidental explosion in a mining passage. Figure 4.1 shows the characteristic timings of the process, t_{sph} , Eq. (3.21), and t_{wall} , Eq. (3.29), for $R = H = 1$ m and the DL exponent $n = 1.4$. These quantities, t_{sph} and t_{wall} , play the key roles for the flame acceleration (and, thereby, fire evolution) scenario. Indeed, it is recalled that just after an ignition, the flame tip moves in the same manner as the flame skirt, Eqs. (3.14) – (3.16), exhibiting a globally-spherical (cellular) shape of an expanding flame front as soon as $t < t_{sph}$. In contrast, when $t = t_{sph}$, the flame skirt slows down, while the flame tip accelerates, thereby leading to a very strong flame elongation/acceleration within the time interval $t_{sph} < t < t_{wall}$. It is recalled that this strong acceleration is limited in time: it stops when the flame skirt touches the wall, $t = t_{wall}$.

Fig. 4.1: Time limitations of the finger flame acceleration, t_{sph} , Eq. (3.21), and t_{wall} , Eq. (3.32), versus the equivalence ratio ϕ for propane- and methane-air flames, $R = H = 1$ m, $n = 1.4$.

Fig. 4.2: Time evolution of flame tip position Z_{tip} in a stoichiometric mixture within the interval $t_{sph} < t < t_{wall}$, with t_{sph} given by Eq. (3.23), and t_{wall} given by Eq. (3.29). The methane-air and propane-air mixtures are shown by the dashed and solid lines, respectively.

In Fig. 4.2, the flame tip position, Eq. (3.26), is plotted for stoichiometric ($\phi = 1$) methane-air and propane-air mixtures within the time interval of its finger-like acceleration, $t_{sph} < t < t_{wall}$. It is clearly seen that the finger-like acceleration is very strong: the flame tip spreads through 8 m during only ~ 0.05 sec! Obviously, this is crucial for miner's safety in the case of an accidental fire. We recall that the acceleration terminates at the time t_{wall} , when the flame skirt contacts the tunnel wall. The flame tip position at this terminal instant, $Z_{tip}(t_{wall})$, Eq. (3.31), is presented in Fig. 4.3 versus the equivalence ratio ϕ , within a wide range from lean to rich mixtures for both methane and propane. Obviously, $Z_{tip}(t_{wall})$ determines a distance that a flame can travel before its skirt contacts the wall. As we can see from Eq. (3.31), this quantity is directly proportional to the thermal expansion ratio Θ and distance from the tunnel wall H , where the accidental ignition occurred. Again, it is noted that this value, $Z_{tip}(t_{wall})$, is quite large, 5~8 m, and it is maximal at stoichiometric or near-stoichiometric conditions.

Fig. 4.3: Flame tip position at the time when the finger flame mechanism terminates, $Z_{tip}(t_{wall})$, Eq. (3.31) versus the equivalence ratio ϕ . The methane-air and propane-air mixtures are shown by the dashed and solid lines, respectively.

Fig. 4.4: Time evolution of flame tip velocity dZ_{tip}/dt , Eq. (3.27), within the interval $t_{sph} < t < t_{wall}$, with t_{sph} of Eq. (3.21) and t_{wall} of Eq. (3.32). The methane-air and propane-air mixtures are shown by the dashed and solid lines, respectively.

Figure 4.4 presents the time evolution of the flame tip velocity, Eq. (3.27), in the time range $t_{sph} < t < t_{wall}$, for the stoichiometric methane-air and propane-air mixtures. It is seen here that at the characteristic time t_{sph} , the flame tip speed have already risen by an order of magnitude due to the Darrius-Landau instability. Then, by the time t_{wall} , the finger flame scenario provides one

more order of magnitude increase in the flame velocity. As a result, the maximal flame speed is very high: 460 m/s for a stoichiometric methane-air flame and 720 m/s for a stoichiometric propane-air mixture, which exceeds the sound speed of the fuel mixture in both cases. The sound speeds of the mixtures are calculated using GASEQ equilibrium solver [38] for each equivalence ratio value. This solver allows us to predict the effects of changes in temperature, pressure, and concentration on a system at equilibrium. It states that if a system at equilibrium experiences a change, then the system will shift its equilibrium to try to compensate for the change.

Fig. 4.5: The maximal flame tip velocity $(dZ_{tip}/dt)_{wall}$, Eq. (3.27), vs the equivalence ratio ϕ . The methane-air and propane-air mixtures are shown by the dashed and solid lines, respectively.

