Simulating the Effect of Release of Pressure and Dust Lifting on Coal Dust Explosions

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Abstract

Dispersion of accumulated layers of combustible dust by turbulent flow or shock waves ahead of a propagating flame can play an important role for explosion propagation in coal mines. In 1924, Greenwald and Wheeler investigated this process in a series of large-scale dust explosion experiments, performed in a 750 feet long experimental gallery [1]. In the present paper, these experiments are simulated with the computational fluid dynamics code DESC (Dust Explosion Simulation Code), using a simple empirical model to describe the process of dust lifting.

1 Introduction

The hazard posed by accumulated layers of coal dust in mine galleries has been recognized since Faraday and Lyell for the first time documented the significant role played by the coal dust in major coal mine explosions [2,3]. The sequence of events leading up to such accidents often starts out with the formation of a flammable gaseous mixture, usually methane/air (or 'fire-damp'). If an ignition source is present, turbulent flow or shock waves generated by a primary gas explosion may disperse accumulated layers of coal dust, and a secondary dust explosion may propagate through the mine gallery [4]. Accumulated layers of dust also pose a serious, and often overlooked, hazard in industrial plants where combustible dusts are produced, stored, transported, or processed [5].

The CFD-code DESC (Dust Explosion Simulation Code) was developed during a project supported by the European Commission under the Fifth Framework Programme [6,7]. As part of the DESC project, a research group at Warsaw University of Technology (WUT) investigated the mechanism of dust lifting both theoretically and experimentally, and developed an empirical model for dust lifting [8,9]. The following relation gives the mass flux of dust as an injection velocity v_z in m s^{-1}, assuming a dust concentration c_d equal to 1 kg m^{-3}:

$$v_z = 0.004\, h_l^{0.216}\, u^{1.743}\, d_p^{-0.054}\, \rho_p^{-0.159}\, A_p^{0.957} \tag{1}$$

where h_l is layer thickness in millimetres, u is flow velocity above the layer in m s^{-1}, d_p is characteristic particle size in μm, ρ_p is particle density in kg m^{-3}, and A_p is a dimensionless empirical constant. The same model was used to simulate some large-scale dust explosion experiments in a 100-meter surface gallery, 2 meters in diameter, at Experimental Mine Barbara [10,11]. However, due to the limited amount of dust used in the experiments, and the modest L/D ratio of the gallery, the initiating

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methane explosions dominated the pressure development. The effect of dust lifting was nevertheless evident from the extended length of flame propagation in scenarios involving dust layers, compared to scenarios without such layers. In the present paper, DESC simulations are compared with the data reported by H.P. Greenwald and R.V. Wheeler in their 1925 paper on the effect of the release of pressure on the development of coal dust explosions in a 750 feet gallery [1].

2 Experiments

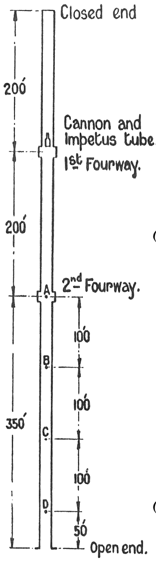
Greenwald and Wheeler described the original experiments in a joint publication by the United States Bureau of Mines and the Safety in Mines Research Board in 1925 [1]. The work had been carried out during the summer of 1924 at the experiment station at Eskmeals, England. Earlier studies of coal-dust explosions had primarily *"been with regard to their development when travelling from a closed to an open end* [of a straight tube]*"*. However, these experiments were performed *"to determine to what extent the development of a coal-dust explosion was aided or retarded by release of pressure, either at the origin of the explosion or at some point in its path, such as would be given in a roadway of a mine by openings to side galleries or drifts"*.

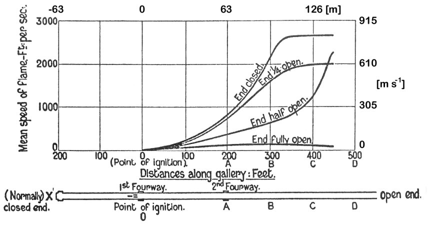
The experimental gallery consisted of a series of Lancashire boiler shells bolted together, forming a straight tube of 2.29 m (7½ ft) internal diameter and 229 m (750 ft) long. At points 63 and 126 m (200 and 400 ft) from the normally closed end, four-way peaces were inserted, allowing extensions 1.83 m (6 ft) in diameter, at right angles to the main gallery. The interior of the gallery was clear of obstructions, except for rivet heads and five wooden shelves for dust on each side along the portion of the gallery between the two four-way pieces.

The explosions were ignited by a blow-out shot of 0.78 kg (28 oz) black powder, fired into an open-ended impetus tube, 0.91 m in diameter and 3.1 m long. Table 1 lists the properties of the coal dust; 20 oz (9 kg) was placed in the impetus tube, an additional amount on a plank in front thereof, and 1.5 kg per meter (one pound per linear foot) was distributed along the gallery from the cannon to the open end. Fig. 1 shows the results from the original flame speed measurements, and illustrates how the position and size of the vent openings varied; vent areas are reported as fraction of the total cross section area of the gallery.

