Pulverised biomass flame propagation and explosion characteristics:
problems and solutions

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United Kingdom Explosions Liaison Group, UKELG
University of Leeds, 23.9.14

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Figure 2-8: Contribution of renewables including solar PV to electricity generation, from (DECC, 2014g)

Some recent incidents in different countries with biomass for power stations

<u>In May 2011</u>

- Explosion at UK biomass power plant.
  - Rupture of a PF pipe from a pulverised coal mill used with coal/biomass [1].
  - Pipe was pressure rated at 8 bar!
- 1.Private communication

<u>20th June 2011</u>

- Dust explosion at RWE's 750,000 ton wood pellet factory in Georgia, US [2].
  - Known as the world's largest pellet plant facility.
  - An overheated roller/bearing assembly in a pelletizer sparked the blast at the factory[3].

2. Renewables International Magazine, 'Following explosion, world's largest pellet plant resumes operation', 15 July 2011, available at http://www.renewablesinternational.net/following-explosion-worlds-largest-pellet-plant-resumes-operation/150/515/31440

3.http://woodbioenergymagazine.com/blog/2011/georgia-biomass-off-line-after-incident

A dust explosion test in large scale facility[2]

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   Hartmann for MEC

   20L sphere

   ISO 1 m³
5. **The unburned particle mass in the ISO 1m³**
6. **Modifications of the ISO 1 m³ vessel for woody biomass.**
7. **Leeds MEC results for woody biomass**
8. **Leeds ISO 1 m³ vessel results for biomass (Clara Huescar Medina will present this in the next lecture).**

Biomass dust have high volatiles that release at low temperatures relative to coal

- **Biomass dusts contain higher amount of volatiles compared to coal that make them more reactive.**
- **Biomass dusts release almost 70% of volatiles at low temperature (300-400ºC) as compared to coal.**
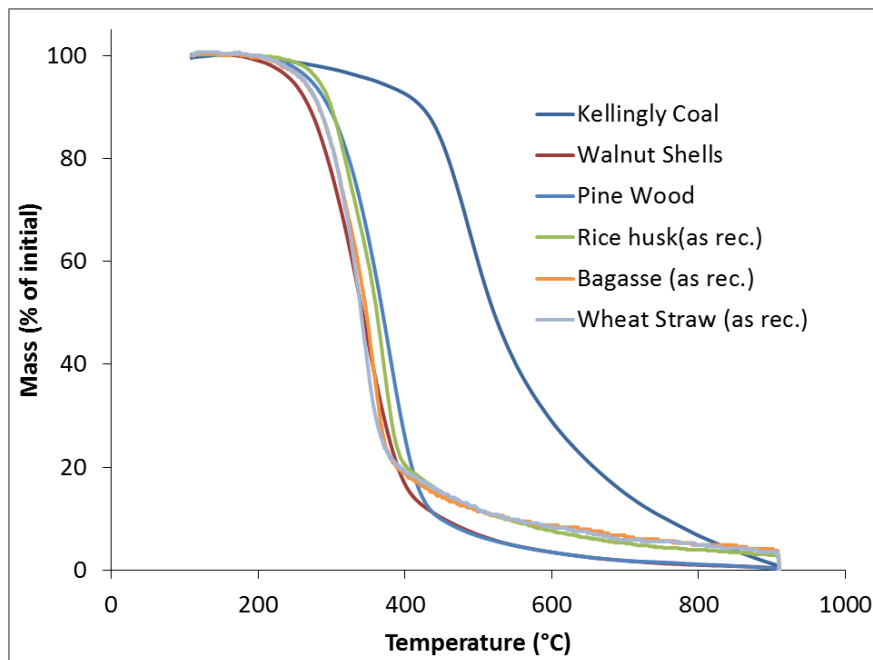
These volatiles cannot be HCs as there is insufficient H in the fuel. Pyrolysis analysis shows that the volatiles are mainly CO and H_2. This can also be shown by HCO balance with volatile mass.

% loss of volatiles as a function of temperature

Tenth International Symposium on Hazards, Prevention and Mitigation of Industrial Explosions XISHPMIE Bergen, Norway 10-14 June 2014
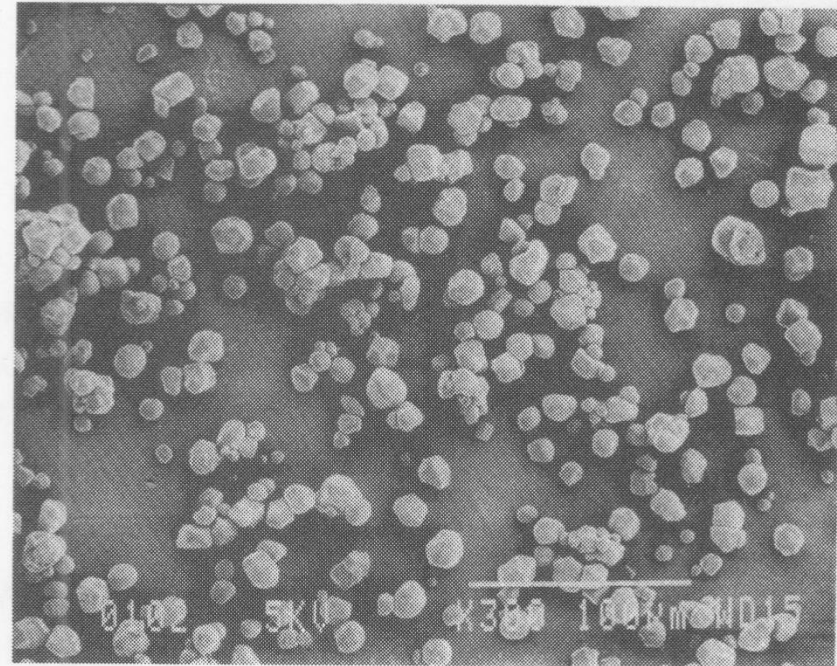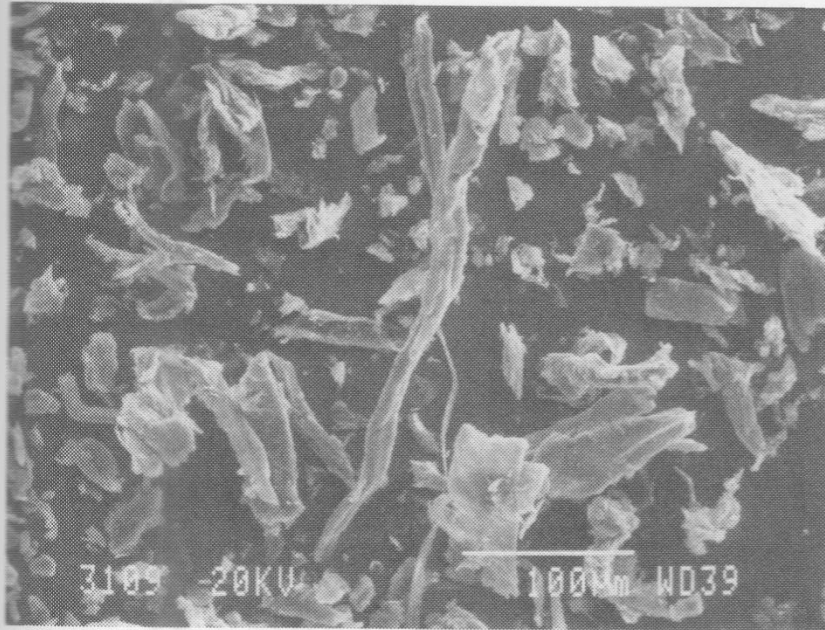
Figure 1.21 *Scanning electron microscope picture of wood dust (Courtesy of W. C. Wedberg).* Eckhoff, Dust Explosions, 2003, p.28.

Figure 1.22 *Scanning electron microscope picture of native maize starch; typical particle size 10–15 µm (Courtesy of W. C. Wedberg).*

The particle size and shape of pulverised 'woody' biomass is different to that of other agricultural dusts such as maize startch, where near spherical particles exist. Woody or fibrous biomass is also difficult to mill to <63µm, which is the required size for standard dust explosion characterisation.

United Kingdom Explosions Liaison Group, UKELG, meeting on Biomass Dust Explosions University of Leeds, 23.9.2014

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25.2.2013. Final Report 301007168 FPInnovations

Sawmill Wood Dust Sampling, Analysis and Explosibility
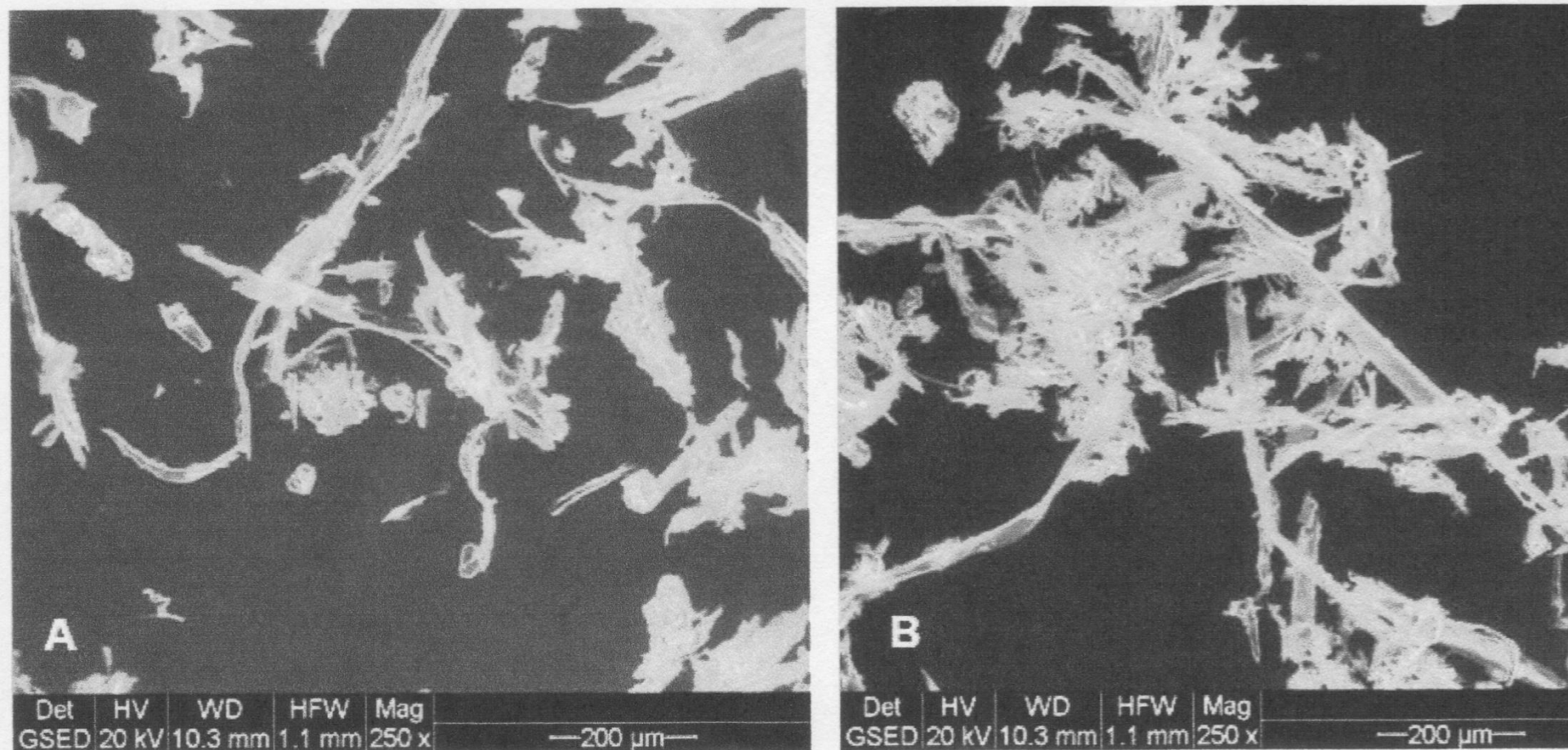
SEM analysis of wood sawdust that passed through a 1mm sieve but were Retained by a 425 μm sieve.

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Raw Spruce
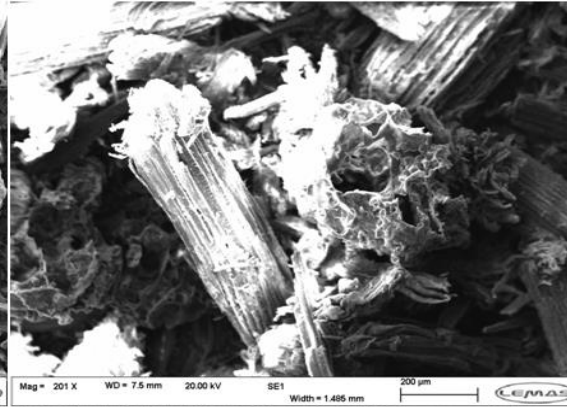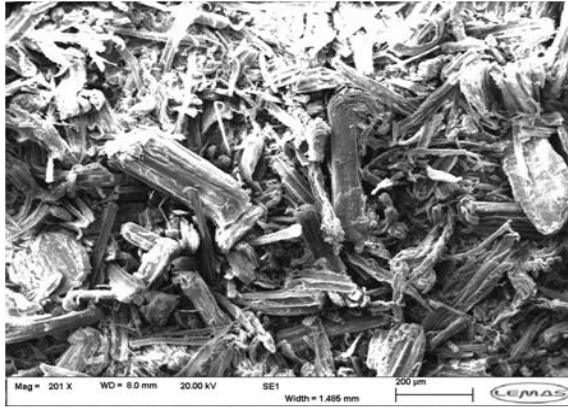
Debris after wood spruce explosion

Torrefied spruce
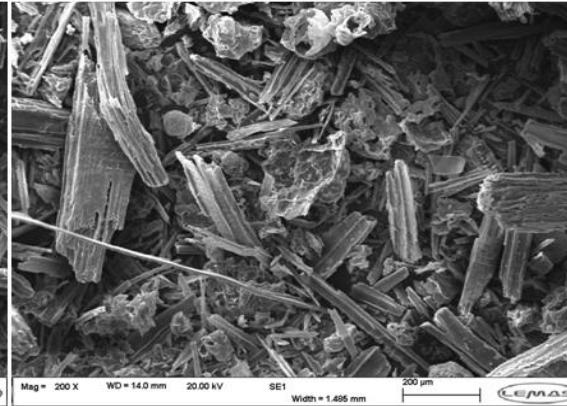
Debris after Torrefied spruce explosion

SEM images of the raw and torrefied wood samples.
The raw wood sample shows bigger particles than the torrefied sample which was confirmed by particle size analysis.
Explosions in the ISO 1 m³ have ~50% of the original biomass unburned and of a size and shape very similar to the original biomass, as confirmed by particle size analysis.

The particle size distribution of biomass makes the explosion characterisation more difficult than for gases.

Particle size – pulverised biomass reactivity depends on particle size and I will show evidence from our work and the literature that very coarse biomass particles will explode to up to 500μm.

The results I will show come from work we have done using the Hartmann explosion tube for biomass dusts that show large particles will explode.

Examples of biomass sent to us from power stations show that it is large particles that are being burned and the requirement in dust explosion standards to mill below 63 μm is unrealistic as biomass is not being burned and not exploding in this size range. Typically <2% of the biomass in power stations is <63μm.

However, for regulation compliance you have to mill the biomass into this size range and this is a major problem for the Kg quantities required for the 1 m³ equipment, but easier for the 1g quantities required for the Hartmann explosion tube,

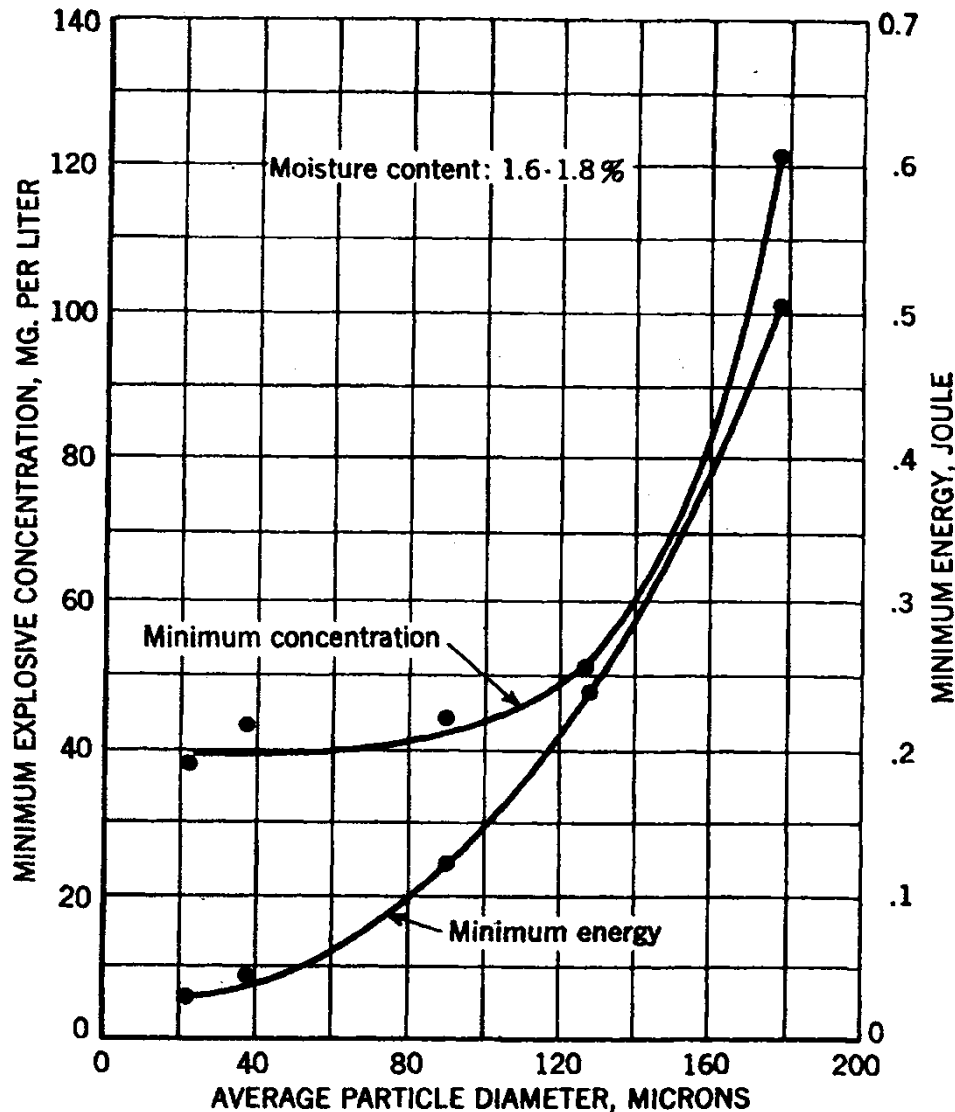Fig 3. Effect of particle size on lower explosive limit and minimum energy required for ignition of cornstarch dust clouds in air.

Hartmann, I., Dust explosions in coal Mining and industry.
The Scientific Monthly, Vol.79, pp.97-108, 1954

Cornstarch MEC depends on particle size down to 80-90μm and is then independent of size. Minimum ignition energy continues to decrease as the size is reduced.

Influence of particle size on MEC for coal and polyethylene

Hertberg and Cashdollar, US BM, 1987.
Introduction to Dust Explosions, ASTM SP 958 p.5-32
Also in Eckhoff Dust Explosions, 2003, p. 32

Equipment – 20L sphere
Coal has an MEC independent of particle size for <30μm for low volatile coal and <50μm for high volatile coal.
Polyethylene is 100% volatile and has an MEC independent of particle size for <80μm.
Kerosene sprays behave in the same way with the MEC independent of spray mean drop size for <70μm (Zabetakis, US BM, 1965)
There is nothing in the literature for coal, HC polymers or metal dusts that would lead to an expectation for biomass to explode at high particle sizes. Hartmann's work on cornstarch is the only indicator that HCO dust may behave differently.
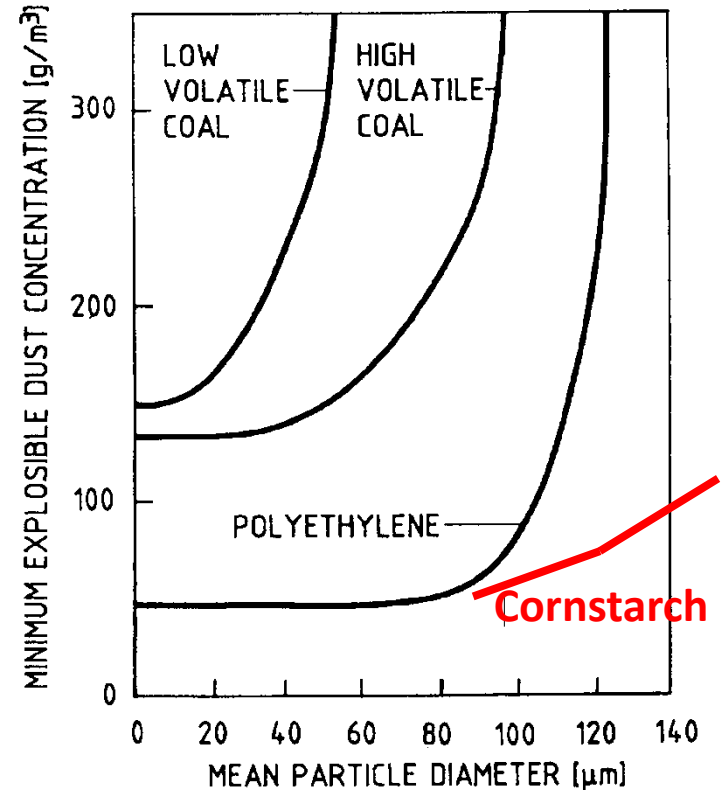
Figure 1.29 *Influence of mean particle diameter on minimum explosible concentration for three different dusts in 20 litre USBM vessel (From Hertzberg and Cashdollar, 1987)*

MEC Results v. particle size

Log scale MEC g/m³

MEC vs Particle Size

Agglomeration of particles after Milling in the injection Process.
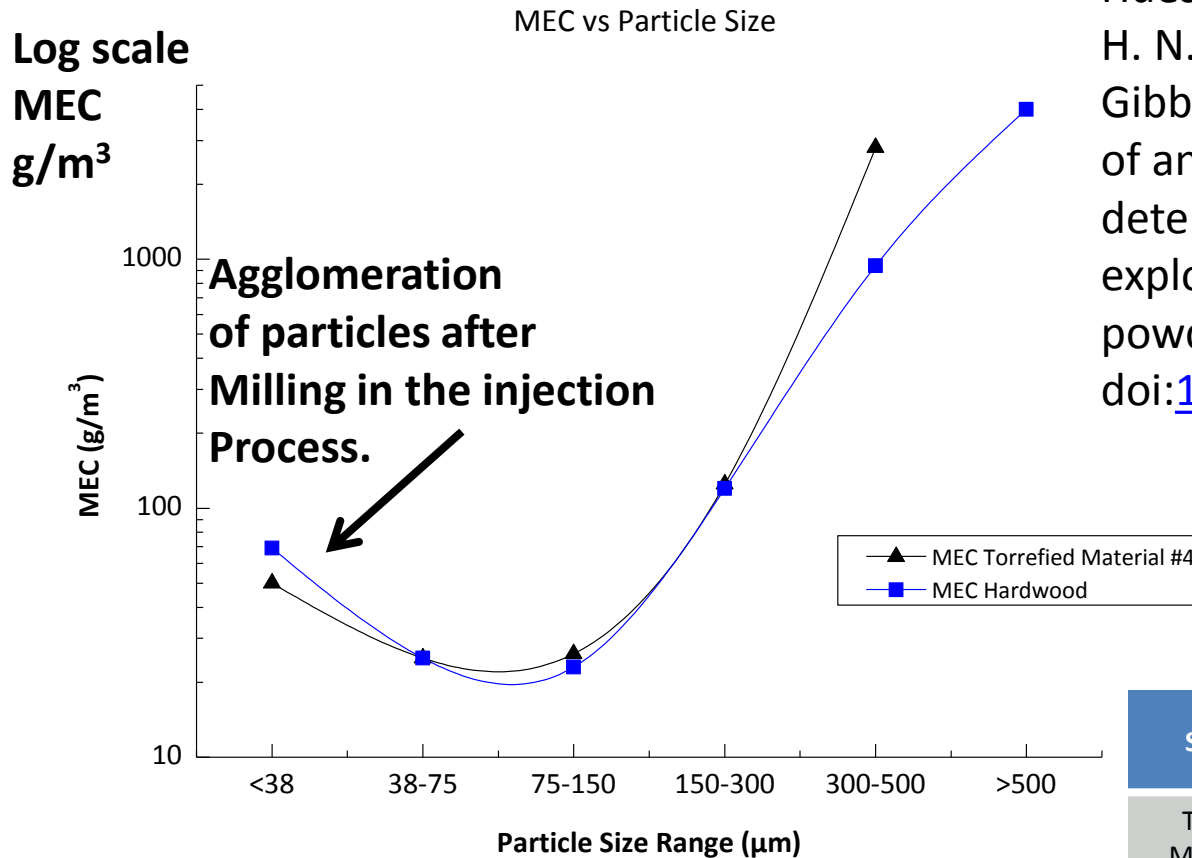
Huéscar Medina, C., Phylaktou, H. N., Sattar, H., Andrews, G. E., & Gibbs, B. M. (2013). The development of an experimental method for the determination of the minimum explosible concentration of biomass powders. *Biomass and Bioenergy*. doi:10.1016/j.biombioe.2013.03.008

Sample*	C	H	N	S
Torrefied Material #4	49.60	5.86	Trace**	Trace**
Hardwood	43.24	5.49	0.08	0.00

*As received
**trace: <0.3 wt%

David Slatter et al. U. Leeds. Proc. 7th Int. Sem. Fire and Exp. Haz. 2013
Influence of Particle Size and Volatile content on the reactivity of
HC and HCO Chemical and Biomass Dusts. P. 846 – 855.
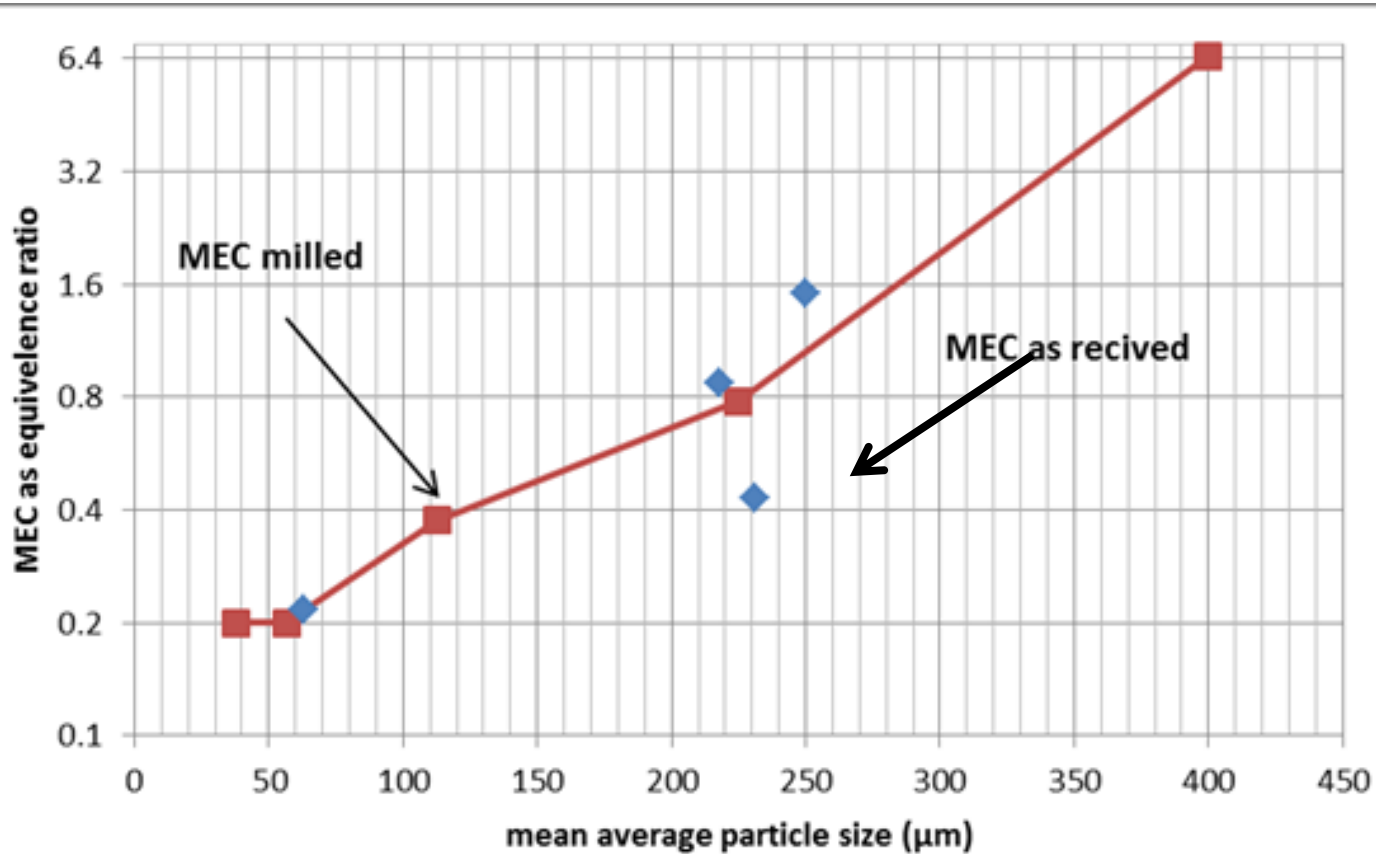
Mills for biomass are operated rich in the hope that they are outside the rich limit. These results show that this is not the case and very rich mixtures of coarse biomass can still explode. Their reactivity is very low but the pressure rise is high.