Well, these quantities would nevertheless diminish if we deal with a lean or a rich premixture. This is justified in Fig. 4.5, where the maximal flame tip velocity, $(dZ_{tip}/dt)_{wall}$, Eq. (3.27), is plotted versus the equivalence ratio in the range $0.6 < \phi < 1.4$. We observe that the flame velocity decreases twice for $\phi = 1.4$ as compared to that for $\phi = 1$, while for $\phi = 0.6$ such a reduction is by an order of magnitude as compared to that for $\phi = 1$.

It is seen that the flame tip velocity exceeds the associated sound speed for the propane-air mixtures in the range of $0.8 < \phi < 1.3$, and for the methane-air mixtures in the range of $0.9 < \phi < 1.2$. Consequently, we may expect a deflagration-to-detonation transition (DDT) to occur in these cases. In fact, a reasonable and conventional parameter to analyze the possibility of DDT and its potential locus is the so-called *flame run-up distance* – a distance that a flame front propagates from its ignition and until the detonation initiation. In the present formulation, we shall approximate the flame run-up distance as the flame tip position at the instant when its velocity is equal to the local sound speed, $dZ_{tip}/dt = c_0$, although it is recognized that such a definition is not accurate, and the detonation does not occur exactly at the instance when the flame speed in the laboratory flame penetrates the sound barrier. Still these values correlate, and therefore this is a reasonable approximation within the overall frame of this work. Then Eq. (3.25) yields

$$c_o = \left. \frac{dZ_{tip}}{dt} \right|_{r.u.d} = 2(\Theta - 1)U_{DL}(t) \frac{R_f(t)Z_{r.u.d}}{H^2} + \Theta U_{DL}(t) , \quad (4.1)$$

and the associated flame run-up distance is given by

$$Z_{r.u.d} = \frac{(c_o - \Theta U_{DL}(t))H^2}{2(\Theta - 1)R_f(t)U_{DL}(t)} . \quad (4.2)$$

In the Eq. (4.2), it should not be confused that run up distance depend on instantaneous time. The time showed here is not instantaneous but it is integrated value which is approximated when the flame tip speed for a given equivalence ratio reaches the associated sound speed for the gas. In this regard, it can be calculated as, first, by approximating Eq. (3.27) equal to associated sound speed for the gas, then after iteration process, integral time value can be found and implemented into Eq. 4.2, in order to calculate run up distance.

For the equivalence ratio of a methane-air flow exceeding 0.8, the flame tip velocity in the laboratory reference frame exceeds the sound speed. We can therefore guess that for the equivalence ratios in the range of $0.8 < \phi < 1.3$ the methane-air flame will trigger a detonation by the time when a flame skirt approaches the sidewall. The result is shown in Fig. 4.6. In fact, this plot identifies the distance the flame propagates before the detonation triggers.

Fig. 4.6: Flame run up distance, $Z_{r,u,d}$, Eq. (4.2) versus the equivalence ratio ϕ . The methane-air and propane-air mixtures are shown by the dashed and solid lines, respectively.

Fig. 4.7: Time Evolution of flame tip acceleration $d^2 Z_{tip} / dt^2$, Eq. (3.28) within the interval $t_{sph} < t < t_{wall}$ between t_{sph} , Eq. (3.23), and t_{wall} , Eq. (3.31). The methane-air and propane-air mixtures are shown by the dashed and solid lines, respectively.

Figure 4.7 presents the time evolution of the flame tip acceleration, Eq. (3.28), within the time interval $t_{sph} < t < t_{wall}$, for the stoichiometric methane-air and propane-air mixtures. It is seen here that by the characteristic time t_{sph} , the flame tip acceleration raises noticeably due to the Darrius-Landau instability. Then, by the time t_{wall} , the finger flame scenario amplifies the acceleration by one more order of magnitude. If we compare this acceleration to that due to gravity, $g = 9.8 \text{ m/s}^2$, it will be recognized that the flame-generated acceleration is huge indeed, and it may rise by three orders of magnitude by the time a flame skirt contacts the tunnel wall.

Fig. 4.8: Maximal flame tip acceleration $(d^2 Z_{tip} / dt^2)_{wall}$, Eq. (3.28), taken at the termination time t_{wall} , Eq. (3.29), vs the equivalence ratio ϕ . The methane-air and propane-air mixtures are shown by the dashed and solid lines, respectively.

Figure 4.8 illustrates the maximal flame tip acceleration achieved for both methane-air and propane-air mixtures at the characteristic time t_{wall} . Equation (3.29) shows that short-in-time flame acceleration before the flame skirt contacted the wall is very strong in either case compared.

