Towards Predictive Scenario of Methane and Coal Dust Explosion in a Mining Accident

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Motivation & Broader Impacts

➢ Historically, accidental gas/dust explosions represent a hazard to both personnel and equipment in industries that make, transport, or use flammable gases and/or combustible dusts. Mining industry has one of the highest fatality and injury rates.

Few illustrative numbers. Compare fatalities: Year 1912. Titanic: 1,514 vs US Coal Mines: 2,360

While two orders of magnitude reduction in the mining fatality is achieved during 1912-2012,

- More than 250 combustible dust incidents in US in 1980-2005 (119 deaths, 718 injuries).
- Soma, Turkey, 2014 (>300 deaths); Sunjiawan, China, 2005 (>200); Donetsk, Ukraine, 2007 (>100).
- Major WV incidents: Fairmont, 1907 (361); Eccles, 1914 (183); Bartley, 1940 (91); Farmington, 1968 (78); Upper Branch, 2010 (29).

➢ Concomitant demands: flammable gases are used in residential/commercial buildings (heating and cooking), as well as for industrial manufacturing and electricity generation. Combustible dust accidents have also occurred in different industries.

➢ An important safety consideration is a damage from a blast wave that results from a gas/dust explosion due to accidental release of a flammable gas (leak), dust dispersion or a malicious act.

- Remember, the 03/12/2014 gas explosion in NYC (8 deaths) was likely caused by a gas leak through piping installed > 100 years ago.

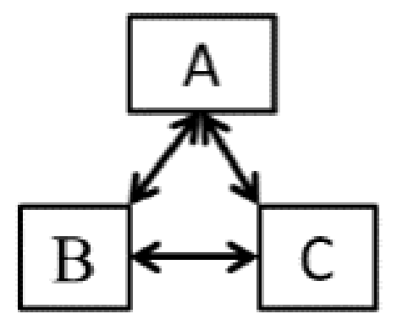
➢ Current industrial bench scale test methods and corresponding analytical/empirical/numerical analysis are not adequate.

- Industrial safety standards are not able to keep up with various types of novel finely divided flammable materials (dusts) resulted from the modern expanding of the machinery, chemical, metallurgical, and pharmaceutical industries.
- Most of exiting computational explosion models (COBRA, EXSIM, FLACS, FLARE, REAGAS etc.) utilize empirical correlations, which makes them linked to a particular case, and thereby they are hard to be extended/generalized.
- Current experimental models are usually limited to small-scale spherical geometries, with no internal obstructions, which prevents their employment/generalizations to a typical structural explosion scenario.
- However, regardless of the cause, it is critical to know if the building or structure (such as a coal mine) will survive an explosion and if simple design changes can be adopted to reduce the explosion threat.

➢ Qualitatively new consideration and techniques, from the first principles, are highly needed to redesign the industrial tests. If successfully developed and deployed, this will allow to transfer the fundamental science into the practical applications.

General Objectives and Technical Approaches

➢ The overall objective of this research is to develop an integrative experimental, computational and analytical platform for gas and dust explosions in complex geometries such as those in coal mines and other industries with serious hazards to life and property. The platform is based, in particular, on the following blocks:



A. Unified formulation for premixed turbulent flame speed

Phase 1: Establish a novel model for gaseous premixed turbulent flame

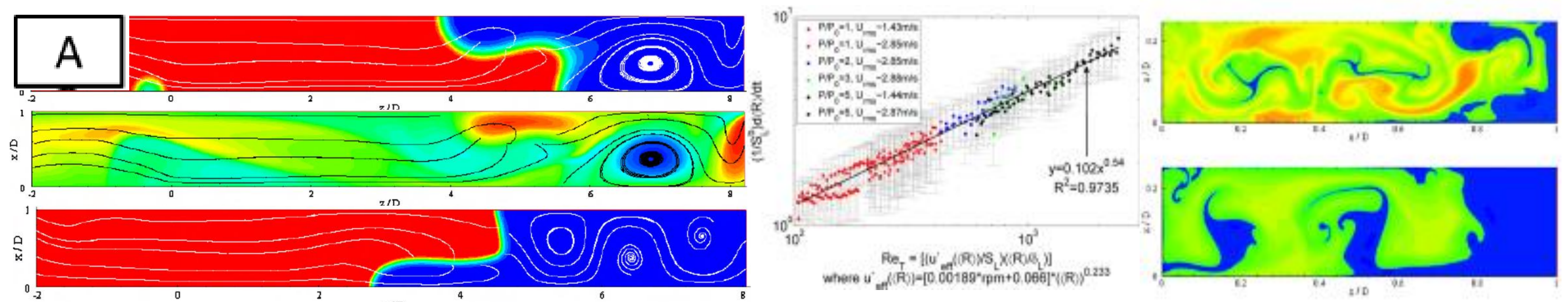
Phase 2: Develop a computational platform, with the model of Phase 1