Pine wood

**The use of the rate of pressure rise and peak explosion pressure
In a closed spherical vessel to characterise dust explosion reactivity.**

6.1.1* The deflagration index, K, shall be computed from the maximum rate of pressure rise attained by combustion in a closed vessel with volume, V, and shall be defined by the following equation:

**The ISO standard requires
V to be 1 m³ but allows
20L as it is claimed to give
the same results.**

$$K = \left(\frac{dP}{dt}\right)_{max} \cdot V^{1/3} \qquad \textbf{(6.1.1)}$$

6.1.2* For dusts, K_{St} and P_{max} shall be determined in approximately spherical calibrated test vessels of at least 20 L capacity per ASTM E 1226, *Standard Test Method for Pressure and Rate of Pressure Rise for Combustible Dusts.*

**US NFPA 68 2007 and in B1.2.4 of the 2013 Ed.
However, all the values given in NFPA 68 are from a 1 m³ vessel.**

Bartknecht, Explosions, 1993, p.500, Springer Verlag

Cellulose

10m³

'C' Ring injector

Rebound nozzle injector

Cellulose : ○ 1 Staubbehälter
         ● 2 " "

Maize Starch
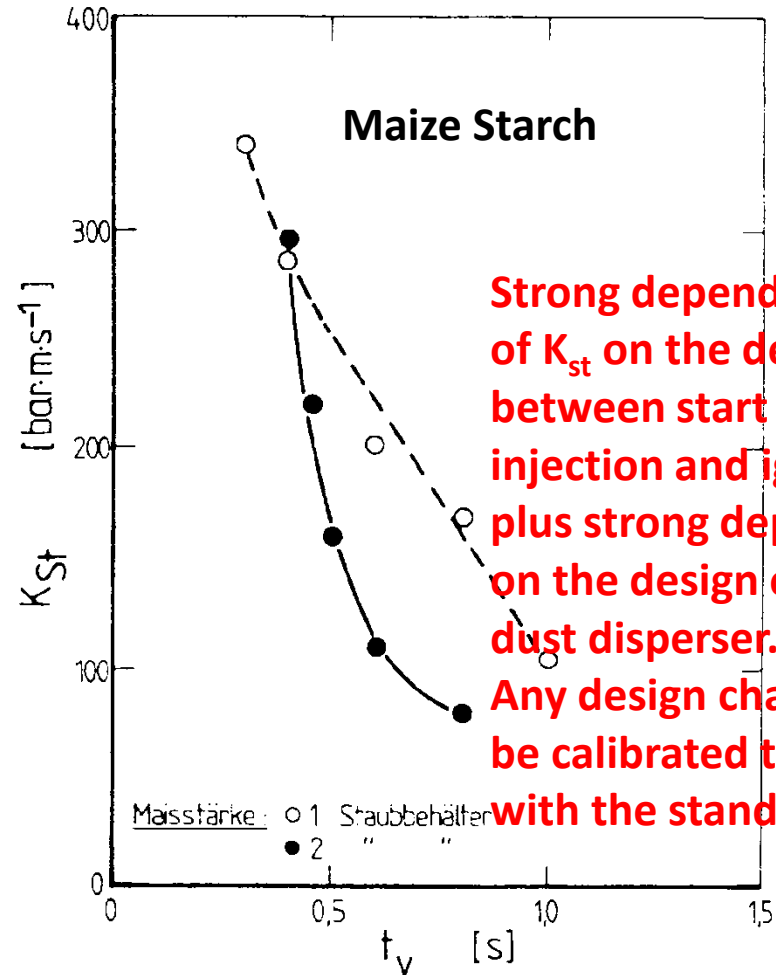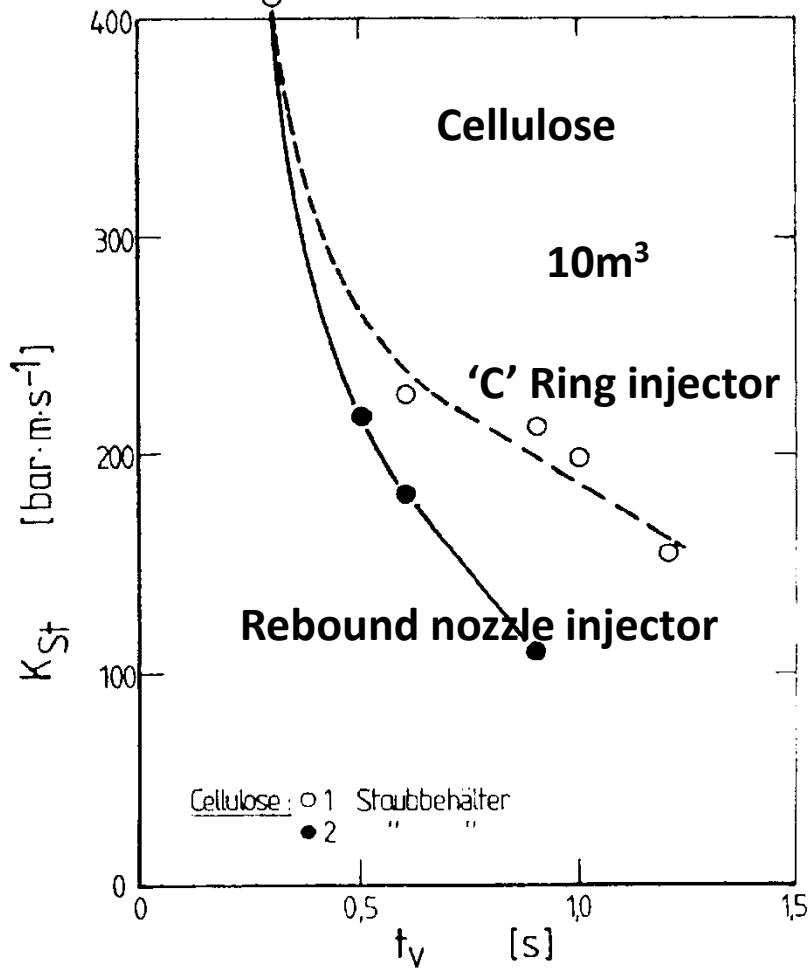
Strong dependence of K_{st} on the delay between start of air injection and ignition. plus strong dependence on the design of the dust disperser. Any design change must be calibrated to agree with the standard 1 m³.

Maisstärke : ○ 1 Staubbehälter
        ● 2 " "

Abb. 2.251. Zusammenhang zwischen staubspezifischer Kenngröße K_{St} und der Zündverzö-
gerungszeit t_v im geschlossenen 10 m³-Behälter (50 l-Staubvorratsbehälter)

Influence of dust injector design on K_{st} for V=10 m³

a
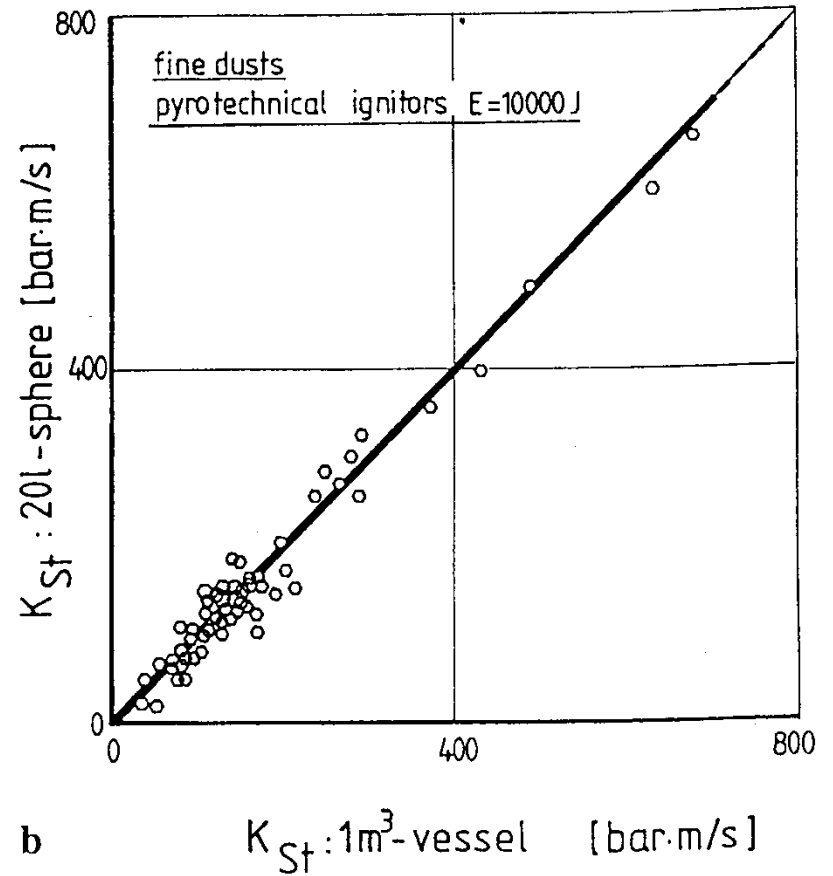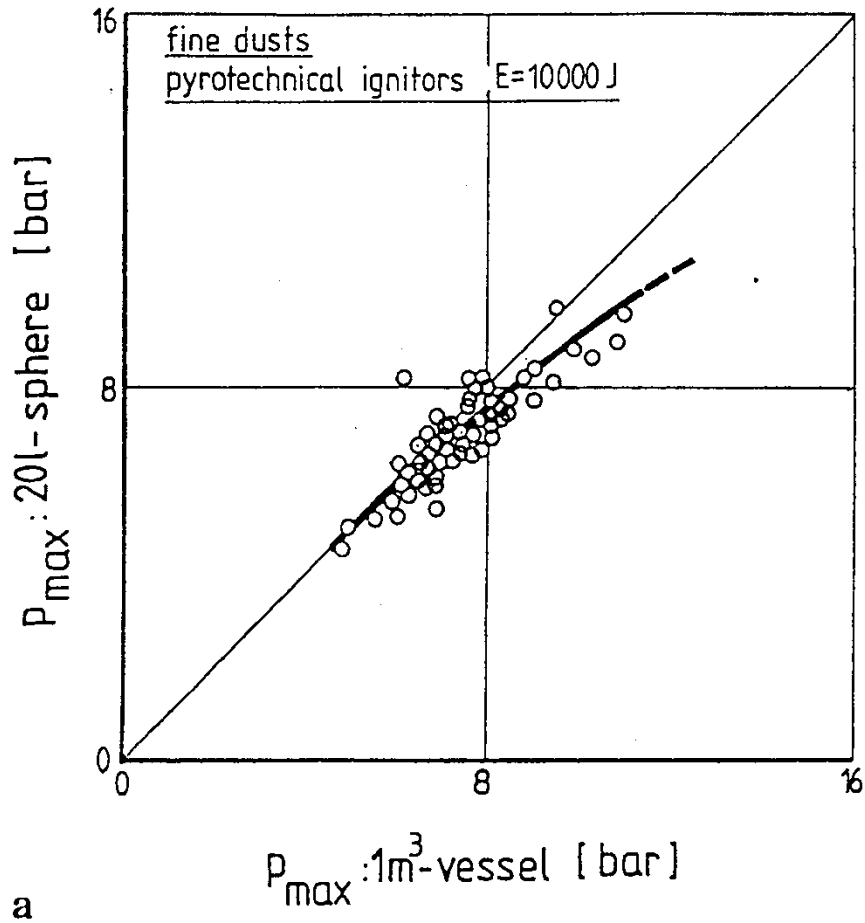
Bartknecht, Dust Explosions 1988
Eckhoff, Dust Explosions, 2003, p.531.

b

Fig. 67 a/b. Comparison of the explosion characteristics of combustible dusts measured in the 20-l laboratory apparatus and in the 1-m³ vessel; $p_i = 1.0$ bar (absolute)
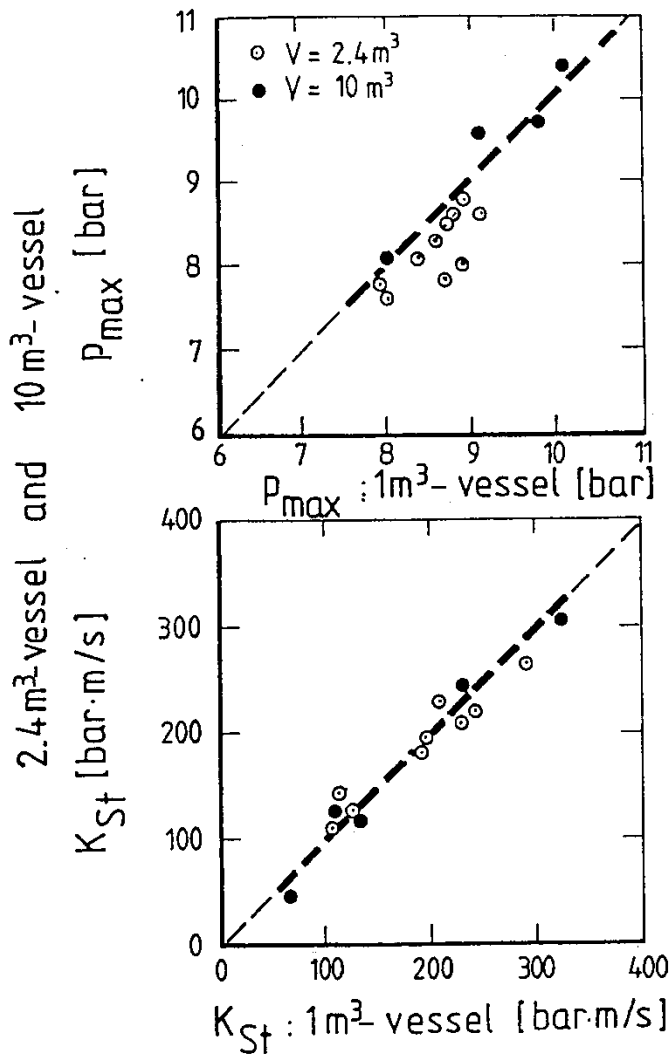
Fig. 64. Comparison of explosion characteristics of combustible dusts in vessels of different volumes

These results appear to show that K_{st} does not depend on the vessel volume. But the ignition delay is varied with volume and no details of the dust injection system is given for the large volumes.

Bartknecht, Dust Explosions 1988 & 1993 p.
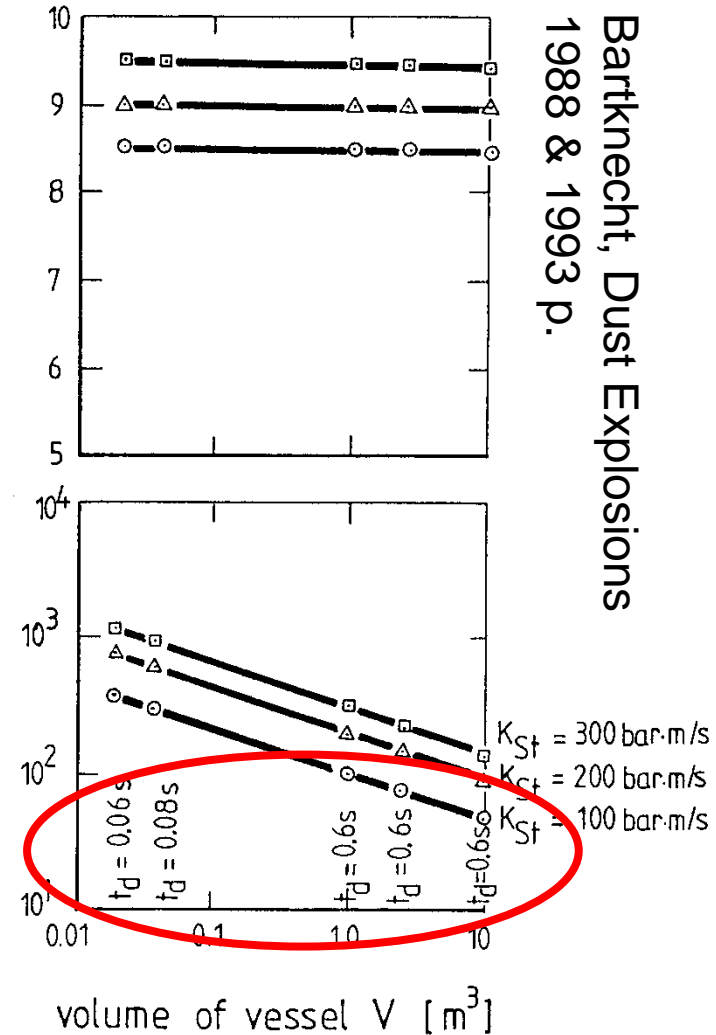
Fig. 72. Influence of vessel volume upon the explosion characteristics of combustible dust

I will describe the standard 1 m^3 dust explosion vessel is detail later. However, **the value of K_{st} is strongly dependent on the ignition delay and any value can be achieved by changing the ignition delay.**

The ignition delay controls the turbulence in the vessel following the injection of the compressed air and hence controls the turbulent acceleration of the flame.

If experiments are carried out in other spherical volumes then the same dust injection system with the same turbulence levels should be used. Although the preceeding slide appears to demonstrate this, this is a false demonstration as the ignition delay in the other volumes is altered to force agreement and the injection system are not simply scaled from one volume to the next.

I believe data on the 20L sphere, which is legal, is not comparable.

The volume scale up 20L to 1 m^3 is a factor of 50 and yet the ignition delay for the same results is changed by a factor of 10. At larger volume there was not change in the ignition delay – **this apparent agreement is a fudge!**

The mass of air used is scaled by a factor of 50 for the same injection pressure and the hole size should be proportionately scaled for the same turbulence. It has not been demonstrated that this has been done.

The reason is that the 20L sphere is not scaled from the 1 m^3. It has different injection system, different relative size of the external pot etc.

R. Pilao et al. (2006)

1 m^3
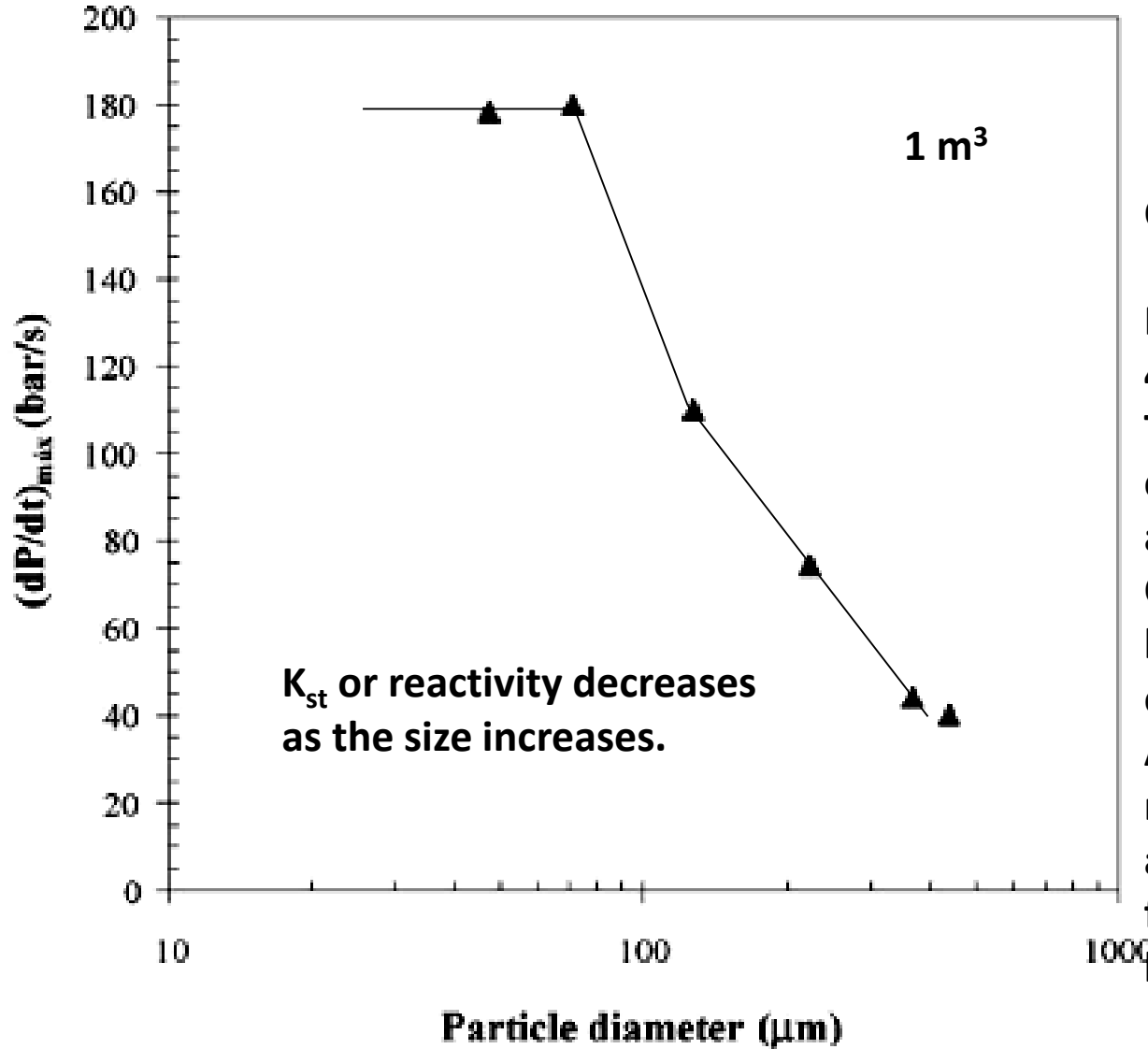
Cork dust

Note that particles of 400 μm will still explode. This will not happen for coal dust or hydrocarbon aerosol sprays. Consequently coarse biomass particles can explode. A legal K$_{st}$ measurement requires the dust to be <63μm as the reactivity is reduced for larger particles as shown here for the biomass cork dust.

K$_{st}$ or reactivity decreases as the size increases.

Axes: y-axis (dP/dt)$_{max}$ (bar/s); x-axis Particle diameter (μm)

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25.2.2013. Final Report 301007168 FPInnovations

Sawmill Wood Dust Sampling, Analysis and Explosibility

Dust Source	Moisture Content Group	Avg Particle Size (µm)	MEC (gm/m³)
MPB	Low	209	140
MPB	Low	274	400
MPB	Low	452	4,000
MPB	Low	726	>5,000
MPB	High	298	2,000
MPB	High	369	>5,000
MPB	High	420	NI
SPF	Low	197	160
SPF	Low	267	300
SPF	Low	386	485 (*)
SPF	Low	1227	>5,000
SPF	Med	221	300
SPF	Med	303	1,125 (*)
SPF	Med	434	>5,000
SPF	Med	993	NI
SPF	High	497	>2,580 (*)
SPF	High	1276	NI
DFC	Low	186	140
DFC	Low	244	160
DFC	Low	376	885 (*)

MPB
Mountain Pine Beetle Killed Lodgepole Pine

SPF
Spruce/ Pine/Fir

DFC
Douglas Fir and Western Red Cedar

Equipment used was the same as for K_{st} which is not stated. However, it is likely to be the 20L sphere as the work was done by Chilworth (US) and this is the equipment that they use.

The MEC for particles >~300µm is >1000 g/m³ which are very rich mixtures. But there is still an explosion hazard.
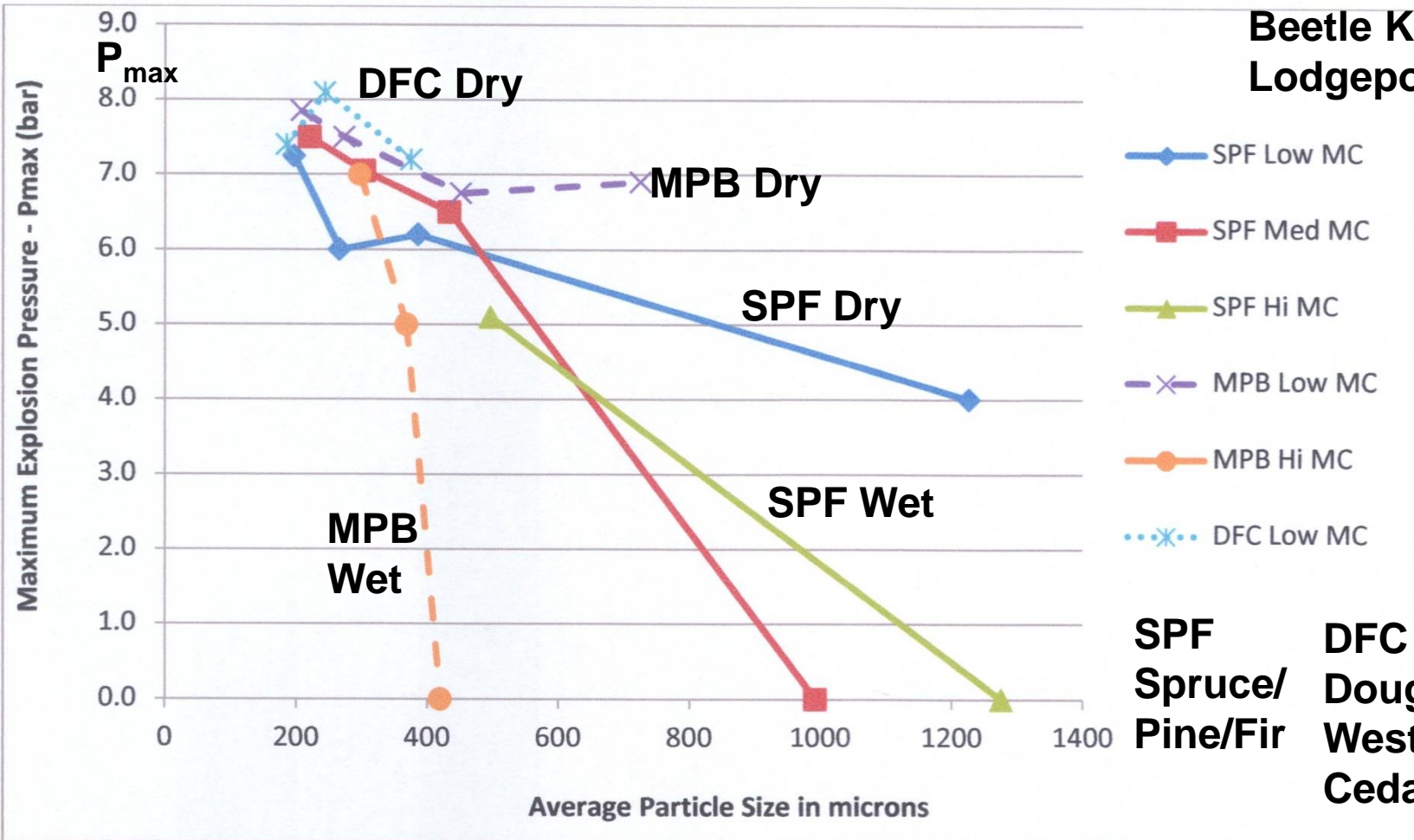
Figure 30   Maximum explosion pressure as a function of the average particle size

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25.2.2013. Final Report 301007168 FPInnovations

Sawmill Wood Dust Sampling, Analysis and Explosibility

Contents

Biomass and other dusts concentration has traditionally been given as g/m^3.

This unit comes from the form of the test equipment where a mass of dust is added to a fixed closed volume of air at atmospheric pressure and the dust is dispersed by a blast of air and the concentration is the mass added divided by the volume of the test vessel at atmospheric pressure.

The uniformity of the dust/air mixture is not given in the test equipment in the standards and whether all the dust injected burns (about 50% is not burned) is not discussed in the standard.

Also there has been, prior to our work at Leeds, no attempt to related measured concentrations to the combustion equivalence ratio. Indeed the stoichiometric A/F by mass is never given in any text book on dust explosions.

Nominal dust concentration (g/m³)

Nominal Equivalence Ratio (dry ash free)
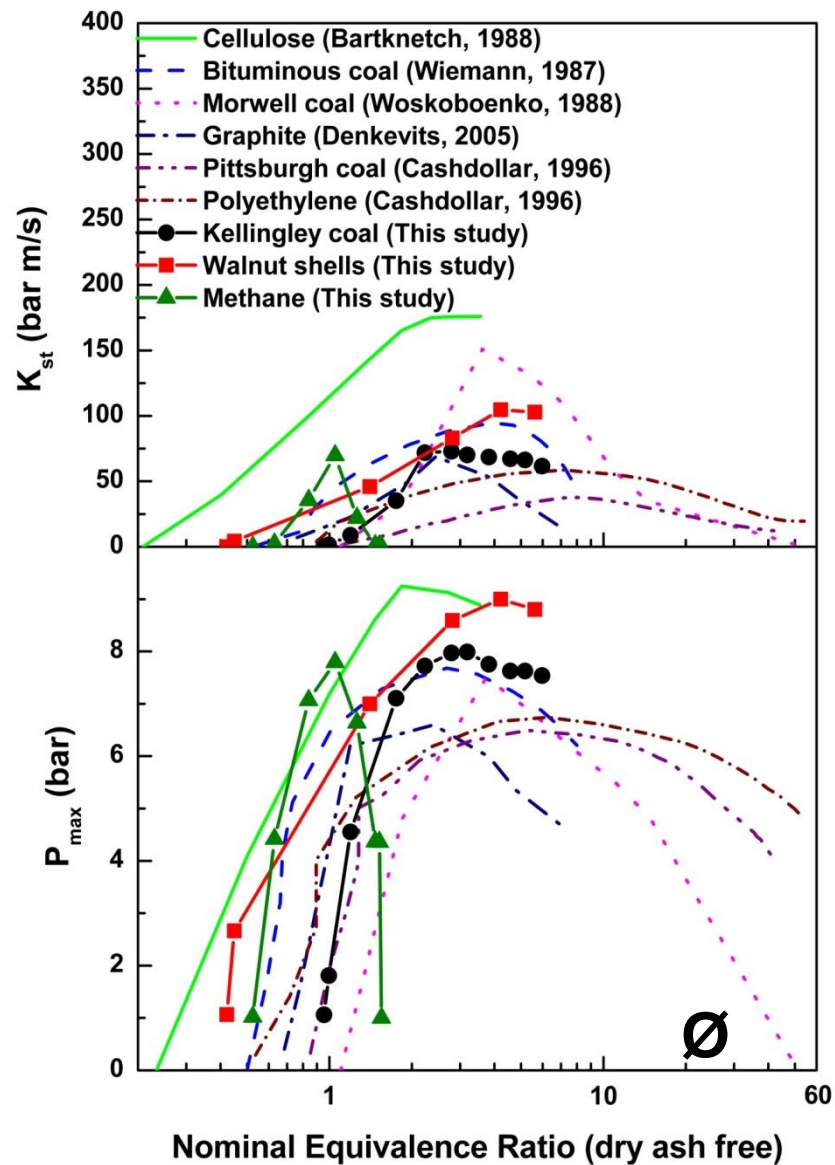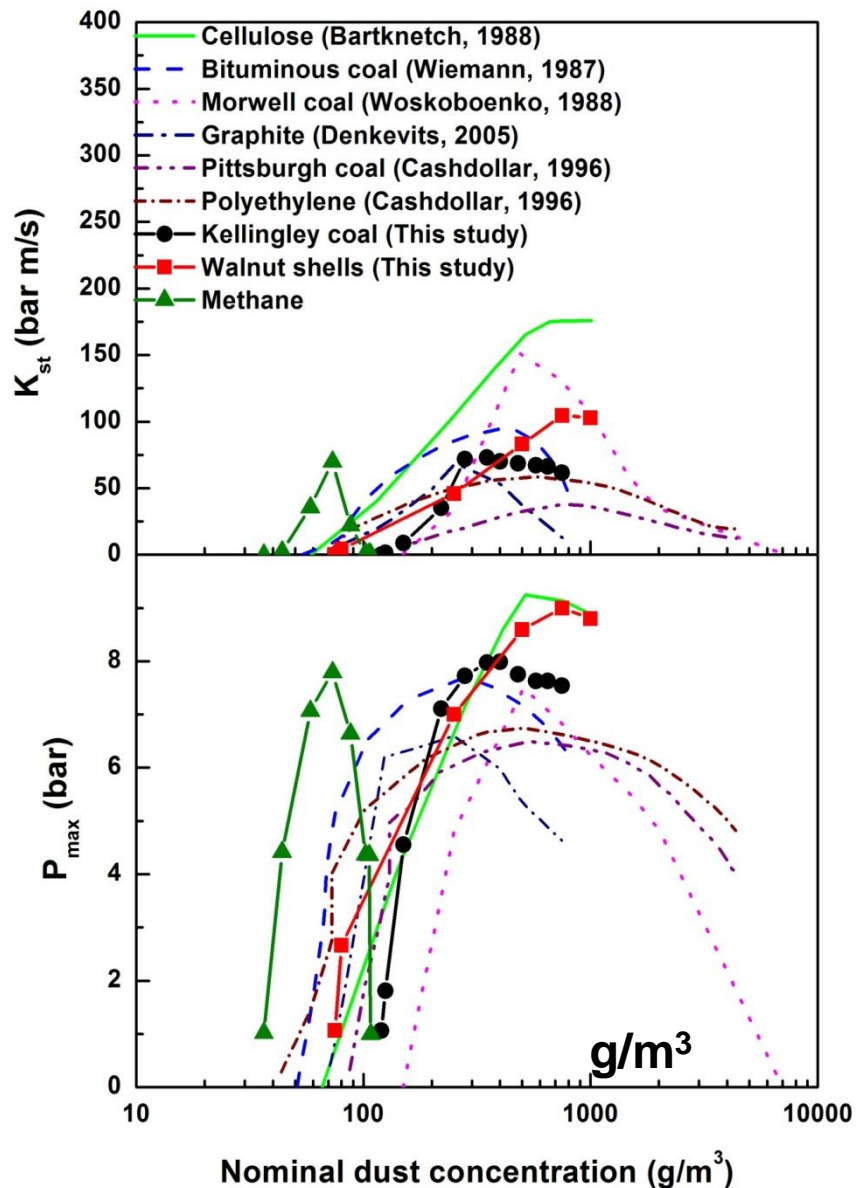
Nominal dust = dust mass loaded into the external pot

A consequence of the small variability in composition of hydrocarbon fuels is that gas composition variability is rarely investigated in gas explosion work.

