HYBRID FLAMMABLE DUST-GAS CLOUD IGNITION USING A MODIFIED STANDARD MINIMUM IGNITION ENERGY DEVICE

A Thesis

by

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ABSTRACT

Hybrid dust-gas explosion is a persistent problem in process industries because of its ease of ignition as well as serious consequences. Ease of ignition is quantified by minimum ignition energy (MIE), which is associated with the probability of ignition for a hybrid mixture. This study aims at improving the MIE measurement of hybrid dust-gas system using a modified Kühner MIKE3 MIE apparatus with an add-on purge device in order to purge the Hartmann tube with the gas mixture before the dust dispersion. It allows the gas composition in the Hartmann tube to be the same as that of the gas used for dispersing the dust.

In this study, a typical hybrid system of Pittsburgh Pulverized Coal (PPC)-methane-air, was utilized to accomplish the tests, where two sizes of PPC with equivalent polydispersity was applied. Methane was pre-blended with ultra-high purity (UHP) air (21% oxygen and 79% nitrogen) at 1 vol %, 2 vol %, and 3 vol %. MIE testing was conducted for the following two cases: case (a) and case (b). Case (a) followed the ASTM E2019-03 standard procedure, while case (b) applied the pre-ignition Hartmann tube purge with 1 vol %, 2 vol %, and 3 vol % methane prior to dust dispersion and ignition. The testing was also divided into two sections: Section 1 including case (a1) and (b1) used the original dried PPC, while section 2 including case (a2) and (b2) used the milled PPC.

Comparison of MIE values for both cases in both sections displayed significant differences. The hybrid MIE values obtained in case (b) are overall lower than those in case (a), illustrating that pre-ignition tube purge decreased the hybrid MIE value and gave more conservative MIE results. While smaller size of dust possessed lower hybrid MIE, similar trends in percent of MIE reduction revealed the impact of gas concentration on decrease of hybrid MIE regardless the particle size. Moreover, this study proves that previous hybrid MIE data generated using the ASTM E2019-03 standard procedure and utilizing the Hartmann apparatus and Kühner MIKE3 device yielded non-conservative results and should be validated through further studies by incorporating pre-ignition Hartmann tube purge into the hybrid MIE test procedure.

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Contributors

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Part 2, student/collaborator contributions

All work for the thesis was completed independently by the student.

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

1.1 Background

Dust explosions are a persistent problem in process industries and can result in catastrophic damage to property and loss of lives. While the occurrence of typical fuel combustion requires fuel, oxygen, and heat (ignition source), the occurrence of dust explosion requires two more crucial elements, i.e. dispersion and confinement of dust, which is presented as the "explosion pentagon" (**Fig. 1**).

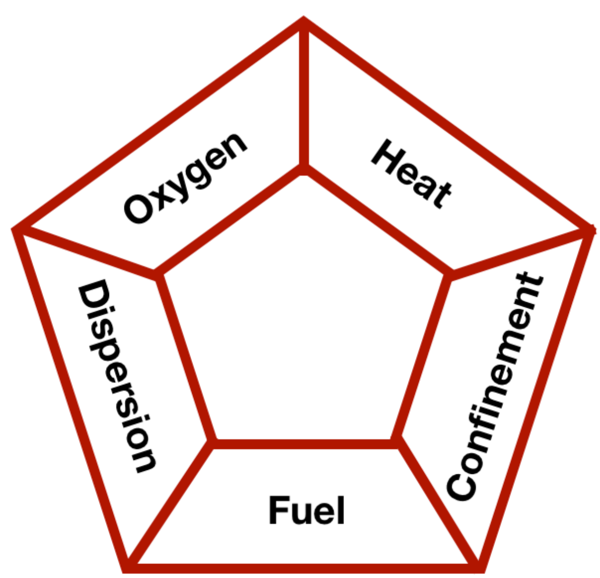


Fig. 1 Explosion Pentagon

Dust explosions have been studied for more than 200 years (Bartknecht, 1989) but studies on hybrid dust-gas explosions, which are generally more hazardous than dust explosions, are not systematic due to limited hybrid explosion incident records and limited capabilities of experimental instruments. The earliest documented hybrid dust-gas explosion study was recorded in 1885, when Engler ignited the mixtures of methane and dusts (soot and charcoal dust), obtaining explosion of these "hybrid mixture" even though neither gas nor dust component was explosible by themselves (Bartknecht, 1989). This study indicated that hybrid mixtures can be flammable even though the dust or gas component alone may not be. This observation has been supported by plenty of studies in the past few years (Addai et al., 2016; Addai et al., 2015a; Denkevits and Hoess, 2015; Sanchirico et al., 2015).

Minimum ignition energy (MIE) of a dust is one of the many characteristic parameters of a dust explosion, including minimum explosion concentration (MEC), maximum pressure - P_{max}, maximum rate of pressure rise, lower flammable limit (LFL), etc. It is associated with the probability and ease of ignition of a dust cloud. For hybrid explosions, the hybrid MIE can be described as the lowest energy required to ignite hybrid dust-gas cloud (Randeberg and Eckhoff, 2007).

1.2 Literature Review

In 1980, Franke studied the MIE for coal dust/methane/air, where preliminary results indicated the decrease in MIE for different types of coal as methane concentration by volume increased (Franke, 1980). The results of hybrid MIE for coal dust/methane/air measured out by Franke possesses an approximately linear relationship between gas concentration and ignition energy.

In 1980, Pellmont conducted MIE testing of various combustible dusts (Dyestuff, Cellulose, polyethylene, and PVC) in the 1-m^3 vessel and observed that the MIE of hybrid mixtures decreases with the increase in propane concentration (Pellmont, 1980). 1-m^3 vessel was estimated as the standard dust explosion apparatus for accurate testing results before the invention of 20-L device. The influence of propane concentration on minimum ignition energy for hybrid mixtures was then replotted by Barknecht in his book (Bartknecht, 1989).

$$HMIE = \exp[\ln D - (C/C_0)\ln(D/G)]\ mJ$$

$$D = MIE\ of\ dust\ alone\ in\ air\ (mJ)$$

$$G = LMIE\ of\ gas\ alone\ in\ air\ (mJ)$$

$$C = gas\ concentration\ in\ hybrid\ mixture\ (\%) < LFL$$

$$C_0 = gas\ concentration\ at\ LMIE\ composition\ (\%)$$

Fig. 2 Hybrid Minimum Ignition Energy Equation Developed by Laurence G. Britton (Britton, 1998)

Based on the results given by Pellmont, Laurence G. Britton (1998) estimated the hybrid minimum ignition energy (HMIE) for dust/gas mixtures by developing an equation relating the HMIE to various dust and gas characteristics (**Fig. 2**). It was claimed that the equation could only apply within the area where gas concentration was lower than its lower flammable limit, while in the meantime no further explanation on the trend of hybrid MIE flowed as the gas concentration exceeded its lower flammable limit. This area was later scientifically defined as the "hybrid explosion area" (Tan and Zhang, 2014). As a result, researchers merely updated hybrid MIE studies in this particular area in future work.

