Chapter V

Results and Discussion

In the past, the causes of dust explosions have been systematically researched by laboratory-testing the combustion, ignition, and explosion behavior of combustible dusts. Step by step, the results and the experience gained have been transferred to industrial practice. Yet, dust explosions still occur, causing major damages and sometimes fatalities.

In this research, dust explosibility was investigated for many dusts found in the domestic industries. Tests for explosibility of dispersed dust clouds were carried out in a specific chamber of known volume. The results and discussions may be categorized into six parts as follows :

5.1 Improvement of The Dust Explosibility Tester : In this part, improvements on the tester were carried out by;

- Installation of silica gel to dry the compressed air
- Varying the spark delay time
- Adjusting the air flow channel
- Adjusting the gap between the sparking electrodes
- Varying the number of pieces of filter paper on top of the explosion chamber

5.2 In this part, comparison of the experimentally obtained LEL values of dusts with that of a standard test powder and published values were carried out. This results were considered and discussed in detail.

5.3 Effect of the average particle size on the LEL values of flour dusts : The apparent LEL values measured by this tester were evaluated to see the effect of particle size.

5.4 Effect of the moisture content : Most dusts contain a certain level of moisture which is believed to act as a suppressant because the moisture requires heat of vaporization to escape. The present research investigated experimentally the effect of the moisture content on the LEL values of flours. The results were reported and discussed in this part.

5.5 Effect of the source of flour dusts : The same type of flours but produced by different companies could give different LEL values. Therefore flour dusts from several sources were tested and the results discussed.

5.6 Comparison between the LEL values of fresh (new) and used (once-through) copier toner : The objective was to see whether the LEL value increased or decreased after the toner passed through the copying process.

5.1 Improvement of The Dust Explosibility Tester

5.1.1 Installation of silica gel to dry the compressed air

The tester uses a compressor to produce compressed air for dispersing the dust and form a dust cloud. Generally the ambient air contains a small amount of humidity. When it is compressed and cooled down, water condenses out and accumulates within the compressor and pneumatic line. When the valve is opened, the moisture-saturated compressed air may even carry some water into the explosion chamber. The entrained moisture can significantly affect the dust explosibility.

As shown in Table 5.1, lycopodium (APPIE Standard Test Powder) was used to evaluate (calibrate) the performance of the tester. The concentration of lycopodium was reduced gradually from 70 g/m^3 to 40 g/m^3 while keeping the gap of the sparking electrodes and the width of the air flow channel at 6 mm and 2 mm, respectively. The LEL of lycopodium was then found to range from 54.5 g/m^3 to 54.8 g/m^3.

After silica gel was installed in the air line to adsorb humidity from the compressed air, the resulting improvement was as shown in Table 5.2. The observed values of LEL were in the range of 50.5 g/m^3 to 50.8 g/m^3.

Thus it may be concluded that the installation of silica gel in the air line reduced the air humidity and led to better ignition. As a result, the average value of the measured LEL values (50.6 g/m^3) was reduced close to APPIE's standard value (45±5 g/m^3).

5.1.2 Varying the sparking delay time

The elapsed time from the activation of the electromagnetic valve on the air tank until the onset of electrical discharges to ignite the dust cloud is the spark delay time.

According to the standard test procedure (APS002-1991), a suitable spark delay time should be selected from the following three values i.e., 0.1, 0.3, 0.5 seconds. The effect of the spark delay time on the LEL values are summerized in Table 5.3 (detailed results are given in Appendix 2).

Table 5.1 Measurement of LEL for lycopodium powder (without drying of compressed air)

Test date	2-Feb	**Name**	Songchai
Instrument	C.U. Explosibility Tester #1		
Name of test powder	Lycopodium		
Type of test powder	APPIE Standard test powder		
Particle size	25 microns+		
Pretreatment	Kept in a dessicator more than 1 day		
Drying condition	no	Temperature: C, Time: h, (Moisture: %)	
Atmospheric temperature and humidity	Temperature: 28^0 C, Relative humidity: 58%		
Spark delay time	0.1 seconds		
Width of air flow channel	2 mm		
Distance of sparking electrode	5 mm		
Compressed air	1.8 kg/cm^{3}G		
Filter paper	1 .piece(s)	**Type:**	Whatman No. 93
Number of measurements	3 Times		

