



Explosibility boundaries for fly ash/pulverized fuel mixtures

A.G. Dastidar, P.R. Amyotte*

Department of Chemical Engineering, Dalhousie University, P.O. Box 1000, Halifax, NS, Canada B3J 2X4

Received 5 July 2001; received in revised form 27 November 2001; accepted 27 November 2001

Abstract

Incomplete combustion and subsequent fuel contamination of a waste stream can pose a serious explosion hazard. An example of this type of incident is the contamination of fly ash with unburned pulverized coal. The coal, if present in sufficient quantities in the mixture, can act as a fuel source for a potential explosion.

Experiments were conducted in a 20 l Siwek explosibility test chamber to determine the minimum fuel contamination of fly ash required to form an explosible mixture. A sample of fly ash from Ontario Power Generation (OPG) (Ont., Canada) was artificially contaminated with Pittsburgh pulverized coal dust (the surrogate used to represent unburned fuel dust). Additionally, the influence of fly ash particle size on the amount of fuel contaminant required to form an explosible mixture was examined. Fine and coarse size fractions of fly ash were obtained by screening the original sample of OPG fly ash.

The results show that at least 21% Pittsburgh pulverized coal (or 10% volatile matter) was required to form an explosible mixture of the original fly ash sample and coal dust. The results also illustrate that fly ash particle size is important when examining the explosibility of the mixture. The fine size fraction of fly ash required a minimum of 25% coal dust (12% volatile matter) in the mixture for explosibility, whereas the coarse fly ash required only 10% coal dust (7% volatile matter). Thus, the larger the particle size of the inert fly ash component in the mixture, the greater the hazard. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Dust explosions; Fly ash

1. Introduction

On the morning of 29 December 1999, an explosion occurred at the Sheldon Station fly ash silo of the Nebraska Public Power District (NPPD) killing two employees and injuring

* Corresponding author. Tel.: +1-902-494-3976; fax: +1-902-420-7639.
E-mail address: paul.amyotte@dal.ca (P.R. Amyotte).

another. The subsequent accident investigation conducted by the company revealed that the ash contained a high concentration of carbon [1]. A possible source of this carbon was from partially combusted pulverized coal that was entrained in the fly ash stream and transported to the fly ash silo [2].

It is often the assumption when dealing with combustion of carbon based fuels that the reaction has gone to completion, and that all the fuel is consumed. The presence of partially combusted fuel, however, poses a serious explosion hazard [3]. The risk of an accident occurring can thus be underestimated, where the risk of an explosion is a function of the likelihood of the accident occurring and the subsequent severity of the explosion if it were to occur. In the case of a possible fly ash explosion, both likelihood and severity are assumed to be negligible. This may cause a false sense of security, and adequate safety precautions may not be implemented. If uncombusted fuel contamination is present with the fly ash, then both the likelihood and severity of an explosion increase significantly. Proper safety precautions need to be implemented in the storage, transport and handling of the fly ash. The question remains as to how much fuel contamination needs to be present to create an explosion hazard.

Additionally, reduction or elimination of incomplete combustion serves to reduce the economic cost of the power generation process. Not only will it reduce the risk of an explosion hazard, and possible ensuing costs, it will help minimize the quantity of raw material (coal) required for the process.

For a dust explosion to occur, five conditions must be met. These five conditions are often referred to as the explosion pentagon and consist of a fuel source, an oxidant, an ignition source, dispersion of the dust into a cloud, and some form of confinement of the dust cloud. The explosion pentagon can be applied to the explosion at the Sheldon Station fly ash silo. The fuel was possibly an unburned coal dust component mixed in the fly ash. The oxidant was the oxygen in the air and the ignition source is unknown. It may have been self heating of the coal dust in the fly ash mixture, a hot surface, electrostatic discharge from flowing dust, or an open spark. The confinement occurred due to the silo structure itself and the dispersion was caused during transfer of the fly ash from the silo to a disposal truck. All these factors contributed to the explosion.

There are two mechanisms for dust cloud combustion: heterogeneous and homogeneous combustion. Both are based on the physical state of the fuel and oxidant at the moment of combustion. In the heterogeneous combustion mechanism, the gaseous oxidant reacts with the solid fuel at the particle surface. In the homogeneous combustion mechanism the ignition source drives off volatile material from the solid fuel particle. This gaseous volatile material then mixes with the available gaseous oxidant and undergoes homogeneous combustion. The explosion propagates through the unburned mixture by volatilizing the fuel particles using heat liberated from the combustion process.

