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Calibration of new dust dispersion systems in the 1m^3 standard dust explosion vessel for fibrous biomass testing

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Abstract

Biomass is considered as an alternative fuel for partial/complete replacement of coal in power generation. The data on coal, agricultural and chemical dusts explosion properties are available in the literature but reliable data on fibrous biomass is not available. This is because the standard C-tube dispersion system in the 1m^3 dust explosion vessel does not allow fibrous biomass to flow. In this paper alternative dust dispersion systems (Rebound nozzle, Hemispherical dispersion cup and Spherical grid nozzle) were designed and calibrated against the standard dispersion system using non-fibrous and fibrous dusts. The criterion for the calibration was the achievement of same P_{max}, K_{st}, mass burned (%), flame speed and spherical flame propagation. The ignition delay and inlet air valve off timing were varied using gas explosions to achieve the same turbulence levels in the vessel that produced similar results as with standard system. The calibrated conditions for the rebound nozzle were; 0.70s ignition delay and 0.75s valve off timing and for spherical grid nozzle were; 0.50s ignition delay and 0.65s valve off timing. All of the injection systems with an external store of the dust were problematic with fibrous dust and would only pass fibrous dusts milled to <63µm and were not suitable for the practical dusts with sizes up to 1mm that are in current use in power stations burning pulverised biomass. The alternative was to place the dust inside the vessel and to disperse it using a blast of compressed air and the hemispherical cup was developed for this purpose. The hemispherical dispersion cup produced reliable results at 0.60s ignition delay and 0.65s valve off timing with gas explosions. The dust explosion tests using the hemispherical dispersion cup produced the same results for P_{max} and proportion of injected mass burned (%) but had lower values of K_{st} and flame speed and the flame propagation was shown to not be spherical.

Keywords: Dust explosion, Deflagration index, ignition delay, explosion pressure, flame speed, dust dispersion systems

1. Introduction

The study of the explosibility and combustion properties of biomass is scarce in the open literature due to problems inherently associated with the structure of biomass. Biomasses generally have a low bulk density and are fibrous in nature. Nut dusts such as walnut are an exception as they have brittle fracture and mill in the same way as coal. The low bulk density biomass cannot be accommodated in the standard 5L dust holding pot pre-pressurised to 20 barg. To overcome this problem the dust pot volume was increased to 10L with 10 barg air injection pressure, compared with the standard 5L and 20 bar injection pressure. This was shown to give the same K_{st} results as for the standard system with the same 0.6s ignition delay (Sattar et al. 2013). The fibrous biomass, on the other hand can easily be trapped or packed inside the standard dispersion systems of dust explosibility testing vessels (Eckhoff 2003). These problems have led to the development of alternative dispersion systems.

The most commonly used alternative disperser in the literature is the rebound nozzle, as originally developed by Bartknecht (1989) for textile flock. The rebound nozzle is given in Appendix-B, page 21 of BSEN14034-3 (2006) as an alternative dispersion system for the study of fibrous materials. The rebound nozzle like the standard dispersion system disperses the dust from an external dust pot. The BSEN 14034-3 (2006) standard along with rebound nozzle also proposed the hemispherical dispersion cup as an alternative dispersion system for biomass study. This is an in-vessel dispersion system, similar to the Hartmann dust explosion equipment, where the dust is placed within the test vessel and is dispersed by a blast of air from the external dust pot.

No significant attempts have been seen in literature for the calibration of these dispersers against the standard dispersion system in the $1m^3$ vessel. The only significant study on the explosibility of straw and woody type biomass dusts was by Wilén et al. (1999). They studied different dispersion devices in the 20L and $1m^3$ vessels. In the $1m^3$ vessel, the dust was dispersed from the external pot using an open nozzle, a ring nozzle and a rebound nozzle whereas in the 20L vessel the dust was placed inside the vessel and was dispersed with the help of three different designs of nozzles. According to the authors, “the experiments did not follow any standard method and do not pursue the performance of any standard test with different materials”. No attempts were made to calibrate the new dispersers with the standard dispersion system. The calibration criteria used for the selection of the best disperser were the achievement of the highest maximum pressure (P_{max}) and deflagration index (K_{st}) and lower residual mass in the dust pot. No information about the ignition delay used was given (Wilén et al. 1999). Wilen et al. (1999) reported 20% of the initial mass loaded remained in the dust holding pot.

Dahoe et al (2001) discussed the calibration of the rebound nozzle and perforated dispersion ring in a 20L spherical vessel. At the standard ignition delay (0.06s) for the 20L vessel, the measured turbulence intensity levels with the perforated dispersion ring (standard disperser for 20L vessel) was 2.68 m/s whereas with the rebound nozzle was 3.75 m/s which suggests longer ignition delays should be used for the rebound nozzle in the 20L vessel (Dahoe et al. 2001). Bartknecht (1989) used ‘medium’ turbulence levels for the determination of P_{max} and K_{st} in the $1m^3$ vessel (Bartknecht 1989). The deflagration index (K_{st}) is very sensitive to the ignition delay, due to the sensitivity of the turbulence to the ignition delay, therefore by decreasing the ignition delay K_{st} will increase. The results produced by any alternative injection system in the literature are not reliable due to the lack of calibration back to the reference standard C ring injection system for a standard dust. There has been no use of the hemispherical dispersion cup found in the open literature. No attempts have been noticed in the literature to calibrate the dust holding pot and dust dispersion systems for voluminous and fibrous biomass, with the standard dispersion system in $1m^3$ dust explosion test vessel.

In this investigation the rebound nozzle, hemispherical dispersion cup and a spherical grid nozzle (similar to the nozzles used in explosion suppressant) were used as alternative dust dispersion systems that may be suitable for use with fibrous biomass. The ignition delay (time from the arrival of air in the main vessel to firing of the 10kJ ignitor) was varied to investigate the explosion parameters (P_{max}, K_{st}, mass burned % and flame speed) dependence on ignition delay and hence on the turbulence level, for gas and dust-air mixtures. The variation in ignition delay was performed using the C-tube dust dispersion system as well as with new dispersion systems. The criteria for calibration of new systems was the achievement of same P_{max}, K_{st}, mass burned (%), flame speed and demonstration of spherical flame propagation, as obtained by using C-tube standard system with the standard ignition delay. It was found that the most critical parameter was the demonstration that a spherical flame had been achieved, as all systems would give an explosion and all the other parameters could be measured.