Sample	Weight of dust sample (g)	Lower Explosion Limit (g/m^3)	Remarks
1	0.0673	54.8	
2	0.0670	54.6	
3	0.0669	54.5	
Average		54.6	
Evaluation (reference)		Explosibility: High	

Note + : Mass-average particle size was measured by micron photo sizer

Table 5.2 Measurement of LEL for lycopodium powder
(after improvement by installation of silica gel to dry compressed air)

Test date	4-Feb	**Name**	Songchai
Instrument	C.U. Explosibility Tester #1		
Name of test powder	Lycopodium		
Type of test powder	APPIE Standard test powder		
Particle size	25 microns+		
Pretreatment	Kept in a dessicator more than 1 day		
Drying condition	no	Temperature: C, Time: h, (Moisture: %)	
Atmospheric temperature and humidity	Temperature: 28^0 C, Relative humidity: 60%		
Spark delay time	0.1 seconds		
Width of air flow channel	2 mm		
Distance of sparking electrode	5 mm		
Compressed air	1.8 kg/cm^{3}G		
Filter paper	1 piece(s)	**Type:**	Whatman No. 93
Number of measurements	3 Times		

Sample	Weight of dust sample (g)	Lower Explosion Limit (g/m^3)	Remarks
1	0.0624	50.8	
2	0.0624	50.8	
3	0.0620	50.5	
Average		50.7	
Evaluation (reference)		Explosibility: High	

Note + : Mass-average particle size was measured by micron photo sizer

Table 5.3 Effect of the spark delay time (duration of sparking = 3 sec.)

Powder name	Spark delay time (seconds)	Average LEL (g/m^3)
Lycopodium	0.1	50.6
	0.3	56.0
	0.5	63.9

The above experimental results show that a spark delay time of 0.1 seconds gives the best average LEL which is quite close to the standard value (45±5 g/m^3).

5.1.3 Adjusting the air flow channel

Adjusting the height of the air flow channel is necessary to improve the performance of the tester. The height of the air flow channel between the dust cup and the mushroom-like umbrella directly affects the dispersion condition of dust in the explosion chamber.

The air flow channel can be adjusted by rotating the screw of the mushroom-like umbrella until the best value of LEL has been obtained. Test results for various channel heights (2.0 mm, 1.5 mm, 1.0 mm and 0.5 mm) were summarized in Table 5.4 (details shown in Appendix 2).

Table 5.4 Effect of the height of the air flow channel

Powder name	Height of air flow channel (mm)	Average LEL (g/m^3)
Lycopodium	2.0	50.6
	1.5	47.9
	1.0	47.2
	0.5	47.7

Table 5.4 reveals that a decrease in the height of the air flow channel essentially reduced the value of the LEL down to a constant. Obviously, a height of 1 mm is the most suitable.

5.1.4 Adjusting the gap between the sparking electrodes

One indispensable requirement for dust explosion is the ignition source. An ignition source of sufficient energy to initiate flame propagation must be in contact with the dust suspension. Therefore, an optimal gap between the sparking electrodes should exist.

The gap can be adjusted by turning the screw on each electrode holder. The APS002-1991 test procedure recommends that the gap between the sparking electrodes should be in the range of 4 mm to 6 mm.

Table 5.5 shows the effect of the gap (4 mm, 5 mm and 6 mm) on the LEL. In the range of 4 mm to 5 mm, the average values of the LEL remained essentially contant, whereas above 5 mm the LEL value increased.

Table 5.5 Results of adjusting the gap between the sparking electrodes

Powder name	Gap between the sparking electrodes (mm)	Average LEL (g/m^3)
Lycopodium	6	47.6
	5	47.2
	4	47.2

A gap of 4 mm gave lycopodium LEL values that fully conform to the standard value (45$\pm$5 g/m^3).

5.1.5 Varying the number of pieces of filter paper

The objective here was to improve the performance of the tester. Filter paper is permeable to air. The rate that compressed air flows through the filter paper to the atmosphere can be controlled by the number of pieces of filter paper, which in turn affects the measured LEL.