Most explosion data is for natural gas or LPG fuels and sometimes the pure fuels methane and propane are used.

This is of current concern with the addition of biomethane to the gas grid, but even then the variability will be small relative to that for biomass.

One of the explosion protection measures is ventilation with a requirement to operate at 25% of the lean flammability limit or minimum explosions concentration for dusts. For HCs this can be set at a fixed ventilation rate and the composition of gas or vapour largely ignored as the lean limits are similar, as will be shown.

This is NOT the case for biomass.

To determine the stoichiometric A/F by mass of a fuel we only need to know the H/C for hydrocarbons

and H/C and O/C for biomass fuels.

The N and S content is usually too low to be significant in affecting the A/F by mass.

Gas fuels do not have ash or water content whereas biomass fuels do – this adds to the variability in the stoichiometric A/F by mass.

Knowing where you are relative to stoichiometric and carrying out explosion protection for the worst case explosion equivalence ratio (~Ø = 1.05) is fundamental to gas explosion research. For dust explosions their explosion behaviour is quite different to gases in terms of the dependence on mixture fraction or Ø and this has rarely been commented on in the literature.

Air/Fuel ratios by mass for a general hydrocarbon CH_y where y = H/C molar ratio

$$Air/Fuel_{Mass} = 137.93\ (1 + y/4)\ /\ (12 + y)$$

For y = 4 this gives 17.24 for methane
For y = 2 this gives 14.78 (typical of most liquid HCs)
For y = 1 this gives 13.26 (Benzene)

Thus for all hydrocarbons the stoichiometric A/F by mass varies only between about 13 and 17, whatever the hydrocarbon. However, the variation in composition of gaseous fuels is smaller than this range and for liquid fuels is also a small range.

General formula for a HCO combustion = $C_\alpha H_\beta O_\gamma$

This would normally be expressed in terms of H/C and O/C ratios using y= H/C and z=O/C as $CH_y O_z$

$CH_y O_z$ + a O_2 = b CO_2 + c H_2O

This is in volume units (molar balance)

Carbon balance gives 1 = b

Hydrogen balance gives y = 2c

Oxygen balance gives z + 2a = 2b + c = 2 +y/2

Thus a = [(2 + y/2) − z] / 2

Oxygen/Fuel by volume = [(2 + y/2) − z] / 2

Oxygen/Fuel$_{Mass}$ ={ [(2+y/2)–z] / 2}x[(2x16)/(12+y+16z)]

Air/Fuel$_{mass}$={ [(2+y/2)–z] / 2}x[(2x16)/(12+y+16z)]x1/0.232

Air/Fuel$_{Mass}$= [(2 + y/2) − z] 68.97 / (12 + y + 16z)

Air/Fuel$_{Mass}$= [(1 + y/4) − z/2] 137.94 / (12 + y + 16z)

Conversion from A/F by mass to mass/volume – g/m^3

Let the stoichiometric A/F be S as g_{air}/g_{fuel}.

Now the density of air at ambient T & P is approximately 1.2 kg/m^3 or 1200 g/m^3. Hence, $1 g_{air}$ = 1/1200 m^3.

Thus the stoichiometric F/A = 1/S = (1200 g_{fuel}) / (S m^3)

Now for a hydrocarbon solid dust such, as polypropylene, S ~ 15

Stoichiometric F/A = 80 g/m^3

Now we know that at ambient conditions the lean flammability of hydrocarbons is ~ 0.5Ø or ~30/1 A/F.

Thus at the lean limit it is expected that a hydrocarbon type dust will have a lean dust/air explosion limit of 40g/m^3.

For biomass dusts S ~ 6 and F/A = 1200/6 = 200 g/m^3

Dust can vary in S from 4 – 8 and this gives F/A$_{stoich.}$ = 150 – 300 g/m^3

The Handbook of Biomass Combustion and Co-Firing, Earthscan, 2008
ISBN 978-1-84407-249-1 Eds. Sjaak van Loo and Jaap Koppejan
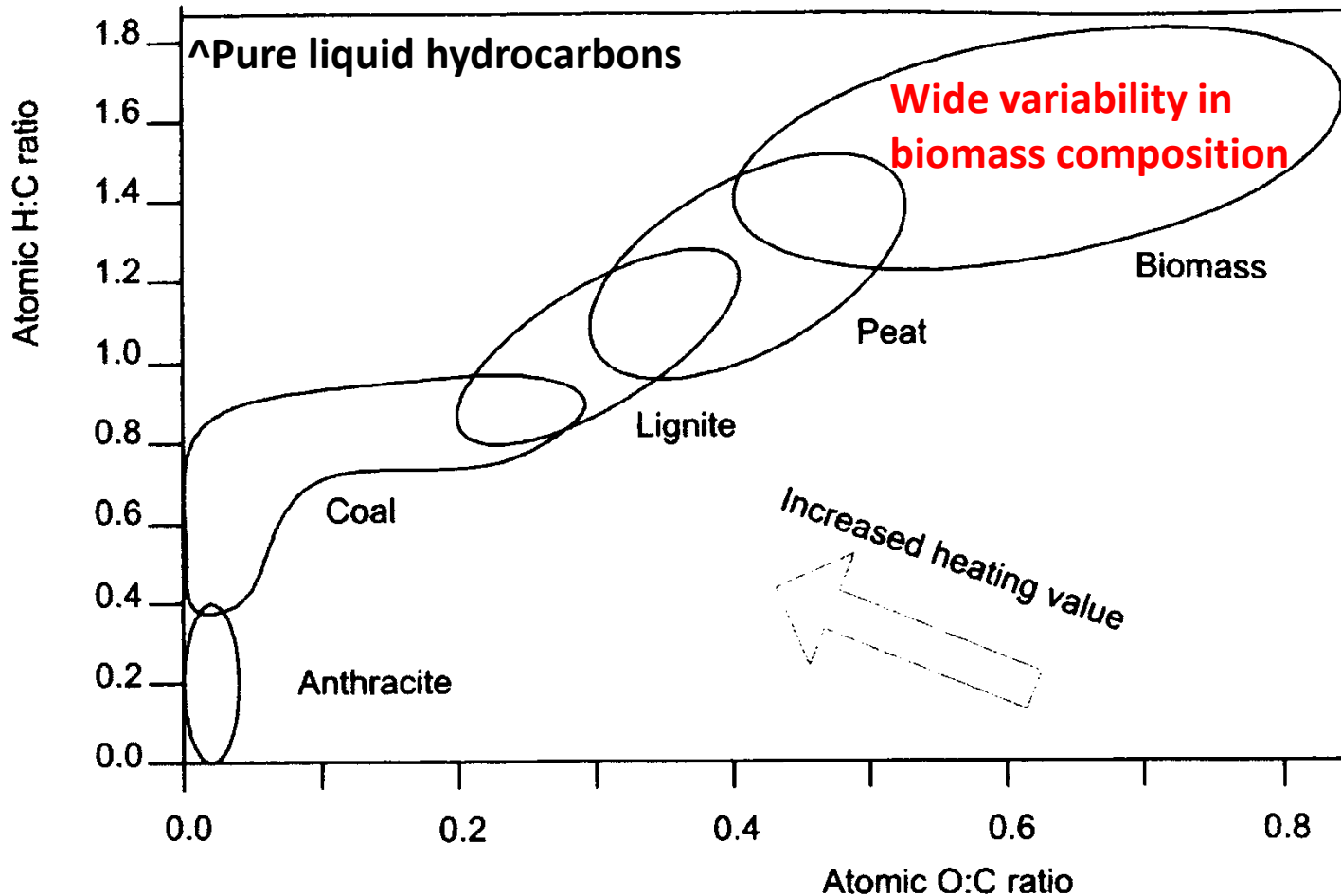
Figure 2.7 *Chemical composition of various solid fuels*

Survey of 100+ biomass – compiled by M. Azam Saeed
H/C and O/C on a dry ash free basis (DAF)
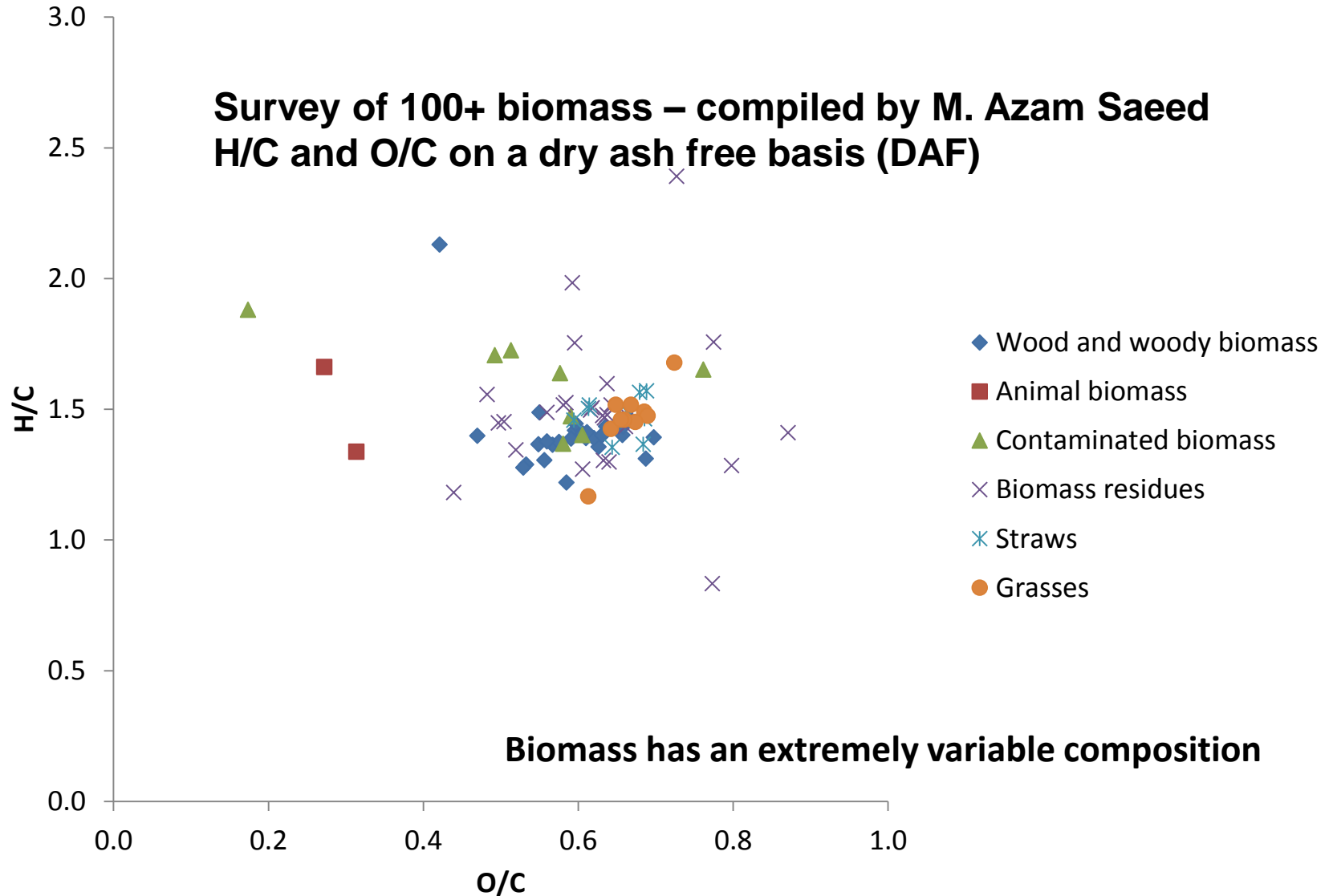
Biomass has an extremely variable composition

Legend:
- ◆ Wood and woody biomass
- ■ Animal biomass
- ▲ Contaminated biomass
- ✕ Biomass residues
- ✳ Straws
- ● Grasses

Axis labels: H/C (y-axis), O/C (x-axis)

Stoich. A/F is mainly in the range 4.5 to 7.5. However there are some biomass where the stoich A/F is as high as 11.5 or as low as 4.
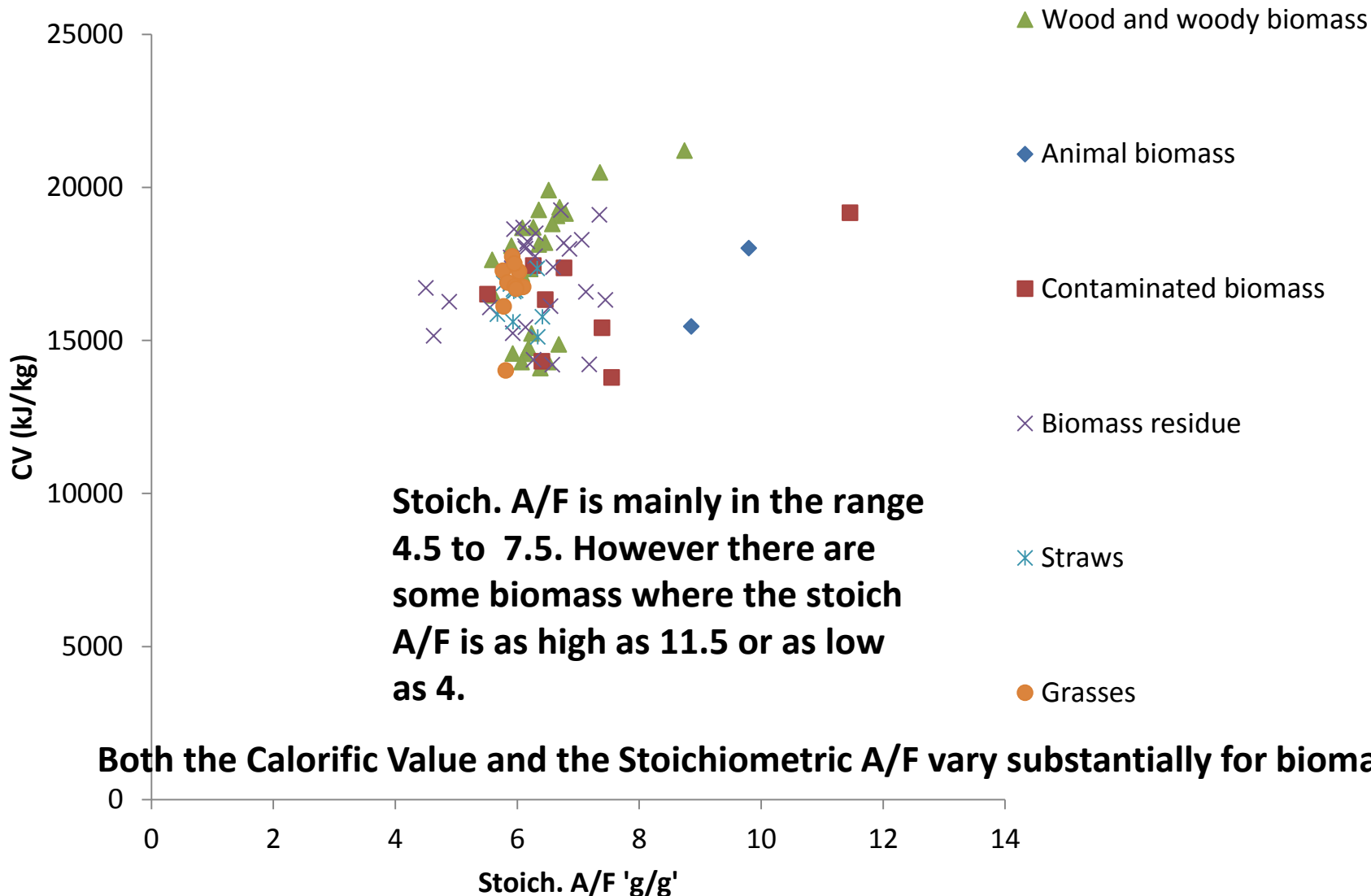
Both the Calorific Value and the Stoichiometric A/F vary substantially for biomass

Gottuk and Roby in the SFPE Handbook of Fire Protection Engineering give the stoichiometric A/F for two woods that are not in the composition range in the above table

Ponderosa Pine – $C_{0.95}H_{2.4}O > CH_{2.53}O_{1.053}$ USA Pine

The reference for this is Beyler, Proc. 1st Int. Fire Safety Sci, 1986, p.431

This is a much higher oxygen content than for any other woods, and is vastly different to pitch pine. They give a stoichiometric A/F by mass of 4.83.

The value from the above formula is 4.862 in good agreement.

Spruce $CH_{3.584}O_{1.55}$ (J. Fire Protection Engineer V. 4, p.133, 1999)   USA Spruce

Gottuck and Roby give the stoichiometric A/F as 3.87

The above formula gives the A/F as 3.83 , again in good agreement with the SFPE value.

Variability of pine wood composition.

Wood	Ref.	H/C	O/C	Stoich. A/F	Stoich. g/m³
Spanish Pine	VTT Publ. 394 1999	1.63	0.729	5.69	211
Pitch Pine	**US Dept. Agric.**	1.46	0.416	8.09	148
Pine	Drax	1.69	0.64	6.30	190
Pine	Tillman, Wood Combustion, 1981 p. 43	1.258	0.532	6.64	181
Ponderosa Pine	Beyler Ist. Int. FSS 1986 p.431 **USA**	2.53	1.053	4.86	248
Pine	Pratt, B&W, 1936	1.48	0.642	6.09	197
Pine	Review paper Bark.chips, prunings, sawdust	1.31 - 1.45	0.56 – 0.63	6.1 – 6.5	185 - 196

**Range for Pine Stoichiometric A/F = 4.86 – 8.09 The two extremes are USA pines
US pines are quite different in the two samples and from the other data**

In addition biomass has variable water content and variable ash content – a problem that also occurs with coal.

Ash and water are inert materials that act as a heat sink that reduces the flame temperature, lowers the reactivity and narrows the flammable range.

Stoichiometric A/F in the previous slides is on a dry ash free bases (DAF). On an actual basis the fuel mass increases due to the addition of the inert ash and water mass, so the stoichiometric A/F decreases.

$$A/F \text{ actual} = (A/F)_{DAF} \ [1 - (w + a)]$$

Where w = water content by mass

a = ash content by mass.

The net effect is to make biomass even more variable than the variability due to H/C and O/C variability.

The stoichiometric A/F by mass can be computed from the $CH_yO_zN_w$ composition using the following equation and the resultant A/F by mass on a dry ash free basis is given in the Table.

Stoichiometric Air/Fuel Mass

$$= \{[(1 + y/4) - z/2 - w/4]\ 137.94\}\ /\ (12 + y + 16z + 14w)$$

Table 3 Stoichiometric A/F by mass on a daf basis

Pellet	A/F daf	A/F actual including water and ash
A1	5.63	5.04 A/F actual = (A/F)daf [1 − (w + a)]
A2	**5.69**	5.09
A$_{Ave}$	5.66	5.07
B1	5.43	**5.00**
B2	5.60	**5.16 27% >C1**
B$_{Ave}$	5.52	5.08
C1$_{Ave}$	4.95	**4.06**
C2$_{Ave}$	**4.66**	4.18
D$_{Ave}$ Olive Stone	5.57	4.75

Douglas Fire Moisture content influence on flame T

THEORETICAL FLAME TEMP
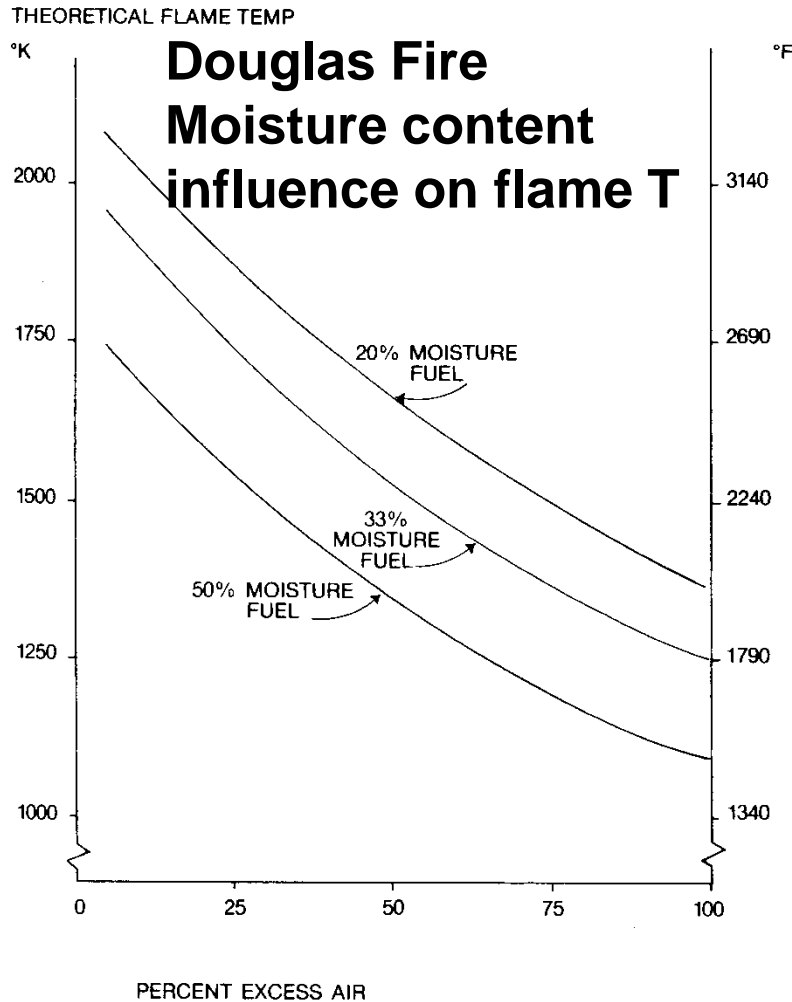
PERCENT EXCESS AIR

FIG. 5-4. Theoretical flame temperature as a function of fuel moisture content and percent excess air for Douglas fir bark. This illustrates the influence of both moisture content and excess air on flame temperature and demonstrates that excess air plays a more significant role in reducing flame temperature than does moisture content (courtesy of L. L. Anderson).

Douglas Fir and Black Oak Flame temperature for 50% water content.
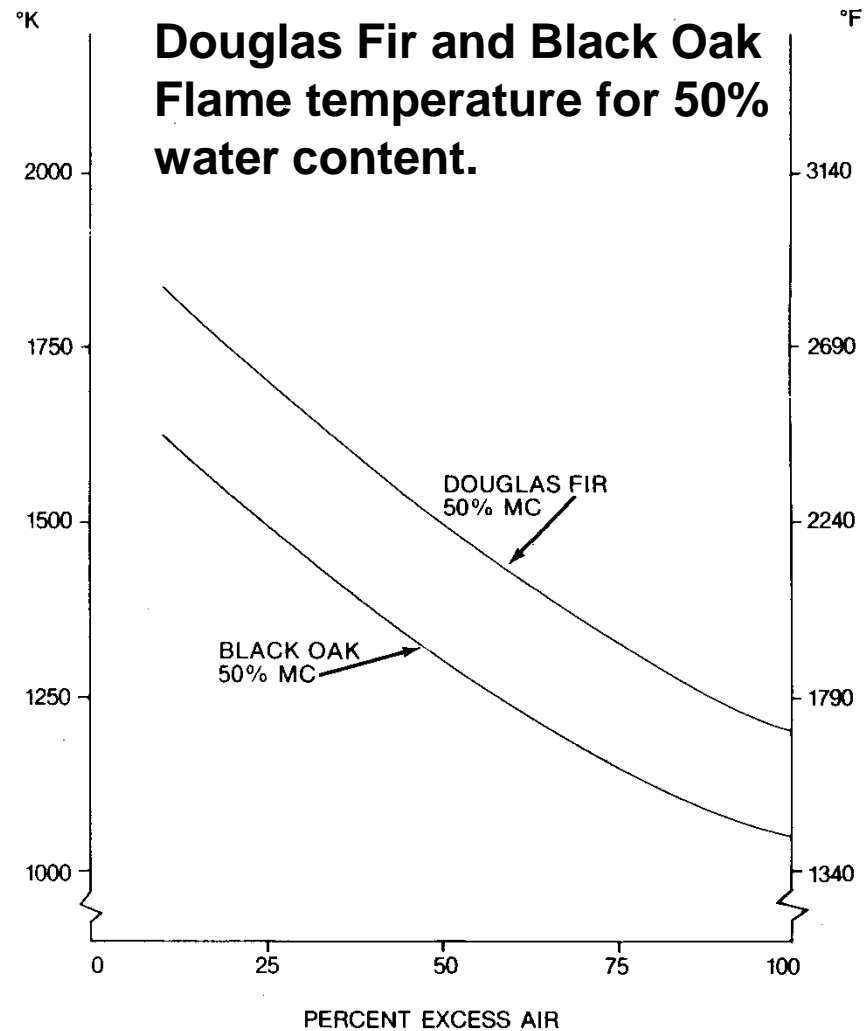
PERCENT EXCESS AIR

FIG. 5-5. Theoretical flame temperature as a function of percent excess air for 50 percent moisture content fuels. Note that differences in species can influence flame temperature by approximately 200 K (courtesy of L. L. Anderson). **NASA**

Correlation between MEC Ø on an actual basis and % of ash+moisture
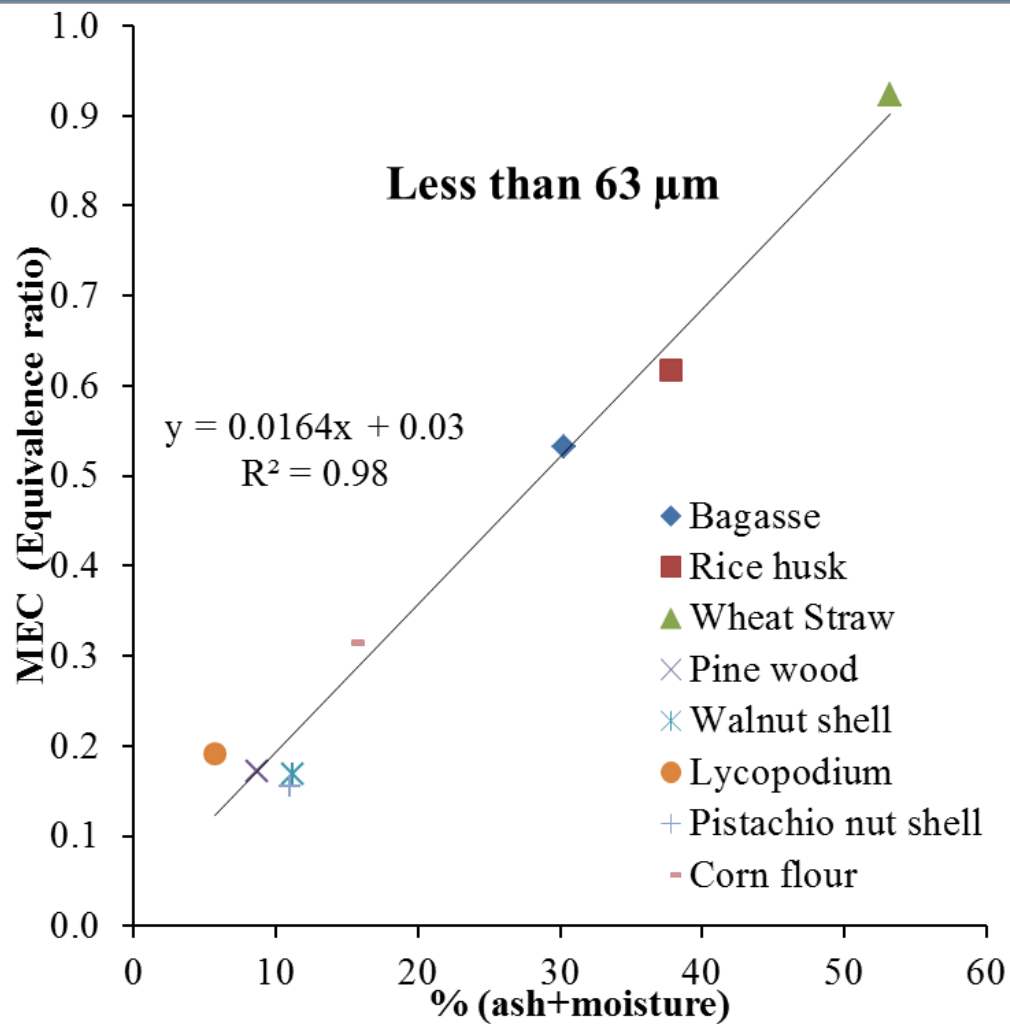
MEC Ø results from Leeds U. work.
Water is not the key variable and it is the ash that varies greatly.
Ash and water acts as an inert that lowers the dust - air temperature and hence lowers the mixture reactivity.