B. Laminar formulation for sporadic flame acceleration and subsequent deflagration-to-detonation transition (DDT) in tunnels

Phase 3: Incorporate the developed platform into the laminar DDT formulation

C. Effect of dust on the explosivity limits and flame propagation

Phase 4: Extend the analyses to particle-gas-air environments (laminar/turbulent)



Turbulent flame propagation in tubes [1] (left) and under the confinement [2] (right). The plot in the center [3,4] (Courtesy of Dr. S. Chaudhuri) justifies a unification for the premixed turbulent flame formulation.

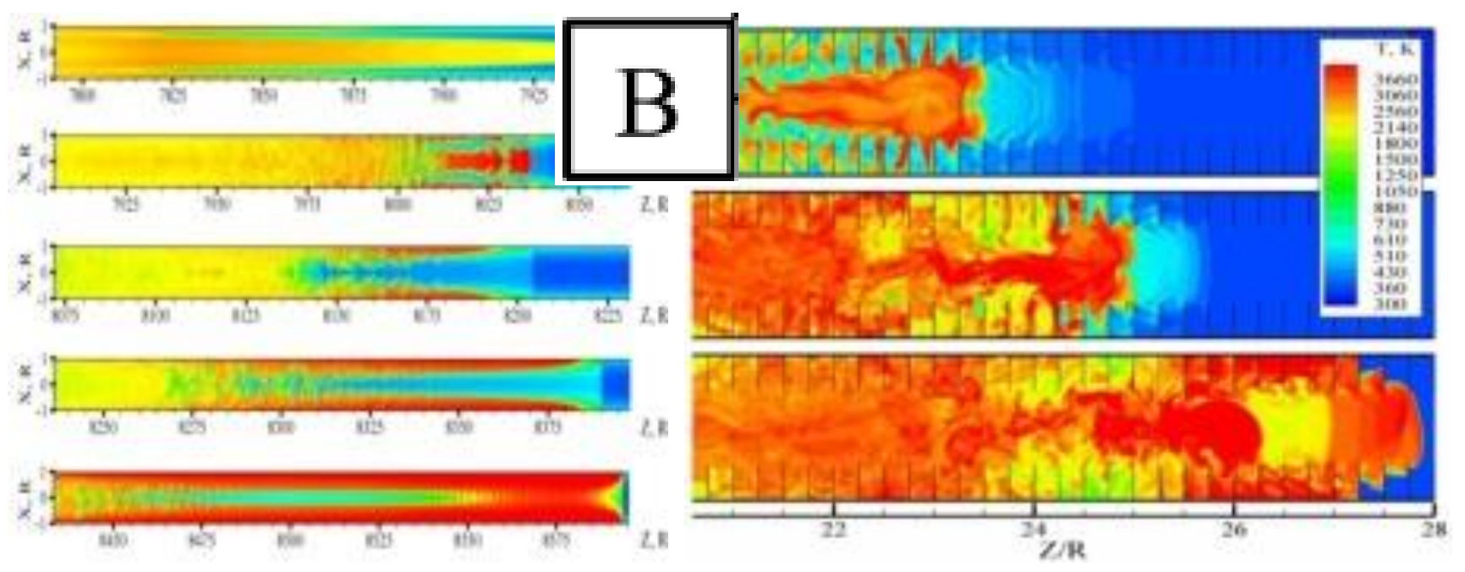
Unified turbulent flame speed model is being developed to incorporate

A1. *Effect of thermal expansion on the flame-flow feedback*

A2. *Centrifugal effect of burning along the turbulent vortex axes*

A4. *Turbulence coupling to the combustion instabilities*

A4. *Ambiguity between measured turbulence and that experienced by a local flame segment*



Flame acceleration and DDT in smooth [5] (left) and obstructed [6] (right) tunnels .

➢ Conceptually-laminar mechanisms of flame acceleration and DDT are revealed.

- Associated computational/analytical platforms are being developed

B1. Three distinctive flame acceleration mechanisms are found and scrutinized.

B2. For each, various flame acceleration stages are found and quantified.

B3. Entire flame evolution is determined.

B4. DDT time and position are predicted.

B5. *Heat losses to be determined*

C

Extension from gaseous methane-air to dust-methane-air environments (ongoing work in progress)

The role of dust in explosion and initiation of the DDT will quantified. The effect of the dust concentration and mean size on the thermal-chemical flame properties and flame evolution will be scrutinized.