It should be noted that in the development of the ISO 1 m^3 or 20L sphere dust explosion test methods it was never a requirement to demonstrate that a spherical flame had been achieved, even though this is a requirement of the definition of the K_{st} parameter as the reason for the $V^{1/3}$ term in this is that this is the diameter of a spherical flame. The present work used two lines of flame arrival thermocouple detectors at 90^o to each other and downward and upward lines of thermocouples to show flame propagation was influenced significantly by buoyancy. A satisfactory system was only deemed viable if a spherical flame was demonstrated. Some of the systems give a sensible peak pressure and K_{st} but did not have a spherical flame and were thus rejected. Even the standard 1 m^3 system does not have a spherical flame, if it is operated with a 10kJ chemical ignitor pointing in one direction as this give rise to jet flame line source ignition and impingement of the initial flame on the wall. This is not recognised in the ISO standard and it is not a requirement to demonstrate that a spherical flame has been achieved. The 1 m^3 ISO vessel was modified to use two 5 kJ ignitors either in opposed jet configuration, or as in all of the present work as two ignitors impinging on a small hemisphere in the centre of the vessel to give a near spherical central ball of hot ignition gases (Phylaktou et al. 2010). The opposed 5 kJ ignitors was an instable ignition configuration as it was difficult to align the two ignitors to give reproducible impingement of the ignition jets.

2. Experimental Work

2.1 Materials tested

Corn flour was used as the primary raw material for the calibration of the different dispersers. A range of nominal (just mass in the external pot divided by the volume of the test vessel at a standard atmosphere) concentrations of corn flour that was tested using the standard C-tube (5L dust pot – 20 barg) dispersion system. The same nominal concentrations were repeated on the new dust dispersers to check the repeatability of results. Fixed nominal concentrations (750 g/m^3) of walnut shells and pistachio nut shells were also tested on the standard system and with the new dispersers to justify the calibration over the range of K_{st} materials. The concentrations of nut dusts were kept at 750 g/m^3, as this is the worst case concentration found in previous work on nut shells biomass dusts (Sattar et al. 2012). Nut shells were used as they pulverise like coal due to their brittle structure and fracture similar to coal. Pine wood dust mixture was used as fibrous biomass with calibrated dispersers. Walnut shells and pistachio nut shells were sieved through a 500μm sieve (rather than 63 μm, as required by the standard) to simulate more realistic particle size distributions whereas pine wood dust mixture and corn flour were received as fine powder so no sieving was done for these materials. The basic characterisations of raw material used in this study are given in previous publications from the authors (Sattar et al. 2012, Sattar et al. 2012).

2.2 The Leeds ISO 1m^3 standard dust explosion vessel

The Leeds ISO 1 m^3 dust explosion vessel was construction in accordance to the specification of the ISO 6184/1 (1985) standard. It is not a sphere and is a cylinder with rounded edges with a length to diameter ratio of ~1 and the volume is actually 1.138 m^3. For reference dust explosions tests using the standard dust injection system (5L dust pot with C-tube as disperser), the test dust was placed inside the standard 5 litre (actual volume 4.6L) external dust pot. The volume of this was later increased to 10 litres as discussed previously (Sattar, Huescar-Medina et al. 2013). The standard C-tube disperser inside the main vessel was connected to the external dust pot via a 19 mm diameter pipe with a fast acting electro pneumatic ball valve in between them. The total perforations area in the C-tube was 331 mm^2. The dust pot was pressurised with air to 20 barg, according to ISO standard 6184/1 (1985). The pressure in the 1 m^3 vessel was reduced to 933 mbara using a vacuum pump. The ball valve was actuated using a sequence generator which resulted in an increase the vessel pressure to nominal pressure (1013 mbara) prior to ignition. The sequence generator actuated the ball valve and after a preset time delay two 5kJ Sobbe igniters were firing into a small perforated hemispherical cup in the centre of the vessel. The ignition in the hemispherical cup was made to avoid the problems of directional ignition effects and to achieve a spherical flame (Phylaktou et al. 2010).

For laminar gas explosions, gas mixtures were made according to the principle of partial pressures in the main vessel after evacuating the vessel to less than 200 mbara. This was followed by the introduction of the required volume of fuel gas and air so that the pressure in the main vessel was maintained at 1013 mbar, prior to ignition. No air was injected from the external dust pot and the vessel was left to mix the gases by diffusion so that laminar flame conditions then occurred in the explosion. For turbulent gas explosion tests, after the injection of fuel, the vessel pressure was increased to 933 mbar (rather than 1013 mbar). The external dust pot was pressurised to 20 barg and operation of the ball valve resulted in increase the vessel pressure by 80 mbar, so that the total pressure in the vessel prior to ignition was 1013 mbara. This was the same air injection as for dust explosions and was assumed to create the same vessel turbulence as for dust explosions. It is possible that the presence of the dust ahead of the air injection alters the turbulence, but there was no way of determining this. After a controlled delay, a 16J capacitance spark (0.5m long electrodes) extended to the centre of the vessel was used to ignite the gas-air mixtures.

The main vessel and the external dust pot were equipped with absolute pressure transducers. The pressure transducers were used to monitor and record the pressure changes against time during the explosion process in main vessel and external pot. The rate of pressure rise in the main vessel was calculated by differentiation of the explosion pressure time record, after the elimination of electronic noise by smoothing the pressure record. A record of the rate of pressure rise as a function of time was then produced and the peak value of this was used in the K_{st} determination. This methodology ensured that any turbulence created by the high energy chemical ignitors was counted as part of the overall turbulence in the dust explosions.

The Leeds ISO 1m^3 dust explosion vessel was modified for the measurement of flame speed. An array of 13 type-K thermocouples was positioned at known distances along the horizontal axial centreline of the vessel. A similar array of 9 thermocouples was positioned along the vertical radial centreline (bottom half of the vessel) shown in Fig 1(b). Further details about the description of the experimental setup is given elsewhere (Sattar et al. 2012, Sattar et al. 2012).