Tenth International Symposium on Hazards, Prevention and Mitigation of Industrial Explosions
XISHPMIE Bergen, Norway 10-14 June 2014
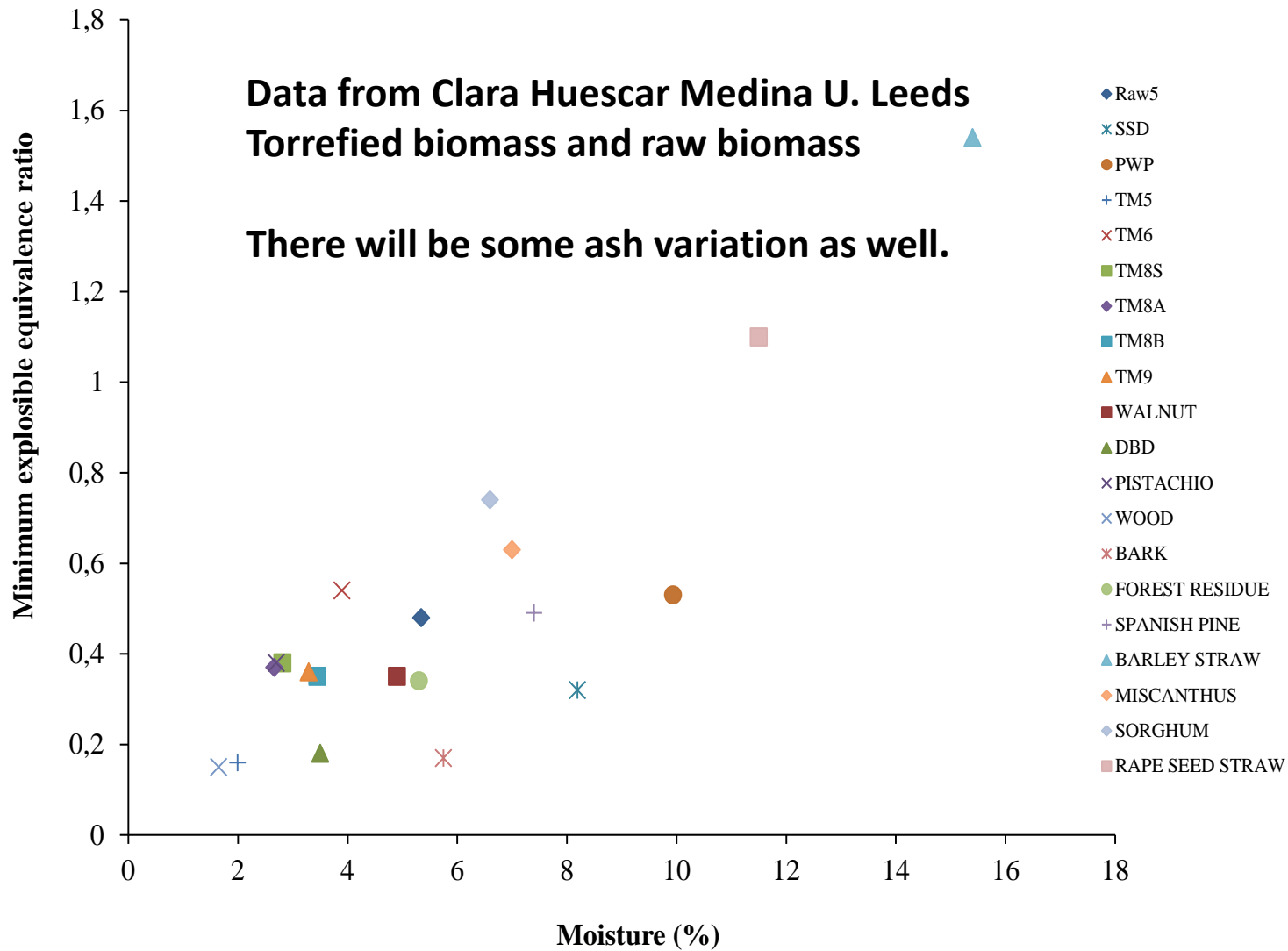
How does the power generation sector cope with this variable composition.

1. **Eliminate the variability by specifying one type of wood from one forest in the USA or Canada.**

2. **Dry the wood at source to a specified level of dryness and then pelletise the wood - the processes are:**

   a. **Mill the wood**

   b. **Dry the wood in a rotating kiln (energy input)**

   c. **Compress the wood into pellets.**

This results in a very low variability of biomass and a fixed stoichiometric A/F.

However, as biomass expands in power generation single source supplies will be rare and acceptance of biomass from any source will be the norm.

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    Hartmann for MEC

    20L sphere

    ISO 1 m^3

5. **The unburned particle mass in the ISO 1m^3**
6. **Modifications of the ISO 1 m^3 vessel for woody biomass.**
7. **Leeds MEC results for woody biomass**
8. **Leeds ISO 1 m^3 vessel results for biomass (Clara Huescar Medina will present this in the next lecture).**

Explosion characterisation for a particular gas requires knowledge of three key parameters:

1. **Lean and Rich flammability limits relative to stoichiometric. First defense against explosions is not to operate inside the flammable range**

2. **Mixture reactivity – the laminar burning velocity, U_L, is usually used in explosion modelling. However, in explosion vent design the explosion index, K_G, is used in the EU standards, but in 2013 the USA in NFPA 68 abandoned this approach and adopted U_L. However, both the USA and Europe still use K_{st} for dust reactivity.**

$$K_G \text{ or } K_{st} = (dP/dt)_{max}/V^{1/3} \text{ bar m/s}$$

3. **Mixture expansion ratio, E_P, which relates U_L to the flame speed U_f.**

$$U_f = E_p U_L$$

This is normally calculated for gas/air mixtures using an adiabatic equilibrium temperature and composition code.
However, for dusts it is more difficult to calculate E_p and the measured ratio of peak to initial pressure is often used instead. This is the expansion ratio at constant volume, E_V, which is typically about 10% higher than E_p.

For gases there is a European standard on how to measure the flammability limits.

There is no such standard on how to measure U_L and no agreement in the literature on how it should be measured (see Andrews and Bradley, 1972, C&F for a review of the problem – no resolution in 42 years since then!).

There is a standard on how to measure K_G and K_{st} which is in the venting standards. For gases this is to use a spherical explosion vessel of a minimum volume 5L. This is a useless standard as it is known that K_G increases with increase in volume. Also the values of Bartknecht that are quoted in the standard must be wrong as propane is nearly twice as reactive as methane, which is not the case.

The situation for dust characterisation is even more problematic and relies on very empirical test methods.

Objectives **Problem of using fibrous or 'woody' biomass dusts**

➢ **There are two basic problems need to be resolved to enable testing of pulverised fibrous biomass in the 1m³ vessel and to address the issue of reliability of data:**

1. **Due to low bulk density of biomass, the standard 5L dust holding pot pre-pressurised to 20 barg is not large enough to hold the required mass of fibrous biomass. Powders are typically tested up to cloud concentrations of 1.5 kg/m³. Many biomass dusts have bulk densities of 150 – 250 kg/m³ and hence 1.5 kg would occupy 6 to 10 litres, approximately. There are some biomass dusts with bulk densities as low as 100 kg/m³ and this would require 10 litres to hold 1kg. and we have calibrated a 10L pot in our work at Leeds.**

2. **The standard C-tube dispersion system becomes blocked/choked when delivering fibrous biomass****, and does not disperse it in the same pattern as coal powder.**

➢ **Both of these issues will result in combustion conditions that are not directly comparable to non-fibrous powder testing and the relative results cannot be comparable either. Hence, recalibration of the whole system is needed to ensure the acceptability of the test results. Although there have been some attempts in the literature to deal with this issue of dispersion of biomass dust, no calibration of new systems for biomass against the standard system exists in the open literature.**

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The figure on the left shows a labelled diagram of the Hartmann Bomb apparatus with the following callouts:

- PRESSURE TRANSDUCER
- STAINLESS STEEL TUBE 76 mm O/D x 69 mm I/D
- MANUAL PRESSURE RELEASE VALVE
- SPARK ELECTRODES ⌀1mm
- DUST DISPERSION MUSHROOM
- DUST SAMPLE
- NONRETURN VALVE
- SOLENOID-OPERATED VALVE
- 60 cm³ COMPRESSED AIR RESERVOIR
- SHUT-OFF VALVE
- PRESS. REDUCTION VALVE

Dimensions shown: 205 mm, 120 mm
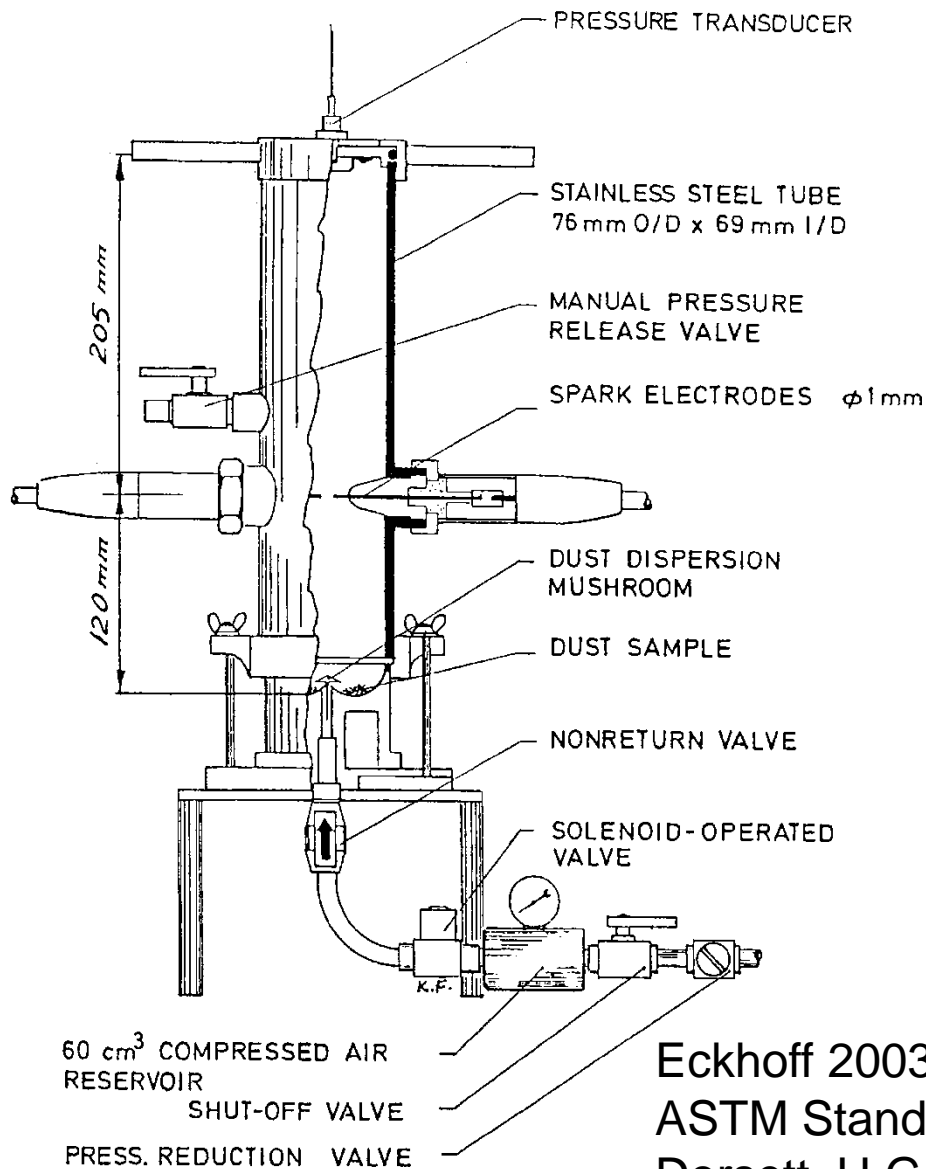
Hartmann Bomb

This was the first widely used quantitative test for dust explosion characterisation.
It is a vertical cylinder of 69mm ID and 325mm length.
The dust is put into a sample holder at the bottom and this known mass of dust is dispersed in the cylinder volume using compressed air jets and the concentration is the mass of dust divided by 1.2 litres, expressed as g/m^3.

Eckhoff 2003 p.526
ASTM Standard E789-86, 1988
Dorsett, H.G., Jacobson and Nagy, US BM RI 5424, 1960

120 mm

DUST DISPERSION MUSHROOM

DUST SAMPLE

NON-RETURN VALVE

SOLENOID-OPERATED VALVE

K.F.

60 cm³ COMPRESSED AIR RESERVOIR

SHUT OFF VALVE

PRESS. REDUCTION VALVE
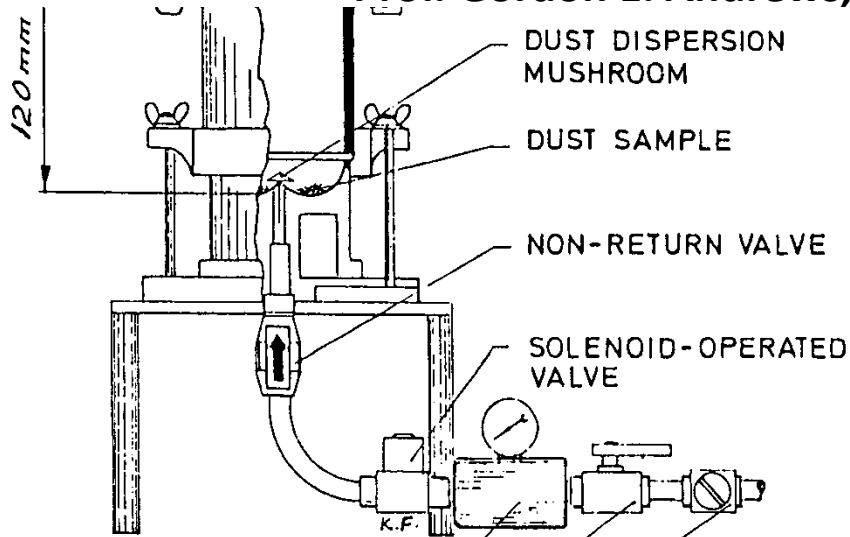
Eckhoff, 2003, p. 523 and 526.

Hartmann

< ---------- 50 mm ---------- >

The 1000cc vessel is evacuated and the 60cc air vessel pumped to 4 bar. This air when released creates high velocity jets and expands to fill the vessel to 1.24 bar (or air vol. is 1240cc at std, atm).
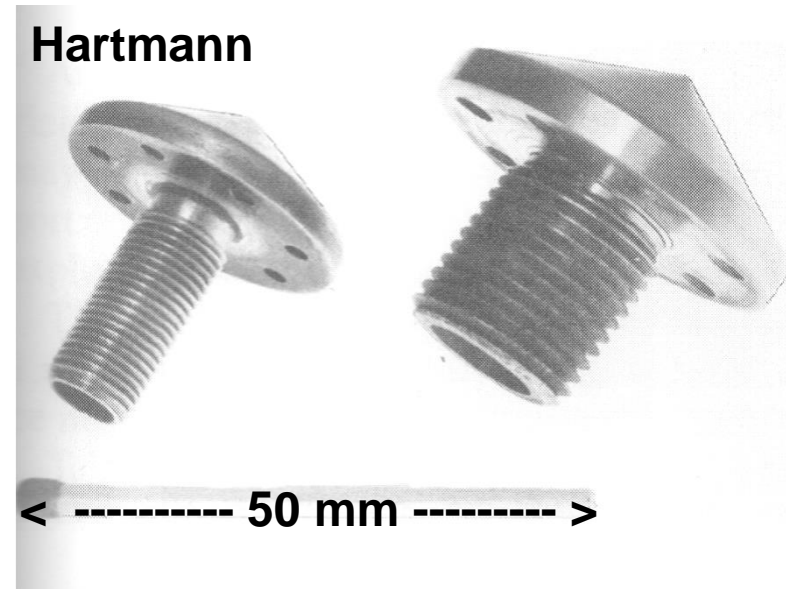
The compressed air flows up the hollow screwed support tube and then inside the cone it is deflected back through the holes as air jets that impinge on the dust in the sample holder and disperse it. *Big advantage for biomass is that the dust is put inside the vessel, no feed tubes to block.*

The Hartmann equipment is very similar to the European Method T for the determination of the lean limit for gaseous fuels.

This has an 80mm diameter tube that is 300mm long and ignited at 60mm from the bottom. The flame is flammable if it moves 100mm from the spark.

These dimensions are very similar to the Hartmann and the difference in diameter will make no difference on gas LEL results and hence, is unlikely to make a difference for dust explosion MEC measurements

The use of the thermocouples as flame detectors in the Leeds modification to this equipment enables a flame movement to 100mm from the spark to be determined.

Hence the same criteria for MEC as LEL can be used.

There are two version of the Hartmann equipment can be used to make the following measurements.

A. **Hartmann Bomb (Pressurised vessel with pressure transducer to measure the pressure rise).**

1. **Lean flammability limit concentration or MEC**

2. **Concentration with the maximum rate of pressure rise and the peak pressure concentration (most reactive mixture concentration).**

3. **Pressure rise and rate of pressure rise as a function of concentration and the peak values of both – not now regarded as valid data due to heat losses. The ISO 1m^3 is the standard method of P$_{max}$ and K$_{st}$.**

4. **Limiting oxygen concentration with inerts.**

B. Hartmann open tube vessel (*we have this version*)

5. Minimum ignition energy

6. Lean flammability or MEC

7. Limiting oxygen concentration with inerts

J. Nagy and H.C. Verikas, Development and Control of Dust Explosions
Marcel Dekker 1983

Pittsburgh coal
Note that coal burns
extremely rich
6 kg/m³ is ~A/F of 0.2
with stoichiometric
~10/1 so this is a Ø~50.
The oxygen consumption
shows that for a vessel
with the same mass of
oxygen, irrespective of
the fuel mass, only sufficient
fuel burns to consume the
oxygen. As the heat release
is 3 MJ/kg of air, irrespective
of the fuel the quantity of fuel is
irrelevant. The pressure drops
because the unburnt fuel is a heat
sink that cools the flame.
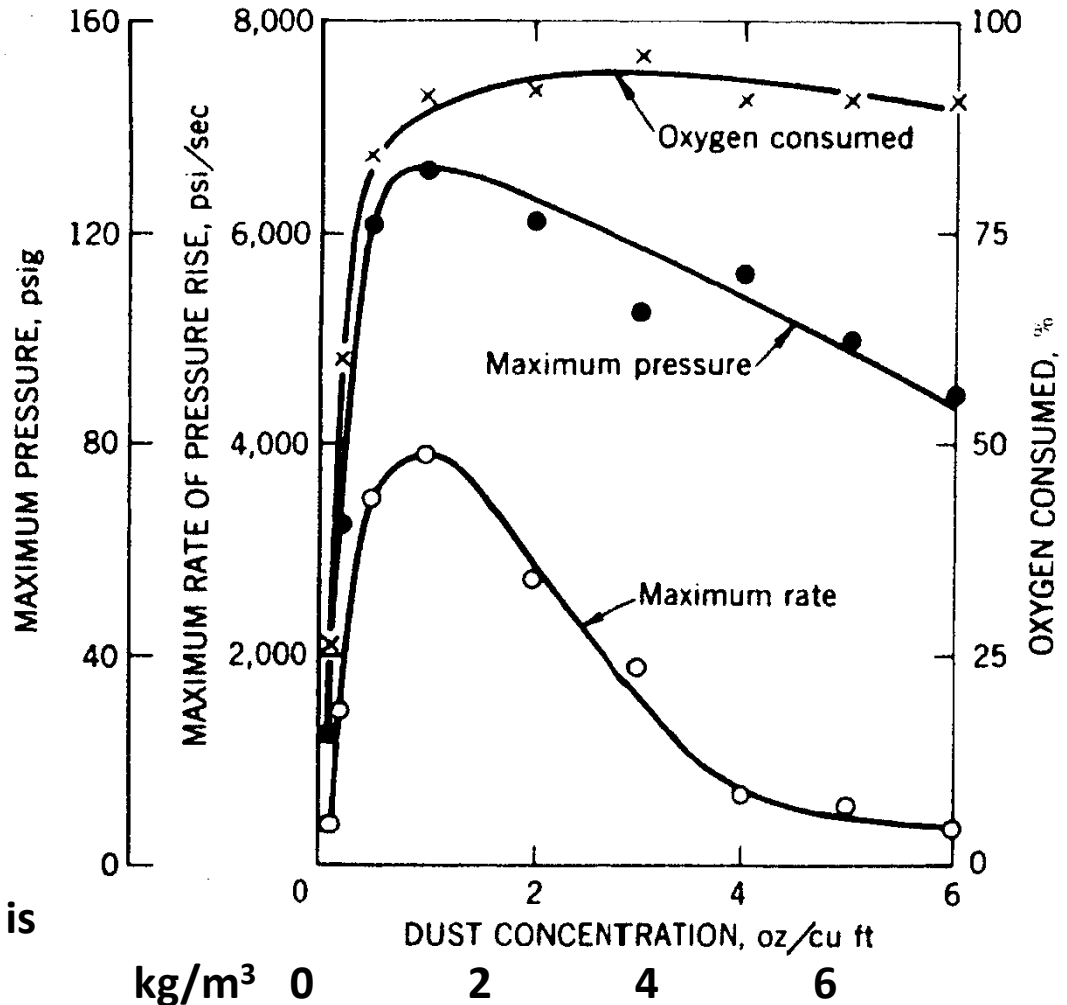
Figure 5.42. Effect of dust concentrations on pressure, rate of pressure rise and oxygen consumed during explosions of Pittsburgh coal dust (Court. USBM).

- The Hartmann tube is 1/1000 of the volume of the 1m³ ISO dust explosion vessel so gms of dust are needed instead of kgs of material for the 1m³ ISO vessel

- Values measured below with Hartmann tube are slightly lower than on the 20L sphere or 1 m³, and therefore it is safe to use these values.

- However, in the standards there is no requirement for precise determination of MEC – and as shown below MEC is either 30 or 60 or 125 or 500. The procedure is halve the initial value until no explosion is achieved and then to halve the diff. This is not acceptable for gas LEL why should it be acceptable for dusts?

Dust	Hartmann (g/m³) 4J [Maisey, Field]	1m³ or 20L sphere (g/m³) [Eckhoff] 10 KJ Ignitor	1m³ (g/m³) [NFPA 68] 10KJ
Sugar	45	60	200
Milk Powder	50	60	60
Aluminium	30 (6μm)-40 (17μm)	30(29-22 μm)- 60 (10-43 μm)	30 (29 μm)
Cellulose	55	60	60
Wheat Starch	45	60	30
Polypropylene	30-35	30-200	30
Sulphur	20	30	30
Peat	100	125	125

Material CH_yO_z	y=H/C	z=O/C	Ø=1 A/F	Ø=1 g/m^3	MEC g/m^3	MEC Ref.	Ø$_{MEC}$
Cellulose	1.67	0.833	5.12	234	55 60	Maisey Eckhoff	0.235 0.256
PMA	1.50	0.50	7.27	165	30	Eckhoff	0.182
PMMA	1.60	0.40	8.28	145	30	Maisey	0.207
polyethylene	2.0	0	14.8	81	30	Maisey Eckhoff	0.37
polypropylene	2.0	0	14.8	81	35	Maisey	0.43
Polyethylene terephthalate (PET)	0.8	0.4	7.18	167	40	Maisey	0.24
Polyvinyl acetate	1.5	0.5	7.22	166	40	Maisey	0.24
Pitch Pine (Tillman)	1.46	0.416	8.09	148	30-60	Eckhoff	~0.3
Spruce (Tillman)	3.58	1.55	3.83	313	20-70	Field	~0.14
Carbon	0	0	11.5	104	60	NFPA Eckhoff	0.55
Bituminous Coal	0.78	0.073	12.7daf	94.5daf	55	Maisey	0.58

MEC in equivalence ratio terms.

We were the first research group to express dust explosion data in equivalence ratio terms, even though this is normal in gaseous combustion. Virtually all dust explosion data prior to our work has been expressed as concentration as g/m^3 and this does not make it clear that existing measurements of MEC were giving much leaner mixtures that were flammable than for gases. Also it did not make it clear that the most reactive mixture was very rich or that there was no effective rich limit.

The implications of these very lean MEC limits for dusts for the mechanism of flame propagation had not been realised as they show that the existing model of devolatilisation of hydrocarbons that then propagated a HC flame could not be correct as the MEC was leaner than 100% HC could give.

For flammability limits for dusts that contain organically bound oxygen the MEC results are quite different to those for hydrocarbons and for methanol, ethanol and isopropanol vapours, where all the lean limits are in the range Ø=0.43 – 0.48.

However, none of the dusts with HCO composition have a lean limit in this range, even though wood type biomass has the same elemental composition as methanol with similar stoich. A/F ~6.

For HCO dusts that are pure chemicals of known composition Table 1 shows that their lean limit lies in the range Ø=0.18-0.24 which is completely different to gaseous hydrocarbons and alcohol vapours.

The only gas with a lean limit comparable to this is hydrogen with Ø=0.14.

This indicates that dusts with HCO composition are extremely reactive and that a model based on decomposition to form a hydrocarbon with the explosion propagating in the hydrocarbon gas is not compatible with the MEC evidence. The question is does this apply to biomass dusts? Our results show that it does with woody biomass of size < 63µm giving MEC ~ 0.2 for dry low ash biomass.

VTT Publication 394 Finland 1999   ISO 1 m^3

Biomass	MEC$_{daf}$ 1m^3	0/C z	H/C y	Stoich A/F	Stoich g/m^3	MEC Ø$_{daf}$	Mean Particle Size µm	VOF daf
Wood	29.4	0.731	1.59	5.63	213	**0.138**	**95**	83.6
Bark	27.8	0.637	1.42	6.03	199	**0.140**	**57**	74.1
Forest Residue	55.3	0.672	1.53	4.78	251	**0.220**	**102**	79.5
Spanish Pine	83.1	0.729	1.63	5.69	211	0.394	247	85.0
Barley Straw	72.5	0.705	1.68	5.91	201	0.357	253	78.6
Miscanthus	110.4	0.771	1.62	5.42	221	0.498	143	79.6
Soghum Straw	105.8	0.647	1.45	6.02	199	0.531	178	79.8
Rapeseed Straw	174.5	0.986	1.88	4.54	264	0.661	318	61.4
German Lignite	51.8	0.450	1.09	7.12	169	0.307	58	53.4
Spanish Lignite	59.6	0.826	1.42	4.88	246	0.242	40	55.3

Contents

The 20 litre sphere method was developed by Siwek in Switzerland at Ciba Geigy (Nov. 1988, Conference on dust explosions, St. Louis). **This was evaluated and adopted by the International Electrotechnical Commission (**IEC,1990, Test methods sheets 2-5 and 2-6, Eckhoff, 2003, p.523**).**

This uses a 10 kJ chemical ignitor in a 20 litre sphere and with no dust present the pressure rise is 1.1 +/-0.1 barg. This is a problem with this test method as this large ignition energy creates compression of the unburnt dust air mixture and the flammability is not that at the initial test conditions of ambient P & T, but that of 1 bar and the compressed temperature. This can artificially extend the lean flammability limit.

This problem goes away when a 1 m³ sphere is used as the larger volume give only ~50mb pressure rise with the same 10 kJ chemical ignitor.

Also the flame curvature is significant so flame stretch effects are important and the fundamental burning velocity is not measured.