Chapter 5: Effect of Environmental Dust on Flame Propagation in Tunnels

5.1. Motivation

Many substances that are non-flammable in a bulk form become explosive if dispersed as a cloud of fine particles in air. From a practical viewpoint, this can be treated as both a benefit and a hazard, depending on whether we would like to trigger/facilitate combustion for, example in coal fired power plants or suppress/prevent the same specifically in industries that manufacture, transport, process and/or use combustible dusts, accidental dust deflagrations represent a real hazard to both personnel and equipment such as in coal mines. An illustrative example is a recent catastrophic dust explosion in the Upper Branch coal mine (West Virginia, April 5, 2010) that killed 29 miners and is considered as one of the most disastrous dusty mining explosion in the recent US history. Another example is a catastrophe in Soma, Turkey in May 13, 2014 that killed more than 300 miners. Generally, most of coal mine explosions often involve a methane deflagration combined with fugitive coal dust that is collected by the combustion wave as it progresses through the mine. First, the dust deposited on the floor, walls, and ceiling can be lifted up by the pressure blast of the initial methane explosion causing a cloud of dust to be suspended in the air. When the methane-air flame front meets the dust cloud, the coal particles pyrolyze and contribute a volatile vapor to the methane-air mixture. The coal particles can also cause combustion instabilities, which could potentially alter the structure of the premixed flame. However, the interaction between solid combustible dust particles and a gaseous premixed flame have been rarely investigated in combustion literature and are also the focus of current work.

5.2 Mathematical Model

5.2.1 Effect of equivalence ratio promotion

Coal dust particles can release volatiles into the gaseous mixture as the result of the elevated particle temperature. It is noted that the volatiles constitutes the addition to the gaseous fuel, which thereby increases the equivalence ratio locally. In order to estimate the fraction of volatiles present in the gaseous mixture, it is necessary to explore the rate of the devolatilization process and quantify such a rate. Overall, there are four possible methods to estimate the devolatilization. 1) The *first* method is based on the assumption that all volatiles are released when particle reach a given temperature. However, such approach excludes the fact that devolatilization is a transient process. 2) The *second* method is to treat the particles as liquid droplets where the vaporization can be estimated as discussed by Suard et al. [35]. This method, however, does not capture the non-linear behavior of devolatilization of coal since the droplet evaporation is fairly linear. 3) According to the *third* method, the devolatilization can be determined by solving a set of Arrhenius-based equations, as described by Solomon and Colket [36]. However this method requires a relatively high computational cost. 4) Finally, within the frame of the *fourth* method, the devolatilization can be estimated based on a temperature-dependent power-law relation as proposed by Seshadri et al [27]. To be specific, Seshadri et al. [27] suggested the following expression to predict the devolatilization rate of coal particles,

$$w'_v = An_s 4\pi r^2 T_s^n, \quad (5.1)$$

where w'_v denotes mass of gaseous fuel vaporized per unit volume. The quantities A and n are constants describing the rate of vaporization of particles and the temperature exponent characterizing rate of vaporization of fuel particles, respectively. The particle temperature is denoted as T_s and it is approximated as

$$T_s = \frac{T_b + T_v}{2}, \quad (5.2)$$

where T_b is the adiabatic flame temperature based on the methane-air equivalence ratio and T_v is the temperature at which devolatilization is initiated. For instance, $T_v \sim 600\text{K}$ for coal particles [37]. The total number of particles per unit volume of mixture is estimated by means of dividing the dust concentration (which is denoted as c_s and should not be confused with sound speed defined in Chapter 4, which is denoted by c_o) by the particle density ρ_s . The number of particles per unit volume, n_s , is

$$n_s = (c_s / \rho_s) / V_s. \quad (5.3)$$

The specific heat capacity of the mixture is given by

$$C = C_p + \frac{c_s C_s}{\rho}, \quad (5.4)$$

where C is total heat capacity of mixture and should not be confused with the factor C which is given in Chapter 3, C_p is heat capacity of the gas phase, C_s is heat capacity of particles and ρ is the overall density of mixture, which is given by

$$\rho = \rho_u + c_s, \quad (5.5)$$

where ρ_u is the density of the gas phase and c_s is the concentration of particles. The characteristic time, t_r , of the particles in preheat vaporization is estimated from Ref. [27] as

$$t_r = \frac{\lambda_u}{\rho_u S_L^2 C}. \quad (5.6)$$

Here S_L is the velocity of gaseous flame without particles for given equivalence ratio. The characteristic time is used to estimate the total mass of released volatiles per unit volume