Table 5.6 Effect of the number of pieces of filter paper (Whatman no. 93)

Powder name	Numbers of paper (pieces)	Average LEL (g/m^3)
Lycopodium	1	47.2
	2	48.0

As seen from Table 5.6, one piece of the filter paper yielded a lower LEL than two pieces of the same filter paper. Therefore, only one piece was used in all subsequent tests.

5.2 Comparison of the experimentally obtained LEL values with standard and published values

The APPIE standard test powder (lycopodium) was used to calibrate the tester. Furthermore, selected dust samples (HDPE, Dextrin and sulfur) were used to compare experimentally obtained LEL values with published values. HDPE powder was obtained from a polyethylene plant, dextrin and sulfur powders came from the Analytical Chemistry Laboratory of the Chemical Engineering Department.

Each test powder sample was prepared as follows :

a) Since powder explosibility depends significantly on its particle size distribution, the test powder was first sieved using a standard sieves (sieve number 45 microns).

b) The sieved test powder was next by kept in a dessicator for at least 1 day. Table 5.7 shows the preparation procedure of the test powders used in this section.

Table 5.7 Preparation Procedure of Test Powders

Powder name	Sub-class by using sieve no. (microns)	Pretreatment (Kept in a dessicator)
Lycopodium	-	Yes
HDPE	under portion, sieve no. 45	Yes
Dextrin	under portion, sieve no. 45	Yes
Sulfur	under portion, sieve no. 45	Yes

After the above preparation, the mass-average particle size of each sample was measured using the Micron Photo Sizer (Seishin Enterprise Model SKC-2000).

Table 5.8 and Fig. 5.1 compare the experimental values of the LEL with the standard and published values for the 4 types of dust.

Table 5.8 Comparison of experimental and published LEL values

Powder name	Experiment/ Standard	Mean particle size (microns)	Lower limit conc. (g/m^3)
Lycopodium	Experiment	26	47
	Standard	35	45
HDPE	Experiment	33.6	26
	Reference	24	20
Dextrin	Experiment	55	58
	Reference	41	60
Sulfur	Experiment	29	37
	Reference	20	30

Note : 1) See Appendix 2 for details

2) The mass-average particle size was measured using the micron photo sizer (Seishin Enterprise Model SKC-2000).

3) Reference above three test samples obtained from NFPA68 (1988).

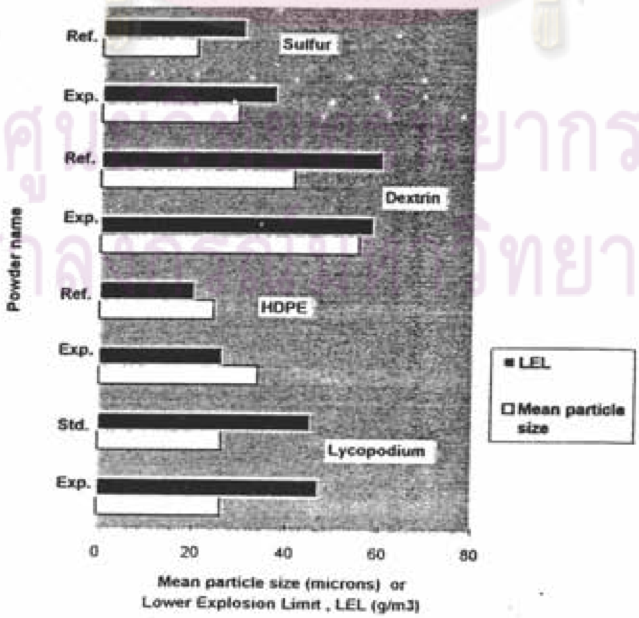


Figure 5.1 Comparison of experimental and published LEL values

Since all the four types of dust samples show LEL values close to the published ones, it may be concluded that the present Dust Explosibility Tester (named C.U.#1) was accurate and reliable after the calibration.

Of the four types of dust studied, lycopodium was APPIE-designated standard test powder, with average particle size of 26 microns. The measured LEL fully conformed to the standard value (45±5 g/m^3).