2.3 Problems with fibrous biomass testing

Fibrous biomass could not flow through the standard C-tube dispersion system. Attempts were made to disperse the fibrous biomass dust through C-tube which resulted in failure of dust dispersion. The fibrous dust blocked the C-tube dispersion completely, it formed the biomass into a pellet which was difficult to extract from the tubes. A pot pressure trace from the dispersion of fibrous biomass dust using the C-tube showed that initially air and dust started to flow out of the dust pot, but was restricted after discharging almost 7 bara of air pressure. Very little of the dust was able to pass through the C-tube disperser which resulted in ‘no explosion’ as the injected mixture was too lean to burn. Thus there was a need to develop a new dispersion system which could disperse the fibrous biomass dust successfully in the test vessel before explosions with coarse particle size biomass dusts could be investigated.

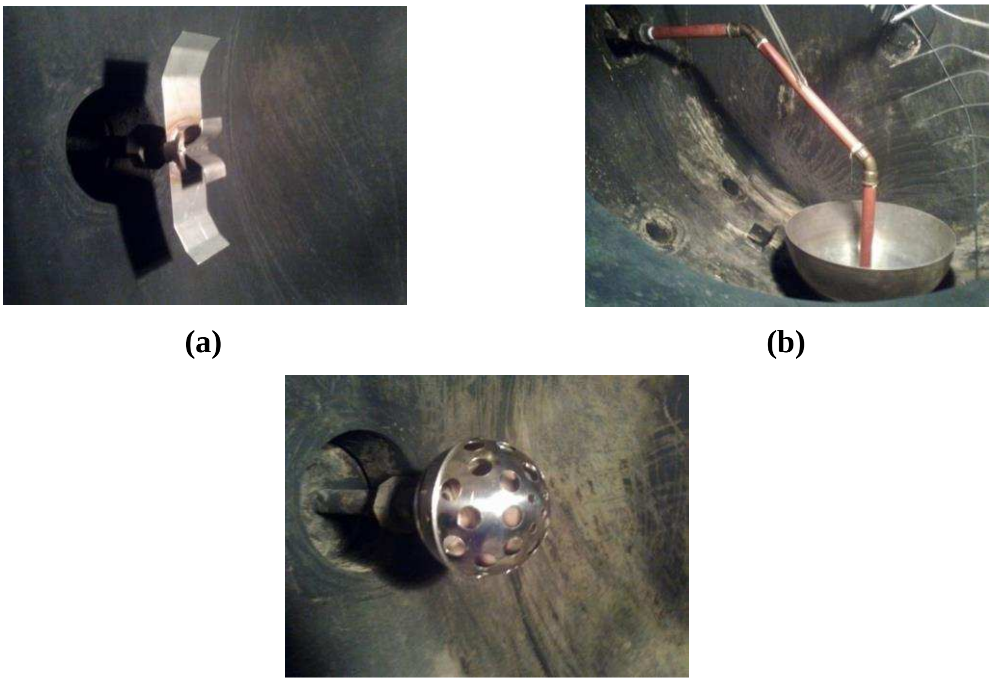
3. Design of new dispersion systems for the dispersion of fibrous biomass in 1m^3 dust explosion vessel

In order to deal with the poor flowability of fibrous biomass dust, three dust dispersers were initially selected and designed for this investigation, as shown in Fig. 1;:

1) the rebound nozzle,

2) the hemispherical dispersion cup and

3) the spherical grid nozzle.



(a) **(b)**

(c)

Fig. 1: Dust dispersion systems developed for the study of fibrous biomass dusts. **(a)** Rebound nozzle, **(b)** Hemispherical dispersion cup and **(c)** Spherical grid nozzle.

The rebound nozzle and the hemispherical dispersion cup were selected because these were mentioned in the European standard for fibrous dust testing with no calibration details and no design details for the hemispherical cup (BSEN14034-3 2006). The spherical grid nozzle was developed as a part of this investigation, the design used was similar to those used for explosion dry powder suppressants.

3.1 Rebound nozzle

The basic design of the rebound nozzle was taken from BSEN 14034-3 (2006). The rebound nozzle contained a V-shaped disperser located on the centre of a 20mm internal diameter hole (see **Fig. 2a**). In the notch of V-shaped three additional holes of 4mm diameter were drilled. The dust comes out of the 20mm hole of the round nozzle, strikes the V-shaped disperser and deflects towards the deflector plate. After striking the deflector plate it gets dispersed in the test vessel (Wilén et al. 1999). The total cross-sectional flow area of the rebound nozzle was around 320mm^2. In this study, the dust in the case of the rebound nozzle flows from the external 10L dust holding pot pre-pressurised to 10barg. The calibration of the 10L dust against standard system has already been published (Sattar et al. 2013).