Khalili et al. (2012) tested the MIE for sunflower oilcakes/hexane and starch/hexane using Hartmann apparatus and proposed an equation similar to the equation proposed by Britton (1998). The MIE for hybrid systems based on experiment, Bartknecht's model, and Khalili's model was presented in their study. The equation (**Fig. 3**) was validated to be merely applicable to the two hybrid systems (sunflower oilcakes/hexane and starch/hexane) employed in this study.

$$HMIE = MIE_{gas} + \left(MIE_{dust} - MIE_{gas}\right) \cdot \left(\frac{D^3_{c-hybrid} - D^3_{c-gas}}{D^3_{c-dust} - D^3_{c-gas}}\right)$$

$$D_{c-hybrid} = D_{c-d}.\exp\left[-\frac{C}{C_0}.ln\left(\frac{D_{c-d}}{D_{c-g}}\right)\right]$$

D_c Diameter of the critical ignition kernel (m)

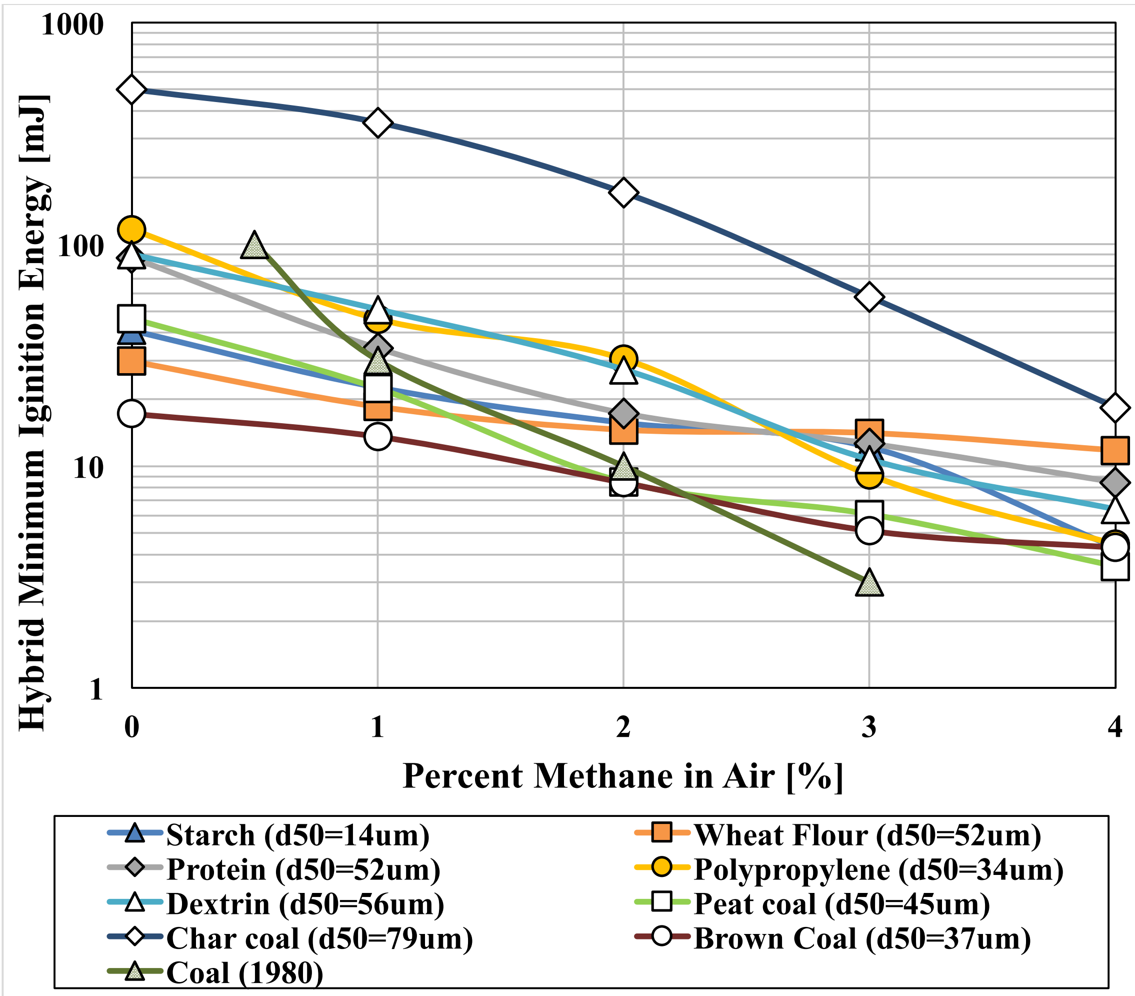
Fig. 3 Developed Equation Proposed by Khalili et al. (Khalili et al., 2011)

Addai et al. (2016) tested the hybrid MIE for various combinations of flammable gases (methane & propane) and combustible dusts (wheat flour, starch, protein, polypropylene, dextrin, peat coal, charcoal, brown coal) in a modified Hartmann apparatus, which generated the lowest ignition energy as 4 mJ. The comparison of both experimental and modeling results indicated that minor quantities of flammable gas significantly affected the hybrid MIE.

Fig.4 (a), (b) and (c) summarize all previous studies on hybrid MIE with different flammable gases (methane, propane, and hexane). It is demonstrated that, regardless the gas component being utilized within the hybrid dust-gas system, the MIE for hybrid dust-gas mixtures decreases as the combustible gas concentration increases.

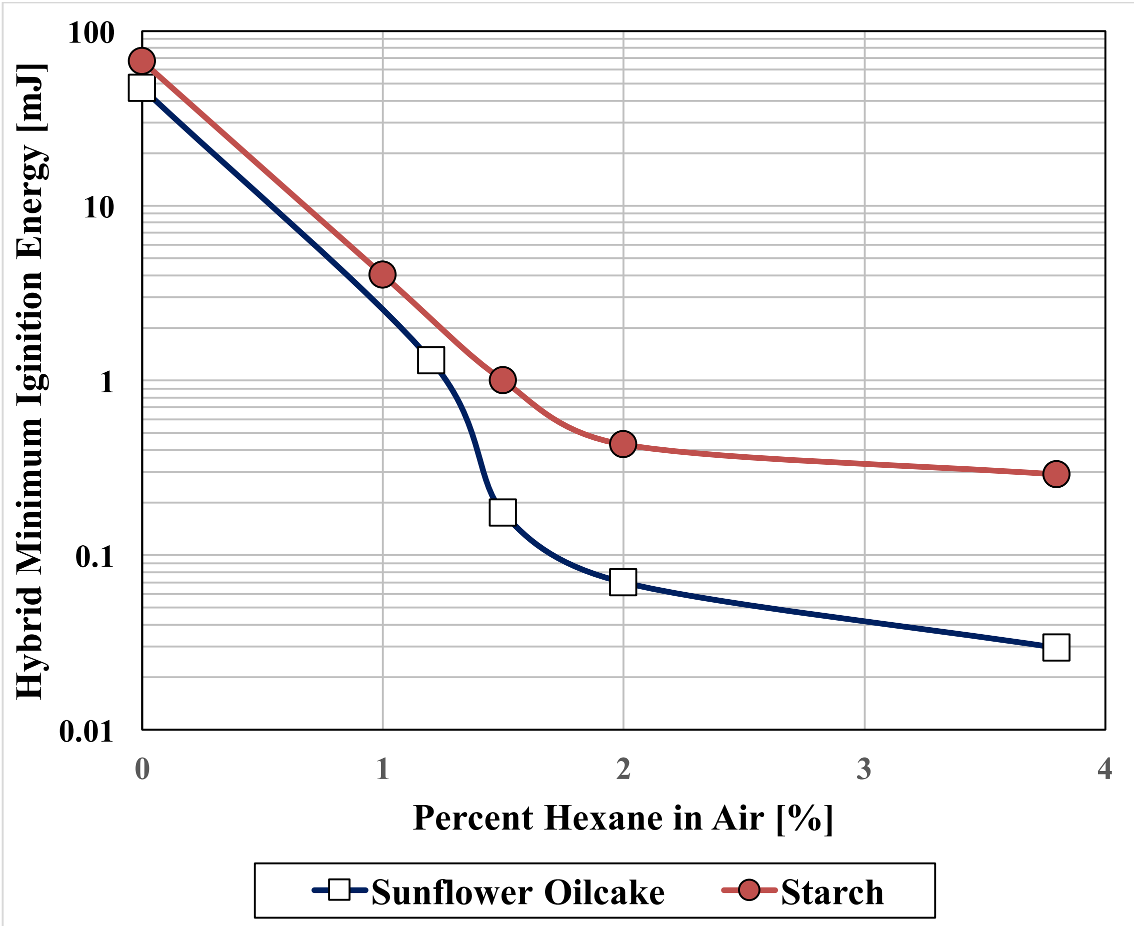
Kühner MIKE3 MIE device is an experimental instrument used worldwide for measuring MIE of combustible dusts and has proven to be accurate in MIE testing as compared to other devices (Janes et al., 2008; Lepik et al., 2015). Standard hybrid MIE testing procedure in the Hartmann apparatus or Kühner MIKE3 device follows the ASTM E2019-03 standard (ASTM E2019-03, 2013).