The HDPE powder was a high-density polyethylene powder which has some volatile matter. When the particle size of HDPE is smaller, its surface area becomes larger and generation of the volatile matter becomes faster, thus reducing the observed LEL value. In fact HDPE powder is classified as highly explosible.

Dextrin was the most difficult to explode among the four types. The sulfur powder had a tendency to agglomerate when it contacted humidity in the air. Chemically, the sulfur powder is highly flammable and easy to ignite.

According to Table 5.8 and Figure 5.1, the LEL values show the following order of increase.

easy to explode at low concentration — difficult to explode

HDPE ⟶ Sulfur ⟶ Lycopodium ⟶ Dextrin

5.3 Effect of average particle size on the LEL values of flour dusts

Most investigations on the effect of particle size on the propagation of flame in a dust cloud have been concerned with particles having roughly equilateral dimensions, often approximated as spheres. Typically the particle diameters were characterized in terms of standard sieve apertures. Generally there is a definite tendency for the LEL values of a monosize dust to decreases and approaches an asymptote as the particle size becomes smaller and smaller. The relationship between the LEL value and mean particle diameter for MMA beads (Enomoto and Matsuda, 1985) has been shown in Fig. 3.21 (Chapter III).

As seen from Table 5.9, five types of dust samples, named F1 to F5, were studied to understand the effect of particle size as well as the different

Table 5.9 Classified flour samples by sieving

Types of dust sample	Fraction	Pretreatment step undergone	Particle size (microns)
F1 (Cassava flour) Tradename : Tauyaymom	Cas-1	(a), (b), (c)	<45
	Cas-2	(a), (b), (c)	45-53
	Cas-3	(a), (b), (c)	53-75
	Cas-4	(b), (c)	as bought (dried)
	Cas-5	None	as bought (undried)
F2 (Cassava flour) Tradename : Dragon Fish	Cas-6	(a), (b), (c)	<45
	Cas-7	(a), (b), (c)	45-53
	Cas-8	(a), (b), (c)	53-75
	Cas-9	(a), (b), (c)	75-106
	Cas-10	(b), (c)	as bought (dried)
	Cas-11	None	as bought (undried)
F3 (Rice flour) Tradename : Erawan	Rice-1	(a), (b), (c)	106-150
	Rice-2	(a), (b), (c)	150-180
	Rice-3	(a), (b), (c)	>180
	Rice-4	(b), (c)	as bought (dried)
	Rice-5	None	as bought (undried)
F4 (Corn flour) Tradename : Tamfood	Corn-1	(a), (b), (c)	<45
	Corn-2	(a), (b), (c)	45-53
	Corn-3	(a), (b), (c)	53-75
	Corn-4	(a), (b), (c)	75-106
	Corn-5	(a), (b), (c)	106-150
	Corn-6	(a), (b), (c)	150-180
	Corn-7	(b), (c)	as bought (dried)
	Corn-8	None	as bought (undried)
F5 (Wheat flour) Tradename : Australian Wheat	Wheat-1	(a), (b), (c)	106-150
	Wheat-2	(a), (b), (c)	150-180
	Wheat-3	(a), (b), (c)	>180
	Wheat-4	(b), (c)	as bought (dried)
	Wheat-5	None	as bought (undried)

source of flour dusts on the LEL values. The particle size of interest lay in the range of <45 to >180 microns. The LEL values were measured using the standard test method of APPIE.

Before the explosion experiment, each type of flour was pretreated as follows :

a) To investigation of the effect of particle size it was necessary to classify the flour samples using the standard vibration sifter. The standard sieves (45, 53, 75, 106, 150, 180 microns) were used for classification flour dust as shown in Table 5.9.

b) Classified flour samples were put in an electric oven to dry at 50^0 C for approximately 1 day while taking care not to alter the powder properties.

c) The dried samples were always kept in a dessicator.

After the above pretreatment procedure has been completed, the test samples are ready for explosibility tests.

Table 5.10 lists the corresponding LEL value for Cas-1, Cas-2 and Cas-3 for Type F1 cassava flour as a function of the nominal average particle size (see detailed results in Appendix 2). As expected, the LEL concentration increased with the particle size, which was presented graphically in Fig. 5.2 (a) as F1 cassava flour. The average particle size ranged from 22.5 to 64 microns. Obviously the LEL value of F1 cassava flour was nearly independent of the particle size for particles finer than 49 microns, whereas the value rises remarkably for particles larger than 49 microns.