$$w_v = w'_v t_r. \quad (5.7)$$

For simplicity, this additional fuel is assumed to be methane (CH_4), as suggested in Ref. [27] and added to the original gaseous mixture to obtain a new equivalence ratio. The new amount of gaseous fuel in the mixture is denoted as

$$M_{fuel}^m = M_{CH_4}^m + w_v, \quad (5.8)$$

where $M_{CH_4}^m$ is the mass of original methane in the mixture, accordingly the new equivalence ratio can be estimated as

$$\phi_s = 17.2 \left(\frac{M_{fuel}^m}{M_{air}^m} \right), \quad (5.9)$$

where the coefficient 17.2 is the mass of methane to mass of air when $\phi=1$, M_{air}^m is the actual mass of air for given equivalence ratio. With this new equivalence ratio, a new flame temperature T_f' is estimated by an equilibrium solver GASEQ [38], which allows us predicting the effects of changes in temperature, pressure, and concentration on a system at equilibrium. It states that if a system at equilibrium experiences a change, then the system will shift its equilibrium trying to compensate for the change [38]. The outcome for methane-air premixed flame is shown in Figs. 5.1 and Fig. 5.2, where the new equivalence ratio ϕ is presented versus the dust concentration for various equivalence ratios. The associated values of the parameters are presented in the Table 5 for dust particles. Because of the presence of extra fuel in a given locus of the premixture promotes the equivalence ratio. This is justified in Figs. 5.1 and Fig. 5.2, where the modified equivalence ratio is plotted versus the dust particles concentration.

B (1/mol)	3.5×10^6	ρ_u (kg/m ³)	1.135
K_u (kJ/msK)	0.52×10^{-4}	ρ_s (kg/m ³)	1000
E (kJ/mol)	88.8	C_p (kJ/kgK)	2.22
kJ (1/molK)	8.314×10^{-3}	C_s (kJ/kgK)	1.26

Table 5: Various parameters of *combustible* particles [19].

Fig 5.1: The modified equivalence ratio vs the concentration of particles of size 75 microns.

Fig 5.2: The modified equivalence ratio vs the concentration of particles of size 25 microns.

Because of the presence of extra fuel due to the coal particles the equivalence ratio is promoted in the premixture. This is justified in Figs. 5.1 and 5.2 where equivalence ratio plotted versus the dust particles concentration. Consequently the temperature increase in Figs. 5.3 and 5.4 is because of addition of coal particles that devolatilize forming a known gaseous compound, which is assumed

to be methane. Also, the particles with lesser size promote the temperature increase even better which can be seen in Fig. 5.4. A light increase in the equivalence ratio is seen in Fig. 5.3., which in turn increases the flame temperature calculated using GASEQ equilibrium solver [38] for lean fuel mixtures considered here ($0.6 < \phi < 1.0$).

Fig 5.3: The modified flame temperature, Eq. (5.9), versus the dust concentration of particle size 75 microns.

Fig 5.4: The modified flame temperature, Eq. (5.9), versus the dust concentration of particle size 25 microns.

The corresponding modified flame temperature T'_f is subsequently used to estimate the “update” in the planar flame speed by means of the Seshadri [27]. Specifically, the dust-induced laminar burning velocity, S'_L , is then calculated as [27]:

$$S'_L = \left[\frac{2Bk_u \varepsilon^2}{\rho_u C_p} \exp\left(-\frac{E}{RT'_f}\right) \right]^{1/2}, \quad (5.10)$$

where

$$\rho_u = 1.135 \frac{g}{cm^3}, \quad \varepsilon = \frac{1}{Z_e}, \quad Z_e = \frac{E(T'_f - T_u)}{RT_f'^2}. \quad (5.11)$$

Fig 5.5: The modified burning velocity, Eq. (5.10), vs the dust concentration of particle size 75 microns for different equivalence ratios.

Fig 5.6: The modified flame temperature, Eq. (5.10), vs the dust concentration of particle size 25 microns for different equivalence ratios.

The calculated laminar burning velocity due to the addition of the coal particles of two different sizes are shown in Figs. 5.5 and 5.6. The promotion in the equivalence ratio due to the temperature rise increases the laminar burning velocity of the flame. The particles of a lesser size promote the burning velocity than those of a bigger size, as shown in Fig. 5.7.

Fig 5.7 Comparison of flame speeds vs the dust concentration of particle size for fixed equivalence ratio.