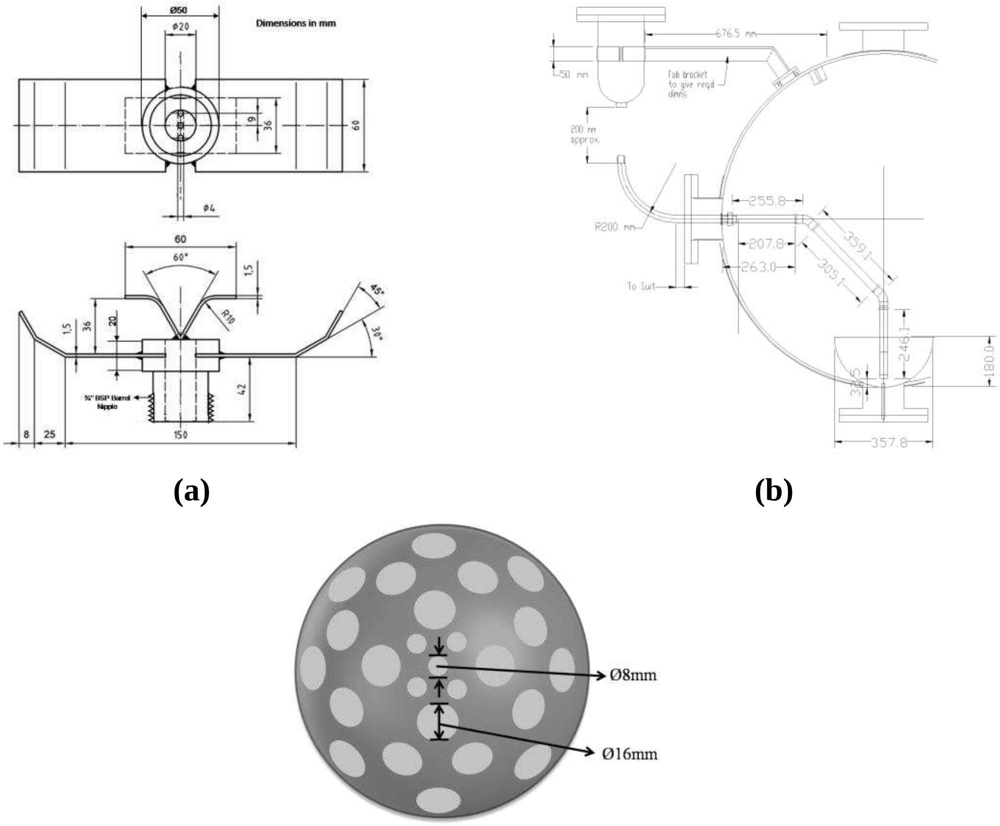
3.2 Hemispherical dispersion cup

The main advantage of this disperser is that the dust does not have to flow from the external dust holding pot so there will be no resistance to the dust flowing from external dust pot. The testing of as milled fibrous biomass samples containing large particles of fibrous dust could be performed using this disperser. The dispersion mechanism of the hemispherical disperser that was investigated in the present work is similar to that in the Hartmann equipment where the dust is placed inside the disperser cup. The dispersion cup is then placed inside the test vessel. The dispersion of dust in the test vessel is with a blast of air flowing from the external dust holding pot outside the test vessel. Although, there is a photograph of a hemispherical disperser in BSEN 14034-3 (2006), there are no details of its size or the method of dispersion of the air at the exit of the air supply pipe from the external pressurised air pot, which had no dust in it.

The lowest bulk density of the biomass that was likely to be tested was 175 kg/m^3, which is based on measurements of this for coarse fibrous biomass. 2 kg of dust in the test is usually required for mixtures close to the maximum pressure and this requires a diameter of the hemisphere to be 350mm. This is a volume of 22L, considerably greater than used in the external pot for holding dust in the standard 1 m^3 vessel and bigger that the modified pot volume investigated by Sattar et al. (2013). The nearest commercially available stainless steel hemisphere was 358mm in diameter which was selected for this study. The design of the air delivery system from the dust holding into the bottom middle of the hemispherical dispersion cup within the Leeds 1m^3 dust explosion vessel is shown in **Fig. 2(b)**. The unobstructed free pipe outlet of the air delivery pipe was placed at one pipe diameter above the bottom surface of the hemisphere to ensure maximum conversion of pressure energy into kinetic energy (Bernoulli’s theorem). As there was no flow of dust from the external pot (only air), so standard 5L dust holding pre-pressurised to 20barg was used with this disperser system. This was an initial design for the hemispherical disperser and it was envisaged that the high velocity single air jet would give jet penetration in reverse flow to the top of the vessel, carrying entrained dust with it. However, this will be shown to be a false assumption and the results will show this proved not to be a suitable design, due to not achieving a spherical flame. Work has continuing on the development of this injection system as it is the only system that can deal with practical coarse fibrous biomass particles. A multi hole outlet to the air injection pipe with the same number and size of holes as in the C ring, has been shown to give an improved performance [Saeed et al., 2015, 2016].

4.3 Spherical grid nozzle

This disperser nozzle is similar in design as the flame suppressant nozzle that contains holes in the front half with no holes were drilled in the back half. The reason for this is that a full spherical grid disperser had previously been tested and although it enabled a dust explosion to take place, much of the dust injected was injected onto the wall and did not participate in the explosions and there was no spherical flame propagation. The diameter of the re-design spherical grid nozzle was 110mm which had 9 holes of 8mm in diameter and 24 holes of 16mm in diameter arranged on a triangular pitch, as shown in **Fig. 2(c)**. Some holes present on the side of the disperser could not be shown in **Fig. 2(c)**. The total flow area of the re-designed spherical grid nozzle was 5278mm^2. The dust was injected for the spherical grid nozzle (as for the rebound nozzle) from the external 10L dust holding pot that was pre-pressurised to 10barg. Both the rebound nozzle and the hemispherical grid dispersion cup still had to deliver fibrous biomass from an external pot to the dispersion head. It was found that the connecting pipe with the fast acting valve would not pass coarse biomass, but would pass biomass milled to <63µm and all the present results for biomass were carried out with biomass milled to <63µm with the non-fibrous characteristics of nut shell dusts. This was because the calibration dusts had to be usable on the standard C tube disperser as well as on the new designs.



(a) **(b)**

(c)

Fig. 2: Design of **(a)** Rebound nozzle, **(b)** Hemispherical dispersion cup and **(c)** Spherical grid nozzle, in Leeds 1m^3 dust explosion vessel for the study of fibrous biomass dust.

4. Results and Discussions

4.1 Evaluation of the turbulent to laminar burning velocity enhancement using gas/air explosions.

The impact of the air injection turbulence on the turbulent to laminar flame speed and K_G ratios for the different dust dispersers was found by varying the ignition delay for each disperser with 10% turbulent methane gas explosions and comparing this with laminar gas explosions, as used by Sattar et al. (2013). The reference turbulent factor based on K_G for the standard C-tube (5L dust pot – 20barg) dispersion system was 4.0, as shown in **Fig. 3**. The criterion for the calibration of the ignition delay was to achieve the same turbulence factor as the C-tube dispersion system for gas explosions.

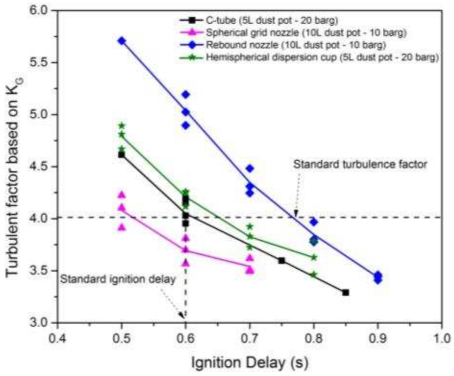


Fig. 3: Effect of ignition delay on the turbulent factors with 10% methane.