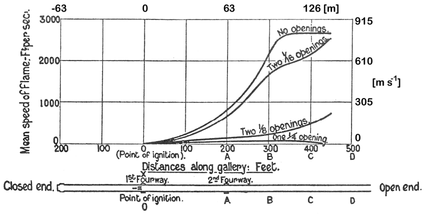
Tab. 1 *Properties of the coal dust used in the experiments described in Ref. [1], and the coal dust used to generate the empirical model for the DESC simulations.*

		Coal dust described in Ref. [1]:	*Coal dust used in empirical model:*
Proximate analysis [wt %]*:*	*Ash:*	1.51	2.85
	Humidity:	1.9	3.16
	Volatiles:	32.92	30.89
	Fixed carbon:	63.67	–
Ultimate analysis [wt%]*:*	*C:*	83.58	79.92
	H:	5.38	5.14
	O:	8.72	1.86
	N:	1.47	< 0.30
	S:	0.85	6.78
Other properties:	*Particle size* [μm]*:*	85 wt% $<$ 74 (200 mesh sieve)	17-18 (mass median diameter)
	Bulk density [kg/m^3]*:*	–	450
	Particle density [kg/m^3]*:*	–	1340
	Net calorific value [kJ/kg]*:*	–	30800
	Heat of combustion [kJ/kg]*:*	–	31900

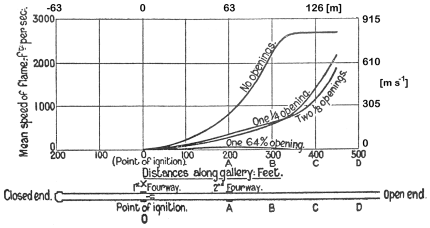




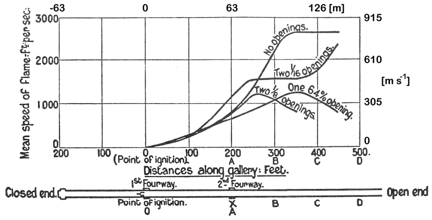
(A) The effect of openings in the gallery 200 ft. (63 m) behind the point of ignition on the development of a coal dust explosion. Changes effected at **X**. (FIG. 4 in [1]).



(B) The effect of openings in the gallery immediately in front of the point of ignition on the development of a coal dust explosion. Changes effected at **X**. (FIG. 5 in [1]).



(C) The effect of openings in the gallery immediately behind the point of ignition on the development of a coal dust explosion. Changes effected at **X**. (FIG. 6 in [1]).



(D) The effect of openings in the gallery 200 ft. (63 m) in advance of the point of ignition on the development of a coal dust explosion. Changes effected at **X**. (FIG. 7 in [1]).

Fig. 1 *Arrangement of the 750 ft. experimental gallery, where pressures were measured with continuously recording pressure gauges in positions B-D, and flame arrival times were measured in positions A-D with screen wires (FIG. 1 from Ref. [1]); and summaries of the experimental results on flame speeds (FIGS. 4-7 from Ref. [1], added axes in metric units).*

3 Simulations

The simulations were performed with the CFD code DESC 1.0 [7]. The dust specific parameters in Eq. (1) were taken from a coal dust used in the DESC project: ρ_p = 1340 kg m^{-3}, ρ_b = 450 kg m^{-3}, d_p = 18 μm and A_p= 1.2. Although this coal dust resembles the dust used in the experiments, there are significant uncertainties associated with the properties of the powder, especially the reactivity of the dust clouds. Hence, the estimated laminar burning velocity S_{L0}, was varied, see Fig. 2(i), and the value 1.75 S_{L0} was used in the remaining simulations. The ignition source was simulated by 'converting' the energy release and volume expansion of the black powder to combustion products, and suddenly releasing the hot pressurized gas, from an enclosure imitation the cannon, into the impetus tube. Cubical grid cells of size 17.6 cm were used throughout the gallery, and outside the gallery, the grid was stretched towards the outer boundaries. However, some of the simulations stopped due to numerical instabilities before the flame could exit from the open end of the gallery.

4 Results

Fig. 2 summarizes the results from both experiments and simulations. Fig. 2(ii) shows the results from some hypothetical simulations of homogeneous gas and dust clouds. These simulations were included to serve as reference for the simulations with dust lifting. Fig. 2(A-D) contains the simulation results from the explosion scenarios summarized in Fig. 1(A-D). The most significant deviation between simulations and experiments are the significantly higher flame speeds in some of the experiments, compared to the simulations. However, the simulations in Fig 2(i-ii) illustrate how sensitive the results are with respect to the reactivity of the coal dust. The results are also sensitive to the way the ignition process is modelled. Nevertheless, most of the simulations follow the overall trend from the experiments reasonably well.