5.3. Results and Discussion

With a modified, dust-induced laminar burning velocity, Eq. (5.10), resulted from the increase in the flame temperature as well as that in the equivalence ratio, we next revisit our formulations and analyses of Chapters 3 and 4. Namely, we employ the modified equivalence ratio and the modified laminar burning velocity to calculate the characteristics of a globally-spherically-expanding and subsequently a finger-like flame front such as the characteristic timing, the flame tip position and velocity, as well as the burning rate. Specifically, the characteristic time instant devoted to a transition from a globally-spherical to a finger-like shape, t_{sph} , can be evaluated as

$$t \approx \left(\frac{\Theta H}{2\alpha C} \right) = \frac{n}{\Theta S} \left(\frac{\Theta H}{2\alpha k} \right), \quad (5.12)$$

whereas the instant when the flame skirt contacts the tunnel sidewall, thereby terminating the finger-flame acceleration scenario, in the gaseous-dusty environment reads

$$t_{wall} = \left\{ \frac{\Theta' H}{2\alpha' C'} \ln \left(\frac{\Theta' + \alpha'}{\Theta' - \alpha'} \right) \right\}^{1/n} = \frac{n}{\Theta' S'_L} \left\{ \frac{\Theta' H}{2\alpha' k_{DL}^{n-1}} \ln \left(\frac{\Theta' + \alpha'}{\Theta' - \alpha'} \right) \right\}^{1/n}. \quad (5.13)$$

Then the “dusty” counterparts of Eqs. (3.26) – (3.28) acquire the form

$$Z_{tip} = \frac{\Theta' H}{2\alpha'} \sinh \left(2 \frac{\alpha' C' t^n}{\Theta' H} \right) = \frac{H}{2} \sqrt{\frac{\Theta'}{\Theta' - 1}} \sinh \left(2 \sqrt{\frac{\Theta' - 1}{\Theta'}} \frac{k_{DL}^{n-1}}{H} \left(\frac{\Theta' S'_L}{n} \right)^n t^n \right), \quad (5.14)$$

$$\frac{dZ_{tip}}{dt} = n C' t^{n-1} \cosh \left(2 \frac{\alpha' C' t^n}{\Theta' H} \right), \quad (5.15)$$

$$\frac{d^2 Z_{tip}}{dt^2} = n C' t^{n-2} \left(2 \frac{\alpha' C'}{\Theta' H} n t^n \sinh \left(2 \frac{\alpha' C' t^n}{\Theta' H} \right) + (n-1) \cosh \left(2 \frac{\alpha' C' t^n}{\Theta' H} \right) \right). \quad (5.16)$$

The modified laminar burning velocity is implemented into the formulation of spherical and finger flame scenarios to investigate effect of the equivalence ratio promotion at different dust concentration values. So, the formulation of Chapter 3 is extended to the new parameters obtained after the fuel addition, which changes the equivalence ratio, gas expansion rate and the flame speed because of the increase in flame temperature.

In Fig. 5.8, the evolution of flame tip position, Eq. (5.15), at the time t_{wall} , Eq. (5.13), is plotted.

We can see the shift in the flame tip position when the finger flame scenario stops. This shift in position is observed because of the addition of particles up to 250(g/m³) with size of 75 microns and 25 microns. In Fig. 5.9, the characteristic time t_{sph} , Eq. (5.12), for flames with combustible particles is less than that without particles for a given equivalence ratio. So, methane-air flames with particles exhibits globally-spherical (cellular) shape of an expanding flame even earlier as

compared to methane-air flames without particles. The characteristic time t_{wall} , Eq. (5.13), will also get promoted to occur before for methane-air flames with particles as compared to those without particles. Also, the difference in size promotes the characteristic time to occur even earlier for the smaller size of particles.

Fig 5.8: Flame tip position, Eq. (5.15), at the time t_{wall} given by Eq. (5.13), vs the concentration of coal particles for a set of fixed equivalence ratios.

Fig. 5.9: The time limitations of the finger flame acceleration, t_{sph} of Eq. (5.12) and t_{wall} of Eq. (5.13), versus the equivalence ratio ϕ for methane-air mixture with and without dust particles.

Fig. 5.10: The maximal flame tip velocity $(dZ_{tip}/dt)_{wall}$, Eq. (5.16), at t_{wall} , Eq. (5.14), vs ϕ for the methane-air mixture without particles and that with particles of size 75 microns.