Similarly, Table 5.10 summarizes the effect of the nominal particle size of F2 cassava flour on the LEL concentration (see details in Appendix 2). As expected, the trend is the same as that of F1, but the LEL increases steeply between 49 and 64 microns (Fig. 5.2).

Figure 5.2 clearly illustrated that even cassava flour samples of the same nominal average size could had different LEL values (Cas-1 vs Cas-6 ; Cas-3 vs Cas-8). There are two possible explanations for the difference in LEL concentrations. Fig. 5.2 (b) reveals that type F1 had a much narrow particle size distribution and a smaller average and mean particle size than had F2 because of certain difference in their production equipment, especially the product classification specifications. Thus it is reasonable to assume that

Table 5.10 Effect of particle size of F1 cassava flour on the LEL value

Tradename	Powder name	Nominal particle size (microns)	Average LEL (g/m^3)
F1	Cas-1	22.5	161.6
	Cas-2	49	164.1
	Cas-3	64	207.2
F2	Cas-6	22.5	121.9
	Cas-7	49	165.6
	Cas-8	64	289.7
	Cas-9	90.5	307.5

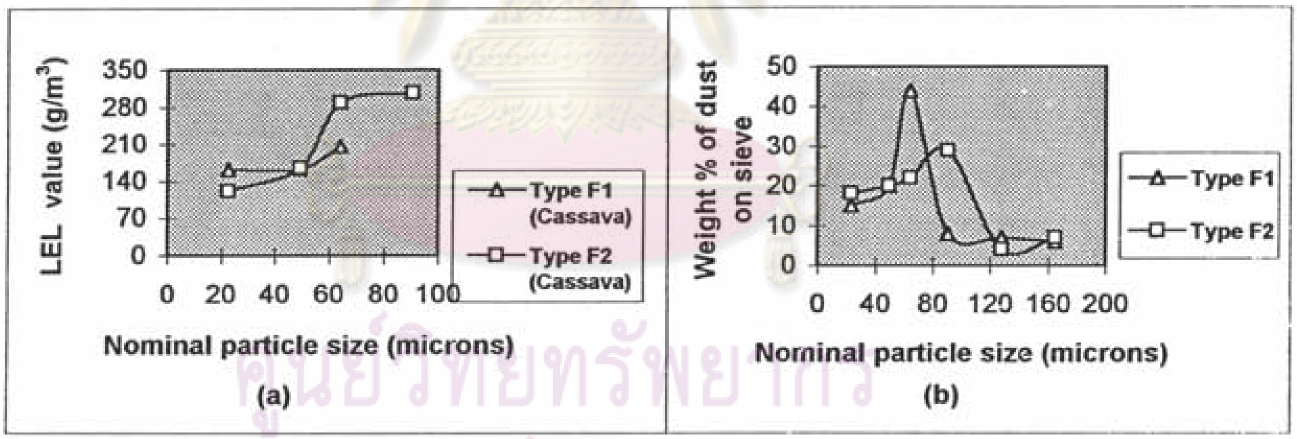


Figure 5.2 (a) Effect of particle size of cassava flour on the LEL
(b) Particle size distribution of cassava flour

fraction Cas-6 of F2 had a higher proportion of finer particles than fraction Cas-1 of F1, though their nominal average sizes were the same. As a consequence, the LEL value of Cas-6 (121.9) was lower than Cas-1 (161.6).

On the other hand, Cas-8 of F2 had a higher LEL value than Cas-3 of F1 because the latter had a higher proportion of rougher particles since its size distribution was very broad.

The second possible explanation attributes the different LEL values to the assumption that F1 and F2 might have different chemical compositions because they came from different sources. However, it can not logically explain why F2 should have a lower LEL in Cas-6 and a higher LEL in Cas-8 at the same time. Thus it may be concluded that any difference in chemical properties, should it exist, either would be quite samll or had much less effect on the LEL value than the size distribution.