It has been proposed that coal dust explosions primarily occur by a homogeneous combustion mechanism [4]. This implies that the volatile component of coal is the primary fuel source for the explosion and that the fixed carbon, ash, and moisture do not take part in the combustion process. Instead, these components act as a heat sink which inhibits combustion.

The implication of this mechanism is that as the volatile component of the coal dust decreases, the explosion hazard is also reduced. This is the physical principle behind the use of limestone dust in coal mines to mitigate explosion hazards. The limestone, in conjunction

with the moisture, ash and fixed carbon component of the coal dust, abstract heat from the combustion of the volatile matter, thereby preventing flame propagation. In effect, the addition of the limestone decreases the volatile concentration in the coal dust/rock dust mixture.

Fly ash explosibility can be modeled in a similar fashion. In this case it is the higher ash content that is effectively diluting the volatile matter. To determine the minimum fuel contamination required to create an explosible fly ash mixture experimentally, the volatile component of the fly ash must be increased. This can be achieved by adding pulverized coal dust to the fly ash as a surrogate for the unburned fuel contaminant, thereby increasing the volatile material in the mixture.

Previous work by the current authors and other researchers [5–8] has shown that the particle size of the inert matter used to prevent coal dust explosions has a significant influence on the amount of inertant required. As the inert particle diameter becomes smaller, less inert material is required to prevent an explosion. The relative particle size of inert fly ash can therefore be expected to have an influence on the amount of fuel contaminant required to yield an explosible mixture. Accordingly, the objectives of this work were to determine the minimum amount of fuel contaminant (in the form of coal dust) required to create an explosible mixture with fly ash, and to investigate the influence of fly ash particle size on the amount of fuel contaminant required to create an explosible mixture.

2. Experimental

Previous experiments from our research group have been focused on the inerting of fuel dust explosions with an inert solid inhibitor [5,6,9–11]. In these cases, a variable quantity of inert material (i.e. dolomite, limestone, sodium bicarbonate or monoammonium phosphate) was added to a given quantity of fuel dust (i.e. coal, cornstarch, aluminium, polyethylene or anthraquinone). Fig. 1 from Dastidar [5] depicts this type of experiment.

As the quantity of dolomite was increased for a fixed concentration of coal dust (500 g/m^3), the result was a decrease of the system pressure from 780 to 100 kPa. With this methodology, the quantity of inert matter required to prevent an explosion of a given concentration of fuel dust can be determined. The concentration of inert matter at which the resulting system pressure crosses the 200 kPa explosion criterion marks the quantity of inert material required to prevent an explosion (i.e. the inerting level). The system pressures depicted in Fig. 1 (and subsequent figures in this paper) are absolute pressures. The criterion that is generally used for dust cloud explosibility is that of a net 1 bar explosion overpressure above the initial test chamber pressure (i.e. accounting for the increase in system pressure produced by the ignition source) [12]. For the purposes of this paper the results have been converted to absolute system pressures in SI units. Therefore, the 1 bar (gauge) explosion criterion becomes a 200 kPa system pressure explosion criterion.

In the current work, our objective was to determine the explosibility of an inert dust when a fuel dust contaminant is present. This warrants an approach to the experimental procedure different from that described above. In this case a variable quantity of fuel contaminant, coal dust, is to be added to a fixed quantity of inert material, fly ash. The concentration of fuel contaminant required to produce a system pressure greater than 200 kPa represents the quantity of combustible material required to create an explosible mixture.