Fig. 3 shows that the rebound nozzle for the same ignition delay as the C ring disperser had higher turbulence and hence if used without recalibration of the ignition delay will give high values of K_{st}. To achieve the same value of turbulence factor as the C ring Fig. 5 shows that the rebound nozzle requires an ignition delay of between 0.70 and 0.80s ignition delay. The repeated tests with the rebound nozzle at 0.7s ignition delay were closer to the repeated tests on the C-tube dispersion system at standard ignition delay of 0.6s. The Spherical grid nozzle for the same ignition delay gave lower turbulence than for the C ring and to achieve a comparable turbulent factor to that of the C-tube dispersion system a 0.50s ignition delay was required. The hemispherical dispersion cup is shown in **Fig. 3** to have turbulence factors slightly higher than for the C ring and the standard C ring ignition delay of 0.6s could be used.

4.2 Ignition delay variation for new dispersion systems for dust/air mixtures

In order to validate the findings of turbulence levels determined at different ignition delays using 10% methane gas/air explosions, ignition delays were varied with dust explosion tests carried out using cornflour at 750g/m^3 nominal dust concentration which is the worst case found for many dusts with the standard dispersion system (Eckhoff 2003). The ignition delay was varied with the standard C-tube (5L dust pot – 20barg) dispersion system and the new dispersion systems using cornflour dust explosions as a reference dust with the aim of achieving similar K_{st} and P_{max} as for the standard C ring disperser. The results for P_{max} and K_{st} for all the dispersers are shown in **Fig. 4** as a function of the ignition delay. The variation in the results of P_{max} and K_{st} in the standard system at the standard ignition delay and valve off timing (0.60s and 0.65s respectively) is shown in **Fig. 4** as the horizontal dotted line. The range of values was determined by repeat testing as detailed by Sattar et al. (2014).

The valve off timing (time difference between when the valve begins to open and when the valve begins to close) with the new dispersion systems was increased/decreased with the same time as that of the change in ignition delay, to tune the ignition delay and valve off timing sequence as for the standard dispersion system. This was to ensure the maximum delivery of dust from the holding pot into the test vessel at the ignition time. For the spherical grid nozzle at 0.50s ignition delay the valve off timing was not changed and was kept at 0.65s.

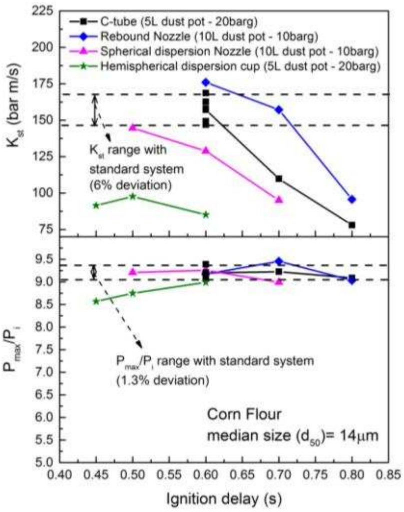


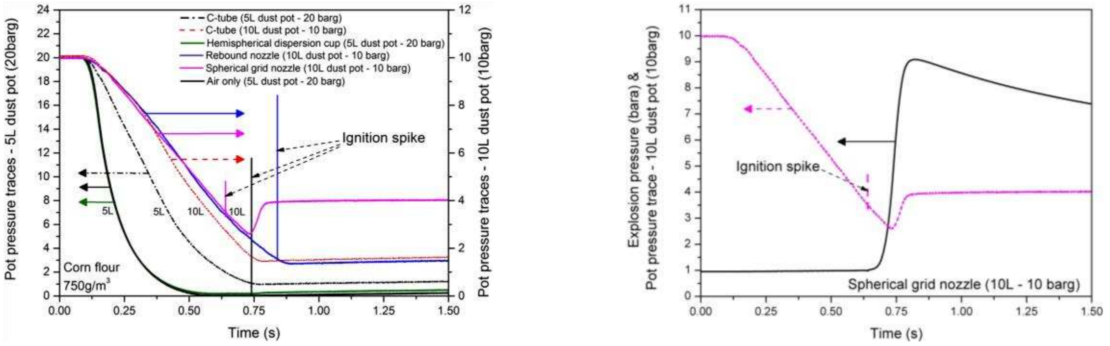
Fig. 4: Impact of the ignition delay on P_m/P_i and K_{st} for 750 g/m^3 cornflour.

Fig. 4 shows that there was no significant effect of the ignition delay on the maximum explosion pressure (P_{max}) apart from at low ignition delays for the hemispherical dispersion cup, but this did have the reference P_m/P_i at the 0.6s ignition delay. The deflagration index (K_{st}) was more sensitive to the ignition delay for all the dust dispersers. K_{st} decreased with increase in ignition delay for all the dispersers as shown in **Fig. 4**. The rebound nozzle gave comparable results in terms of P_{max} and K_{st} with the standard C-tube dispersion system at 0.70s ignition delay. The deviation in P_{max} was 2% but the K_{st} value obtained was similar to the standard dispersion system (almost same K_{st}). The 0.70s ignition delay found for the rebound nozzle with dust explosion tests confirmed the turbulence level findings with gas explosions as shown in **Fig. 3**. The turbulence level findings with gas explosions was also confirmed with the spherical grid nozzle which showed comparable results of P_{max} and K_{st} with the standard C-tube dispersion system at 0.50s ignition delay (**Fig. 3** and **4**). At 0.50s ignition delay the spherical grid nozzle produced similar explosion pressure (P_{max}) as the standard dispersion system, but the K_{st} showed 8% deviation from the standard C-tube dispersion system.