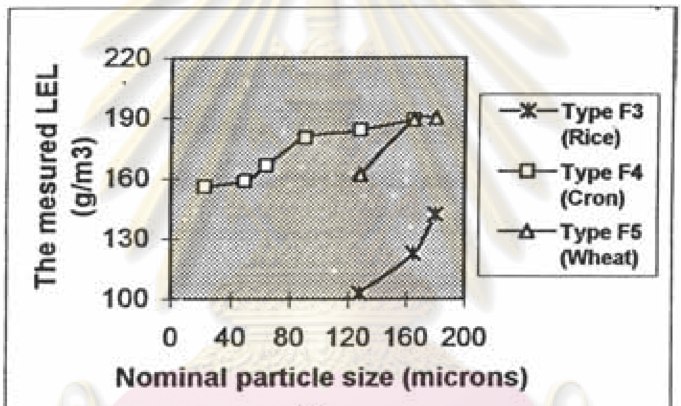
Table 5.11 summarizes the effect of particle size for, the cases of rice flour (Type F3), Corn flour (Type F4) and Wheat flour (Type F5) (detailed results recorded in Appendix 2).

Table 5.11 Effect of particle size on the LEL value for each type of flour

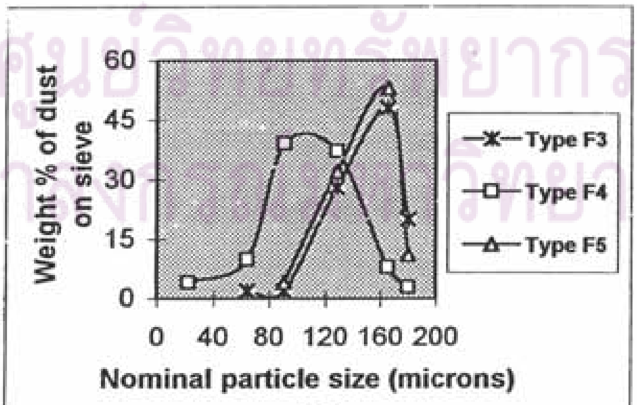
Type	Fraction	Nominal particle size (microns)	Average LEL (g/m^3)
F3	Rice -1	128	103
	Rice -2	165	122.6
	Rice -3	>180	142
F4	Corn-1	22.5	155.9
	Corn-2	49	158.6
	Corn-3	64	166.3
	Corn-4	90.5	180
	Corn-5	128	183.9
	Corn-6	165	189.1
F5	Wheat-1	128	162
	Wheat-2	165	188.9
	Wheat-3	>180	190.1

As is well known, the effect of particle size on the LEL exhibits a rising trend for all the cases (Fig. 5.3 (a)). Fig.5.3 (b) shows the particle size distribution of the three types of flour obtained using the standard sieve.

Fig. 5.3 (a) and (b) reveal that for the corn flour (Type F4) with a very broad particle size distribution (22.5-180 microns), the LEL value shows a rather steep increase in the size range of 49 to 90.5 microns. Below 49 microns, the value is essentially constant at 155-160 g/m^3, which conforms to the fact that the LEL value generally approach an asymtotic minimum as the particle size becomes finer and finer. On the other hand, as the particle size increases there would be a "take-off" region in which the LEL value



(a)



(b)

Figure 5.3 (a) Effect of particle size of rice, corn and wheat flour on the LEL

(b) Particle size distribution of group F3, F4, and F5 rises steeply, until a maximum size is reached beyond which explosion cannot occur. The experimental results for F4, which shows a gradual rise in the LEL as the nominal particle size increases from 90.5 to 165 microns, imply that the observed LEL of each fraction was mostly determined by the portion of finest particles existing within each fraction.

In the cases of rice flour (F3) and wheat flour (F5), both of which had rather narrow size distributions, their LEL values were found to increase rather steeply in the range of 128 to >180 microns, the so-called "take-off" region.