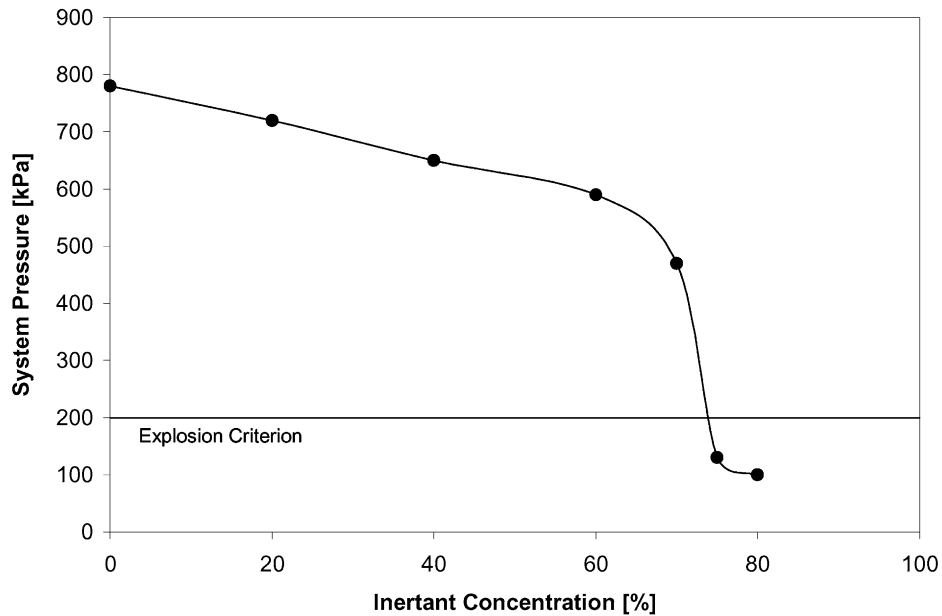


Fig. 1. Effect of rock dust (dolomite) concentration on system pressure of 500 g/m^3 mine-size coal dust in a 20 l Siwek chamber using a 5 kJ ignition source [5].

A sample of conditioned coal fly ash was obtained from Ontario Power Generation (OPG) (Ont., Canada). This sample was tested as received. The coal dust used to simulate fuel contamination of the fly ash was Pittsburgh pulverized coal dust (high volatile bituminous), which was obtained from the Pittsburgh Research Laboratory of the National Institute for Occupational Safety and Health (NIOSH PRL) and was tested as received. This is the same material used by the NIOSH PRL for their full-scale and laboratory-scale experiments of coal dust explosibility.

To compare the influence of fly ash particle size on the amount of coal dust required to form a combustible mixture, a portion of the original fly ash sample was sieved through 200 mesh and 400 mesh screens to produce two additional size fractions (coarse and fine). The coarse size fraction was comprised of material that did not pass through the 200 mesh screen (i.e. $>75 \mu\text{m}$), and the fine fraction was derived from material which passed through the 400 mesh screen (i.e. $<37 \mu\text{m}$). Particle size measurements of the dust samples were made by an independent laboratory using a Malvern Instruments 2600 Series analyzer based on the principle of laser diffraction (with the exception of the size distribution of the coarse fly ash fraction, which was determined by sieve analysis). The results of the particle size analyses are given in Table 1, in which the arithmetic volume or mass mean diameter, D_w , is also shown.

Proximate analyses (moisture, ash, volatile matter and fixed carbon contents) of the fly ash and coal dust samples are given in Table 2. To assist in the analysis of the explosibility data, the carbon content of the fly ash and coal dust samples can also be found in Table 2. To

Table 1
Particle size analyses of fly ash and coal dust samples

Dust	<500 μm (wt.%)	<125 μm (wt.%)	<75 μm (wt.%)	<45 μm (wt.%)	<20 μm (wt.%)	D_w (μm)
OPG fly ash	100	96	82	68	45	39
OPG fine fly ash	100	100	100	98	79	14
OPG coarse fly ash	96	72	14	–	–	106
Pittsburgh pulverized coal	100	93	69	42	14	60

Table 2
Proximate analyses of fly ash and coal dust samples

	OPG fly ash	OPG fine fly ash	OPG coarse fly ash	Pittsburgh pulverized coal
Moisture (wt.%)	0.2	0.2	0.3	2.0
Ash (wt.%)	89.8	95.5	75.1	6.0
Volatile matter (wt.%)	3.5	3.9	3.0	36.0
Fixed carbon (wt.%)	6.6	0.3	21.5	56.0
Total carbon (wt.%)	8.5	3.4	25.5	77.7

prevent loss of volatiles and surface oxidation, the coal dust was kept in air-tight containers over the testing period.

The explosibility experiments were performed in a 20 l Siwek chamber [13] manufactured by Kühner AG of Switzerland. A schematic diagram of the chamber and auxiliary equipment is shown in Fig. 2. The spherical test chamber has a volume of 20 l and is made of stainless steel with a maximum allowable working pressure of 2000 kPa. The vessel is surrounded by a water jacket which is used to control the initial temperature of the test chamber. The top