Bartknecht Explosions 1993 p.179
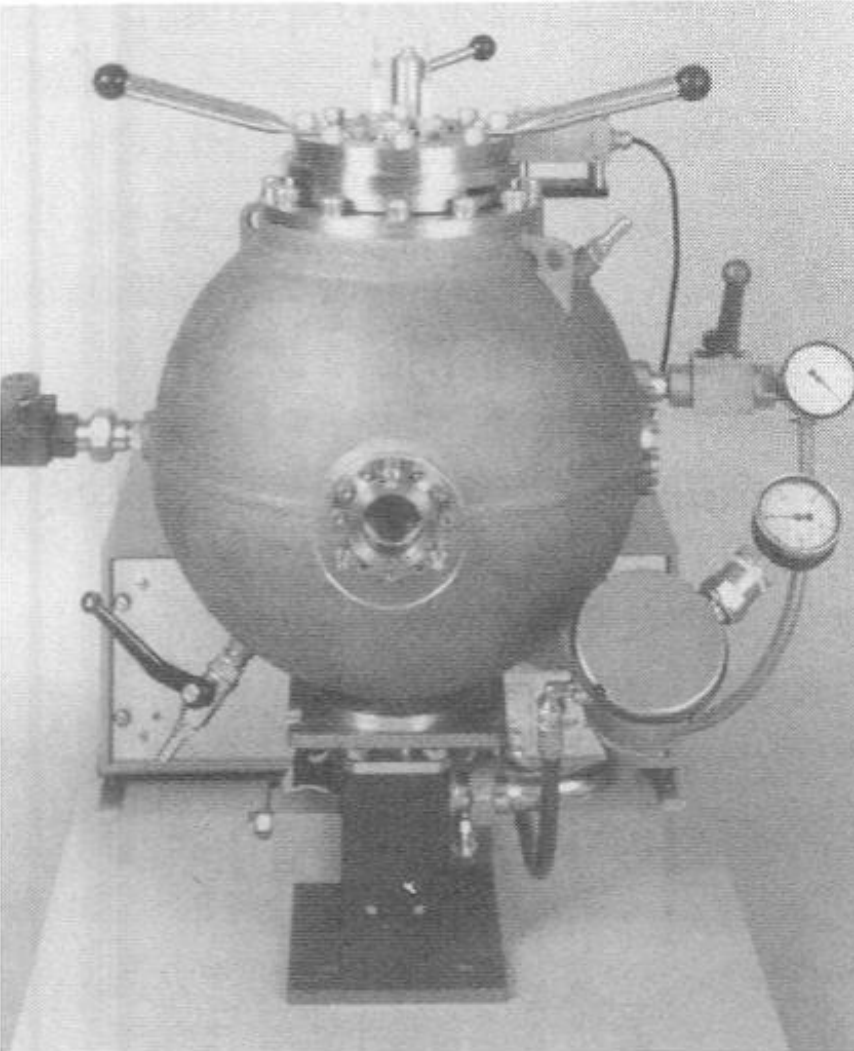
Siwek 20 litre sphere
Eckhoff 2003 p. 531
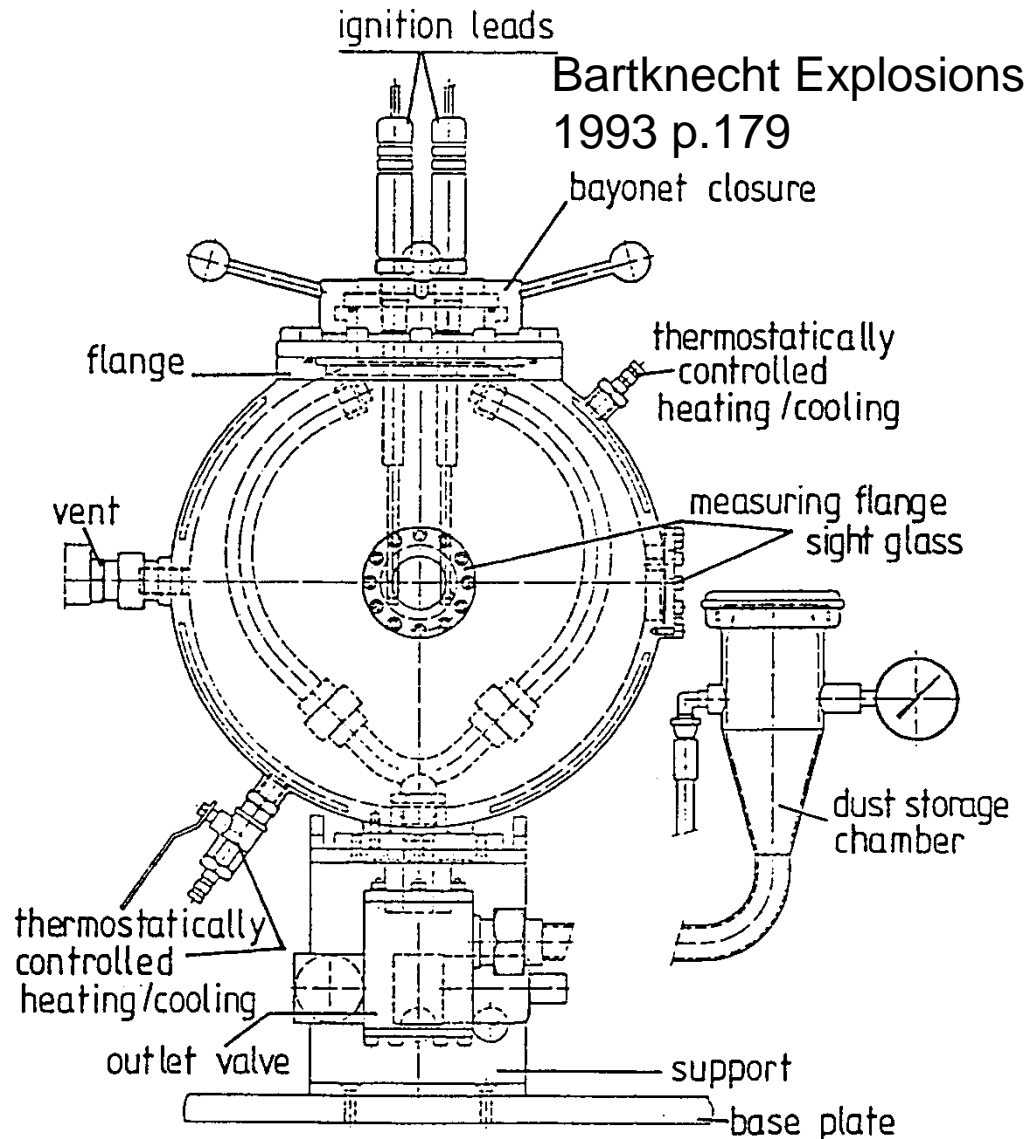
Note the two 'C' dispersion rings

$V_1/V_2 = 0.03$ compared with 0.005 in 1 m^3

20 LITER EXPLOSION CHAMBER

PRINTER

COMPUTER

IGNITOR LEADS

RUPTURE DISC ——— FILTERED EXHAU

DISPERSION TUBE

CONTROL PANEL

FILTERED EXHAUST

AMPLIFIER

PRESSURE TRANSDUCER

VACUUM GAUGE

Note that the sample and air are in different volumes

VACUUM LINE

SAMPLE LOADING CYLINDER

REGULATOR & GAUGE

HIGH PRESSURE AIR

.6 LITER DISCHARGE VESSEL

AIR ACTUATED BALL VALVE

PRESSURE TRANSDUCER

The 0.6 litre air vessel will need To be pressurised to 33 bar to give 1 bar when discharged into the evacuated 20 litre vessel.

20 litre sphere At Fike Corp USA, Eckhoff 2003, p.533.

Figure 7.60 *Complete 20 liter sphere system to determine explosibility properties of dusts (C*

Calle, S. et al. Influence of the size distribution and concentration on wood dust explosion: experiments and reaction modelling.

Powder Technology 157 (2005) 144-148

Wood dust was produced by sanding a mixture of beech and oak and then

Sieving into four size fractions 25 – 40 (23.5 mean); 45-71 (42.7);71-90 (62.5); 90-125 (82.5); raw wood 36 μm.
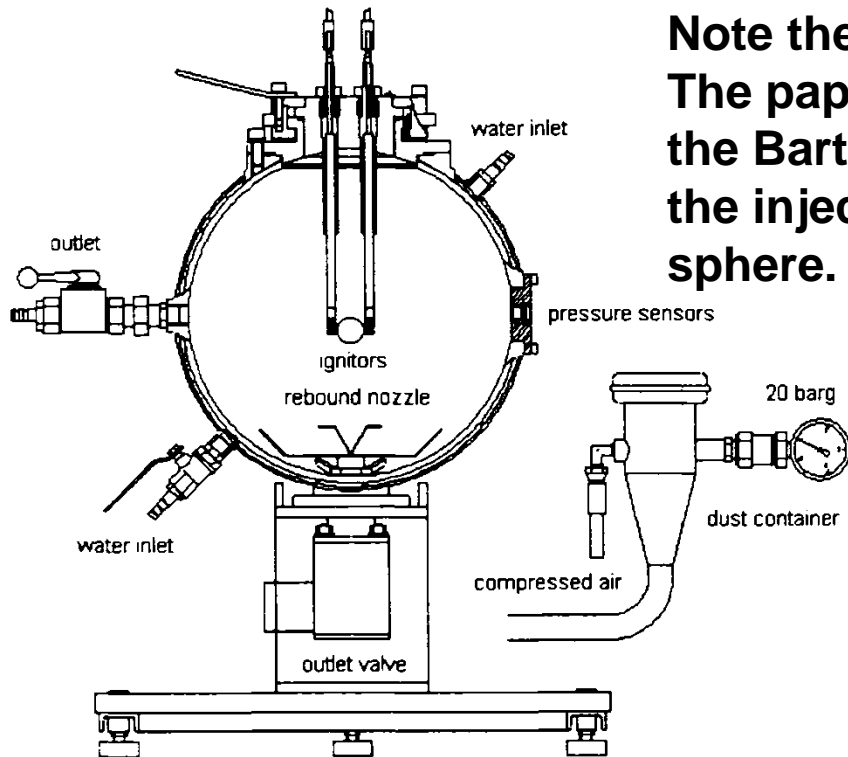
Fig. 2. The 20 L explosion sphere.

Note the non-standard dust injection system that The paper does not comment on or describe. It is the Bartknecht rebound nozzle used for Flox. This is the injection method in some standards for the 20L sphere. I have seen no calibration of this system against the ISO 1 m³ standard vessel.

No details of the calibration of this injector are given, so difficult to relate the results to the standard injection system.

This is at the Laboratory for Chemical Engineering Science, LSGC-CNRS, Nancy, France

At the *10th Euro. Conf. on Coal Research and its Applications, Univ. Hull, UK. 15 – 17th Sept. 2014*. **Edinburgh University presented work on biomass explosions using a 20L sphere with a different injection system.**

This was a multihole hozzle (like a shower head) that injected compressed air onto an internal container that contained the biomass. They said that this was a US IOSH (was US Bureau of Mines) design. However, I can find no reference to it and no calibration for it (against the 1 m^3). The injection system is similar to the Hartmann and overcomes the problem of injecting the biomass from an external chamber.

10th ECCRIA (European Conference on Coal Research and its Applications, Sept.15-17, 2014, University of Hull)

Experimental ignition of biomass and coal particles in oxy-fuel atmospheres for CO$_2$ capture

Hannah Chalmers, University of Edinburgh, UK

Very bad agreement of the 20L sphere MEC with the ISO 1 m³ for woody biomass.

VTT Publication 394 Finland 1999

Biomass	MEC g/m³ 20 L sphere	MEC g/m³ 1 m³ Lab.1	MEC g/m³ 1 m³ Lab.2	Particle Size µm	
Wood	100	30	50	95	
Bark	100	30		57	
Forest Residue	150	60		102	
Spanish Pine	350	90		247	
Barley Straw	250	90	200	253	
Miscanthus	450	120		143	
Soghum Straw	1150	120		178	
Rapeseed Straw	750	210		318	
German Lignite	60	60	50	58	
Spanish Lignite	60	90	100	40	

VTT Publication 394 Finland 1999   *Poor agreement between 20L and 1 m³ for K_{st} & P_m*

Biomass	P_m 20L bara	P_m 1m³ bara	K_{st} 20L bar m/s	K_{st} 1 m³	LOC 20L
Wood	8.6	8.8	115	87	10
Bark	9.0	9.7	132	98	10
Forest Residue	8.6	9.1	87	84	10
Spanish Pine	7.7	8.2	44	23	17
Barley Straw	7.9	9.3	72	58	13
Miscanthus	7.8	8.1	53	31	20
Soghum Straw	7.3	8.2	41	28	20
Rapeseed Straw	6.7	8.3	23	32	20
German Lignite	8.6	8.7	146	105	9
Spanish Lignite	8.6	8.8	164	107	8

P_m occurred at 750 – 1500 g/m³ for biomass and 375 – 750 for lignites

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8. **Leeds ISO 1 m^3 vessel results for biomass (Clara Huescar Medina will present this in the next lecture).**

The 1 m³ ISO standard vessel was originally developed by Bartknecht and is considered to be the most reliable dust explosion test vessel and the one against which all the smaller 20 litre spheres must give comparable results, using the same 10 kJ chemical ignitors.

The problem is that the ISO vessel is of different design to the 20 litre spheres and has only one large 'C' dust dispersion ring, compared with two in most of the 20 litre spheres. Also the rate of pressure rise depends on the delay between the start of injection and the ignition. This is due to the turbulence created by the compressed air injection process. If different injectors are used then different turbulence levels and dust dispersion (uniformity) characteristics will occur.

The 20 litre sphere is made to agree with the 1 m³ by adjusting the ignition delay. The two methods are thus forced to agree and it is assumed that the turbulence levels must be the same.
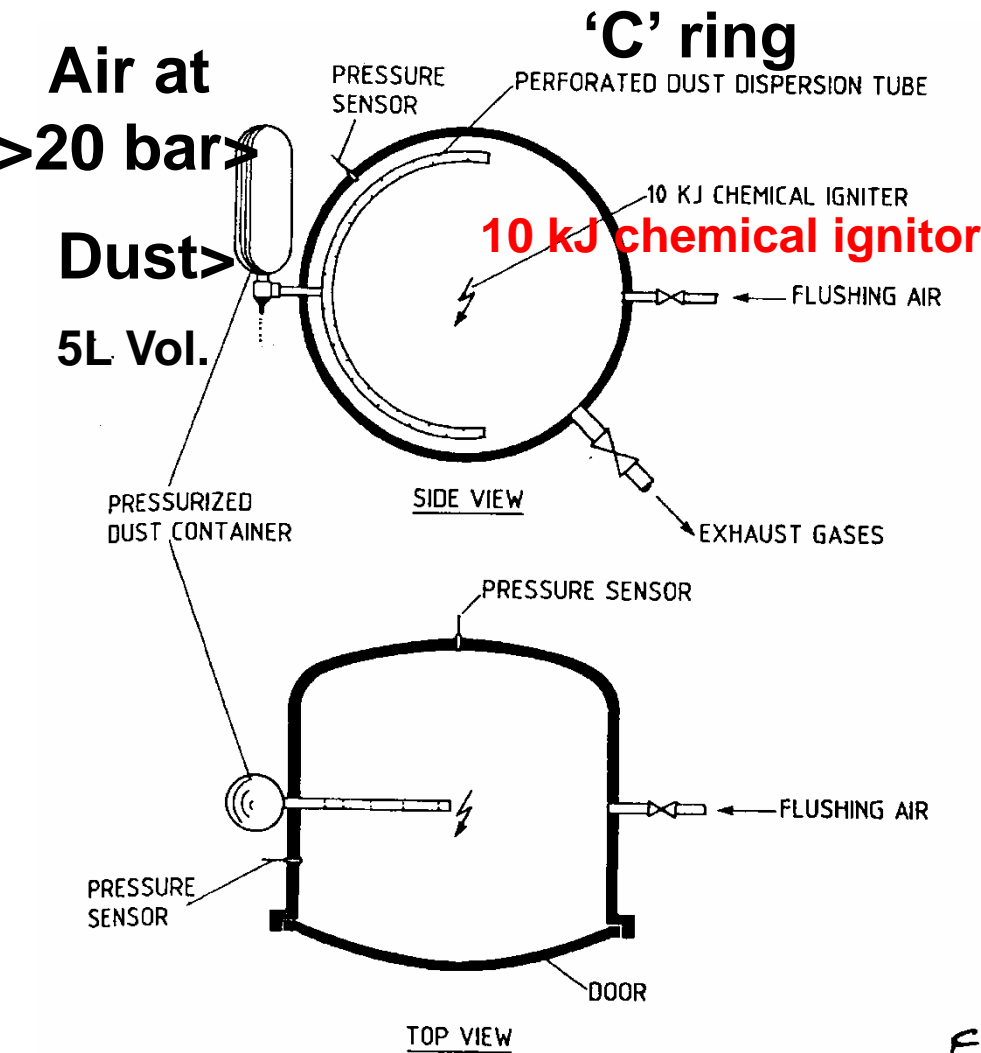
The air container is about 5 litre capacity and is pressurised to >20 bar with air. This air container is connected to the 1 m³ test vessel via a 19mm dia. valve with a 10 ms opening time. This pipe is then connected inside the vessel to a 19mm dia. 'C' ring with perforated holes at defined positions, to give dispersion of the dust. The hole dia. Is 4-6mm and the total hole area is 300 mm².

'C' ring

PRESSURE SENSOR

PERFORATED DUST DISPERSION TUBE

Air at
>20 bar>

Dust>

5L Vol.

10 KJ CHEMICAL IGNITER

10 kJ chemical ignitor

FLUSHING AIR

PRESSURIZED DUST CONTAINER

SIDE VIEW

EXHAUST GASES

PRESSURE SENSOR

FLUSHING AIR

PRESSURE SENSOR

DOOR

TOP VIEW

Eckhoff 1997 & 2003, p.529

Figure 7.54 *1 m³ closed vessel specified by the International Standardization Organization (1985) for determination of maximum explosion pressures and maximum rates of pressure rise of dust clouds in air (From Verein deutsche Ingenieure, 1988)*   VDI 2263

5L Dust Holding injection pot (20barg)

Electro pneumatic Ball Valve

Dust Delivery Pipe
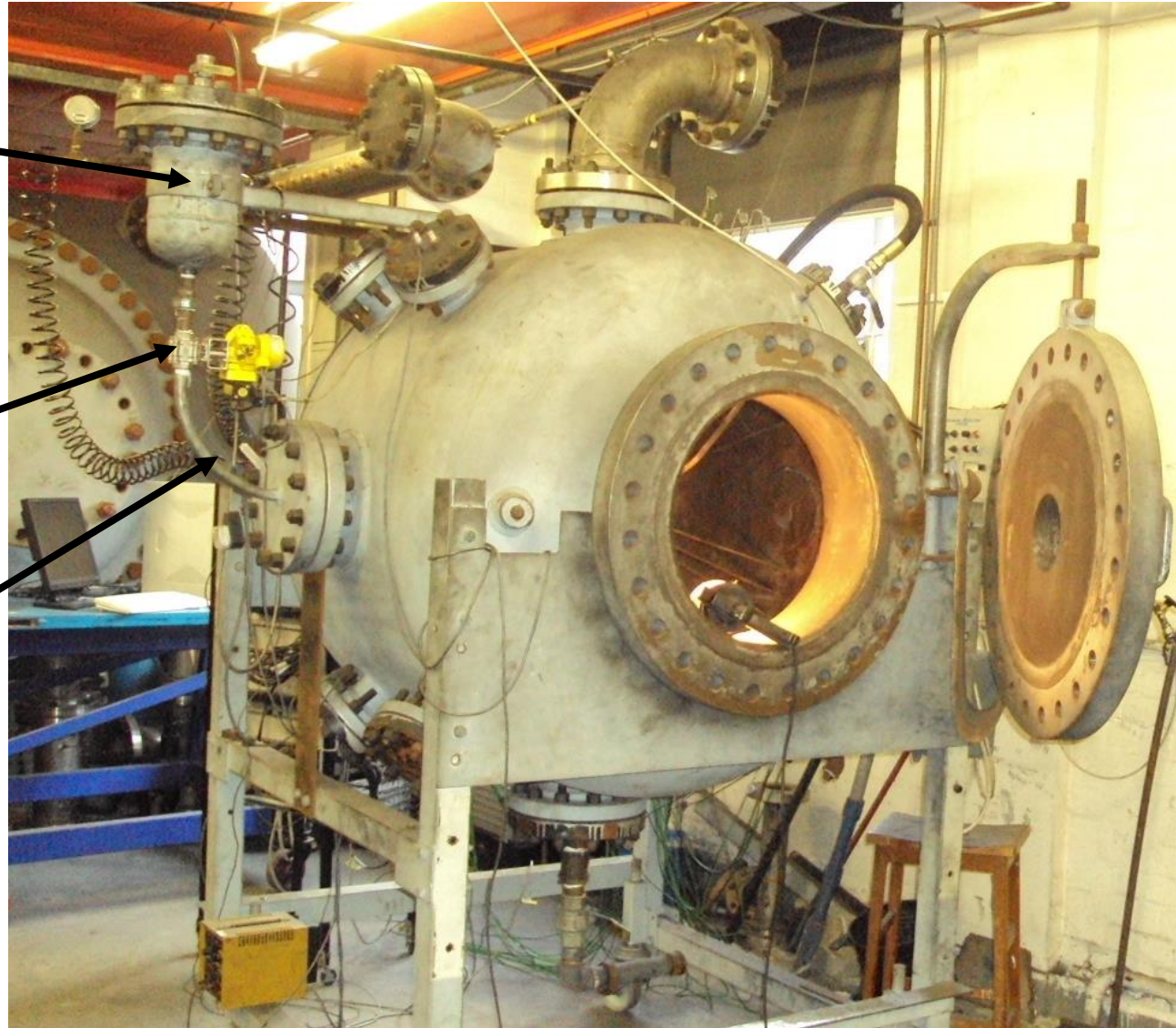
Section of C-tube with injection holes. Coal and walnut dusts passed through the C ring. Wood dust did not.

Bartknecht
Dust Explosions
1988

$V_1 = 1 m^3$
$V_2 = 5.4 L$ & $10 L$
P_2 & P_1 not given.
Results show
that dp/dt
depends on V_2.

K_{st} is a strong
function of the
ignition delay
which must be
standardised.
0.6s for 1m³

22 µm Cellulose Dust

1m³ - vessel
Cellulose:M=22µm
E = 10000 J

Both at 20bar

turbulence:
high   medium   low

10l container

5.4l container

1m³ vessel
Cellulose: M= 22 µm
E= 10000 J

Ignition delay
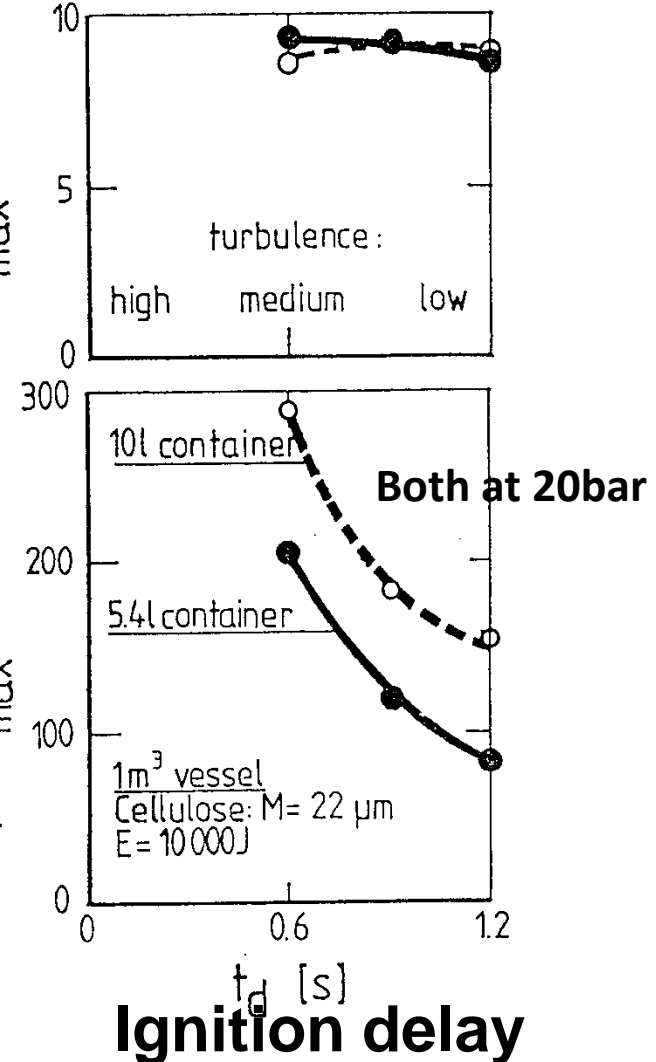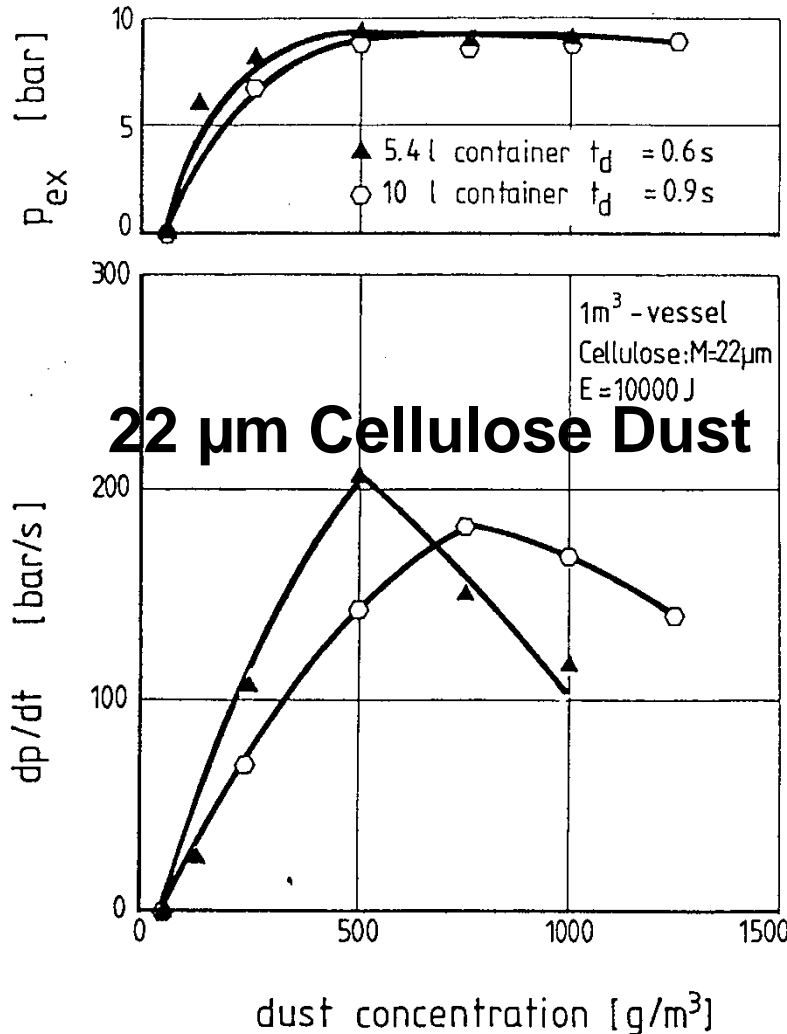
External air pot size influences the ignition delay

**Fig. 63.** Correlation between the dust concentration and the explosion characteristics using different dust containers and ignition delay times

Fig. 62. Influence of the container volume and the ignition delay time upon the explosion characteristics of a dust

5.4 l container t_d = 0.6 s
10 l container t_d = 0.9 s

Modification of the ISO 1 m^3 to allow low bulk density biomass in the external driver pot

➢ The standard 5L dust holding volume (actual volume 4.6L) was enlarged to 10L volume (actual volume 9.6L) by adding 5L cylindrical extension section (similar in diameter to the standard dust pot) on the top of the standard pot.

➢ The compressed air supply port was moved to the upper extension section to pressurise the dust holding pot from the top.

➢ As a part of the calibration process, the 10L dust pot was pre-pressurised to two different pressures,

• 10 barg and 20 barg - the 10 barg pressurisation gave the same mass of air as at 20barg in the 5L pot. Changing the mass of external air changes the air delivery time and this changes the required ignition delay.

➢ whereas 5L dust was only tested at

• 20 barg

➢ Calibration of the two dust holding pots was done with air only injections by varying the valve off timing to deliver the full contents of mass of air in the vessel from the two volumes of pots.

➢ Calibration was also done with gas and dust explosions at different ignition delays.

Ignition delay variation – with dust/air mixture
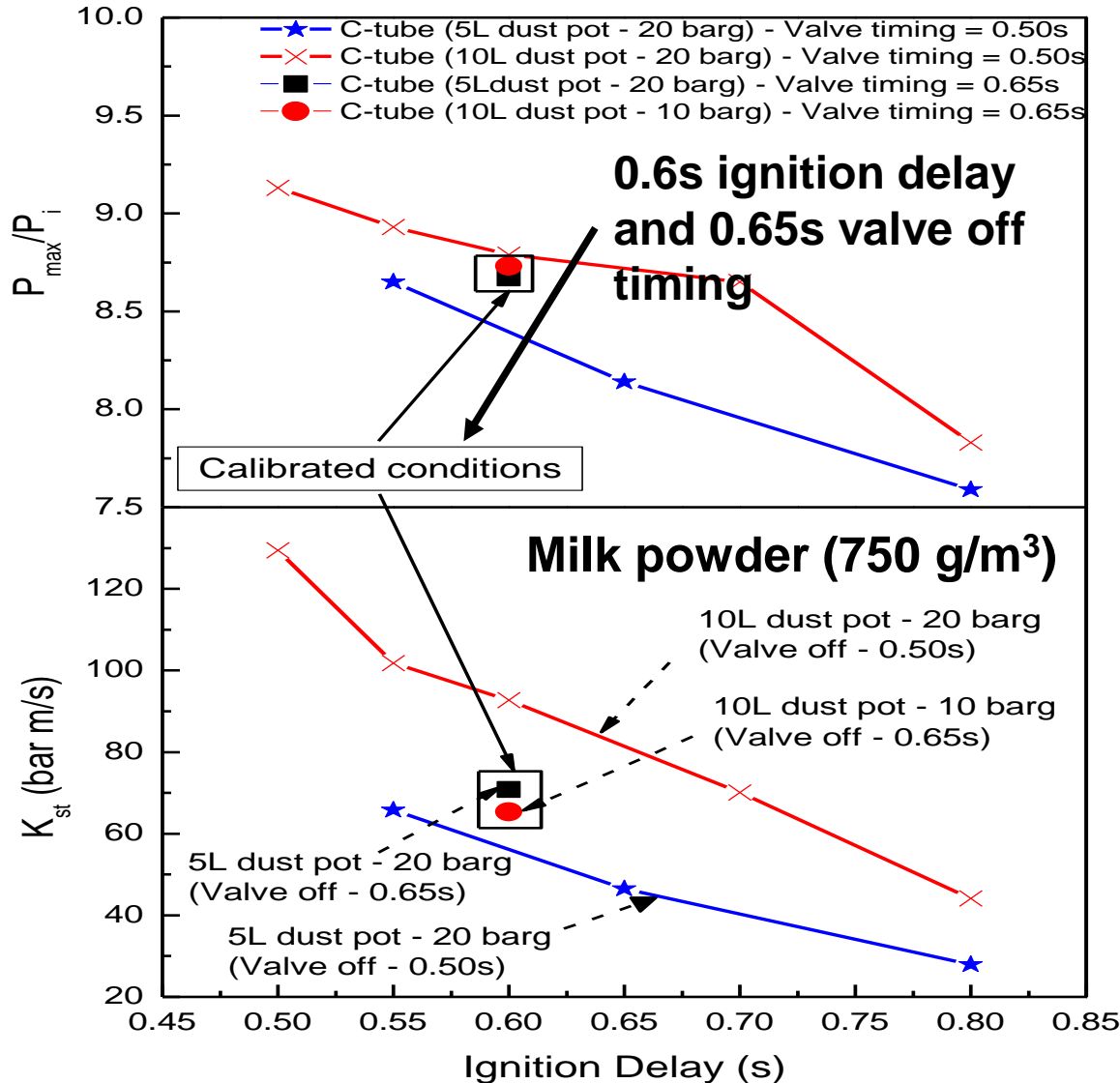
- The ignition delay was varied for the 10L pot pressurised to 20 barg and using 750 g/m^3 milk powder.

- The change in K_{st} and P_{max} as a function of the ignition delay is compared to the corresponding data from the using the 5L (20 barg) pot.