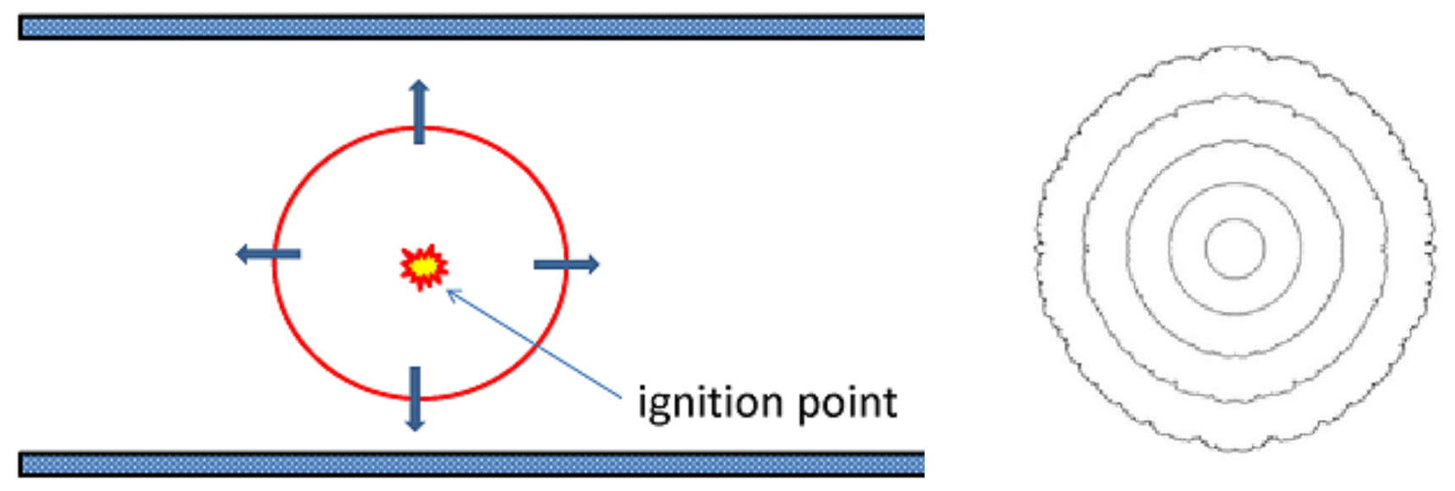
Scenario of a Mining Fire (Methane Flame) in a Coal Dust Environment

➢ Fundamental formulations [4-8] are employed to scrutinize the evolution and key stages of the methane and coal dust explosions in a mining accident. Specifically, we identify the key characteristics of these stages, predicting the timing for each stage, the speed of flame spreading, as well as the expected pressure rise. The flame evolution stages include (see figures on the right):

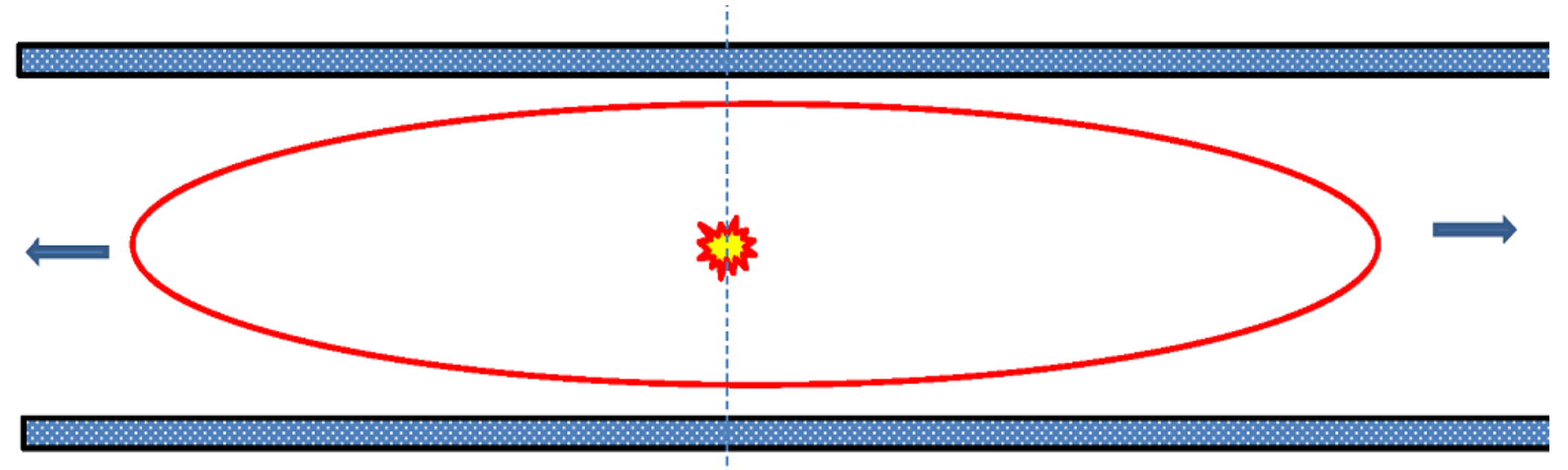
1) Initial quasi-spherical expansion of a centrally-ignited, embryonic flame, with the possibility of self-similar acceleration due to the hydrodynamic (Darrieus-Landau; DL) instability;
2) Intermediate, so-called "finger-flame" acceleration; and
3) Latest, large-scale-based acceleration due to wall friction and/or in-built obstacles/roughness.