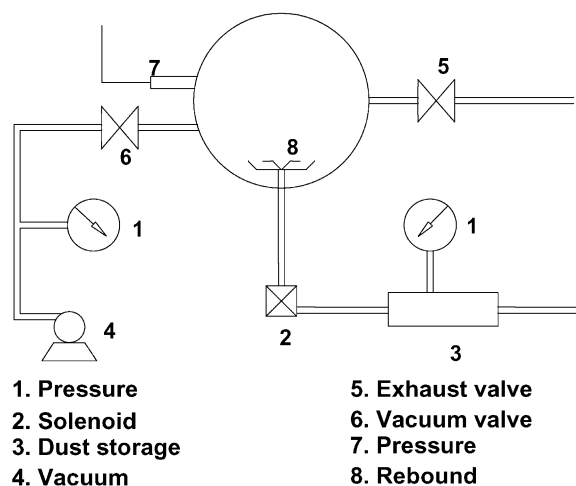


Fig. 2. Schematic diagram of the 20 l Siwek chamber.

access cover is fitted with ignition leads to which are connected Sobbe chemical ignitors. These pyrotechnic ignitors are composed of 40 mass% zirconium, 30% barium nitrate and 30% barium peroxide; they provide a reliable, multiple-point ignition source. An ignitor with a stored energy of 5 kJ has 1.2 g of this mixture, and the energy is released in about 10 ms.

A 5 kJ ignitor was used as the ignition source in the current experiments. Previous work on inerting coal dust explosions with rock dust has shown that a 5 kJ ignition source produces inerting levels in the 20 l test volume that are comparable to mine-scale inerting levels [5,7]. A stronger ignition strength of 10 kJ may lead to a phenomenon known as overdriving (burning of the dust cloud within the ignition volume with no real propagation beyond this region). When this occurs, the resulting pressure rise from the burning of the dust cloud can exceed the explosion criterion of 200 kPa, which may lead one to inaccurately conclude that a dust mixture is explosible. However, a weaker ignition strength may not be sufficient to ignite the fly ash/coal dust mixture [14].

The desired amounts of fly ash and coal dust for a given experiment were premixed and placed in the dust storage chamber (volume of 0.6 l). The ignitor was attached to the ignition leads and the test chamber was sealed and partially evacuated to 40 kPa. The computer control program was then initiated and the dust storage chamber pressurized to 2100 kPa with extra dry compressed air. The computer then opened the solenoid valve between the dust storage chamber and the test chamber, dispersing the air and dust mixture into the test chamber through a Kühner rebound nozzle and raising the chamber pressure from 40 to 100 kPa.

The computer then energized the ignition source after a time delay of 60 ms. The computer recorded the pressure–time history of the explosion using two piezoelectric transducers installed flush with the interior of the chamber. The pressure–time trace provides the maximum overpressure (P_{ex}), the maximum overpressure due to the explosion of the dust mixture (P_m) using a correction algorithm to compensate for the pressure increase from the ignitor itself, and the maximum rate of pressure rise ($(dP/dt)_m$) for a given test.

As previously mentioned, the criterion used for an explosion was a system pressure of 200 kPa. Repeat testing was performed, when warranted, for experiments with the lowest fuel contaminant concentration that did not produce an explosion for a given fly ash concentration. The effect of the fuel contaminant was then determined for each fly ash concentration by measuring the explosion parameters as coal dust was added to the mixture. Experiments were conducted on pure fly ash at various concentrations to determine its explosibility without any fuel contamination. The experimental test matrix is given in Table 3.

Table 3
Experimental test matrix

Fly ash type	Fly ash concentration (g/m ³)	Coal dust type
OPG fly ash	250, 500, 750, 1000, 1250, 1500, 1750, 2000	None
	250, 500, 750, 1000, 1250, 1500, 1750, 2000	Pittsburgh pulverized coal dust
OPG fine fly ash	750, 1000, 1250	Pittsburgh pulverized coal dust
OPG coarse fly ash	750, 1000, 1250	Pittsburgh pulverized coal dust