Fig. 5.11: Evolution of flame tip velocity dZ_{tip}/dt , Eq. (5.16), vs the time interval between t_{sph} , Eq. (5.13), and t_{wall} , Eq. (5.14), $t_{sph} < t < t_{wall}$. The methane-air with particles and methane-air without particles mixtures are shown for the lean fuel ratio $\phi = 0.7$.

Similar to Fig. 4.5, the maximal flame tip velocity decreases for $0.6 < \phi < 1.4$, but here, in Fig. 5.10, the maximal flame tip velocity $(dZ_{tip} / dt)_{wall}$, Eq. (5.16), is shown for the lean methane-air mixture ($0.7 < \phi < 0.9$) with and without particles. Eventually, Fig. 5.11 presents the time evolution of the flame tip velocity, Eq. (5.16), for the lean methane-air fuel, $\phi = 0.7$, with and without combustible particles. It is seen here that the addition of combustible particles to the fuel promotes the flame speed and therefore the termination time t_{wall} reduces. Anyway, similar to Chapter 3, the flame velocity is increased by two orders of magnitude. Indeed the flame velocity is also increasing with addition of fuel from the coal particles thereby making the fuel rich.

Chapter 6: Effect of Inert Particles

6.1 Mathematical model

In contrast to combustible (say, coal) particles, inert (say, sand) particles will act as a heat sink as they absorb the heat from the flame and thereby decrease the flame temperature. This effect will be considered in the following section to develop an expression for such a reduced flame temperature. In order to estimate this effect, first, the heat released for flame without dust has to be calculated. For a lean or stoichiometric methane-air mixture, the chemical reaction for combustion with equivalence ratio ϕ is given by

The heat consumed to raise the temperature for $\phi / 2$ moles of methane and 4.76 moles of air, is given by [27]

$$[(T_b - T_u) \sum C_p n_{product}]. \quad (6.2)$$

With the assumption that the entire heat release is used to raise the temperature of the mixture, the heat release rate of the methane-air premixed flame for a given flow of air and a given equivalence ratio is calculated as

$$\dot{Q} = [(T_b - T_u) \sum C_p n_{product}] \frac{n_{air}}{4.76}, \quad (6.3)$$

where $n_{product}$ is the number of moles of the products that depends on the equivalence ratio ϕ .

Assuming that the flame with particles releases the same amount of heat while it is also influenced by the temperature rise of particles, a modified flame temperature can be estimated using the energy conservation law

$$\dot{Q} = [(T_b - T_u) \sum C_p n_{product}] \frac{n_{air}}{4.76} + n'_s C_s (T_f'' - T_u). \quad (6.4)$$

Rearranging the terms of Eq. (6.4), we express the new flame temperature, T_f'' , in the form

$$T_f'' = \frac{Q}{\frac{n_{air}}{4.76} \sum C_p n_{product} + n'_s C_s} + T_u, \quad (6.5)$$

where n'_s is the number of moles of particle per unit volume passing through the flame, and it is calculated as

$$n'_s = \frac{c_s}{M_c}. \quad (6.6)$$

The new flame temperature, accounting for the heat sink effect, is estimated using the equilibrium solver GASEQ [38], and it indicates a continuous decrease in the flame temperature with the addition of sand. The corresponding flame temperature is then used to estimate the new laminar burning velocity, S_L'' , using the model developed by Seshadri et al. [27]:

$$S_L'' = \left[\frac{2Bk_u \varepsilon^2}{\rho_u C_p} \exp\left(-\frac{E}{RT_f''}\right) \right]^{1/2}, \quad (6.7)$$

where

$$\rho_u = 1.135 \text{ g/cm}^3, \quad \varepsilon = 1/Ze, \quad Ze = \frac{E(T_f'' - T_u)}{RT_f''^2}. \quad (6.8)$$

The associated modifications are presented in Figs. 6.1 – 6.4. Specifically, Figs. 6.1 and 6.2 illustrates the decreasing trend in the flame temperature for a methane-air flame with addition of inert particles of a concentration ranging from 0 till 250 (g/m³) with the size of particles being 75 microns and 120 microns. As stated above, inert particles decrease the flame temperature which is resulted increase in the flame speed. Such a reduction in the flame burning velocity is also seen in Figs. 6.3 and 6.4, where the modified planar flame speed, induced by the inert dust, is plotted versus the particle concentration. To be specific, the decrease in the flame temperature and propagation velocity is shown for the lean mixture-air in the range of $\phi = 0.7 - 0.9$.

Fig 6.1: Decrease in flame temperature T''_f , Eq. (6.5), versus concentration of particles c_s with size of 75 microns.