The hemispherical dispersion cup showed lower K_{st} than the standard C-tube dispersion system for all the studied ignition delays. The maximum explosion pressure (P_{max}) was comparable to the standard dispersion system (2% deviation) at 0.6s ignition delay which is the ignition delay found with gas explosion studies but the K_{st} values were lower than the standard dispersion system and showed a minimum 48% deviation. The implication of these results is that although the hemispherical disperser is burning the same amount of dusts as for the other dispersers, which controls the peak pressure, it is doing so more slowly and this implies less turbulence or non-uniform distribution of the dust inside the vessel. However, the gas studies showed that the turbulence factor was similar to that of the other dispersers at the calibrated ignition delay. The implication is that the presence of dust in this injection system reduces the turbulence or that the concentration of the dust in the initial period of flame propagation is lower than the average. This initial design of the hemispherical dispersion cup is not satisfactory and further development is required [Saeed et al., 2015a, 2016]

4.3 Justification of valve off timing

The dust pot pressure traces from the dust explosion tests with 750g/m^3 of cornflour for all the dispersion systems are shown in **Fig. 5(a)**. These dust pot pressure traces are all for explosions with the calibrated ignition delay that gave comparable results for P_{max} and K_{st} with the standard C-tube dust disperser,The dust pot pressure traces of the standard system at 0.60s ignition delay and 0.65s valve off timing is also shown in **Fig. 5(a)** for air only injection and dust-air mixture injection. **Fig. 5(a)** shows that the presence of the dust gives additional pressure loss compared to air only injection. The rebound nozzle and the C tube, both with a 10L dust pot and 10 barg air pressure, delivered almost the same content of dust-air mixtures from the dust pot into the test vessel, by increasing the valve off timing from 0.65s to 0.75s. Sattar et al. (2013) calibrated the C-tube with a 10L dust pot and 10barg air pressure against the standard system.



(a) **(b)**

Fig. 5: (a) Dust pot pressure traces for air only and air with dust (cornflour) injections from different dispersers, **(b)** Explosion pressure and dust pot delivery pressure trace from 750g/m^3 cornflour dust explosion using the spherical grid nozzle (10L dust pot – 10 barg)

The valve off timing for the spherical grid nozzle was kept at 0.65s for the optimum ignition delay of 0.5s. **Fig. 5(a & b)** show that keeping the valve opened for longer than the ignition delay resulted in some explosion pressure entered into the dust pot. The dust pot delivered its contents as long as the explosion pressure is less than the delivery pressure from the dust pot (**Fig. 5b**). The propagation of the explosion pressure into the dust pot with the new dispersers was also recognised and allowed for in BSEN14034-2 (2006) p. 11. The difference in the residual dust pot pressure from the spherical grid nozzle and rebound nozzle was almost 1 barg, as shown in **Fig. 5a**, which means that less air has entered the explosion vessel. The change in the explosion vessel overall air to fuel ratio/ A/F, as a results of this was small as the volume of the 10L dust holding was only 1% of the volume of test vessel and 1 bar pressure left there meant that only 10% of the air had not been injected, which is 0.1% of the total air. The comparable explosion pressure and rate of pressure rise generated from the spherical grid nozzle at 0.5s ignition delay and 0.65s valve off timing is shown in **Fig. 4**. This also illustrate that the same mass of air and dust was delivered into the test vessel from the dust pot. The phenomenon of explosion pressure entering into the dust pot was only seen with rich dust/air mixtures, but not with mixtures leaner than the concentration for the highest K_{st}.

In the case of the hemispherical dispersion cup where no dust was placed in the external dust holding pot, there was no restriction to the flow of air from the dust pot as shown in **Fig. 5a** and the air flowed into the vessel much faster than for the other systems. It was anticipated that the reason for having a low K_{st} in **Fig. 4** could be due to the presence of the dust around the air injection pipe outlet that offered some resistance to the jet of air flowing out of the delivery pipe. This is not shown in **Fig. 5(a)** as the delivery rate of the air flow in case of hemispherical dispersion cup system was similar to the air only injection from standard C-tube dispersion system. The low K_{st} in Fig. 4 for the hemispherical cup with the open tube air injector is not due to low turbulence or inadequate air injection. Thus it must be due to a poor distribution of the dust. It was found after the tests that there was evidence of dust deposits on the ceiling of the vessel, indicating that the air jet velocity was too powerful and was reflecting off the bottom of the hemisphere and flowing up the centre part of the vessel carrying dust into the top part of the vessel. This could then leave the central ignition region lean of fuel resulting in a slower initial flame and lower K_{st}.

4.4 Proposed setting for new dust dispersion systems

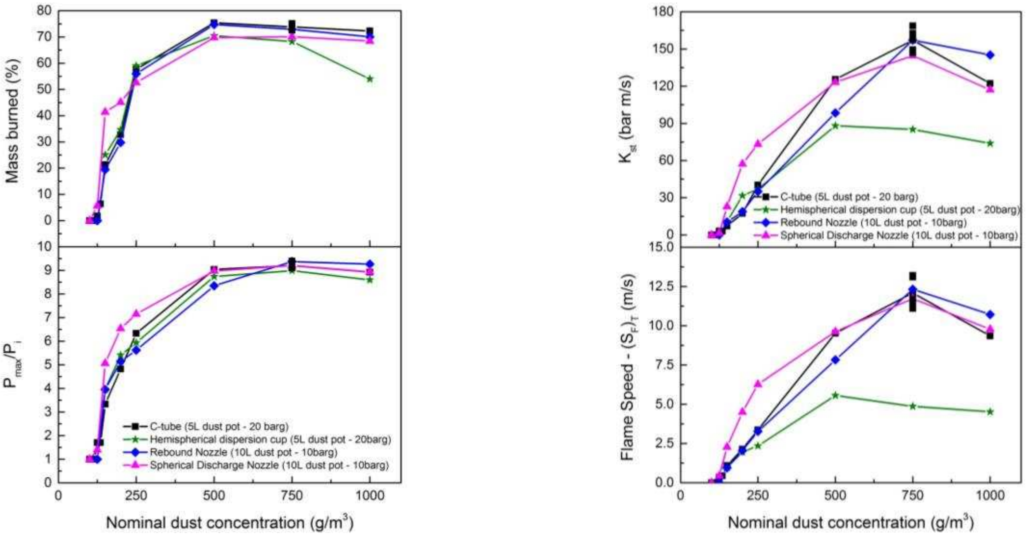
In replacing the standard C-tube dust disperser with the rebound nozzle, spherical grid nozzle or hemispherical dispersion cup in the standard ISO $1m^3$ dust explosion vessel, the new calibrated settings are summarised in **Table 1**. The hemispherical cup showed turbulence levels similar to the standard system at 0.6s ignition delay using gas explosion tests as shown in **Fig. 3**. It also produced similar P_{max} as the standard system with dust explosion tests. The only problem was the lower K_{st} shown in **Fig. 4**. It was possible that the design of the dust injector influenced the concentration at which the peak K_{st} occurred and that this was the reason for the lower K_{st} for the hemispherical cup. Therefore, dust explosions were carried our at different nominal dust concentrations at the ignition delay timings in Table 1.