➢ The input parameters for the formulation are (i) the planar flame speed; (ii) the thermal expansion coefficient (coupled to the equivalence ratio); and (iii) transport properties of the air/methane/dust mixture. Another set of input parameters is coupled to the size and configuration a mining passage.

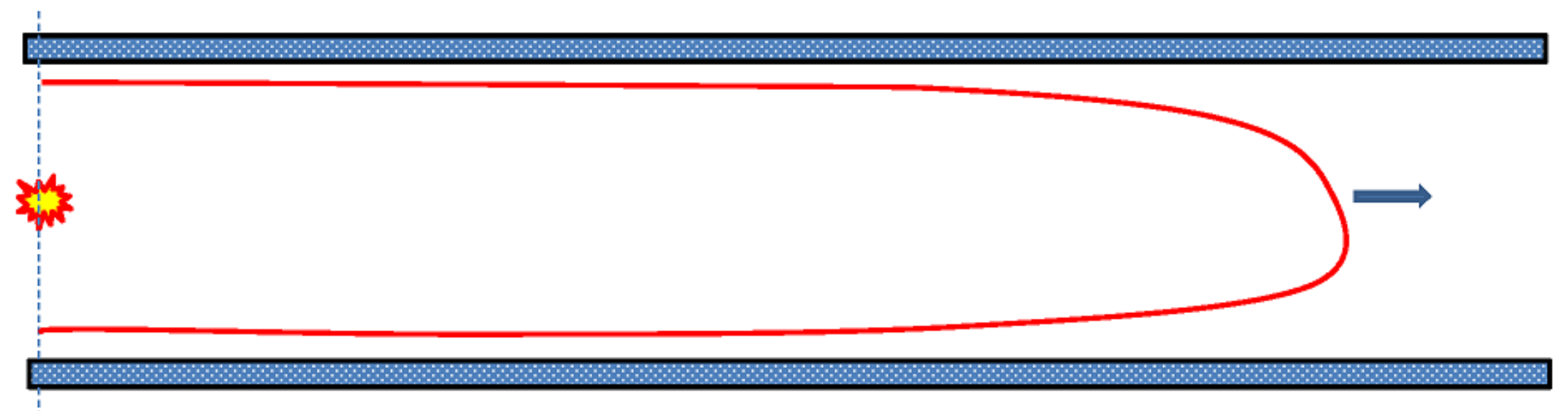
➢ While the fundamental formulation on flame acceleration in tubes [5,6] is conceptually laminar, with turbulence playing only a supplementary role, imposed or self-generated turbulence is a key factor in the practical reality. For this reason, the formulation is next being combined with the fundamental study, theoretical and experimental, of homogenous-gaseous and particle-gas-air combustion in turbulent environment. Specifically, the analyses of premixed turbulent flame velocity, namely, the renormalization approach and the spectral formulation are being reconciled, and will be validated by the Hybrid-Flame Analyzer experiments on turbulent methane-air burning, and subsequently incorporated into the generalized formulation. The turbulent flame velocity is tabulated as a function of various flame parameters, flow parameters, and the size/concentrations of the impurity particles. Specifically, it is shown that the particles typically intensify turbulent combustion. The formulation accounts for the flame-flow feedback due to thermal expansion as well as turbulence coupling to the intrinsic combustion instabilities.



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



Stage 2: Finger-like flame acceleration.



Stage 3: Effect of wall friction and roughness (obstacles)

Conclusion

- ➢ The integrative research, consisting of blocks A–C with Phases 1–4, is being developed.
- ➢ **Block A**: The analytical components for A1–A4 are practically completed, with a slight revisiting required, while computational implementation will need additional efforts.
- ➢ **Block B**: We have worked on block B for a decade now, and are happy to report that the laminar formulation is practically completed now. The only serious task remained in block B is B5. It is nevertheless noted that, while B5 is relevant to the multitude of academic problems and is critical for micro-channels, it plays a minor role in the mining safety issues.
- ➢ **Block C**: This is an almost new research, with minor pilot studies performed so far.

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