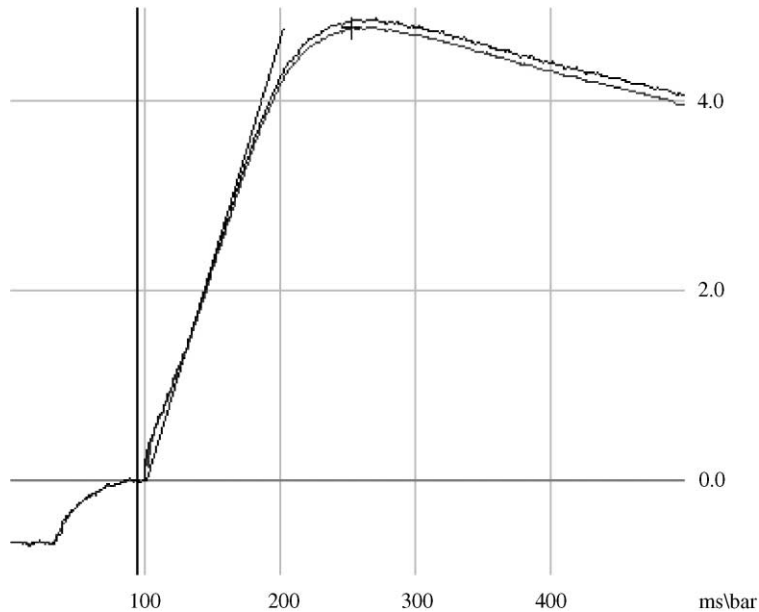


Fig. 3. Pressure–time trace for the combustion of 500 g/m^3 OPG fly ash with 30% Pittsburgh pulverized coal dust contamination. (Axes are horizontal: time in ms, and vertical pressure in bar (gauge)).

3. Results and discussion

Fig. 3 shows an example of a pressure–time trace. In this particular experiment, 500 g/m^3 of OPG fly ash was contaminated with 214 g/m^3 of Pittsburgh pulverized coal dust so that the composition of coal dust was 30% of the total mixture. After the initial pressure rise due to the dispersion of the dust into the explosion chamber, the pressure rise due to the explosion can be observed. The maximum explosion pressure of 4.8 bar (g) (580 kPa) can be observed at 250 ms. In subsequent tests the concentration of the coal dust was decreased to determine the least amount of fuel required to produce an explosion (i.e. reduce the peak explosion pressure to 200 kPa, absolute).

Fig. 4 is a plot of this procedure. The concentration of the fly ash used here was again 500 g/m^3 ; however, the amount of coal dust added as a contaminant was reduced from 30 to 25% and then to 20%. It is apparent from Fig. 4 that decreasing the Pittsburgh pulverized coal concentration to 25% of the mixture results in a system pressure that is just slightly lower than the 200 kPa explosion criterion. A subsequent reduction to 20% coal dust contamination produces a system pressure that is well below the explosion criterion. The explosion pressure for the pure fly ash (also given in Fig. 4) was not above ambient pressure (i.e. the system pressure remained near 100 kPa). The minimum amount of coal dust required to produce an explosible mixture containing 500 g/m^3 of fly ash is therefore 25%.

The shape of the explosibility graph in Fig. 4 is different than that of the inerting graph in Fig. 1. Fig. 4, however, does resemble the shape of a minimum explosible concentration

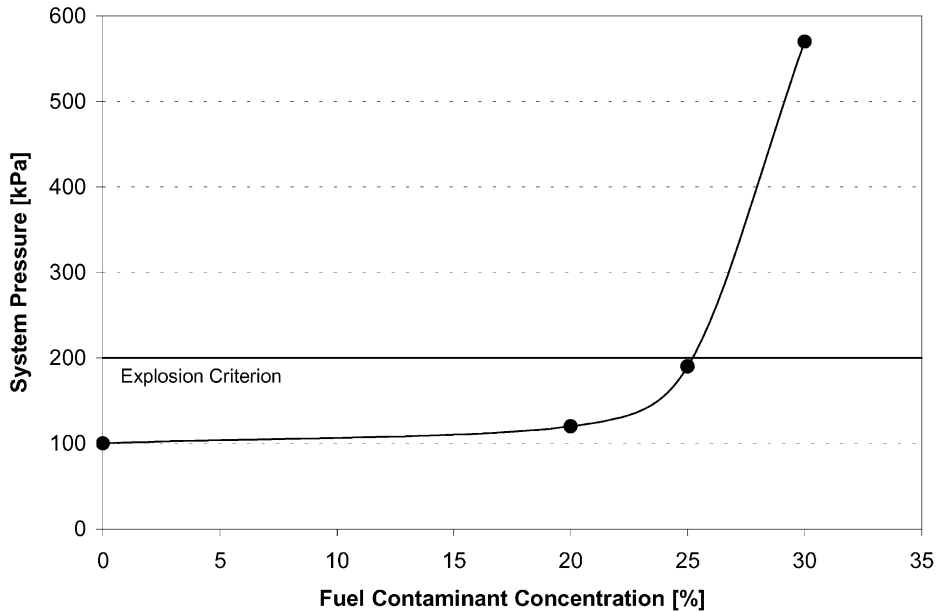


Fig. 4. Effect of fuel contaminant concentration on the system pressure of 500 g/m^3 OPG fly ash in a 201 Siwek chamber using a 5 kJ ignition source.

curve [14,15]. This stands to reason since by decreasing the volatile content in the mixture, a lower flammable limit is achieved.