However, according to recent study on testing the MIE for hybrid systems, standard procedure was questioned to be potentially not conservative. Chaudhari and Mashuga (2017) modified the Kühner MIKE3 device by introducing an add-on purging device and demonstrated the impact of this modification on the MIE values of Niacin dust. Inerting gas was purged into the Hartmann tube prior to ignition. Results show the impact of top purging on MIE for niacin through partial inerting procedure in Chaudhari and Mashuga's research, where the MIE values significantly changed due to top purging the Hartmann tube.



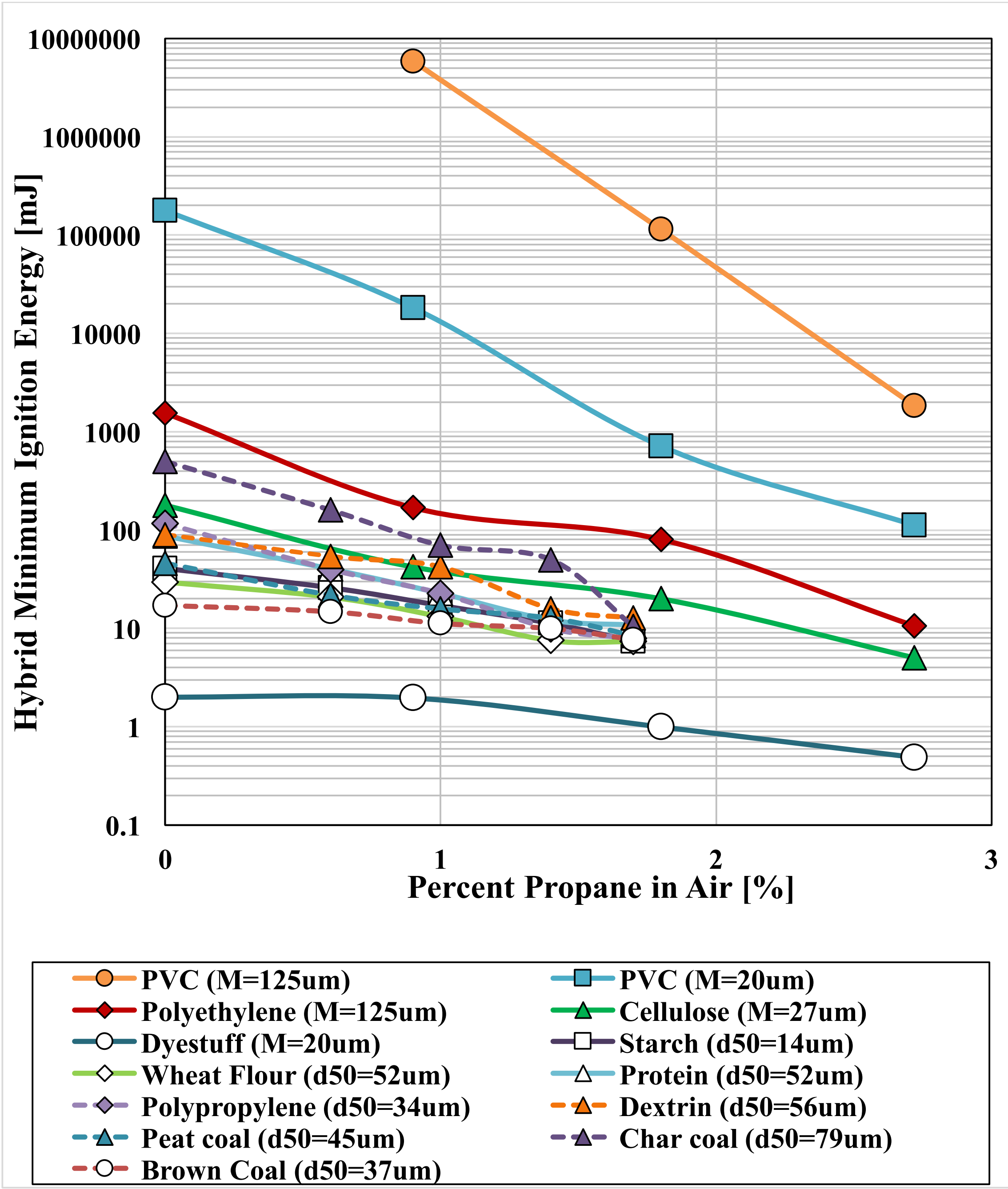
(A)

Fig. 4 Summary of All Previous Studies on Hybrid Minimum Ignition Energy (MIE). (A) Hybrid MIE of Previous Studies with Methane. (B) Hybrid MIE of Previous Studies with Hexane. (C) Continued Hybrid MIE of Previous Studies with Propane (Addai et al., 2016; Bartknecht, 1989; Franke, 1980; Khalili et al., 2011; Pellmont, 1980)



(B)

Fig. 4 Continued.



(C)

Fig. 4 Continued.

Additionally, they also studied the effect of turbulence due to purging the Hartmann tube pre-ignition. In their study, the Hartmann tube was sealed and purge-to-ignition time was lengthened from 1 second to 120 seconds in a new series of tests, in order to eliminate the turbulence left in the tube before ignition. It was concluded that turbulence due to purging the Hartmann tube had a minor influence on MIE value which could be ignored. This approach of testing is scientifically predicted to be extended to hybrid testing which can result in conservative MIE values.

1.3 Research Objectives

This study presents a developed hybrid MIE testing method by purging the Hartmann tube in the modified Kühner MIKE3 MIE device. The Hartmann tube is to be filled with the applied gas component in hybrid dust-gas system prior to dust dispersion and hybrid mixture cloud ignition. This study will be divided into two sections. The first section is to test the MIE for hybrid system following both standard approach and developed method. The MIE value will be compared between two procedures.

In the second section of testing, dust will be milled into smaller size and the hybrid MIE with the same gas component will be tested following the same procedure as in the first section. Comparisons of hybrid MIE obtained from both sections will be employed. It is to be determined that the effect of pre-ignition tube purge on hybrid MIE testing is valid regardless the particle size of the dust.

The objective of this study is to generate accurate data for MIE of dust-gas hybrid mixture using the modified Kühner MIKE3 MIE device and demonstrate the difference between MIE values recorded by pre-purging the tube before dust dispersion and without pre-purging the tube. This study will eventually provide insight into correct way of testing MIE of hybrid mixtures so that the explosion risk of combustible dusts is not underestimated.

CHAPTER II

MATERIALS AND EXPERIMENTAL PROCEDURE

2.1 Materials

This work has utilized Pittsburgh Pulverized Coal (PPC), which is one of the characteristic coals in the U.S (Shaddix and Molina, 2009), as the dust component and methane as the gas component for the hybrid system. Furthermore, despite the high MIE > 1000 mJ of PPC (Norman et al., 2013), which exceeds the energy range (1 mJ to 1000 mJ) generated by Kühner MIKE3 device, PPC was selected considering addition of methane gas would decrease the hybrid MIE making it suitable for testing in the energy range of Kühner MIKE3 device.