Fig 6.2: The decrease in the flame temperature T''_f , Eq. (6.5), vs the concentration of particles C_s for the particles of size 120 microns.

Fig 6.3: Decrease in the burning velocity S_L'' , Eq. (6.7), versus concentration of particles c_s with size of 75 microns.

Fig 6.4: Decrease in the burning velocity S_L'' , Eq. (6.7), vs concentration of particles c_s with size of 120 microns.

The calculated laminar burning velocity due to the addition of inert particles of two different sizes is shown in Figs. 6.3 and 6.4. The temperature decreases due to the heat sink effect of particles, which in turn, reduces the laminar burning velocity. The particles of larger size diminish the laminar burning velocity as compared to the particles of smaller size, see Figs. 6.5 and 6.6, ultimately leading to the mitigation of even termination of a fire;

Fig. 6.5: The flame temperature T_f'' with the dust concentration for the particles of size 75 and 120 microns and fixed equivalence ratio $\phi=0.7$.

Fig. 6.6: The laminar flame speed S_L'' with the dust concentration for the particles of size 75 and 120 microns and fixed equivalence ratio $\phi=0.7$.

6.2 Results and Discussion

New laminar burning velocity obtained due to the decrease in the flame temperature and the equivalence ratio changes the spherically-expanding and the finger flame scenarios. As we employ the new equivalence ratio and new laminar burning velocity to the formulations obtained in Chapters 3-5, all the parameters, which are functions of the equivalence ratio and the laminar burning velocity will change, and there will be a new estimations for the key stages such as characteristic timing, the flame tip position and velocity, and the burning rate. The “inert” counterparts of Eqs. (3.26) – (3.28) acquire the form

$$Z_{tip} = \frac{\Theta H}{2\alpha} \sinh\left(2 \frac{\alpha}{\Theta} \frac{C'' t^n}{H}\right) = \frac{H}{2} \sqrt{\frac{\Theta}{\Theta-1}} \sinh\left(2 \sqrt{\frac{\Theta-1}{\Theta}} \frac{k_{DL}^{n-1}}{H} \left(\frac{\Theta S_L''}{n}\right)^n t^n\right), \quad (6.9)$$

$$\frac{dZ_{tip}}{dt} = n C'' t^{n-1} \cosh\left(2 \frac{\alpha C'' t^n}{\Theta H}\right), \quad (6.10)$$

$$\frac{d^2 Z_{tip}}{dt^2} = n C'' t^{n-2} \left(2 \frac{\alpha C''}{\Theta H} n t^n \sinh\left(2 \frac{\alpha C'' t^n}{\Theta H}\right) + (n-1) \cosh\left(2 \frac{\alpha C'' t^n}{\Theta H}\right)\right), \quad (6.11)$$

with the characteristic timings

$$t_{sph} \approx \left(\frac{\Theta H}{2\alpha C''}\right)^{1/n} = \frac{n}{\Theta S_L''} \left(\frac{\Theta H}{2\alpha k_{DL}^{n-1}}\right)^{1/n}, \quad (6.12)$$

$$t_{wall} = \left\{ \frac{\Theta H}{2\alpha C''} \ln\left(\frac{\Theta+\alpha}{\Theta-\alpha}\right) \right\}^{1/n} = \frac{n}{\Theta S_L''} \left\{ \frac{\Theta H}{2\alpha k_{DL}^{n-1}} \ln\left(\frac{\Theta+\alpha}{\Theta-\alpha}\right) \right\}^{1/n}. \quad (6.13)$$

In Fig. 6.7, the time limitations of the finger flame acceleration for a methane-air flame with inert particles at equivalence ratio $\phi = 0.7 - 0.9$ are showed. The characteristic times, t_{wall} , Eq. (6.13), and t_{sph} , Eq. (6.12), for the case of no particles and at zero concentration and $\phi = 0.9$ are same as those for a flame with inert particles of the size 120 microns, and $\phi = 0.9$. When the addition of

inert particles increases the time interval is also increasing, which is an indication for the reduction of short acceleration happening in the finger flame scenario.

Fig 6.7 The time limitations of the finger flame acceleration, t_{sph} of Eq. (6.12), and t_{wall} of Eq. (6.13), at equivalence ratio $\phi = 0.7 - 0.9$ versus concentration of particles for methane-air flames.

Fig 6.8: The flame tip position, Eq. (6.9), at the termination time t_{wall} , Eq. (6.13), versus the concentration of inert particles for fixed equivalence ratio.