- The results from this study show significantly higher K_{st} with the 10L 20 barg pot at the standard ignition delay.

- These results confirms Bartknecht findings.

Evaluation of turbulence levels using gas/air mixtures

➢   **Gas explosion tests were carried out for the two volumes of dust holding pots with 10% methane in air at different ignition delays and were compared to 10% methane laminar gas explosions in the same vessel.**

➢   **The ratio of turbulent to laminar gas deflagration index (K_G) provided the reference turbulence factor (β) which was useful for the calibration of the new volume of dust holding pot.**

$$\beta = \frac{\left(K_G\right)_{\text{Turbulent}}}{\left(K_G\right)_{\text{La min ar}}}$$

Presented at the Seventh Fire and Explosion Hazards Seminar, Providence, USA, 2013. Hamed Sattar et al. U. Leeds

Evaluation of turbulence levels using gas/air mixtures (Ignition delay variation)
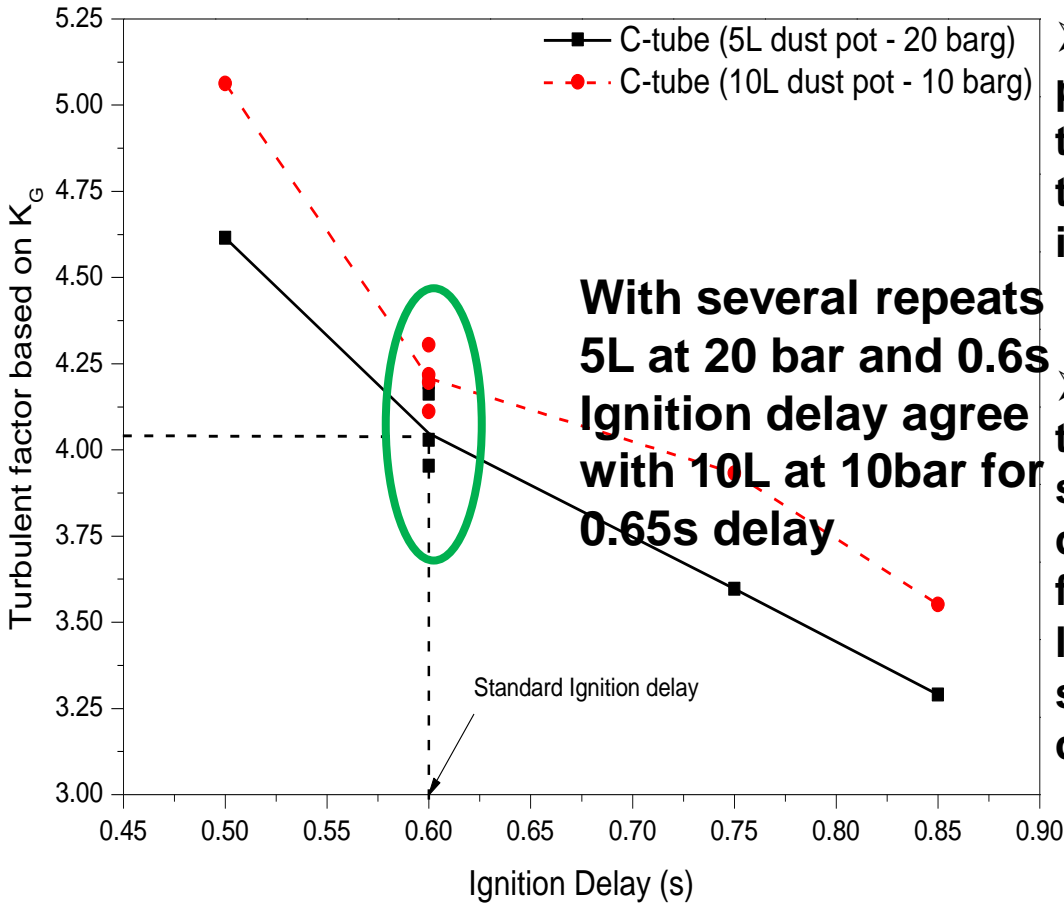
➢ **Halving of the pressure of 10L dust pot (from 20 barg to 10 barg) and keeping the ignition delay at 0.60s was sufficient to produce comparable turbulence levels in the test vessel.**

➢ **The turbulence factor (β) of 4.0 for the 5L - 20 barg pot can form a reference standard for calibrating other dust dispersion systems (for delivering fibrous biomass) and in calculating the laminar flame speed from turbulent flame speeds and hence burning velocities for dust-air mixtures.**

Note: All the results presented here have less than 3.7% deviation for P_{max}/P_i and less than 6% deviation for dP/dt.

Thermocouple Arrays inside the vessel: Flame Speed Measurements

**Thermocouples
Leeds modification
of the 1 m³ ISO vessel**

Electrodes

**Hemispherical
Ignitor holder**
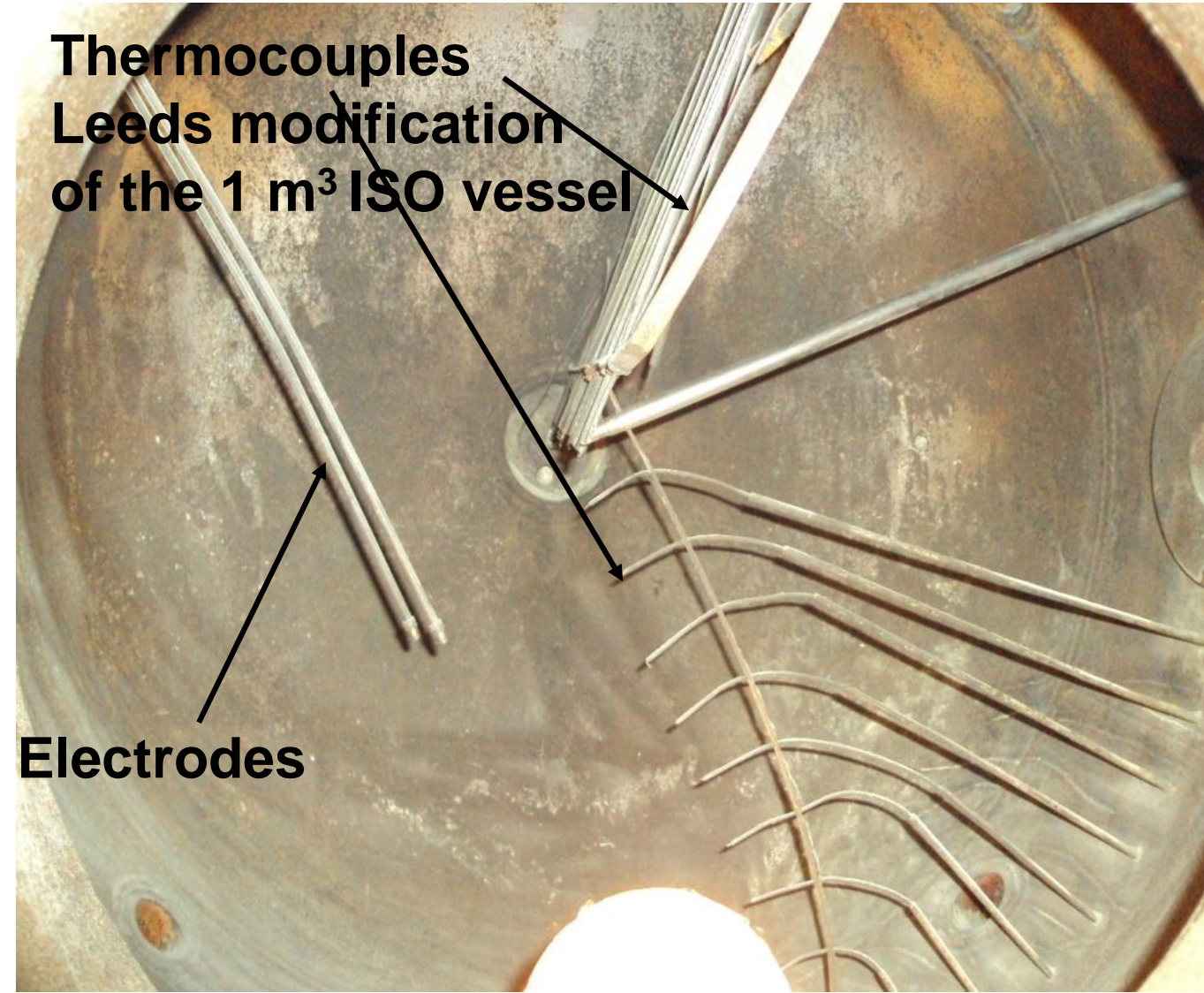
Results – Flame Position
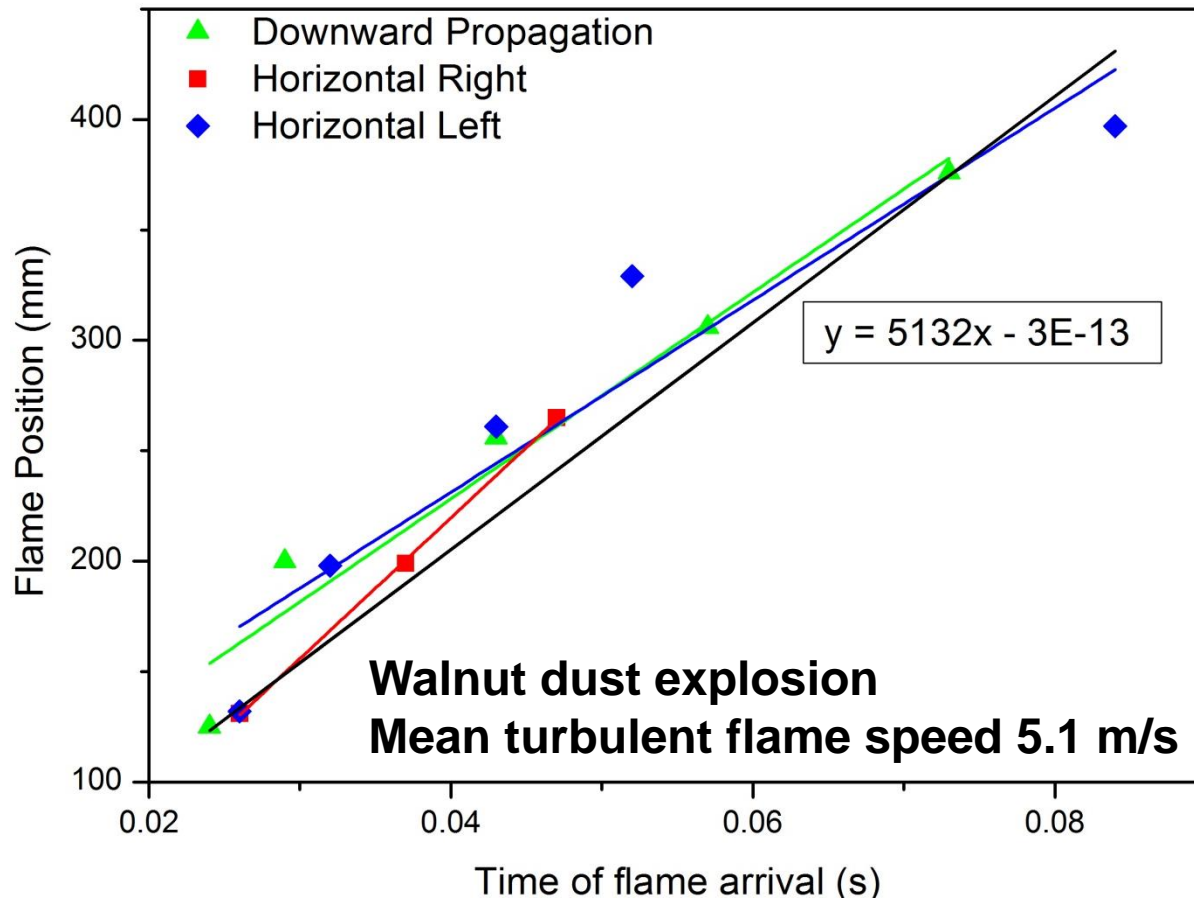
The slope of each line is the average flame speed in that direction, therefore near spherical propagation

- Here the flame is spherical as the flame speed in 3 directions are similar.
- The issue of non-sperical flames in the standard ISO equipment is a serious problem as the theory for K_{st} and if the flame is not spherical the measured K_{st} is in error.
- The standard ISO equipment does not use the method of ignition used here and cannot produce a spherical flame.
- The ISO std. has no requirement to demonstrate a spherical flame has been achieved.

Turbulent Flames Speeds and Laminar Burning Velocities of Dusts using the ISO 1 m³ Dust Expl. Method
Professor Gordon E. Andrews, Energy Research Institute,

	Injected concentration (g/m³)	Mass burned (%)	P_{max}/P_i	K_{st} (bar m/s)	$(S_F)_T$ (m/s)
Corn Flour repeat tests	742	72.6	9.1	158.0	11.69
	741	72.9	9.4	146.9	11.33
	741	75.1	9.2	149.3	11.11
	742	74.5	9.1	168.7	13.21
	740	74.3	9.2	162.7	13.1
Mean	741	74	9.2	157	12
Standard deviation	0.8	1.1	0.1	9	1
%age deviation	0.1	1.5	1.3	5.8	8.24

Turbulent Flames Speeds and Laminar Burning Velocities of Dusts using the ISO 1 m³ Dust Expl. Method
Professor Gordon E. Andrews, Energy Research Institute,

School of Chemical and Process Eng., U. Leeds , UK   **79**

Comparison with other measurements of K_{st} for cornflour dust

Reference	Measurement equipment	Min. Conc. (g/m³)	Particle Size (micron)	P_{max} (bara)	K_{st} (bar m/s)
Eckhoff, 2003	20L or 1m³	60	16	9.7	158
Kumar et al., 1992	10.3 m³ Cylinder	----	----	6 Low	155
Skjold et al., 2005	20L	----	----	9	160
Tamanini and Ural, 1992	20L	----	----	8.4	158
This Study	1m³	113	15	9.1	158

Turbulent Flames Speeds and Laminar Burning Velocities of Dusts using the ISO 1 m^3 Dust Expl. Method
Professor Gordon E. Andrews, Energy Research Institute,
School of Chemical and Process Eng., U. Leeds , UK   80

An approximately valid view of a spherical vessel explosion is that there is little pressure rise in the first half of the flame travel distance and 98% of the adiabatic pressure rises in the last half of the flame travel.

Assume a constant burning velocity, U_L, through the flame travel (constant flame speed, S_L, where $S_L = U_L \rho_u/\rho_f = U_L E$, where $E = \rho_u/\rho_f$).
Let the adiabatic pressure rise be $(P_m – P_i)$
The time for this pressure rise = $(D/4)/S$ (D=1.24m for V=1 m³)
Thus the rate of pressure rise = $(P_m – P_i) S / (D/4)$
Hence $K_G = dP/dt \, V^{1/3} = [0.98(P_m – P_i) S /(D/4)] (\pi/6)^{1/3}D$
      $K_G = 3.16 (P_m – P_i) S = 3.16 (P_m-P_i)U_L E_p$ bar m/s

The rate of P/P_i rise = $K_G/P_i = 3.16(P_m/P_i – 1)U_L E_p$ m/s

where P_i is the initial pressure. This is the preferred formulation as this is independent of the initial pressure.
Thus , K_G and U_L should be linearly related and similarly K_{st} and the flame speed measured in a dust explosion should be linearly related.

Turbulent Flames Speeds and Laminar Burning Velocities of Dusts using the ISO 1 m³ Dust Expl. Method
Professor Gordon E. Andrews, Energy Research Institute,
School of Chemical and Process Eng., U. Leeds , UK   **81**

Present results for K_G and U_L reactivities in the 1 m³ ISO vessel

This is **the first demonstration of a linear relationship between laminar burning velocity and K_G using the same ISO 1 m³ explosion vessel to determine both parameters**

$y = 206.12x - 5.57$
$R^2 = 0.996$

Laminar burning velocity U_L S_L (m/s)

Turbulent Flames Speeds and Laminar Burning Velocities of Dusts using the ISO 1 m^3 Dust Expl. Method
Professor Gordon E. Andrews, Energy Research Institute,
School of Chemical and Process Eng., U. Leeds , UK   82

It is proposed that the dust ISO standard explosion vessel to be used to measure laminar burning velocities.
For dusts the turbulent flame speed would be measured and the laminar flame speed calculated from the knowledge of the turbulence enhancement factor β = 4 in the ISO standard air injection method for dust explosions.
This was evaluated by carrying out laminar and turbulent gas explosions in the vessel

$$U_L = S_s/\beta E_p$$

where U_L is the laminar burning velocity
   S_s is the measured laminar flame speed in the constant pressure period of the explosion (up to 65% of the radius of the vessel)
   E_p is the flame adiabatic expansion ratio at constant pressure
   β   Turbulence factor evaluated from gas explosions in the ISO 1 m^3 dust explosion vessel

This equation is valid for an infinitely thin reaction zone. The key issue is at what size of flame is the infinitely thin reaction zone assumption valid. This was determined using gas explosions, but could have to be larger for dust explosions.

Turbulent Flames Speeds and Laminar Burning Velocities of Dusts using the ISO 1 m³ Dust Expl. Method
Professor Gordon E. Andrews, Energy Research Institute,
School of Chemical and Process Eng., U. Leeds , UK   **83**

The thin flame assumption is also the same as that of zero flame stretch.

The thin flame assumption is valid if the vessel is large enough for the flame thickness volume to be <1% of the burnt gas volume.

For a 1mm typical laminar flame thickness of 10% methane-air flames, and a requirement for the flame thickness volume to be <1% of the burnt gas volume, the flame is >600mm diameter.

A 1 m³ vessel is the MINIMUM size of explosion vessel for this to be valid in the constant pressure period of flame propagation which is 800mm diameter in this ISO 1 m³ vessel (dia 1.24m).

For dusts, flame thickness is greater than for gases and this makes the minimum vessel size potentially larger than that for gas flames.

Do we need even larger experimental vessels for dust explosion flame speed and burning velocity measurement? We have a 10m³ vessel that could be adapted for this purpose in Leeds.
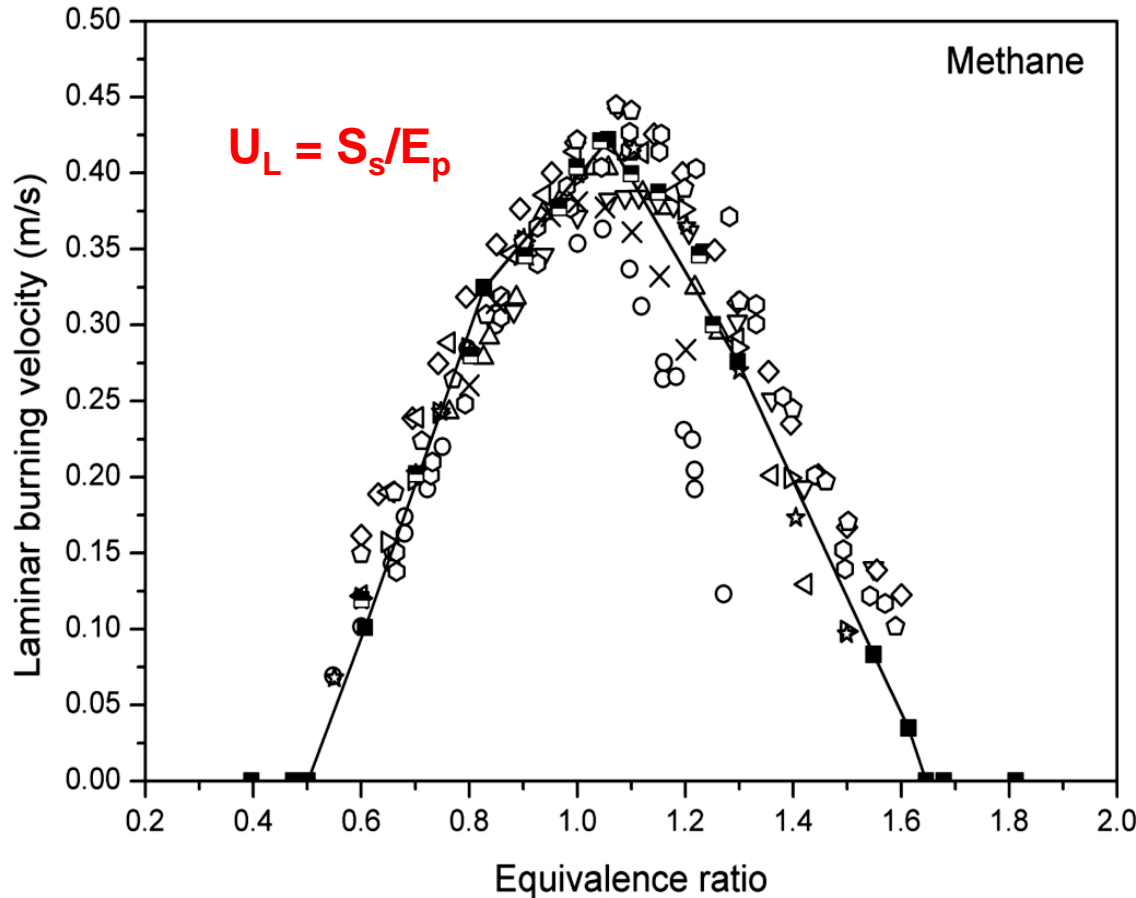
In our opinion the 20L sphere dust explosion equipment is too small and the flame is too curved to make reliable measurements for thick dust flames.

Hamed Sattar, PhD Thesis, U. Leeds, 2013.

Flame speed in large laminar spherical flame in 1m³ explosion vessel in the constant pressure period.
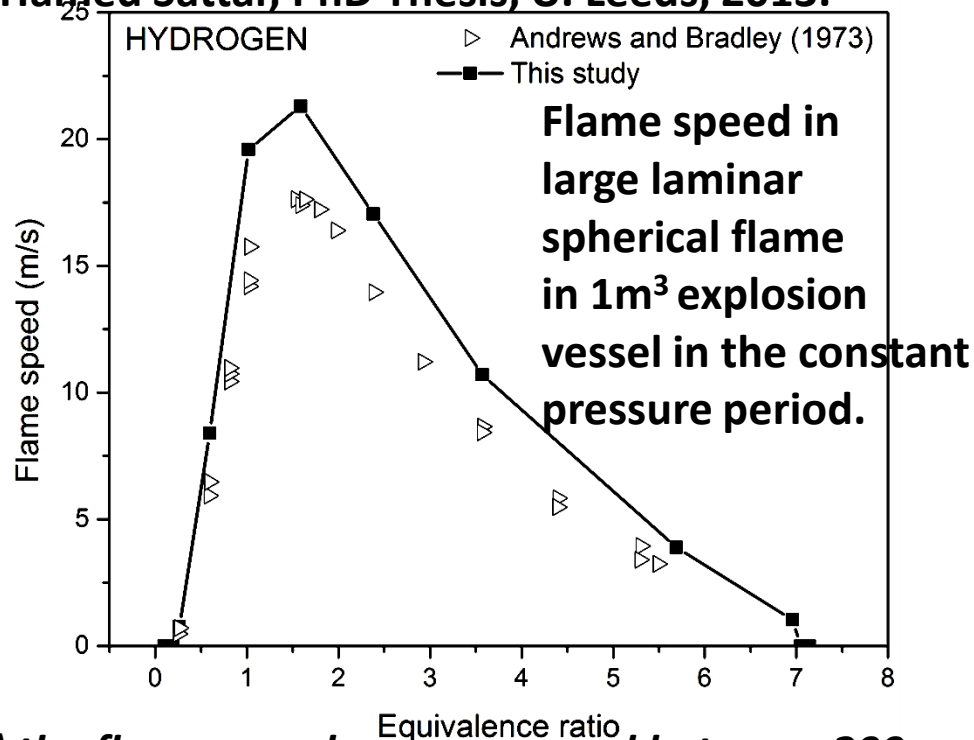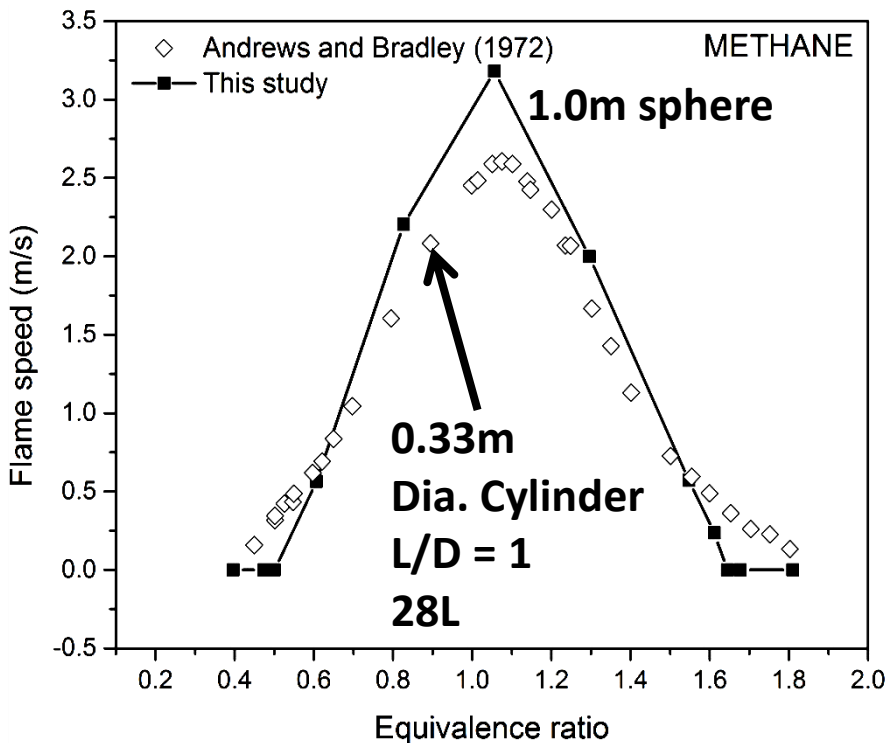
In the 1m³ vessel (as used in dust explosions) the flame speed was measured between 200 and 800mm diameter, where the pressure was constant. There is then negligible flame curvature and the flame thickness is <1% of the burned gas volume so the infinitely thin flame front assumption is valid. The laminar burning velocity is then $U_L = S_s/E_p$ where E_p is the adiabatic expansion ratio.
The maximum burning velocity for methane-air is then 0.42 m/s

10th Euro. Conf. on Coal Research and its Applications, Univ. Hull, UK. 15 – 17th Sept. 2014.

Turbulent Flames Speeds and Laminar Burning Velocities of Dusts using the ISO 1 m³ Dust Expl. Method
Professor Gordon E. Andrews, Energy Research Institute,
School of Chemical and Process Eng., U. Leeds , UK   **85**

$U_L = S_s/E_p$

Effect of methane equivalence ratio on the laminar burning velocity of methane/air as a function of equivalence ratio. Comparison of the present measurements with previous measurements.

$U_{L\ max} = 0.42$ m/s

In good agreement with other error free methods.

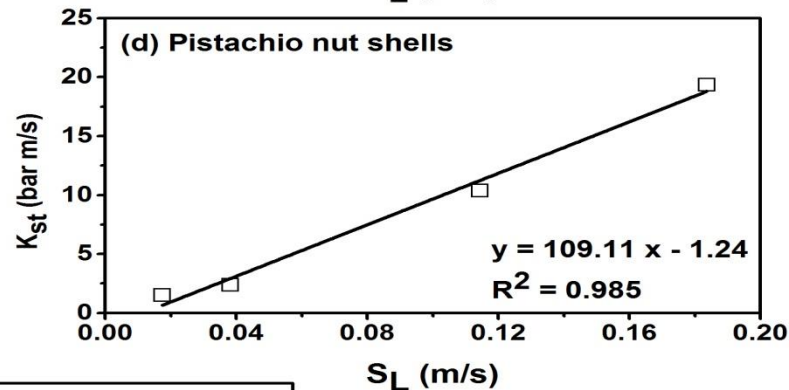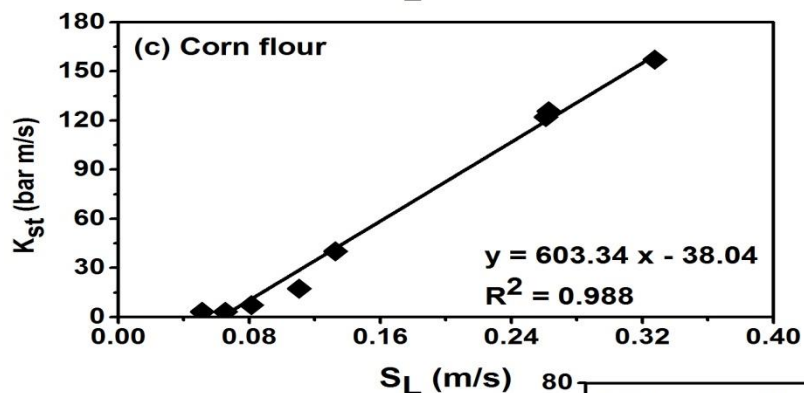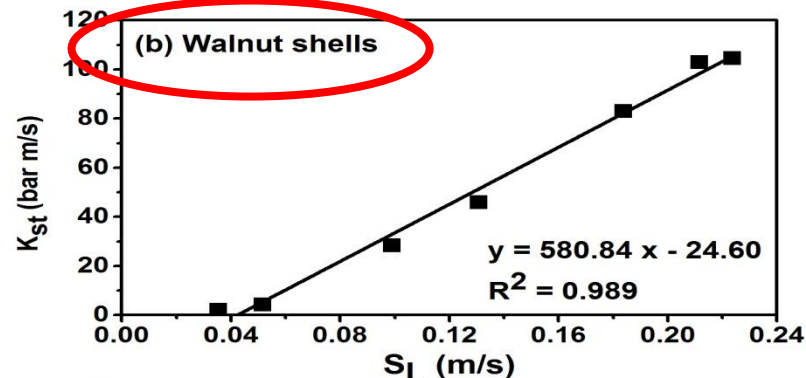**Turbulent Flames Speeds and Laminar Burning Velocities of Dusts using the ISO 1 m³ Dust Expl. Method**
**Professor Gordon E. Andrews, Energy Research Institute,**
School of Chemical and Process Eng., U. Leeds , UK   **86**
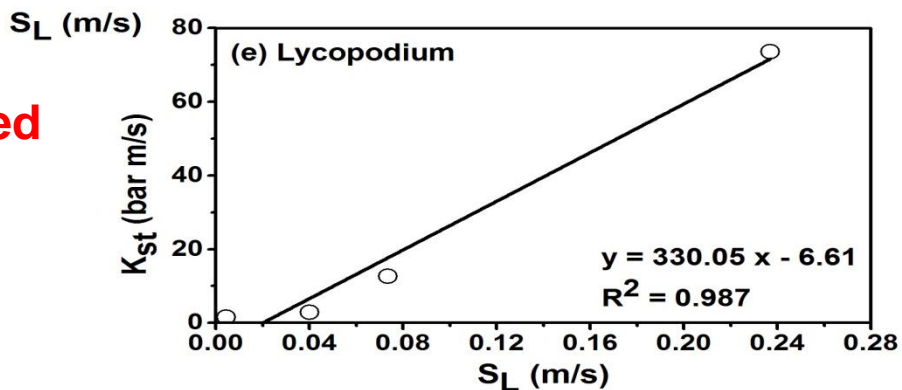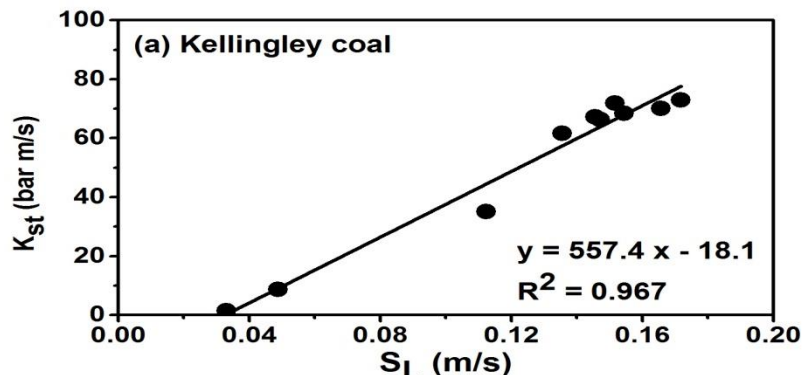
Kst and S_L were varied for the same dust by varying the conc.