Before testing, PPC was dried at 60ºC for 6 hours in a nitrogen pre-purged oven to remove moisture as well as prevent oxidation. The particle size distribution of PPC before and after drying was measured in the Beckman Coulter Particle Size Analyzer LS 13320. **Fig. 5** shows the particle size distribution of PPC before and after drying, which strongly indicates that the distribution of PPC remained constant after drying. **Table 1** presents the difference in particle size distribution before and after the drying process. By comparing the values, minor quantitative difference reveals the consistency of PPC. After drying, the PPC dust was stored in a sealed desiccator to avoid any moisture retention in the dust while testing.

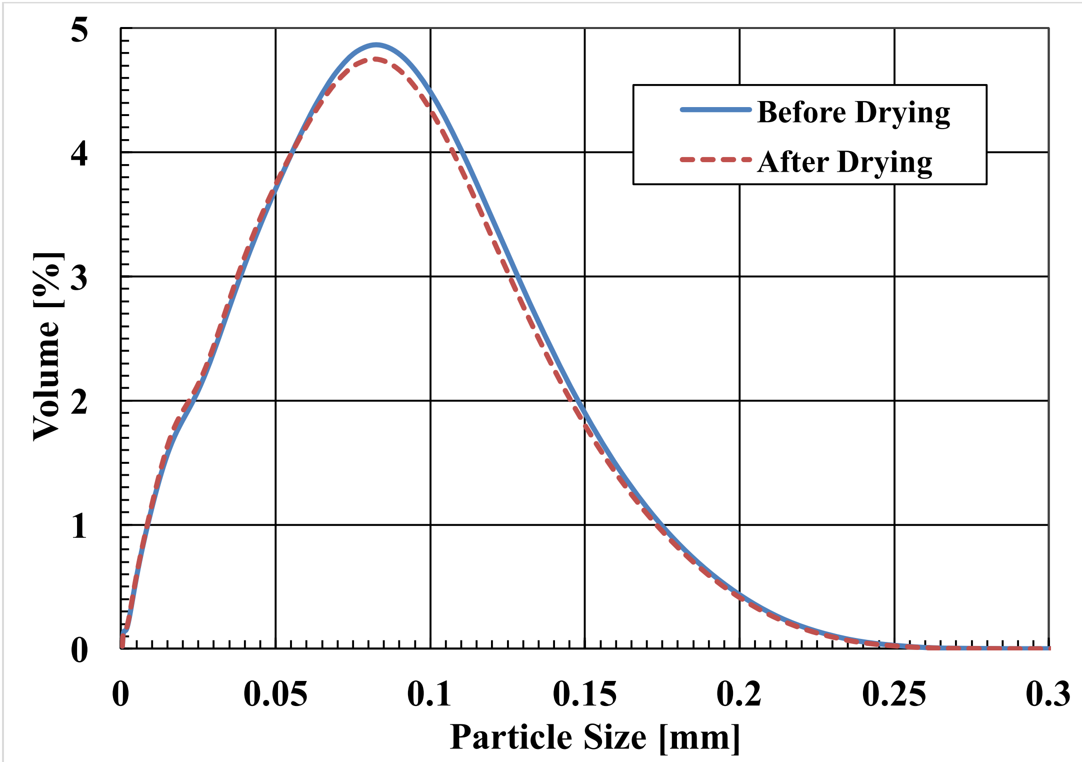


Fig. 5 Particle Size Distribution for Pittsburgh Pulverized Coal (PPC) before & after Drying

Meanwhile, roughly half of the dried PPC was milled using Retsch Ultra Centrifugal Mill Type ZM 200 (**Fig. 6**) with 6-tooth rotor, 10000 rpm rotating speed, and 0.08mm ring sieve. Milled PPC was then collected from the device. Its particle size distribution was measured in the Beckman Coulter Particle Size Analyzer LS 13320. **Fig. 7** shows the particle size distribution of the dried PPC before and after milling, where the polydispersity of both samples remained approximately equivalent. Previous study proved that polydispersity vastly elevated the severity of explosion at a constant d_{50}. As a result, equivalent polydispersity is necessary in this study in order to eliminate the effect on the explosibility of dusts (Castellanos et al., 2014). **Table 2** presents the difference in particle size distribution before and after the milling process.

Table 1. Difference in Particle Size Distribution of PPC before and after Drying Process

Property/ µm	d_{10}	d_{50}	d_{90}	Mean	Mode	D(3,2)
Before Drying	8.95	54.26	126.62	61.97	87.90	16.2336
After Drying	8.68	52.50	124.78	60.65	87.90	15.6869

Fig. 6 Retsch Ultra Centrifugal Mill Type ZM 200

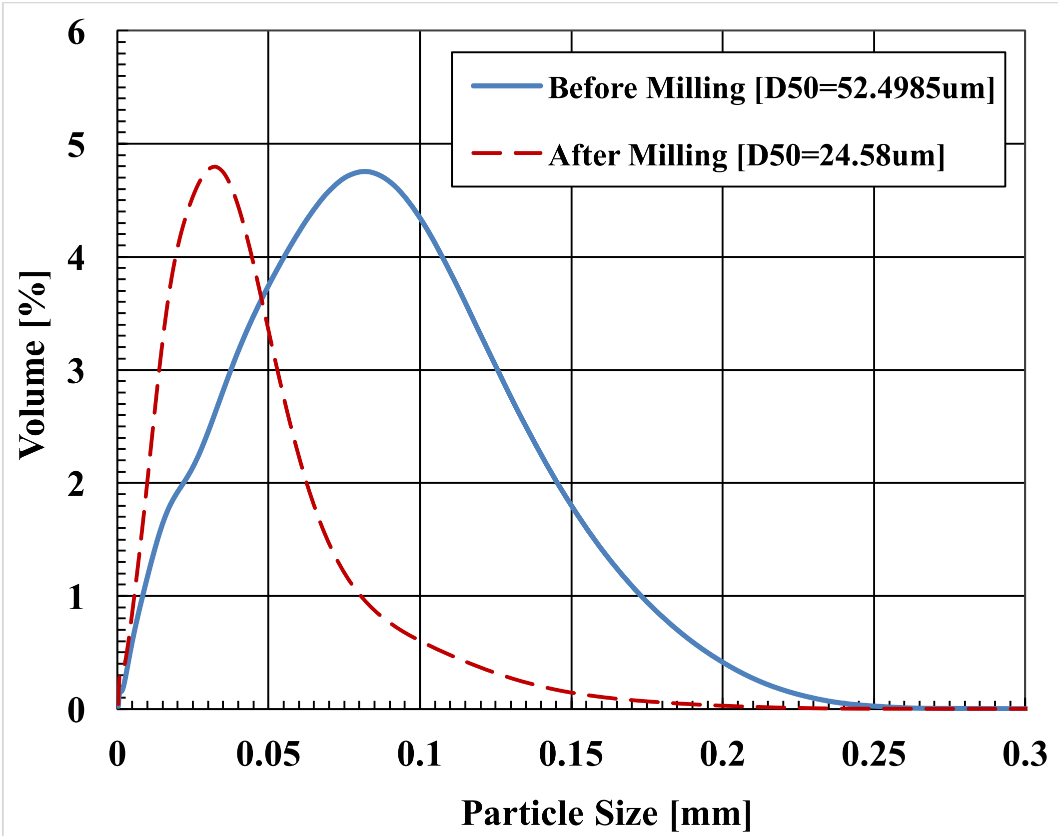


Fig. 7 Particle Size Distribution for Pittsburgh Pulverized Coal (PPC) before & after Milling

Table 2. Difference in Particle Size Distribution of PPC before and after Milling Process

Property/ µm	d_{10}	d_{50}	d_{90}	Mean	Mode	D(3,2)	Polydispersity
Before Milling	8.68	52.50	124.78	60.65	87.90	15.6869	~2.21
After Milling	5.28	24.58	59.25	29.95	34.59	9.2000	~2.20

Methane was used as the flammable gas component in the hybrid MIE test, which is a common material in previous hybrid explosion tests (Addai et al., 2016; Addai et al., 2015b; Franke, 1980; Sanchirico et al., 2015; Zhou et al., 2012) for decades. In this work, three different volume percentages of methane (1 vol %, 2 vol % and 3 vol %) were pre-blended with Ultra High Purity synthesized air (21% oxygen and 79% nitrogen) and stored in cylinders, respectively. Thus, the composition of the pre-blended gas mixtures for testing were (1 vol % methane, 99 vol % UHP air), (2 vol % methane, 98 vol % UHP air) and (3 vol % methane, 97 vol % UHP air). The compositional variation of the gas mixtures was equal to or less than ±1%. It is also important to note that the gas strictly adhered to the standards of < 0.1 ppm carbon dioxide and < 0.36 ppm moisture.