It would not be prudent to use only one fly ash concentration as a basis for making risk reduction decisions concerning fuel-contaminated fly ash explosibility. The series of experiments depicted in Fig. 4 was therefore repeated for additional fly ash concentrations. Fig. 5 shows the explosion pressure obtained as a function of fly ash concentration for various levels of fuel contamination. It can be seen that the sample of pure fly ash obtained from Ontario Power Generation is not explosible. It can, however, become explosible as coal dust (fuel contamination) is added. Low and high concentrations of fly ash require the greatest amount of coal dust to become explosible, while the intermediate concentrations of fly ash ($750\text{--}1500 \text{ g/m}^3$) require the least amount of coal dust to become explosible.

This observation can be better depicted if the interpolated explosibility coal dust concentrations are plotted against fly ash concentration as shown in Fig. 6. These coal dust concentrations are interpolated between the “go” and “no go” fuel percentages shown in Fig. 5. Here it can be clearly seen that lower fly ash concentrations require greater amounts of coal dust to create an explosible mixture. This is due to the fact that the coal dust concentrations in the mixture are below the minimum explosible concentration of the coal itself (50 g/m^3 in the 201 Siwek chamber [15]). The fly ash/coal dust mixture became explosible when the coal dust concentration in the mixture exceeded 100 g/m^3 .

The coal dust concentrations required to form a combustible mixture are lowest (21%) for fly ash concentrations between 750 and 1750 g/m^3 . In this range the coal dust is present

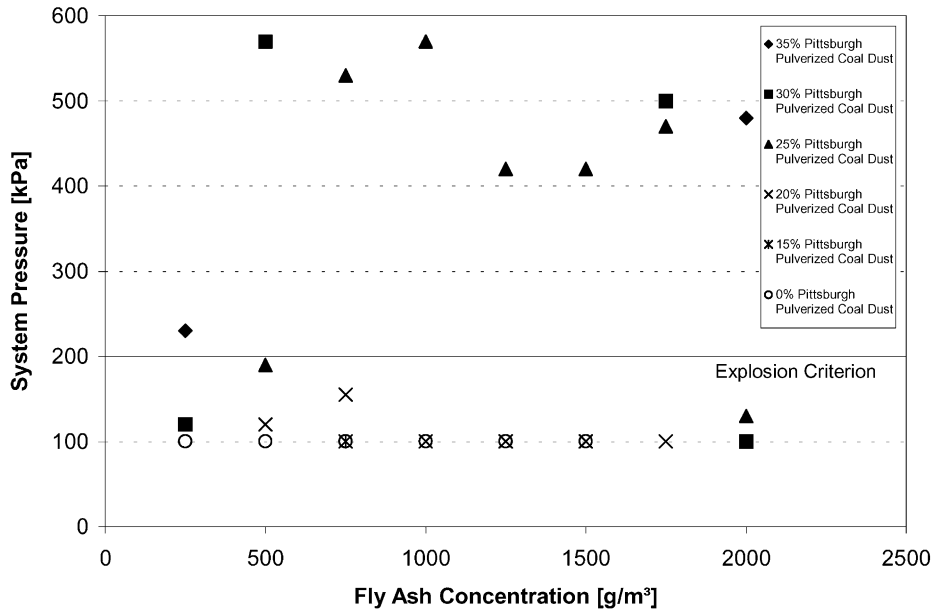


Fig. 5. Effect of fuel contaminant concentration on the system pressure over a broad concentration range of OPG fly ash.