Turbulent Flames Speeds and Laminar Burning Velocities of Dusts using the ISO 1 m³ Dust Expl. Method
Professor Gordon E. Andrews, Energy Research Institute,
School of Chemical and Process Eng., U. Leeds , UK   **87**
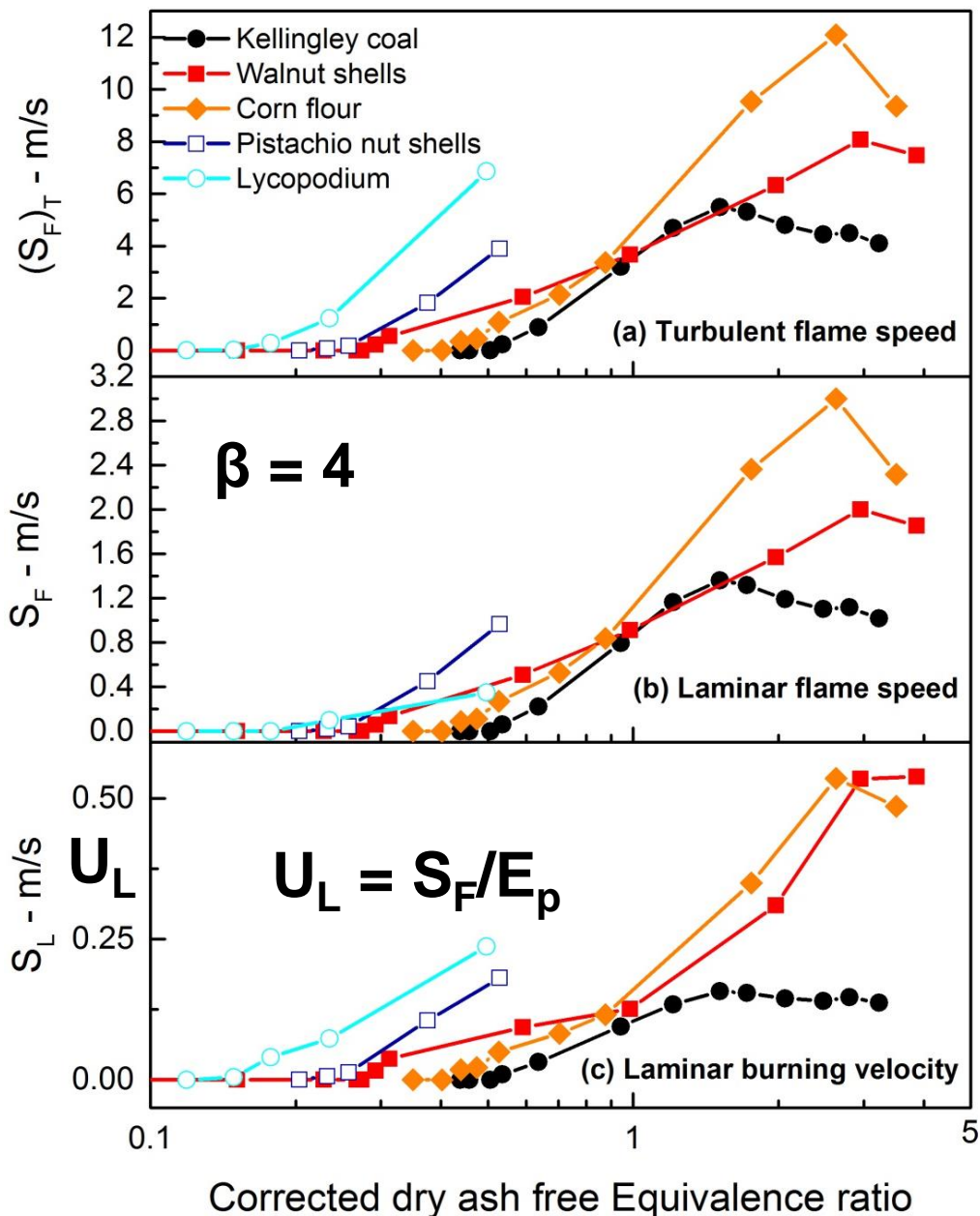
Comparison of
(a) measured turbulent
flame speeds in ISO 1 m³ dust exp.
(b) laminar flame speeds
from turbulent flame speeds using
turbulence factor (β = 4) and
(c) laminar burning velocities derived
from laminar flame speed using
constant pressure expansion ratio for
Kellingley coal, walnut shells,
cornflour, pistachio nut shells and
lycopodium against dry ash free
corrected equivalence ratio.

Turbulent Flames Speeds and Laminar
Burning Velocities of Dusts using
the ISO 1 m³ Dust Explosion Method Satter,
Andrews[*], Phylaktou, Gibbs
CISAP6 Paper 56 Bologna, Italy
Chem. Eng. Trans. Vol.36, 2014

Global Energy Release

The global energy release is the MW per unit area of the flame front.

Mass burn rate = S_S/E_p x A_f x ρ_u = (air + fuel) mass consumption rate

Heat release = Fuel Mass burn rate x CV

Global heat release MW/m^2 = Heat release/A_f

Thus Global Heat Release = (S_s/E_p) ρ_u CV /(1+A/F) MW/m^2

For dusts E_p is often replaced by the measured $E_v=P_{max}/P_i$ due to the problem of calculating the adiabatic flame temperature. In this work the constant pressure flame temperature has been calculated.
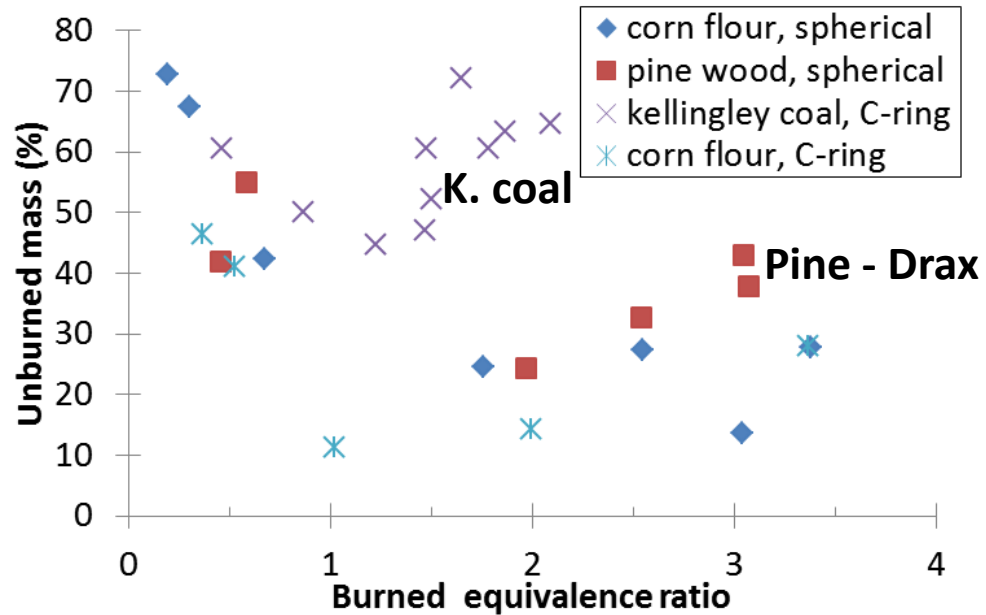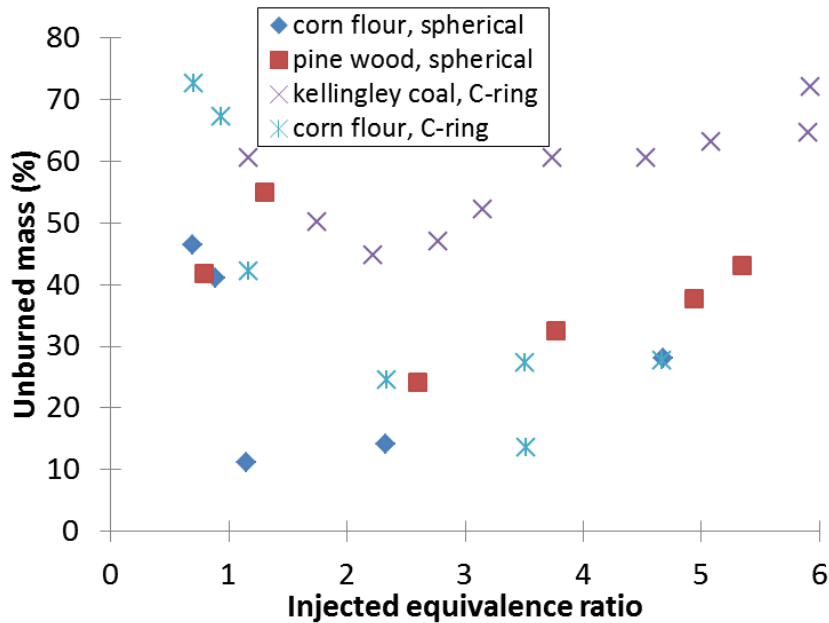
Taking ρ_u as 1.2 kg/m^3 the Global Heat Release for the turbulent flame of Colombian coal dust with flame speed of 5.2 m/s at Ø = 2.8, with CV 33.5 MK/kg and taking E_p as 7.7 and stoich. A/F as 11.1 (actual A/F 4.0) gives the global heat release rate as 5.4 MW/m^2.

This is close to furnace pf coal burners and this explosion technique is a simple way of studying coal combustion under realistic turbulent flame front conditions. It is an improvement on other small scale experimental techniques such as drop tube furnaces, TGA, and shows that this test rig has relevance to real furnace flame conditions and is not just an explosion hazard mesurement procedure.
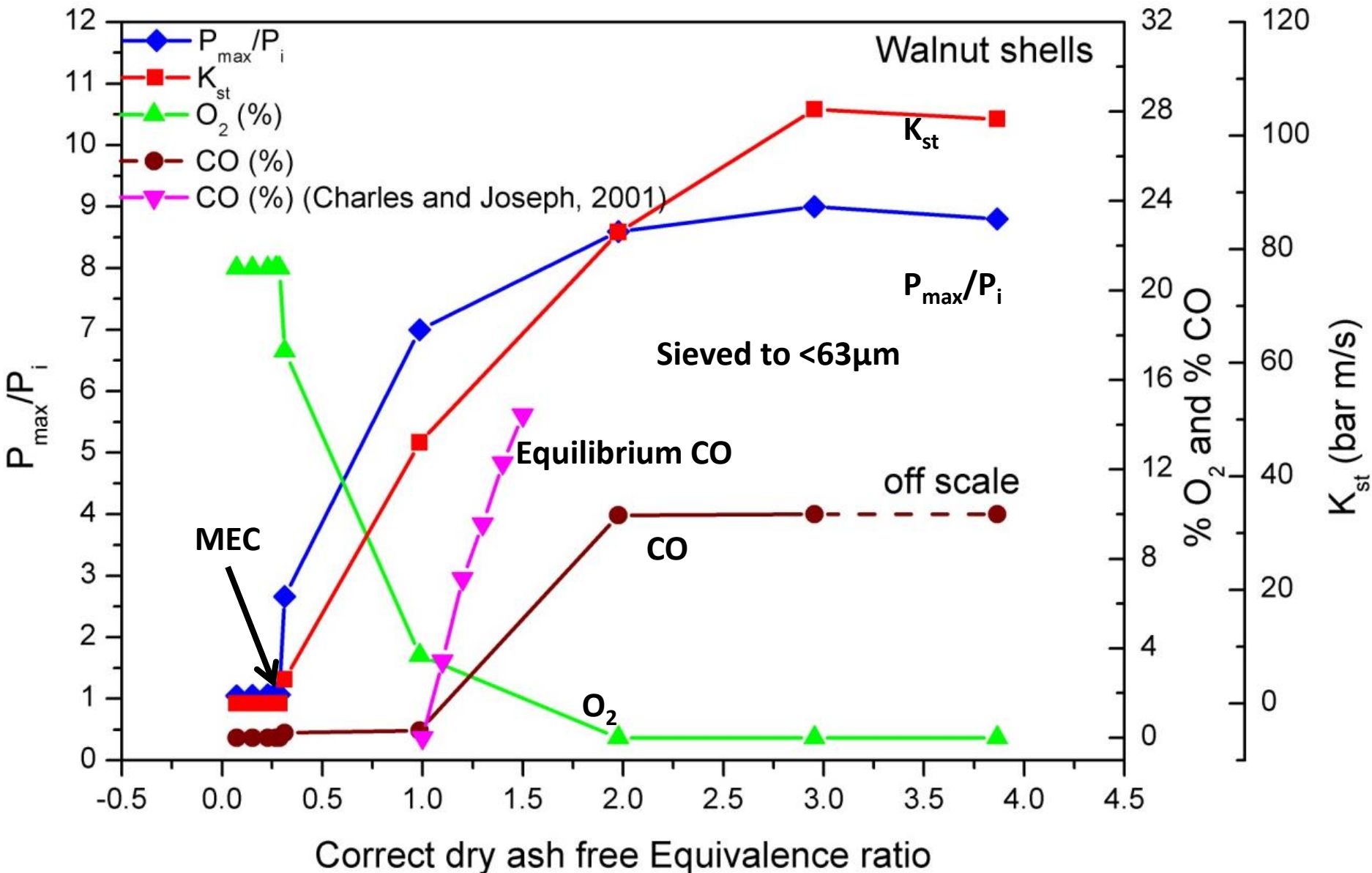
Contents

1. **Introduction**
2. **Biomass stoichiometry and variable composition**
3. **Problems with biomass explosion characterisation.**
4. **Dust explosion characterisation equipment.**

   Hartmann for MEC

   20L sphere

   ISO 1 m^3

5. **The unburned particle mass in the ISO 1m^3**
6. **Modifications of the ISO 1 m^3 vessel for woody biomass.**
7. **Leeds MEC results for woody biomass**
8. **Leeds ISO 1 m^3 vessel results for biomass (Clara Huescar Medina will present this in the next lecture).**

Pulverised biomass flame propagation and explosion characteristics with comparison with coal combustion.
Prof. Gordon E. Andrews, Energy Research Institute, SCAPE, Univ. Leeds, UK

Pulverised biomass flame propagation and explosion characteristics with comparison with coal combustion.
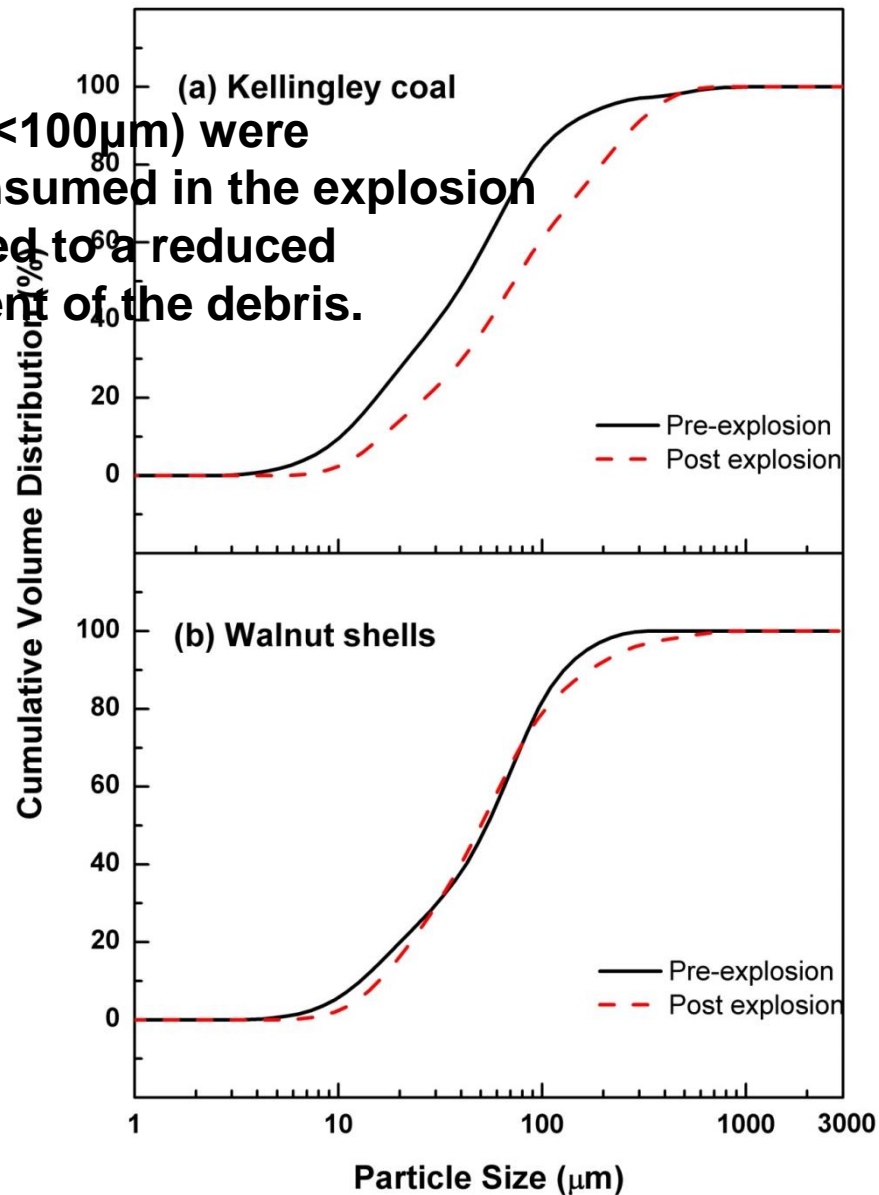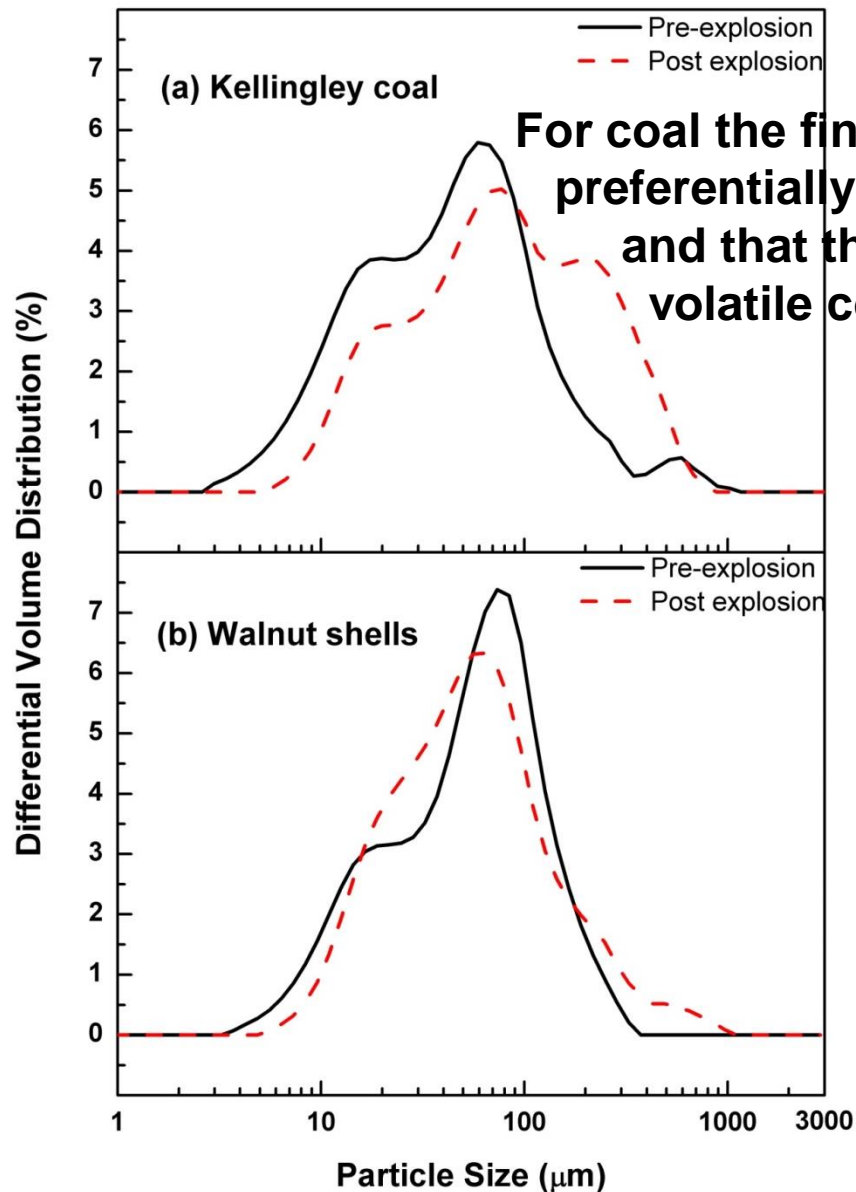Prof. Gordon E. Andrews, Energy Research Institute, SCAPE, Univ. Leeds, UK

The biomass that does not burn is due to entrainment by the explosion induced wind ahead of the flame, which carries particles to the wall. Here they form a layer of coal that insulates the flame from the metal wall and this reduces the rate of pressure loss compared with a gas explosion. The actual flame front concentration is the injected concentration minus the dust that remains. This is then the burned equivalence ratio or corrected equivalence ratio.

Conference on Green Transport, Renewable Energy and Environment (ICGTREE 2014),
August 23-24, 2014, Tianjin, China

For most dusts after the explosion unburned dust is found to lie on the bottom of the chamber. However, milkpowder behaved differently and was attached to the wall as a cake after the explosions, which was easily removed.

These results indicate that the dust that does not burn is due to the unburned gas flow ahead of the flame due to the burned gas explosions, entrains the dust and carries it to the wall where the flame quenches before it can burn this dust. After peak pressure decays this dust falls off onto the floor – normally.

For coal the fines (<100µm) were preferentially consumed in the explosion and that this led to a reduced volatile content of the debris.

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7. Leeds MEC results for woody biomass
8. Leeds ISO 1 m^3 vessel results for biomass (Clara Huescar Medina will present this in the next lecture).

The problem with the 20L sphere and 1 m³ dust explosion vessels is that they will not operate with woody biomass, even if they are milled to <63μm. We have no 20L sphere experience but can certify that the standard C ring will not pass any biomass that is fibrous. This is why we started our biomass work with nut shell biomass, as these are brittle and will pass through the standard injection system.

New injection systems are required and they must be cross referenced to the standard system by calibration with a dust of known K_{st}. We use cornflour as our reference dust.

We have calibrated various injection system for biomass and have concluded that for coarse fibrous biomass it is essential to place the biomass in the explosion vessel and disperse it with the usual external compressed air source.

New dust injection dispersers for fibrous biomass – designs investigated

Initial Spherical nozzle injector – too much dust sent back onto the near wall which then did not participate in the explosion.

Rebound Nozzle

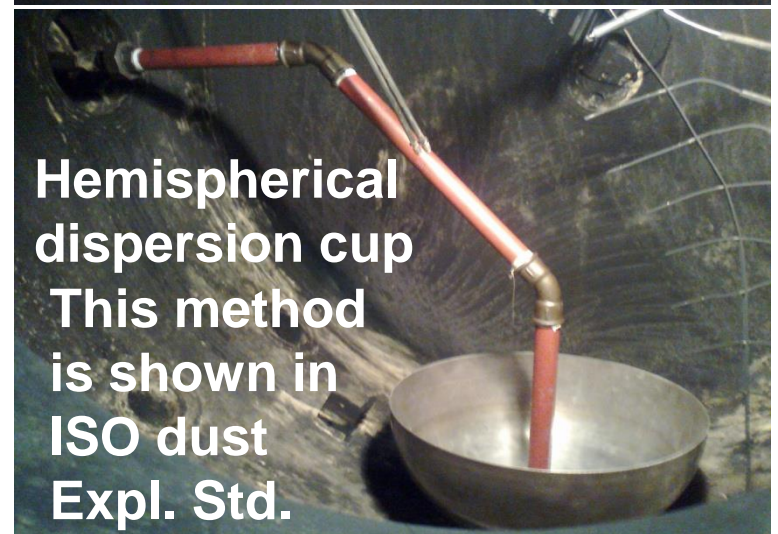This is Bartknecht's design for Flox dusts mentioned in ISO dust Expl. Std.
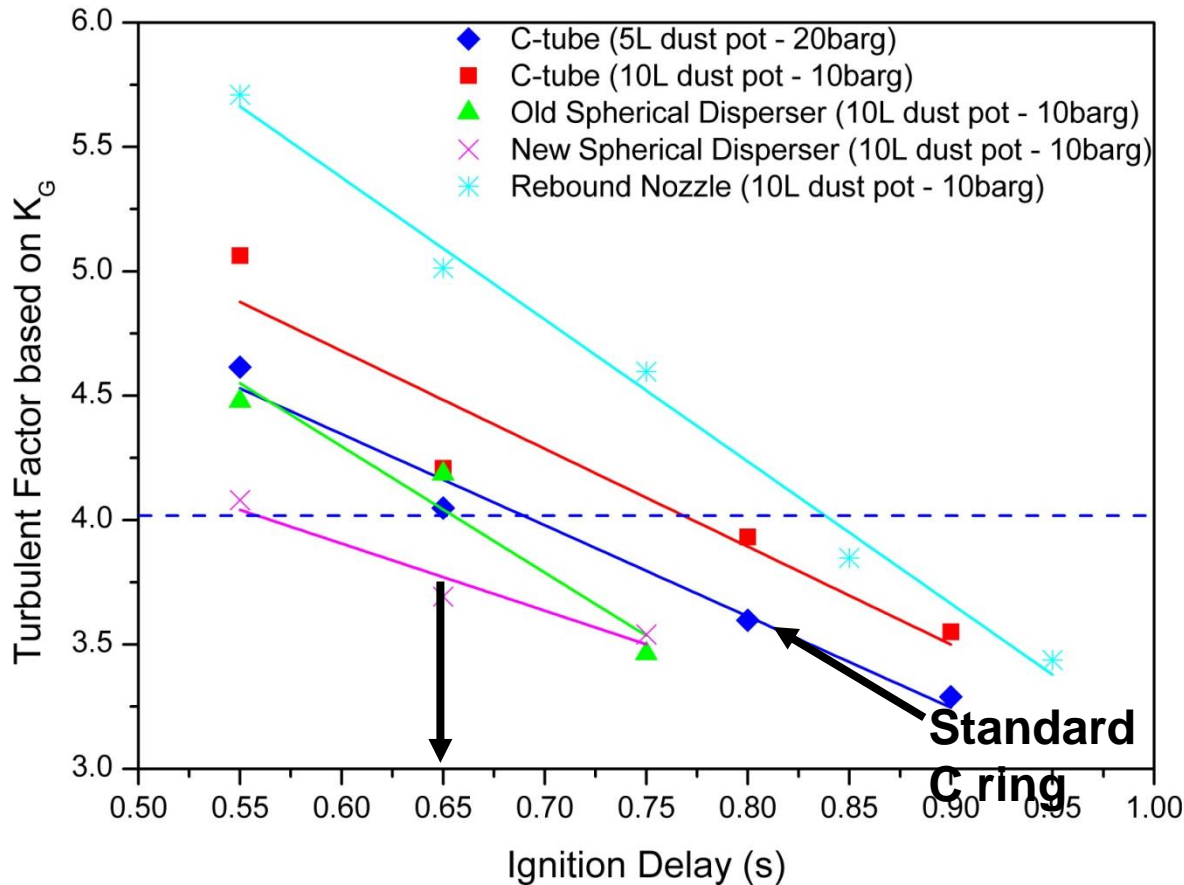

Redesigned Spherical nozzle injector

This is similar to flame suppressant injectors

Hemispherical dispersion cup
This method is shown in ISO dust Expl. Std.

Results – Delivery system Calibration

Calibrated turbulence factors at different ignition delays

- Standard C-tube with 5L dust pot, the turbulence factor found through 10% methane test, is 4.

- Each dispersion system must give the same turbulence factor as of standard system.

- It is possible to study the combustion study the near actual plant conditions by decreasing the ignition delay.

The standard 0.6s delay is after the air has entered and the total delay is 0.05s longer due to the time for the air to move from the pot to the C ring outlet.

The new spherical nozzle was shown to give a spherical flame for dusts and was a good injector for biomass dusts. However, this only passed biomass dusts that were milled to <63μm. This size would not pass through the standard C ring.

The rebound nozzle was also OK and had a spherical flame. But its turbulence level was higher than the standard method. It also would not pass biomass >63μm.

We consider that there is an urgent need to get data on flame speeds and K_{st} for the actual biomass size range used in power stations and this is >>63μm.