2.2 Experimental Procedure

The hybrid MIE testing was conducted in the Kühner MIKE3 MIE device (**Fig. 8**). The device enables testing at various ignition energies of 1 mJ, 3 mJ, 10 mJ, 30 mJ, 100 mJ, 300 mJ, and 1000 mJ. The dust concentration tested in this device can range from 125 kg/m^3 to 3000 kg/m^3. The ignition delay time (Δtv) can be adjusted at 90, 120, 150, or 180 ms. In this study 120 ms was set up to be the ignition delay time. This device also enables testing with or without inductance (1 mH or 0 mH). Standard hybrid MIE testing procedure using Kühner MIKE3 device is to:

1) set up computer software (MIKE 3.4) and equipment;

2) place combustible dust around the umbrella-shaped nozzle of dust dispersion system;

3) set up the 1.2-L Hartmann tube, electrodes, and the top piece

4) disperse dust with gas mixture into the Hartmann tube at 7 bar as dispersion pressure;

5) ignite hybrid mixture cloud by spark discharge generated by electrodes at varying ignition energies;

6) collect data in MIKE 3.4 software connected to the Kühner MIKE3 device.

Fig. 8 Kühner MIKE3 device

The aforementioned testing procedure is in compliance with ASTM E2019-03 standard. However, when dispersing the dust (PPC for our case) with the gas mixture (methane for our case) in the Hartmann tube (step 4), the gas component can potentially be diluted because of mixing with the atmospheric air already existing in the Hartmann tube. Chaudhari and Mashuga (2017) demonstrated that utilizing the standard procedure for MIE testing resulted in inaccuracies in the MIE data for partial inerting. In their work, they modified the device using a purge add-on at the top which ensured that the tube contained the same gas composition which was used to disperse the dust. Hence, in this study, purging of the tube was conducted before dust dispersion and ignition for hybrid dust-gas mixture MIE testing. With a set flow rate of 10L/min, the tube was filled with the methane-air gas mixture for 21 seconds prior to dust dispersion. 21-second purging time was employed because it is the time required to completely displace 1.2-L of air from the tube at 10L/min flowrate. All the tests in this work were conducted at an inductance of 0 mH and at 120ms ignition time delay. Further, the dust was dispersed through a nozzle at the bottom of the MIE tube and spark was generated by electrodes using capacitive discharge. Humidity and temperature conditions in lab were recorded during experimentation.

Several data points were collected consisting of both ignition at one energy level and no ignition at the next lower energy level. Every data point, at a specific energy level and a specified dust concentration, consists of 10 dust dispersions. After every dust dispersion, a brush was used to sweep off the dust on the inner wall of tube, electrodes, and the top surface of nozzle to the bottom. Dust sample was replaced every 3 dispersions with no ignition to maintain the concentration for next dispersion. The MIE for hybrid mixtures was statistically calculated by the software using the following equation:

$$\text{MIE} = 10^{\frac{\log \text{E2} - \text{I[E2]}(\log \text{E2} - \log \text{E1})}{(\text{NI}+\text{I})[\text{E2}]+1}}$$

where, $[\text{E1}], [\text{E2}]$ represent the range of energy level in tests, $\text{I}[\text{E2}]$ represents the number of ignitions at energy level E2, and $(\text{NI} + \text{I})[\text{E2}]$ represents the total number of tests at energy level E2.

Throughout the experimentation, the methane gas concentration was varied at 0 vol %, 1 vol %, 2 vol % and 3 vol %, and hybrid MIE was determined by testing at different dust concentrations and energy levels. All other parameters were maintained constant, e.g., laboratory temperature, laboratory humidity, source of materials, ignition delay time.

MIE testing was conducted for the following two cases: Case (a) tested the hybrid MIE without purging the Hartmann tube prior to dust dispersion. Case (b) tested hybrid MIE by purging the tube for 21 seconds prior to dust dispersion. Meanwhile, the testing was also divided into two sections: Section 1 including case (a1) and (b1) utilized the original dried PPC with d_{50}=52.50µm as the dust component in the hybrid system. Section 2 including case (a2) and (b2) utilized the milled PPC with d_{50}=24.58µm as the dust component in the hybrid system with the same gas component as in section 1.

CHAPTER III

RESULTS AND DISCUSSION

Fig. 9 shows the raw test data for hybrid MIE including both ignition and no ignition points at particular energy levels (unit in mJ) versus dust concentrations (unit in mg), which are recorded in MIKE 3.4 software, where the original dried PPC [d_{50}=52.50µm] was applied as dust component. **Fig. 10** shows the raw test data for hybrid MIE including both ignition and no ignition points where milled PPC [d_{50}=24.58µm] was applied as dust component.

Case (a1) and (a2) represents the MIE value tested following standard ASTM E2019-03 procedure, where the Hartmann tube was not purged with dispersion gas and the dispersion gas was merely used to disperse PPC. Case (b1) and (b2) represent the MIE testing where the Hartmann tube was purged with the methane-air gas mixtures prior to dust dispersion. **Fig. 11** shows the MIE for both PPC-Methane-Air hybrid systems versus percent methane in air. Comparing the MIE value between case (a1) and case (b1) at every concentration of methane, **Fig. 11** demonstrates that the hybrid MIE in case (b1) is overall lower than that in case (a1), indicating that pre-ignition tube purge decreases the hybrid MIE value and provides more conservative MIE results. This significant difference in MIE values proves the impact of pre-dispersion tube purge in hybrid MIE testing. The above conclusion is also true for case (a2) and (b2).