Table 1: Proposed settings for newly designed of dust dispersion systems that give comparable results with the standard C-tube dust dispersion system

Dispersion system	**Ignition delay (s)**	**Valve off timing (s)**
Rebound nozzle **(10L dust pot – 10 barg)**	0.70	0.75
Spherical grid nozzle **(10L dust pot – 10 barg)**	0.50	0.65
Hemispherical dispersion cup (5L dust pot – 20 barg)	0.60	0.65

4.5 Effect of cornflour dust concentrations on Kst and P_m/P_i using the standard C-tube dispersion system and new dust dispersion systems at the calibrations settings in Table 1.

The influence of the nominal cornflour dust concentration on the explosion properties (P_{max}, mass burned%, K_{st} and flame speed) for the new dispersion systems are compared in **Fig. 6(a & b)**. In the case of the hemispherical dispersion cup, the dust was placed inside the test vessel, so there were no injection system dust losses. However, there is a mechanism of dust loss in all dust explosions that was first highlighted by Sattar et al. (2012 a, b) and this was that after the explosion about half of the initial mass of dust was left on the bottom of the vessel. The composition and size distribution of this dust was shown to be practically the same as the initial biomass. This was dust blown ahead of the flame by the explosion induced wind and deposited on the walls, without being consumed by the flame. Thus the equivalence ratio at the flame front was not that based on the mass of dust injected. It was thus explored whether the proportion of dust that burnt in the explosions was influenced by the injection system, which would then result in different nominal concentrations for the peak reactivity. The % of the nominal mass that was the burnt mass is shown in **Fig.6(a)** which shows that the hemispherical dispersion cup had similar values to the other systems apart from at the highest nominal concentrations. Thus, the K_{st} was not low due to much lower burnt concentrations at the point of peak reactivity. All the other dispersers also had similar proportions of the mass burnt to the standard ‘C’ disperser at all nominal concentrations. A feature of **Fig. 6(a)** is the difficulty in using the nominal concentration for MEC measurements, as the proportion of injected dust that participated in the explosion was very low just before the nominal MEC. Hence, the dust concentration that the near limit flame was propagating through is potentially much leaner than the nominal concentration [Saeed et al., 2015b].



(a) **(b)**

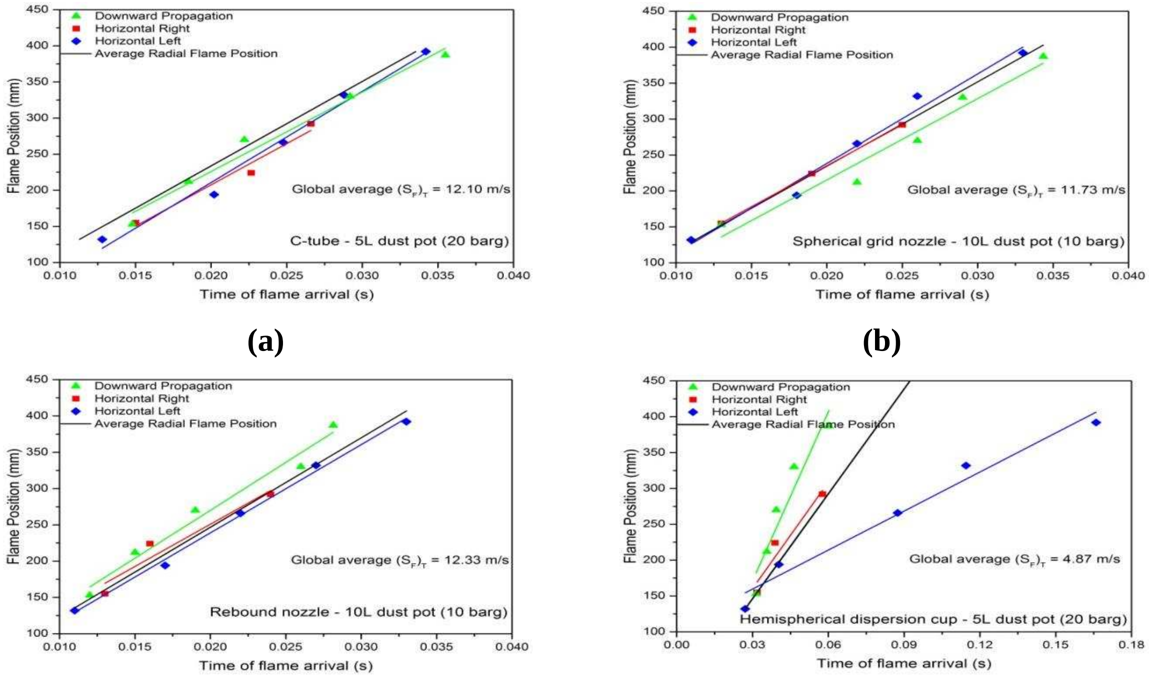
Fig. 6: (a) P_{max}/P_i and mass burned (%), **(b)** Flame speed and K_{st} obtained as a function of cornflour dust concentration from studied dispersion systems in 1m^3 dust explosion vessel at the proposed settings.

Fig. 6(a) shows that all the new dispersion systems with the calibrations in Table 1 gave comparable results in terms of P_{max}/P_i. The spherical grid nozzle produced marginally higher P_{max}/P_i for the mixtures leaner than most reactive mixtures. The higher values of P_{max}/P_i compared to standard dispersion system were due to high percentage of mass burned, as shown by the spherical grid nozzle for low concentrations. The average deviation in P_{max}/P_i for the spherical grid nozzle was within 10% of the standard dispersion system. The reproducibility in the results of K_{st} and flame speed obtained from the spherical grid nozzle was also within the acceptable range (20% average deviation) as shown in **Fig. 6(b)**. The dust concentration was varied from the MEC to beyond the most reactive mixture. The nominal MEC for all the nozzles was the same at 125 g/m^3 for all the dust dispersion methods. **Fig. 6(a & b)** shows that with the calibrations in Table 1 the concentration for the maximum K_{st} and P_m/P_i was the same at 750g/m^3 for all the dispersers, apart from the hemispherical dispersion cup. The hemispherical dispersion cup produced comparable results of P_m/P_i and mass burned (%) to the standard dispersion system but the values for K_{st} and flame speed obtained were lower, 48% lower for K_{st} and 60% lower flame speed.