Next it should be interesting to compare the LEL values of comparable fractions among the four types of flour. Table 5.10 and 5.11 indicate the following sequence of increasing LEL concentration :

Low LEL value — High LEL value

Rice flour → Wheat flour → Corn flour → Cassava flour

According to the general composition of each type of flour (see Appendix 3 for detailed data), the following qualitative correlation may be summarized in Table 5.12 . It may be concluded that the chemical

Table 5.12 Qualitative correlation between flour properties and LEL value (Comparable particle size)

Flour type	% carbohydrates	% proteins	% lipids	LEL value
Cassava	highest	lowest	lowest	highest
Corn	2nd highest	2nd lowest	2nd lowest	2nd highest
Wheat	2nd lowest	2nd highest	2nd highest	2nd lowest
Rice	Lowest	highest	highest	lowest

composition of a flour type has a controlling influence on its LEL value. The higher the percentage of lipids and proteins, the lower the observed LEL value.

So far It is still unclear whether or how the protein and lipid contents of each flour type really influence its LEL value, which is beyond the scope of the present work.

Since the LEL is an indicator of explosion sensitivity, it should not be dependent of the calorific (heating) value of each flour type because the heating value should affect the explosion severity (maximum explosion pressure in particular) once an explosion has occurred. On the other hand, the Gibb's free energy of each flour type is expected to affect the LEL value (ease of ignition) and perhaps the rate of explosion pressure rise (explosion severity).

5.4 Effect of moisture content

In this section the effect of moisture content on, the LEL value for each dust type, namely cassava flour (Tauyaymom), cassava flour (Dragon Fish), rice flour, corn flour and wheat flour, was investigated. All of the test samples were taken from their containers for use within any subsequent size classification. Therefore, the particle size distribution was representative of the products on the market.

Dried test samples were prepared according to the described procedure in Table 5.9. Otherwise moist (undried) test samples were taken directly from the bag containers for testing.

As expected, for each type of flour the observed LEL value of the dried sample was always lower than the moist one. For example, the average LEL values of dried corn flour (essentially 0 % free moisture) and moist corn flour (3.7 % free moisture) were 192.6 and 356.8 g/m^3 respectively (detailed results recorded in Appendix 2). Table 5.13 illustrates how much the moisture content suppressed the LEL value.

Table 5.13 Influence of moisture content on the LEL

Type (Average size)	Sample name	% Moisture content	Average LEL (g/m^3)
F1 (52 microns)	Cas-4	0	114.6
	Cas-5	2.8	120.4
F2 (57 microns)	Cas-10	0	251.7
	Cas-11	3.9	259.7
F3 (140 microns)	Rice-4	0	128.6
	Rice-5	6.6	137.0
F4 (60 microns)	Corn-7	0	192.8
	Corn-8	3.7	356.8
F5 (138 microns)	Wheat-4	0	165.1
	Wheat-5	4.8	183.0

Generally not only the LEL value but also the explosion violence is reduced with increasing dust moisture content because of the specific role of moisture in reducing both the ignition sensitivity and explosion violence of clouds of organic dusts (Van Larr and Zeeuwen, 1985).

5.5 Effect of the source of flour dust

Cassava flour Type F1 and F2 came from two different sources. The effect of a different source on the LEL value was summarized in Table 5.10. As discussed in section 5.3 the particle size distribution seems to have a dominant effect on the LEL whereas any possible difference in chemical composition seems to have small effect. In other words, as long as the particle size distribution and other conditions (such as moisture content) are the same, the source of flour of the same type should have minor effect on the LEL.

5.6 Comparison between LEL values of fresh (new) toner and used (once-through) toner

The toner used in a photocopier is an organic dust. In the step of copying part of the toner is melted on to the paper while the excess toner is skimmed and collected in a storage receiver. This is the so-called "used (once-through) toner". The objective of this section is to see whether the LEL value increases or decreases before and after the toner passes through the copying process.

Samples of fresh and used toner were pretreated and dried according the procedure mentioned in section 5.2. Then they were sieved to obtain the fraction under 45 microns for use in the tests. Table 5.14 compares the observed LEL values.

Table 5.14 Comparison between fresh toner and used toner

Powder name	Average particle size (microns)	Average LEL (g/m^3)
Fresh toner	19.4	40.3
Used toner	22.8	47.5

The LEL of the fresh toner was lower than the used one, while the former had a slightly smaller average particle size than the latter. Because the excess toner could not completely escape the effect of melting, the used toner has slightly larger average particle size than the fresh toner (detailed results shown in Appendix 2). Therefore the used toner had a slightly higher LEL value.