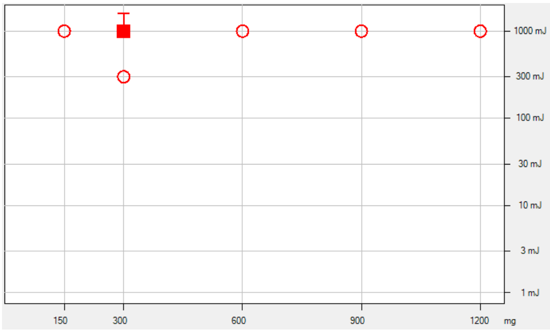


Fig. 9a PPC-Air Tube Not Purged

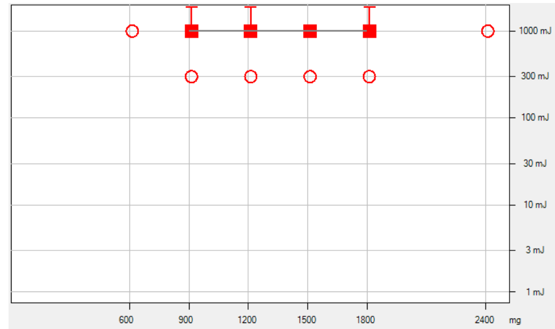


Fig. 9b PPC-Air Pre-Ignition Tube Purge

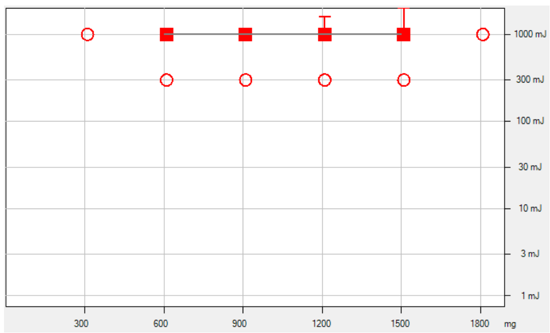


Fig. 9c PPC-1% Methane-Air Tube Not Purged

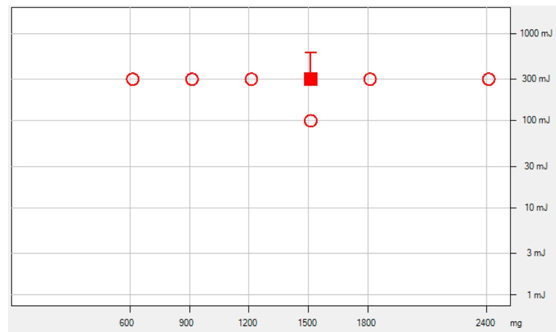


Fig. 9d PPC-1% Methane-Air Pre-Ignition Tube Purge

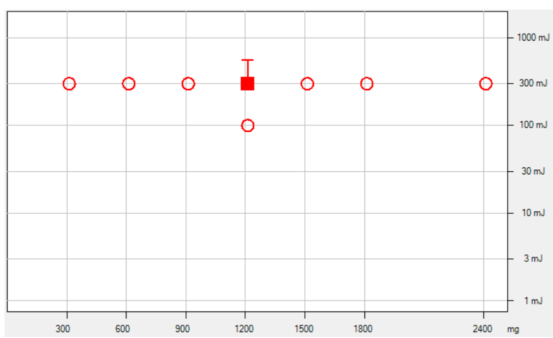


Fig. 9e PPC-2% Methane-Air Tube Not Purged

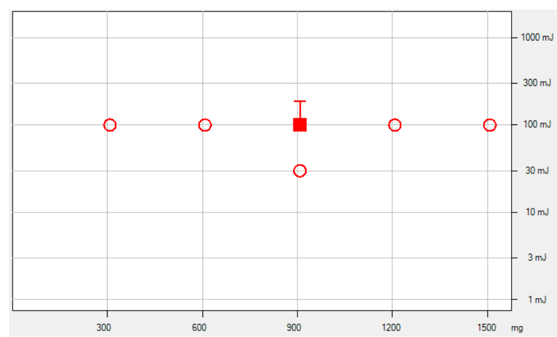


Fig. 9f PPC-2% Methane-Air Pre-Ignition Tube Purge

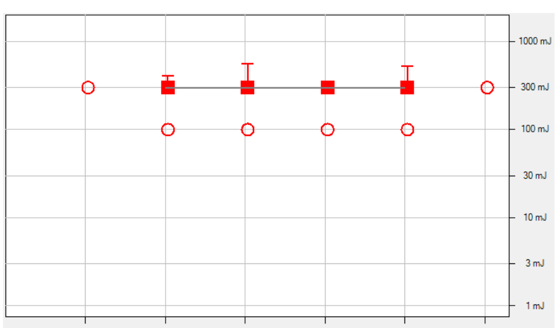


Fig. 9g PPC-3% Methane-Air Tube Not Purged

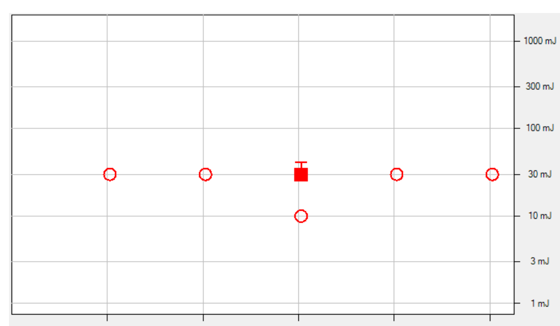


Fig. 9h PPC-3% Methane-Air Pre-Ignition Tube Purge

Fig. 9 Raw Test Data for hybrid PPC[d50=52.50µm]-Methane-Air MIE from MIKE 3.4 Software