One reason for rate of burning to be lower and the peak pressure the same as for the other dispersers, in the case of the hemispheric dispersion cup, was that the flame was not spherical. A spherical flame has the maximum burning rate in a spherical vessel. This was investigated by determining the flame speed in two directions at 90^o to each other. **Fig. 7** shows that the flame travelled spherically for all the dispersers except the hemispherical dispersion cup. **Fig. 7** shows that the flame was propagating faster in the downward direction than in any other direction. It was decided that further work was needed to improve the dispersion of dust in the hemispherical injector to achieve a spherical flame [Saeed et al., 2015b, 2016].

4.6 Verification of proposed setting for new dust dispersion systems with other dusts

Further verification of the proposed settings for the new dispersion systems (rebound nozzle and spherical grid nozzle) was undertaken with dust explosion tests at 750 g/m^3 of walnut shells and pistachio nut shells. These biomass fuels were brittle and would pass through the standard C ring disperser. The explosion pressure traces obtained using the spherical grid and rebound nozzles are compared with the explosion pressure traces obtained from standard dispersion system in **Fig. 8**.

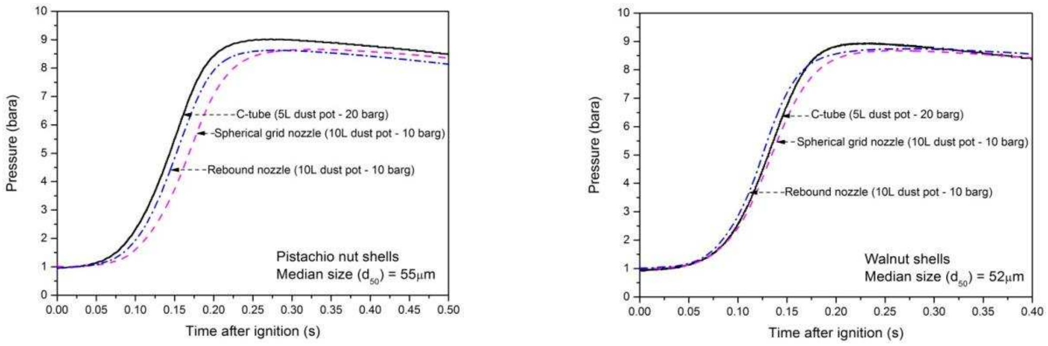


(a) **(b)**

(c) **(d)**

Fig. 7: Comparison of time of flame arrival vs distance from the spark obtained from the cornflour explosion test at 750 g/m^3 nominal dust concentration using **(a)** C-tube (5L dust pot – 20 barg), **(b)** Spherical grid nozzle (10L dust pot – 10 barg), **(c)** Rebound nozzle (10L dust pot – 10 barg) and **(d)** Hemispherical dispersion cup (5L dust pot – 20 barg)

The similarity of the pressure signals was excellent for pistachio nut shells and walnut shells for the different dispersers with the calibrations in Table 1. In general the rebound nozzle produced marginally faster tests and the spherical grid nozzle produced marginally slower tests. The overall spread of the corresponding P_{max} and K_{st} is well within accepted experimental variation, as allowed in BS14034-2 (2006). In line of the guidance in BS14034-2 (2006) on maximum permissible deviations, the new dispersion systems (rebound nozzle and spherical grid nozzle) are adequately calibrated with results comparable to the standard dispersion system for explosion pressure, fraction of mass burnt, flame speed and K_{st} using non-fibrous dusts. The rebound nozzle and spherical grid nozzle system should be suitable be for the determination of explosibility properties of fibrous materials biomass dust milled to <63µm.



(a) Pistachio nut shells **(b) Walnut shells**

Fig. 8: Explosion pressure histories of the dust explosion tests carried on standard dispersion system and new dispersion systems (Spherical grid nozzle and Rebound nozzle) at the determined valve off and ignition delay timing. **(a)** Pistachio nut shells **(b)** Walnut shells.

4 Conclusions

Three alternative dust dispersion systems for fibrous biomass were calibrated against the standard C-tube: 1) Rebound nozzle, 2) Hemispherical dispersion cup and 3) Spherical grid nozzle. This calibration was carried out using gas explosions and dust that would pass through the standard C ring injection system, fibrous biomass could not be used for the calibration as it would not pass through the reference C ring dust disperser. The rebound nozzle and spherical grid nozzle showed promising results against the standard C-tube dispersion system. The new calibrated conditions for the rebound nozzle were determined using gas and dust-air mixture explosions to be 0.70s ignition delay and 0.75s valve off timing and for the spherical grid nozzle were 0.50s ignition delay and 0.65s valve off timing. These calibrated timings were further verified by varying the concentration of cornflour using the standard C-tube disperser and new dispersers. The calibrated timings of the rebound nozzle and spherical grid nozzle were also verified by comparing the results of 750 g/m^3 pistachio nut shells and walnut shells explosion tests on standard dispersion system. The new dust dispersion systems reproduced reliably the P_{max}/P_i, K_{st}, flame speed, fraction of mass burned and spherical flame propagation of the standard C tube system.

The third newly studied dispersion system; hemispherical dispersion system showed good calibration results with gas explosions and dust explosions for the calibrated 0.60s ignition delay and 0.65s valve off timing. However, the dispersion method did not produce a spherical flame and all the other dispersion system did. This led to a slower and non-uniform rate of flame propagation and significantly lower K_{st} values. The disperser produced comparable results in terms of P_{max}/P_i and fraction of mass burned as standard dispersion system but the K_{st} and flame speeds were too low due to the non-spherical flame propagation. This system needs further work as it is the only viable system for very coarse biomass that is currently in use in power generation and experienced in saw mills.

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