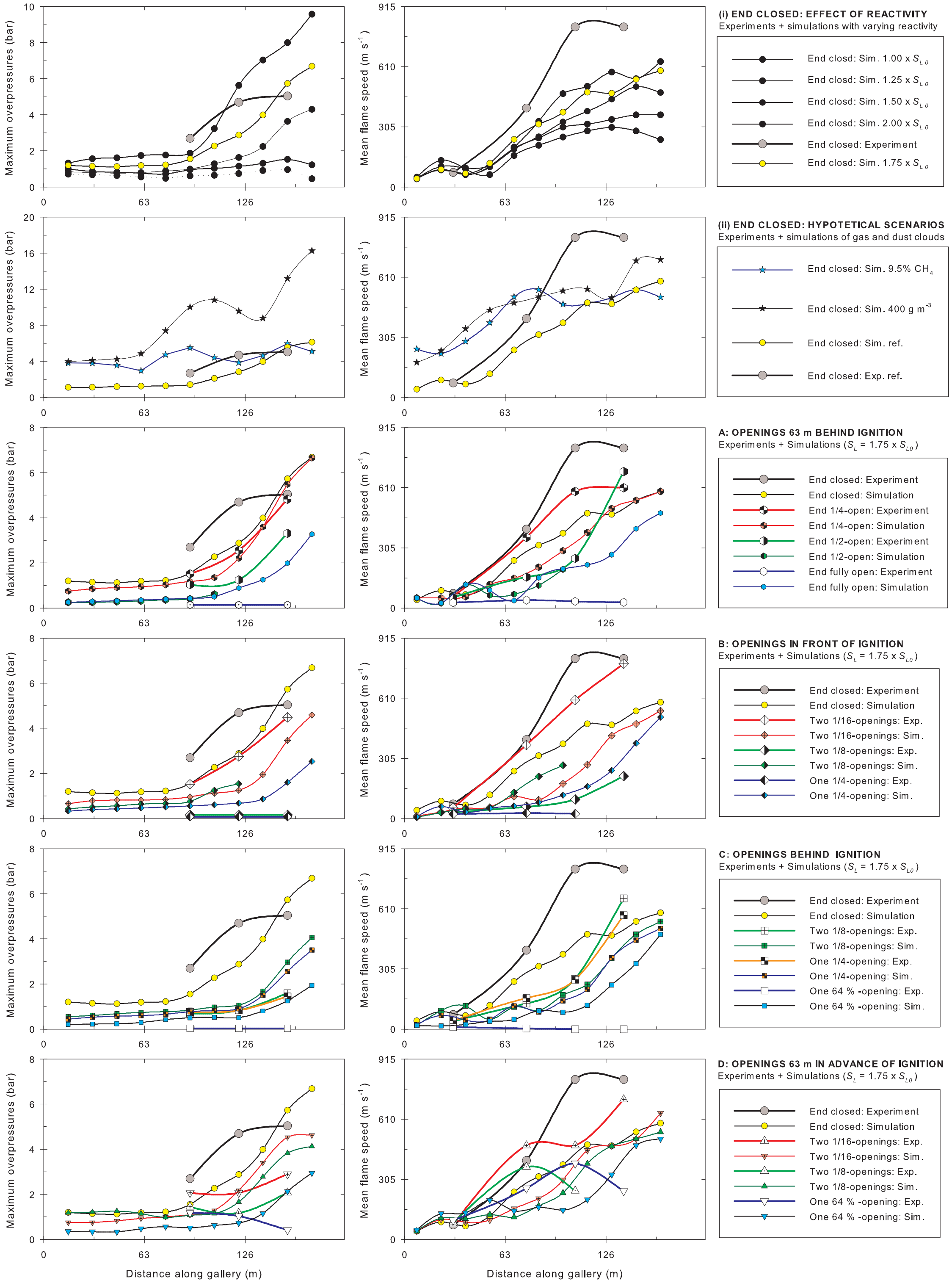


Fig. *2 Maximum overpressures and mean flame speeds from both experiments and simulations.*

5 Conclusions

Dust and gas explosions represent a significant hazard, both in underground coal mines and in the process industries. In the future, consequence assessments based on computational fluid dynamics may provide reliable predictions of the potential consequences of such events. However, efficient use of CFD requires sufficiently accurate models for turbulent particle-laden flow, heterogeneous combustion, and other relevant processes such as dust lifting. Studies of large-scale dust explosion experiments are essential elements in the validation of a CFD-code like DESC. However, it is not straightforward to reproduce conditions from early experimental investigations on dust explosions, and there are often significant uncertainties associated with reported measurements of pressures development and flame arrival times. The results obtained in the present work nevertheless suggest that the use of CFD, together with empirical correlations for phenomena such as turbulent flame propagation and dust lifting, may become a valuable tool for this type of risk assessments in the future.

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