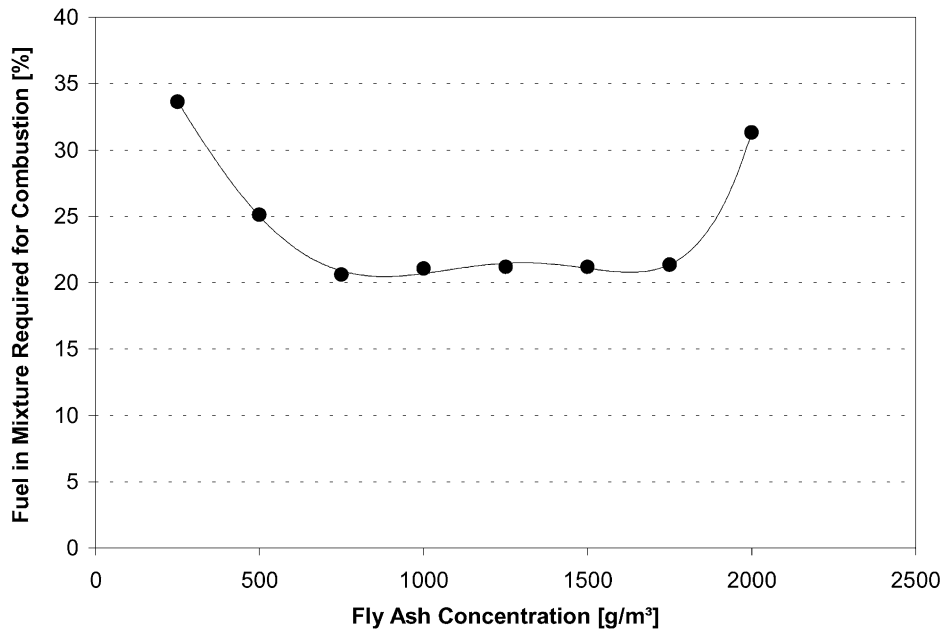


Fig. 6. Percent fuel contaminant required to create an explosible fly ash mixture.

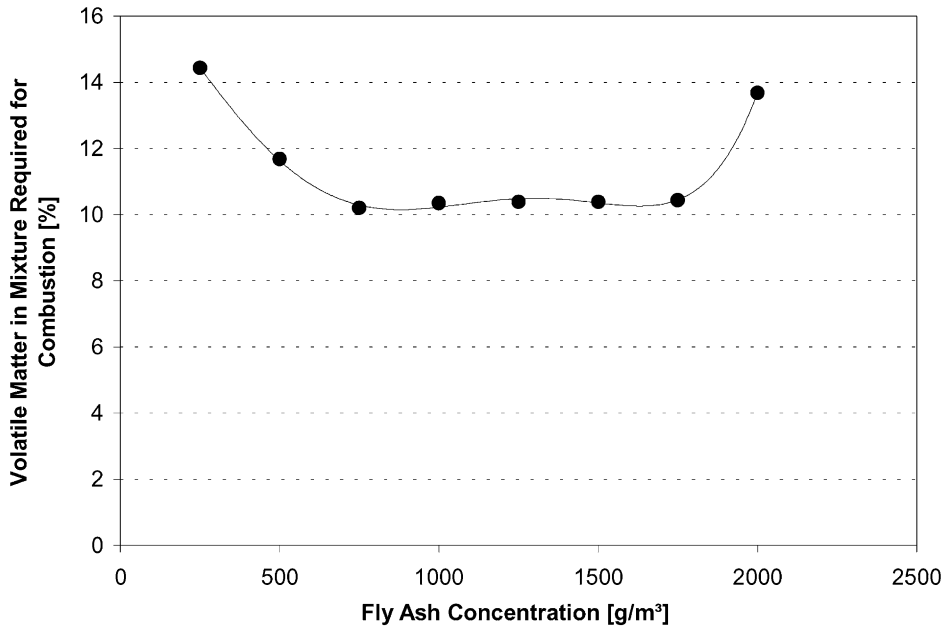


Fig. 7. Percent volatile matter required to create an explosible fly ash mixture.

in the mixture in concentrations ranging from 195 to 475 g/m³. From previous work [5–7], it is known that this range represents the maximum hazard posed by Pittsburgh pulverized coal dust. The explosibility curve for pure Pittsburgh pulverized coal dust is very broad reaching its maximum value near 400 g/m³ [5]. Therefore, a small amount of coal dust is required to produce an explosion. At higher fly ash concentrations (greater than 2000 g/m³), more coal dust is needed to produce an explosion. This is due to the inerting ability of the large amount of fly ash.

Since coal dust undergoes homogeneous combustion, the volatile content in the mixture is of obvious significance. Fig. 7 gives a plot of the volatile matter in the mixture (from both coal dust and fly ash) required to produce a combustible mixture, as a function of fly ash concentration. From Fig. 7 the least amount of volatile material required to create a combustible mixture is 10% of the mixture (between concentrations of 750 and 1750 g/m³ of fly ash). The value of 10% is significant. Previous work by other researchers has shown that 90% inert material is required to prevent combustion of carbonaceous fuels [7,16]. This implies that quantities of volatile material greater than 10% will result in an explosion. This agrees with the findings in the current work. As seen in Fig. 7, however, the value of 10% volatile matter is concentration dependent.