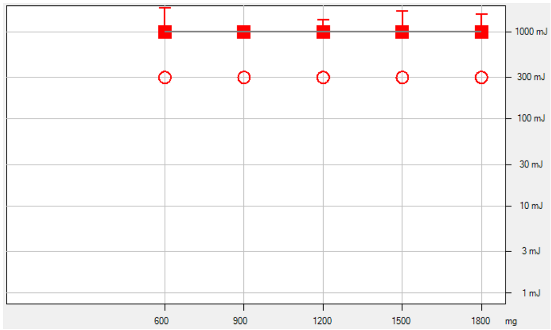


Fig. 10a PPC-Air Tube Not Purged

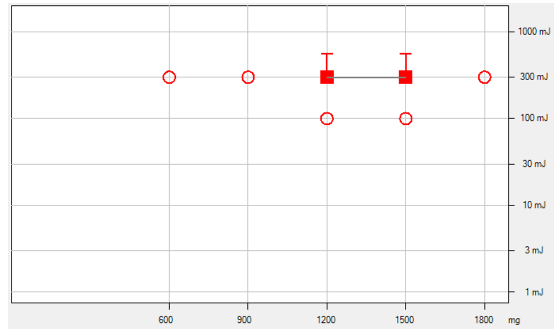


Fig. 10b PPC-Air Pre-Ignition Tube Purge

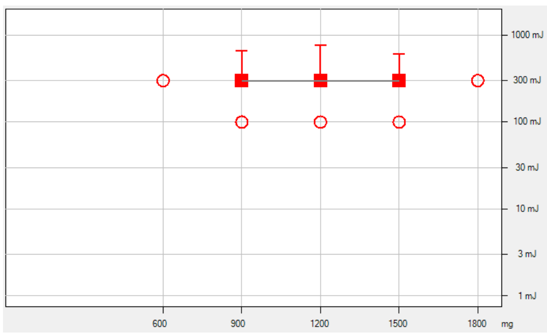


Fig. 10c PPC-1% Methane-Air Tube Not Purged

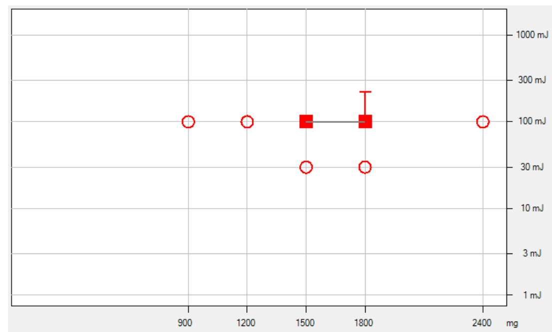


Fig. 10d PPC-1% Methane-Air Pre-Ignition Tube Purge

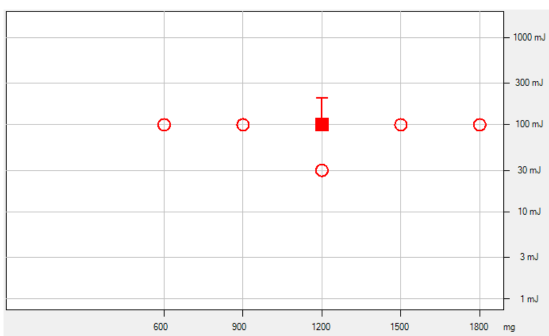


Fig. 10e PPC-2% Methane-Air Tube Not Purged

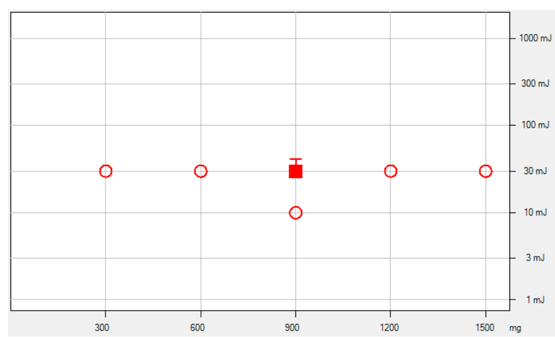


Fig. 10f PPC-2% Methane-Air Pre-Ignition Tube Purge

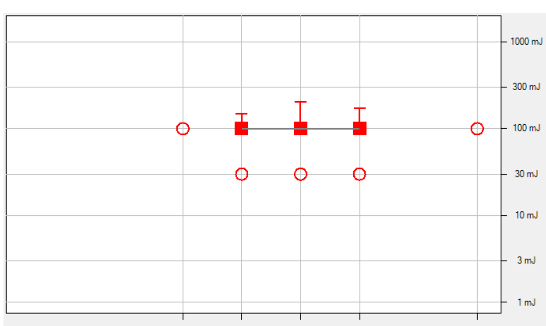


Fig. 10g PPC-3% Methane-Air Tube Not Purged

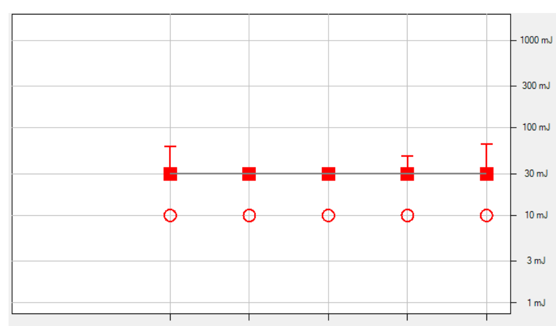


Fig. 10h PPC-3% Methane-Air Pre-Ignition Tube Purge

Fig. 10 Raw Test Data for Milled PPC[d50=24.58µm]-Methane-Air MIE from MIKE 3.4 Software

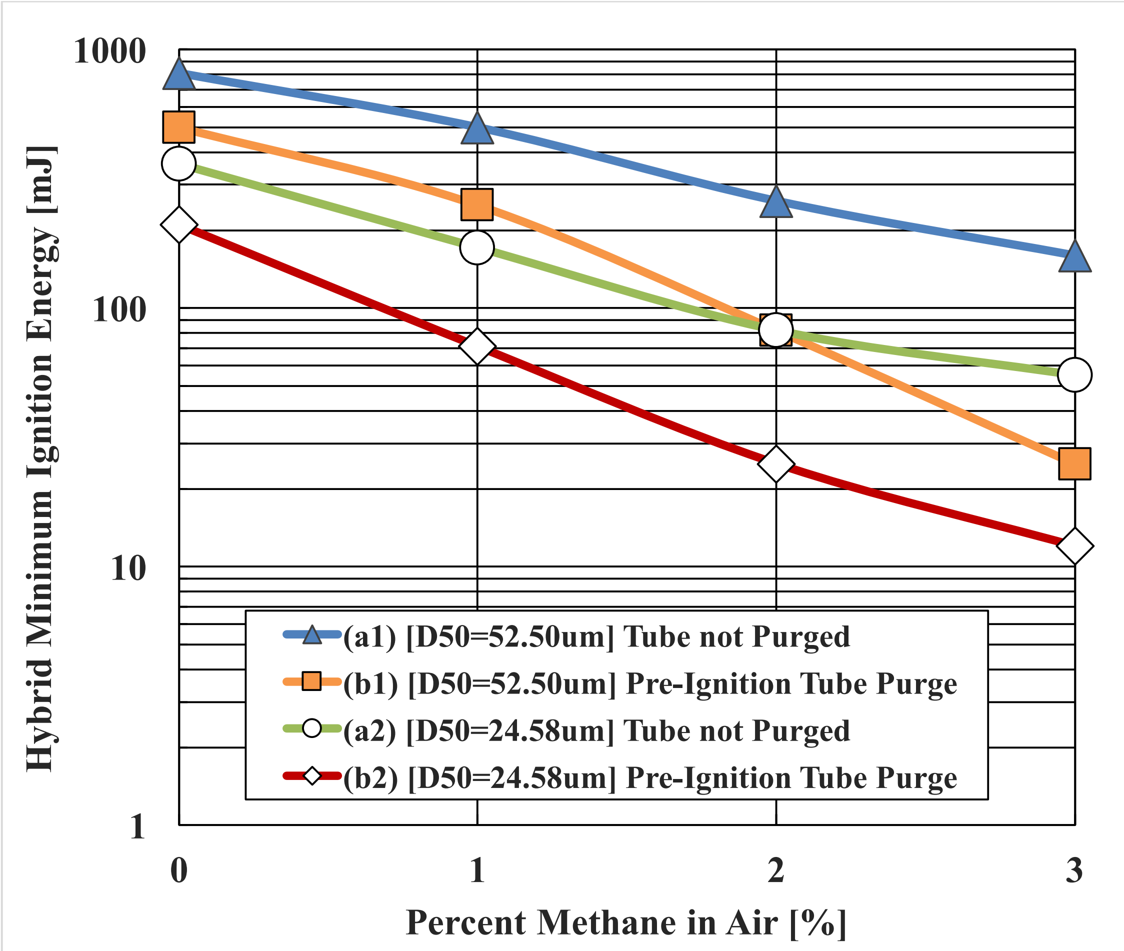


Fig. 11 Hybrid MIE for PPC-Methane-Air Mixtures through Standard Procedure and Modified Procedure: (a1) Tube was not Purged before Dust Dispersion, d_{50}=52.50µm; (b1) Pre-ignition Tube Purge, d_{50}=52.50µm; (a2) Tube was not Purged before Dust Dispersion, d_{50}=24.58µm; ; (b2) Pre-ignition Tube Purge, d_{50}=24.58µm

Table 3 & 4 show the hybrid MIE value for all four cases (a1), (b1), (a2), and (b2) as well as the differences and percent of decrease in MIE value. Meanwhile, the differences of MIE value for tests with before and after milled PPC demonstrate that smaller particle size of dust possesses lower hybrid MIE at all gas concentration.

Table 3. Section 1: Hybrid MIE Value, Differences, and Percent of MIE Reduction for Case (a1) and (b1) Tests [PPC: d_{50}=52.20μm]

Percent Methane in Air	Hybrid MIE (mJ)		Differences (mJ)	Percent of MIE reduction
	(a1) Tube not Purged	(b1) Pre-Ignition Tube Purge		
0 (Air)	810	500	310	38.27%
1%	500	250	250	50.00%
2%	260	82	178	68.46%
3%	160	25	135	84.38%

Table 4. Section 2: Hybrid MIE Value, Differences, and Percent of MIE Reduction for Case (a2) and (b2) Tests [PPC: d_{50}=24.58μm]

Percent Methane in Air	Hybrid MIE (mJ)		Differences (mJ)	Percent of MIE reduction
	(a2) Tube not Purged	(b2) Pre-Ignition Tube Purge		
0 (Air)	360	210	150	41.60%
1%	171	71	100	58.50%
2%	82	25	57	69.51%
3%	55	12	43	78.10%

The differences in hybrid MIE value as well as the percent of decrease between case (a1) and (b1), case (a2) and (b2), are plotted in **Fig. 18**. When 100% air with no methane was used as the gas component, significant difference of 310 mJ in MIE values between case (a1) and case (b1) was observed. It primarily revealed the influence of pre-ignition tube purge, which reflected similar result as in partial inerting tests. Moreover, the MIE for PPC obtained in case (a1) was lower than the value given by previous literature (Norman et al., 2013), which is possibly due to the difference in particle size as well as the oxygen concentration between synthesized air (21% oxygen and 79% nitrogen) and atmospheric air. The above conclusion is applicable for case (a2) and (b2) with the difference of 150 mJ.