The flame tip position at the instant when the flame skirt contacts the wall (which terminating the finger flame acceleration scenario) is shown in Fig. 6.4, thereby illustrating the decrease in the

distance travelled by the flame with the increase in the concentration of particles for different equivalence ratios. This happens because the flame temperature decreases due to the heat sink effect of inert particles, which reduces the (short) period of the finger flame acceleration. Figure 6.9 shows the maximal flame tip velocity at the characteristic time, t_{wall} , Eq. (6.11), It is obvious that inert particles moderate the flame tip velocity with increasing dust concentration.

Fig. 6.9: The maximal flame tip velocity $(dZ_{tip}/dt)_{wall}$, Eq. (6.11), at the time t_{wall} of Eq. (6.13) versus the concentration of inert particles for the methane-air-inert mixtures of different equivalence ratios $\phi = 0.7, 0.8$ and 0.9 with particles of size 75 microns.

Finally, Fig. 6.10 presents the time evolution of the flame tip velocity, Eq. (6.11), in the range $t_{sph} < t < t_{wall}$, for a lean methane-air fuel mixture, $\phi = 0.7$, with and without inert particles. It is seen, again, that the addition of inert particles moderates the flame speed in the interval $t_{sph} < t < t_{wall}$. The plots show the same trends, namely, the flame tip velocity increases in time for methane-air flames without and with dust particles, respectively.

Fig. 6.10: Evolution of flame tip velocity dZ_{tip} / dt , Eq. (6.10), vs the time interval between t_{sph} , Eq. (6.12), and t_{wall} , Eq. (6.13), $t_{sph} < t < t_{wall}$. The methane-air mixture with and without inert particles for the lean fuel of equivalence ratio $\phi = 0.7$.

In the above results, the effect of inert particles is illustrated with inclusion of different size of particles being 75 and 120 microns, respectively. On the other hand, in Chapter 5, the effect of combustible particles is illustrated with particle size being 25 and 75 microns. In both of these cases, the laminar flame speed increases with the presence of combustible particles, but it decreases with the presence of inert particles. Eventually, both the effects are compared in Figs. 6.11 and 6.12 for the limitations of finger flame and maximal flame tip velocities, respectively.

Fig 6.11 The time limitations of the finger flame acceleration, t_{sph} of Eq. (6.12) and (5.12), and t_{wall} of Eq. (6.13) and (5.13), at equivalence ratio $\phi = 0.7 - 0.9$ versus concentration of particles for methane-air flames.

Fig. 6.12: Evolution of flame tip velocity dZ_{tip}/dt , Eq. (6.10) and (5.10), vs the time interval between t_{sph} , Eqs. (6.12) and (5.12), and t_{wall} , Eqs. (6.13) and (5.13). $t_{sph} < t < t_{wall}$. The methane-air with inert particles, combustible and without particles mixtures are shown for the lean fuel ratio $\phi = 0.7$.

Conclusion and future work

In the present thesis a predictive quantitative scenario of an accidental fire in a gaseous or gas-dust environment of a coal mine passage is provided. Specifically, we have quantified the flame front dynamics according to the mechanisms suggested in Refs. [9-11]. When an accidental ignition occurs in a mine, first, a flame develops from a smooth spherical kernel to globally-spherical, cellular (corrugated) structure. This occurs due the development of the Darrieus-Landau flame instability, and is accompanied by self-similar flame acceleration. Subsequently, such a cellular flame converts into a finger-like shape, exhibiting a tremendous acceleration, for a short time, until the flame skirts contacts the passage sidewall. For near-stoichiometric ($0.8 < \phi < 1.3$) methane-air combustion, the overall acceleration scenario may promote the total burning rate (flame speed) by two orders of magnitude, up to supersonic values. In spite of the direct disaster of such a fast fire, this may also facilitate the deflagration-to detonation transition (DDT) event, leading thereby to additional hazards to the mining personal and equipment, associated with detonative shocks.

In the present study, the influences of combustible and inert dust particles are implemented through the mathematical model based on heat sink effect along with the effect of different particle sizes and concentrations are investigated. As a result the influence of combustible particles of size 25 micron increases the flame propagation intensity, whereas increase in the size of particles gradually decreases the flame propagation speed. . On the other hand, when inert particles are considered at 75–120 microns, the burning rate decreases irrespective of a concentration being considered, which means that a flame cannot sustain. These results have better agreement with the experimental results [39].

We will implement spatial and temporal variations of S into the formulation of chapter 3, which is being done by author's colleagues and thereby it can be extended to turbulent environment through the development and employment of a unified turbulent flame formulation.

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