Often in industry the proximate analysis of fly ash is not taken and thus the volatile concentration cannot be determined. In many cases, however, efforts are made to determine the carbon content of the fly ash. This practice is inadequate when determining the explosibility hazard of fly ash. The total carbon content in the fly ash is comprised of both the

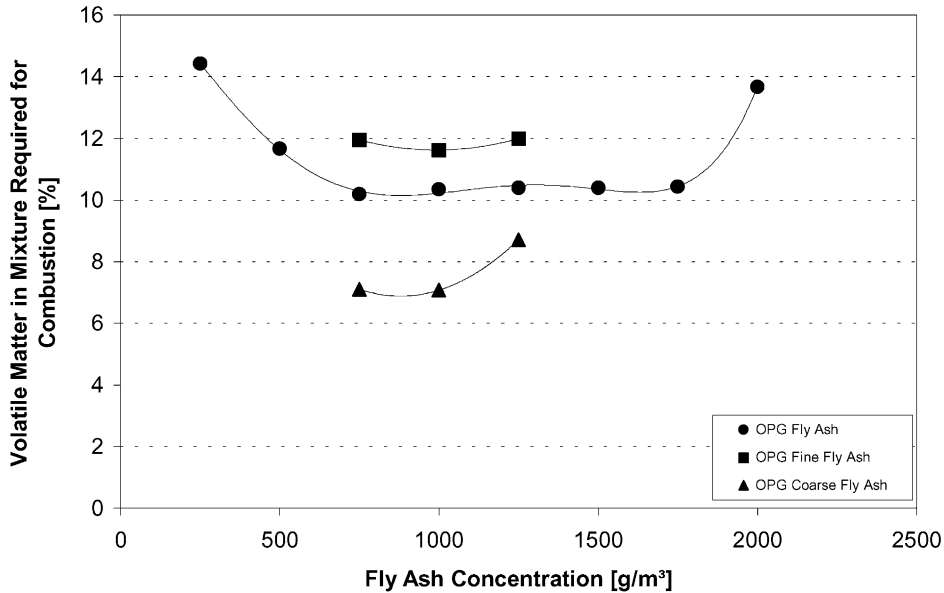


Fig. 8. Influence of particle size on the percent volatile matter required to create an explosible fly ash mixture.

fixed carbon material and hydrocarbons present in the volatile material. However, it is only the volatile material that can participate in explosive dust combustion. There is insufficient time during the rapid combustion process for the fixed carbon material to participate [4]. This implies that fly ash material with a high carbon concentration may be inherently safe (not explosible) if the concentration of volatile material is below 10%. However, if most of the carbon present is in the form of volatile matter, then fly ash with low carbon levels is an explosion hazard. Thus, carbon content alone is not a good indicator of fly ash explosibility and it would be prudent to perform a proximate analysis of the fly ash material.

Fig. 8 shows the influence of fly ash particle size on the amount of fuel contaminant required to create an explosible mixture. As in the case of limestone inerting of coal dust explosions, the finer the particle size of the inert material (limestone or fly ash), the more effective it is in preventing an explosion. With limestone inerting of coal dust explosions, less limestone is required. In the case of fly ash explosibility, more coal dust is required to form a combustible mixture.

Fig. 8 shows that the similarity also holds true for coarse particle size inertants. Greater quantities of coarse limestone are required to prevent a coal dust explosion; lower amounts of coal dust are required to create an explosible mixture with coarse fly ash. Therefore, if one were developing standards for permissible levels of fuel contamination in fly ash, the particle size of the fly ash should also be addressed. Large size fly ash could have lower permissible limits. As shown in Fig. 8, the fine fly ash required about 12% volatile matter for explosibility (corresponding to 25% coal dust), whereas the coarse fly ash required only 7% volatile matter for explosibility (corresponding to 10% coal dust).

4. Conclusion

Results of the experiments conducted in the current work show that fuel contamination of fly ash is a definite hazard. For the particle sizes tested, the minimum amount of fuel contamination to create a combustible mixture was 10% volatile material (representing a coal dust concentration of 21%).

Particle size of the fly ash has an influence on these minimum explosibility levels. Finer particle size fly ash requires more fuel contaminant to create an explosible mixture, thereby potentially decreasing the hazard. Larger particle size fly ash requires less fuel contaminant to form an explosible mixture, thereby increasing the hazard.

Acknowledgements

The authors wish to gratefully acknowledge the Natural Sciences and Engineering Research Council of Canada for financial assistance, and Ontario Power Generation for provision of fly ash samples.

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