With the increase in methane concentration, the value differences in **Table 3 & 4** indicates that lower percentage of methane in air results in relatively higher difference in the value between the MIE with and without pre-dispersion tube purge. In section 1, the difference goes down to 135 mJ when the percentage of methane in air is 3%. In section 2, the difference goes down to 43 mJ when the percentage of methane in air is 3%. This result is probably due to a larger impact of atmospheric air in Hartmann tube to decrease the methane concentration in air after dust dispersion for lower methane concentration, eventually numerically enhancing the difference in MIE values.

Despite the increasing difference in hybrid MIE values, the percent of reduction in MIE value increases with increasing methane percentage. In section 1, the percent of reduction in MIE value increases from 38.27% to 84.38% as the percent methane in air increases from 0 to 3%. In section 2, the percent of reduction in MIE value increases from 41.60% to 78.10% as the percent methane in air increases from 0 to 3%. The impact of increasing concentration of methane in air results in higher deviation in the hybrid MIE values measured in the two cases, which can be attributed to the improved test method. As a result, the overall decrease on hybrid MIE emphasizes the significance of the application of pre-ignition tube purge in hybrid MIE tests. Meanwhile, comparing the percent of MIE reduction between two sections, similar trends indicates the solid impact of methane percentage on the percent of MIE reduction regardless the particle size of PPC with equivalent polydispersity level.

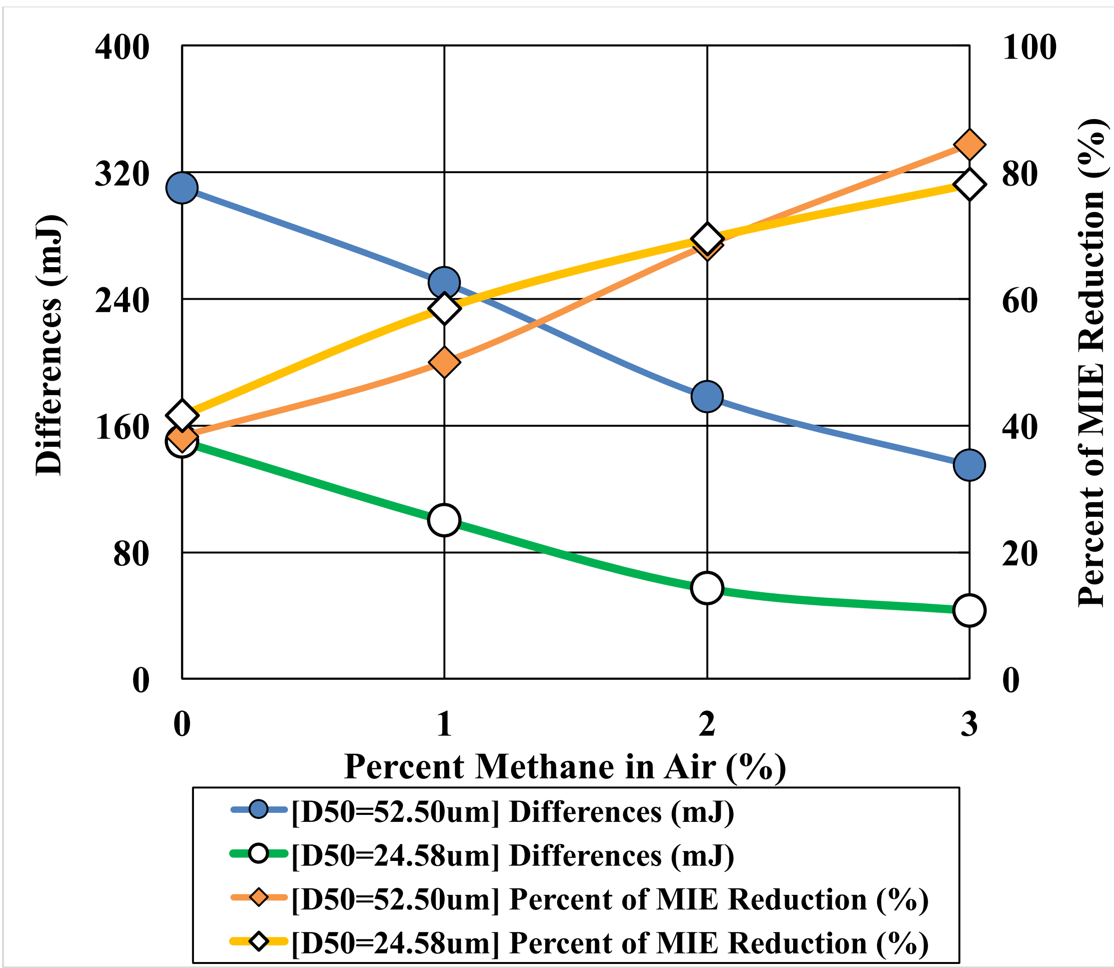


Fig. 12 Differences as well as the Percent of MIE Reduction in Hybrid MIE Value for Both Case (a) and Case (b) in both sections with two particle sizes of PPC

CHAPTER IV

CONCLUSIONS

This study aimed at an improved minimum ignition energy (MIE) measurement of hybrid dust-gas mixture using a modified Kühner MIKE3 MIE apparatus. The modified MIKE3 MIE apparatus uses an add-on purge device, which purges the Hartmann tube with the gas mixture used for dispersing the dust. The purging is done before the dust dispersion so that the composition of the gas in the Hartmann tube is same as that of the gas used for dispersing the dust. This prevented the dilution of the dispersing gas concentration in the Hartmann tube and yielded accurate MIE results. This work used Pittsburgh Pulverized Coal (PPC)-methane-air hybrid mixture for the MIE measurement, which is a typical hybrid system in previous hybrid explosion studies. In this work, PPC was firstly dried before tests and its particle size distribution was measured. Part of PPC was milled into smaller particle size with equivalent polydispersity as the original one. Methane was pre-blended with ultra-high purity (UHP) air at 1 vol %, 2 vol %, and 3 vol %. In order to demonstrate the impact and necessity of the modification in the MIE apparatus, two testing cases were conducted. Case (a) followed the ASTM E2019-03 standard procedure, while case (b) applied a pre-ignition tube purge prior to dust dispersion so that the Hartmann tube was filled with the gas component in hybrid system. Two sections were also conducted with different dust component but same gas component. While section 1 including case (a1) and (b1) used original dried PPC, section 2 including case (a2) and (b2) used milled PPC. Comparison of MIE values for both cases in both sections displayed significant differences existed between purging and not purging the tube before dust dispersion. As the methane concentration elevated from 0 to 3 vol %, the hybrid MIE decreased, respectively at each gas concentration. These results illustrate that pre-ignition tube purge decreases the value of hybrid MIE and generates more conservative results. Despite smaller methane concentration leading to greater numerical difference, the increase of the percent of MIE reduction, which rises from 38.27% to 84.38% in section 1, and from 41.60% to 78.10% in section 2, reflects a larger impact of higher methane concentration on decreasing the hybrid MIE value. Moreover, similar trends of percent of MIE reduction reveals the impact of methane concentration regardless the particle size of PPC with equivalent polydispersity level. Consequently, previous hybrid MIE data utilizing the Hartmann apparatus and Kühner MIKE3 device (Khalili et al., 2011; Addai et al., 2016) might not be sufficiently conservative, and should be validated through further studies by applying pre-ignition tube purge into the test procedure. When conducting MIE testing of hybrid systems, pre-ignition tube purge should become a recommended practice that should be included in the ASTM standard testing procedure in order to obtain conservative and accurate MIE results.

CHAPTER V

FUTURE WORK

Based on the procedure and conclusion in this thesis, some recommendations for future work are listed as follows:

1) Various hybrid dust-gas systems other than PPC-methane-air should be tested following the same procedure as in this study to demonstrate that pre-ignition tube purge in obtaining conservative hybrid MIE value utilizing a Hartmann tube is applicable for other hybrid dust-gas systems
2) Turbulence effect of top purging on hybrid MIE value is needed through modeling in future study to verify the possibility of considering the turbulence generated by top purging in hybrid MIE testing

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