This summer we have just shown that the hemispherical container on the bottom of the vessel with compressed air injected from outside can be calibrated to give spherical flames and a Kst close to that for cornflour using the C ring.
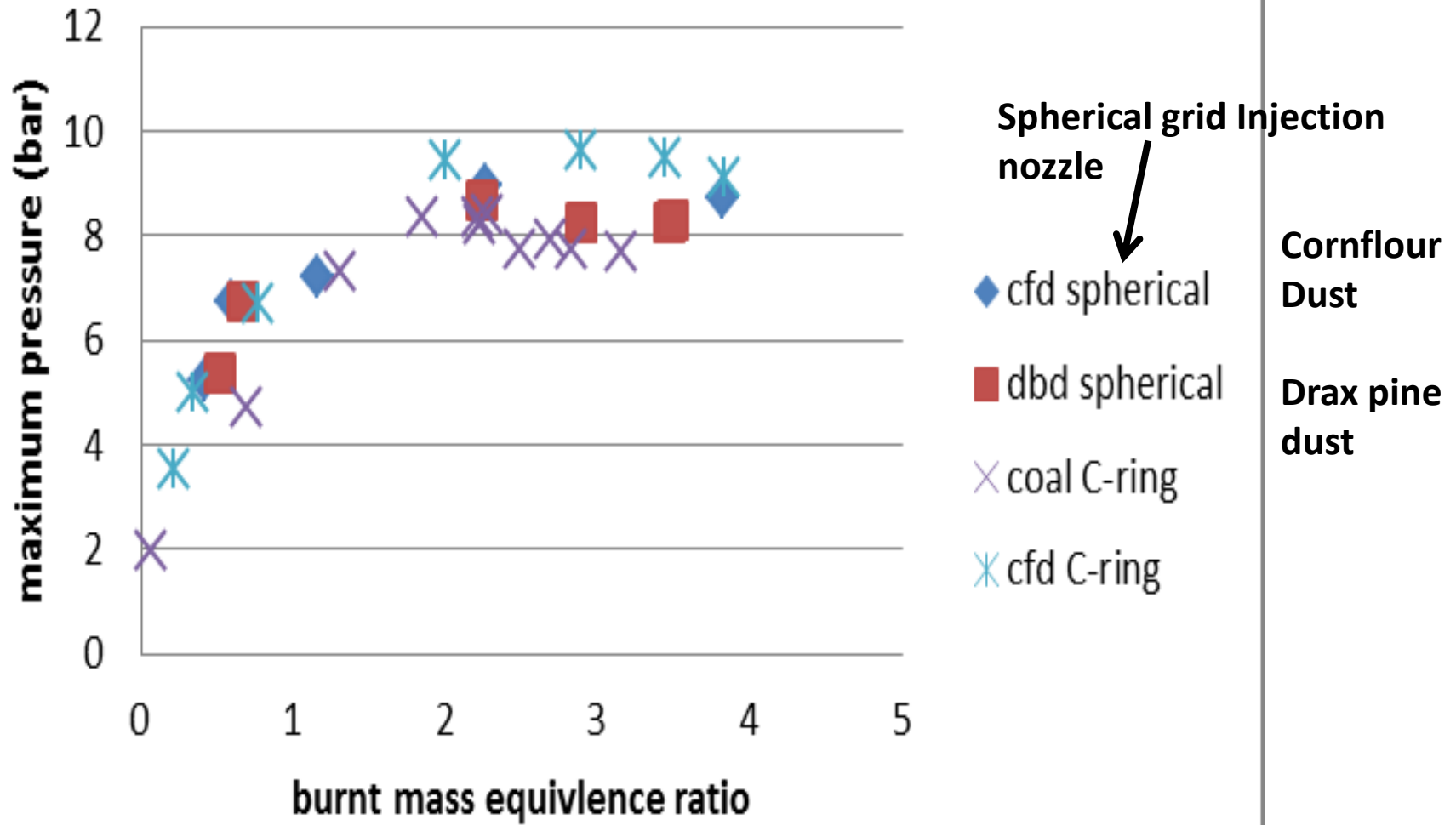
This has also now been demonstrated to work with coarse biomass and we are currently in the process of producing data on coarse woody and other fibrous biomass.

Conference on Green Transport, Renewable Energy and Environment (ICGTREE 2014), August 23-24, 2014, Tianjin, China

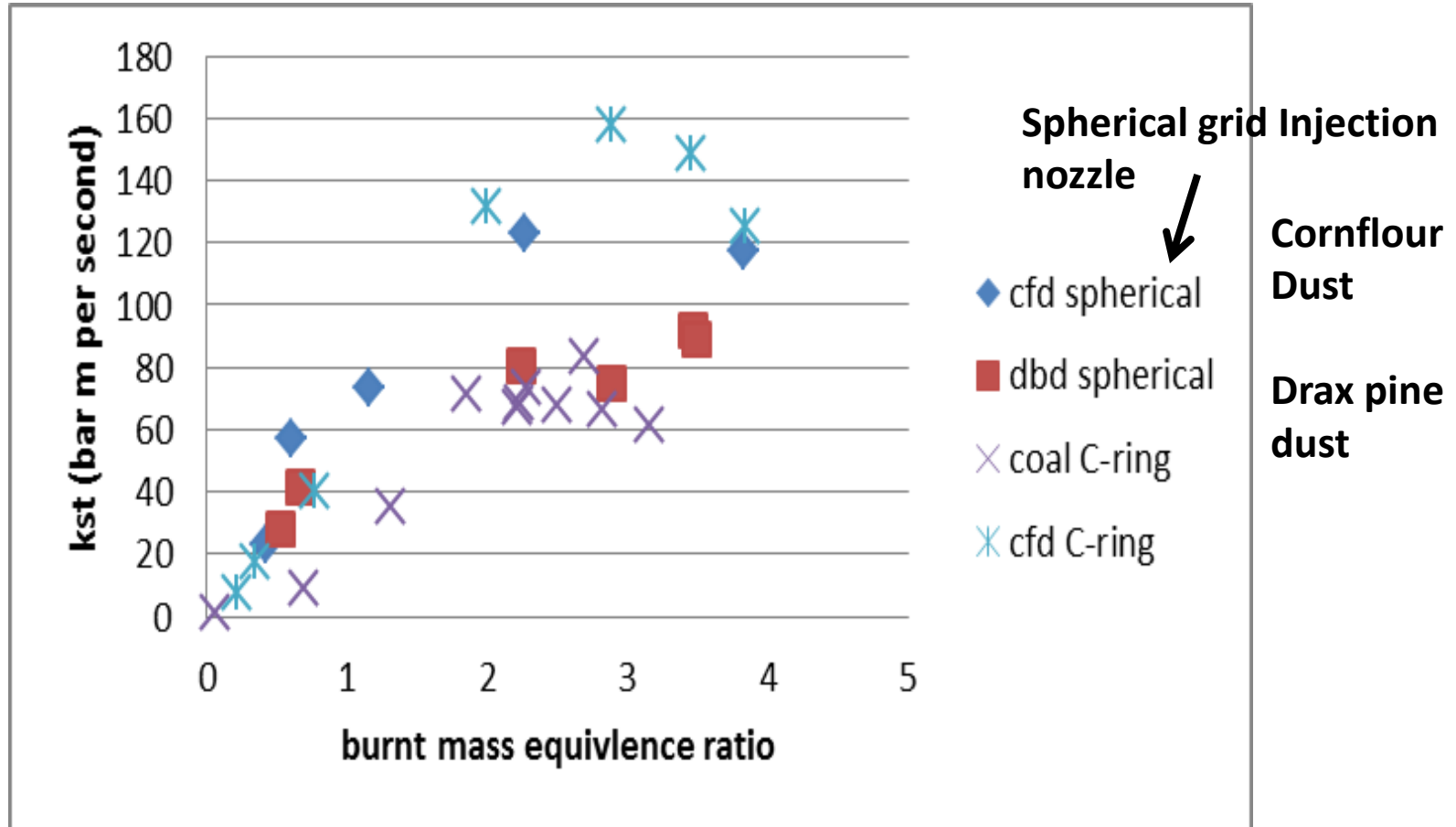**XISHPMIE Bergen 2014 – Slatter et al. U. Leeds**

Peak pressure occurs for very rich mixtures, even after accounting for the dust that does not burn. It is not known why this occurs. Biomass and coal behave in a similar way.

XISHPMIE Bergen 2014 – Slatter et al. U. Leeds

Spherical grid Injection nozzle

Cornflour Dust

Drax pine dust

Legend: cfd spherical, dbd spherical, coal C-ring, cfd C-ring

Axes: kst (bar m per second) vs burnt mass equivlence ratio

Kst reactivity of Kellingley coal and pine dust (Drax) are similar with the Peak reactivity at Ø = 2-4.

Contents

- Initial tests with A/B classification apparatus >>> Visual determination is difficult and dependant on the observer's criteria, therefore the apparatus was modified.

- The combustion chamber is a 1L vertical polycarbonate cylinder (L=322mm, D=61mm) into which a blast of air is introduced at the base. The air disperses the dust located in a dispersion cup at the base of the cylinder and ignition is achieved by a constant arc ignition source.

- The top of the tube is covered with an aluminium foil sheet secured with a locking ring that closes the tube.

- The modified tube has a pressure transducer and three thermocouples have been fitted at 50mm, 100mm and 150mm distance from the ignition source.

Huescar et al. U. Leeds, IX ISHPMIE, Krakow, 2012

Explosion, vent bursting

Pressure rise indicates combustion has occurred.

A 7 bar air injection pressure is used With zero ignition delay and the Ignitor is on before the dust is injected.

NO explosion, NO Bursting

NO explosion, Vent Bursting

Action of the air injection

Pressure (bar)

Time (ms)
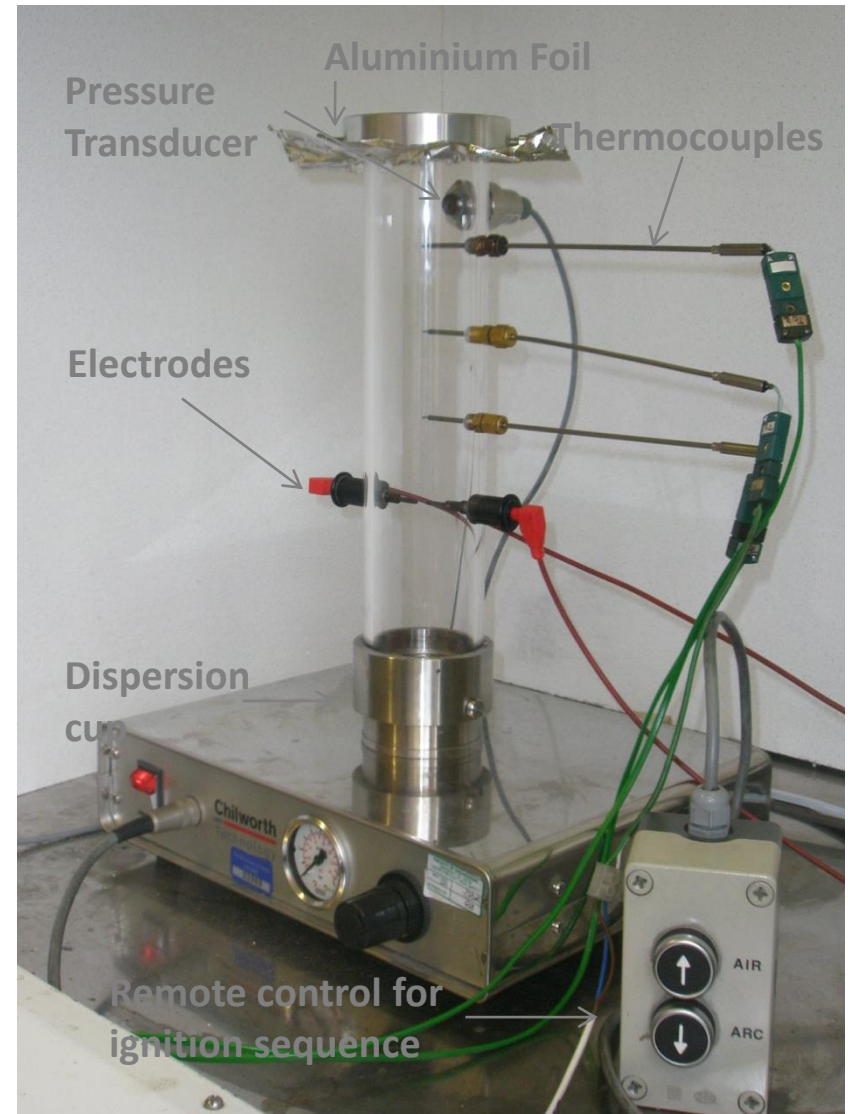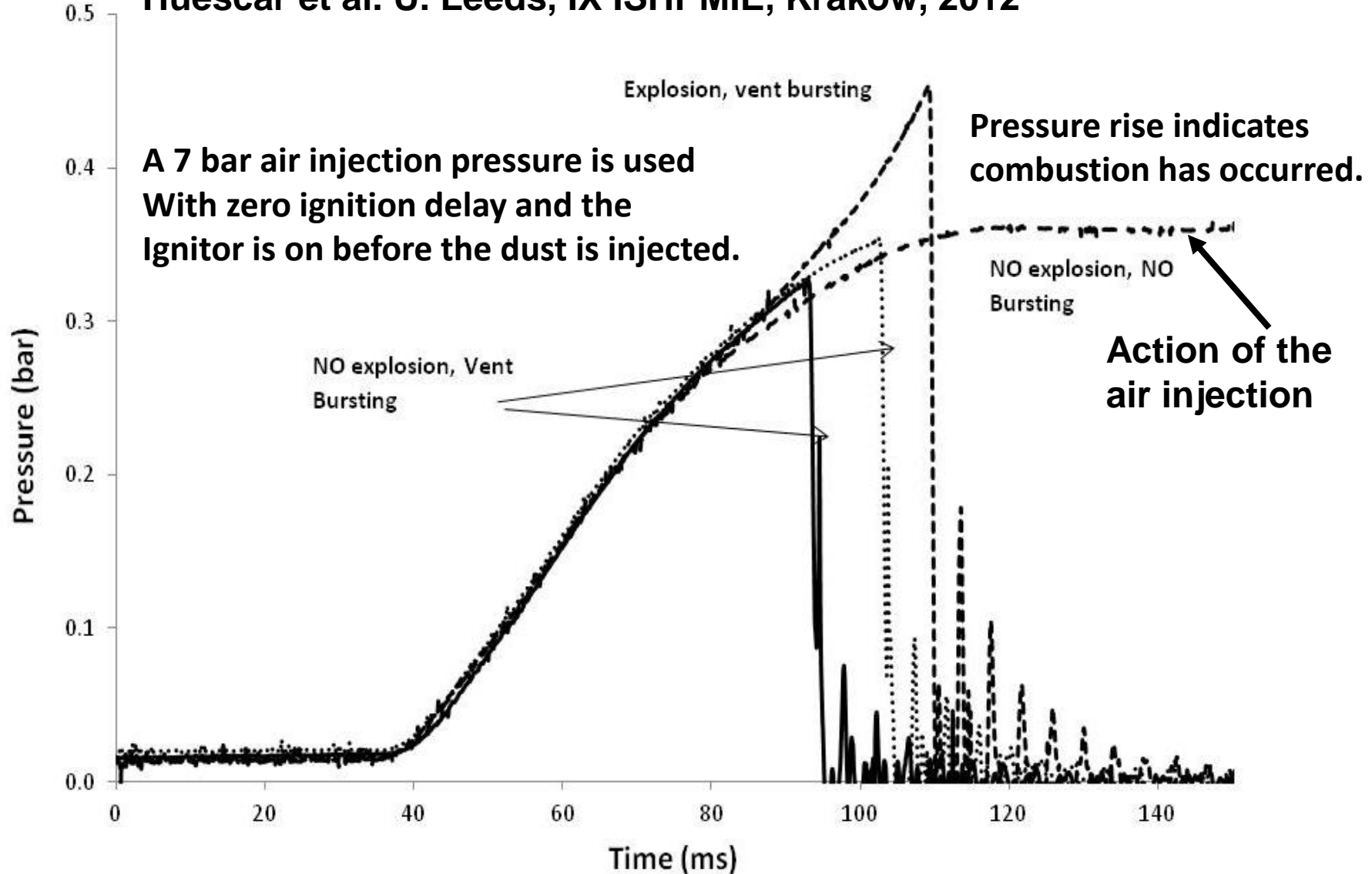
High speed video study of dust explosions in Hartmann equipment

Bagasse<63μm
(Even propagation of dust, efficient ignition)

150<Bagasse<300 μm
(Uneven distribution with delayed ignition)
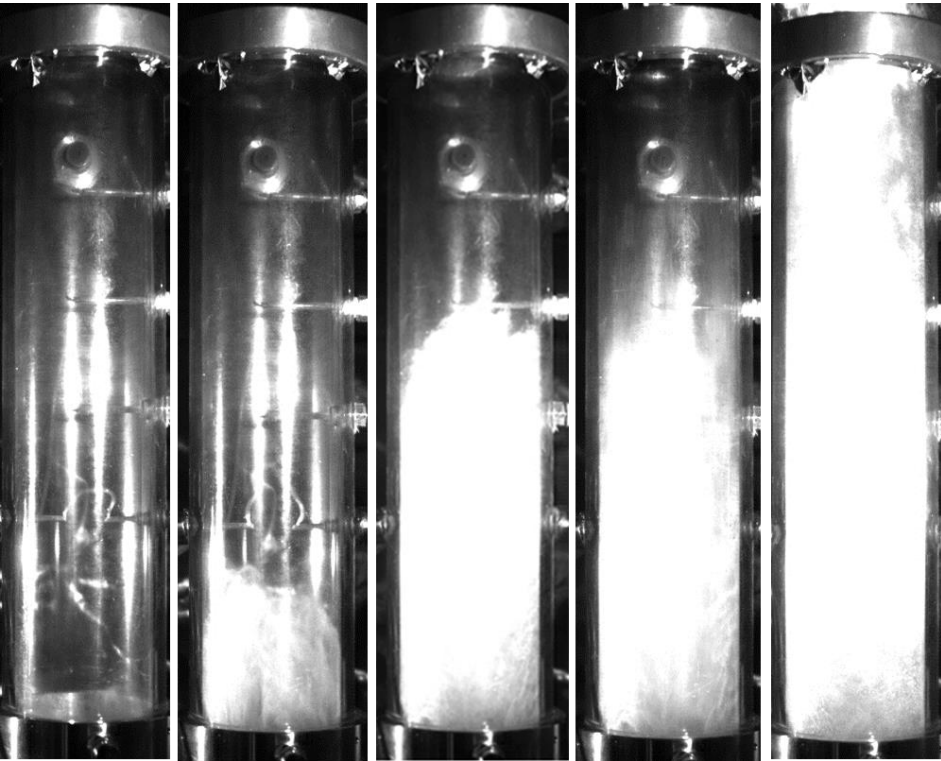
Dust dispersion   **Ignition**   **Ignition**

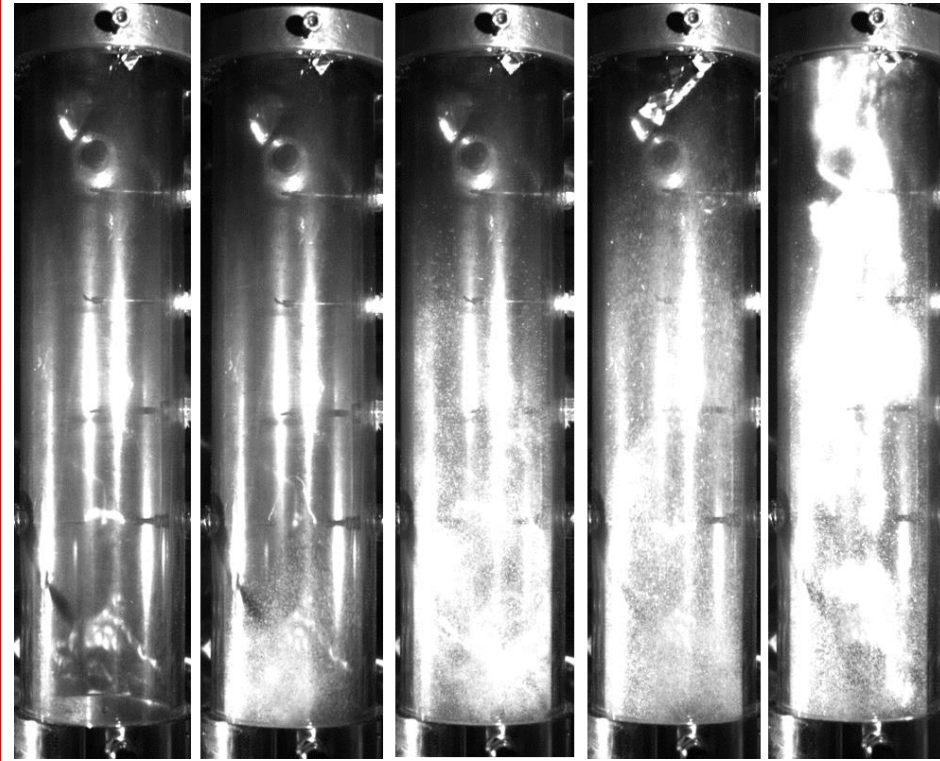*Comparison between fine and coarse bagasse dust in the dust dispersion progress and ignition*

Evidence is that the dust is not dispersed through the volume of air at the time of ignition – does this mean the measured MEC are too lean as there is stratified combustion so that the mixture that ignited is richer then the mean mixture?

Huescar et al. U. Leeds, IX ISHPMIE, Krakow, 2012

Most reactive mixture

Note the very lean MEC for biomass

MEC

v

0.2
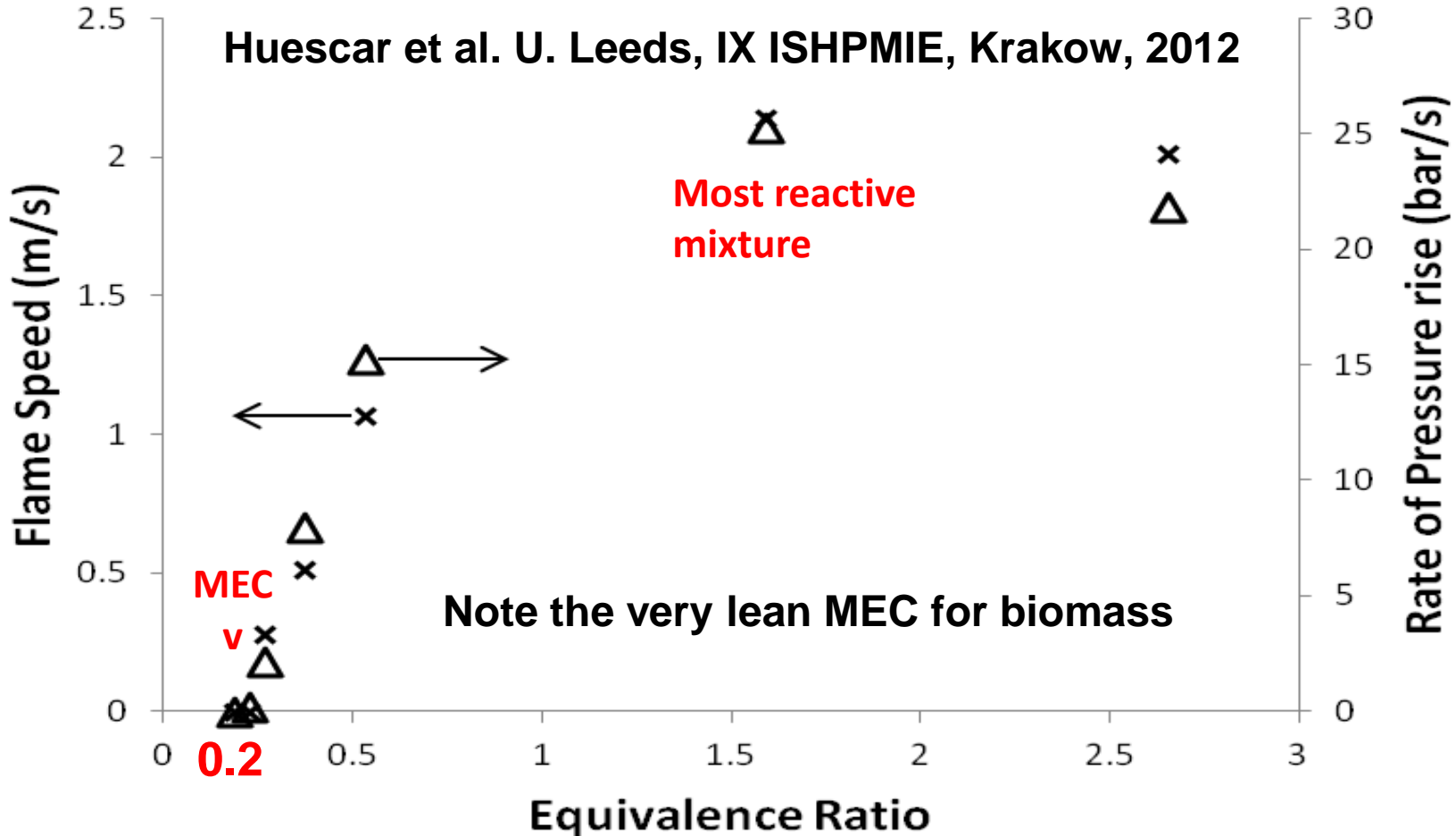
Torrefied biomass flame speeds and initial dp/dt measured on the Hartmann dust explosion equipment. The Hartmann method can be used to identify the most reactive mixture

Clara Huescar-Medina et al. U. Leeds. Proc. 7th Int. Sem. Fire and Exp. Haz. 2013 Torrefaction effects on the reactivity and explosibility of woody biomass. p.876-885

Hartmann

Torrefied biomass
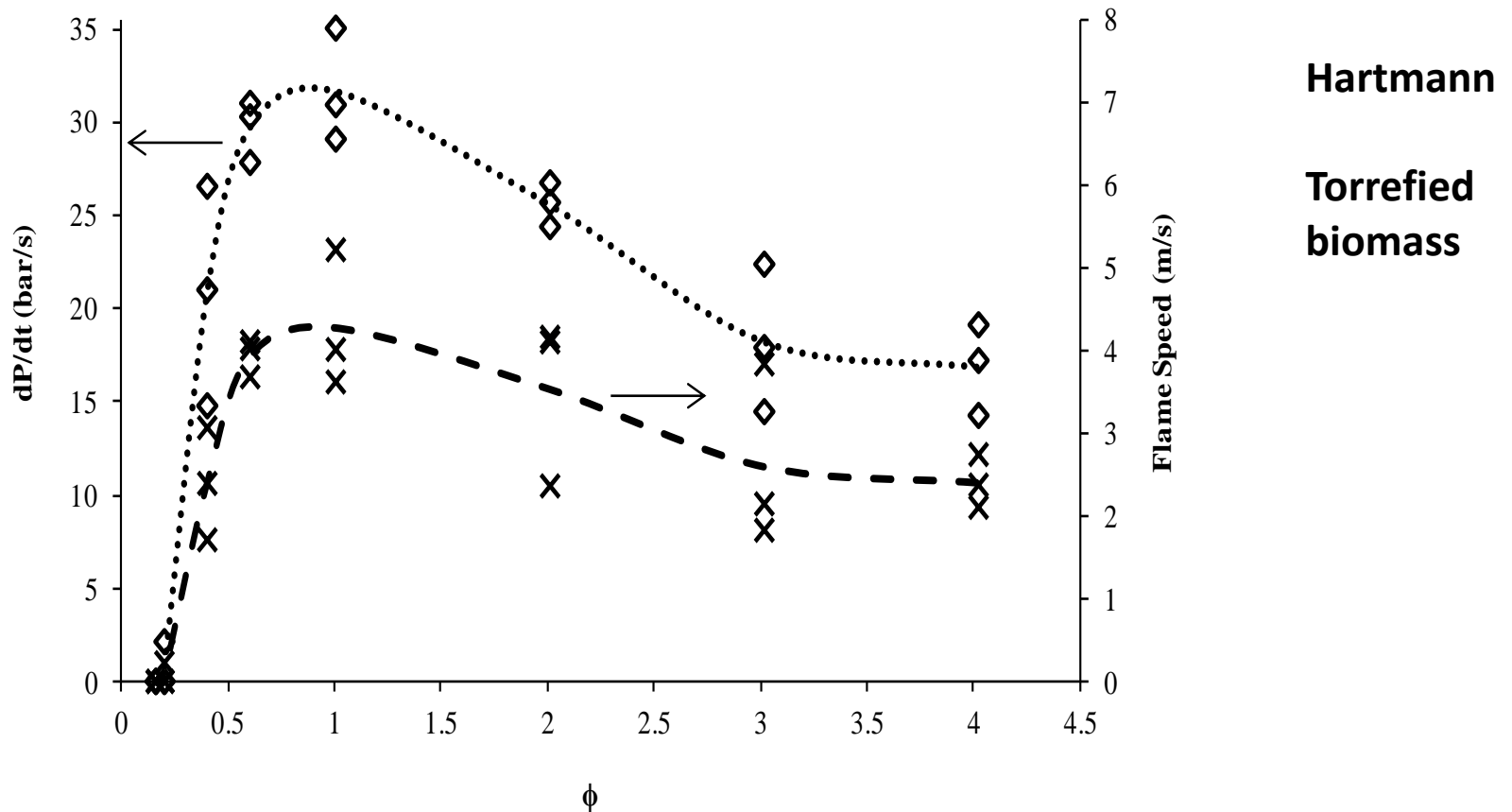
Clara Huescar-Medina et al. U. Leeds. Proc. 7th Int. Sem. Fire and Exp. Haz. 2013
Torrefaction effects on the reactivity and explosibility of woody biomass. p.876-885

Sample	Particle Size (µm)			Stoichiometric F/A ratio (g m^{-3})	Volatile Matter (%)[16]
	d(0.1)	d(0.5)	d(0.9)		
A: T=260°, t=8min ($CH_{1.377}O_{0.617}$)	20.6	60.5	186.1	195	84.0
B: T=260°, t=25min ($CH_{1.321}O_{0.560}$)	17.4	51.9	153.3	184	80.3
C: T=285°, t=16.5min ($CH_{1.217}O_{0.526}$)	18.8	58.3	186.6	181	77.3
D: T=310°, t=8min ($CH_{1.247}O_{0.509}$)	18.1	51.1	136.8	176	76.2
E: T=310°, t=25min ($CH_{0.867}O_{0.271}$)	16.4	44.3	115.9	138	51.5

Hartmann tests
Flame speed and max.
rate of pressure rise
as function of Ø.

Clara Huescar-Medina et al. U. Leeds. Proc. 7th Int. Sem. Fire and Exp. Haz. 2013
Torrefaction effects on the reactivity and explosibility of woody biomass. p.876-885
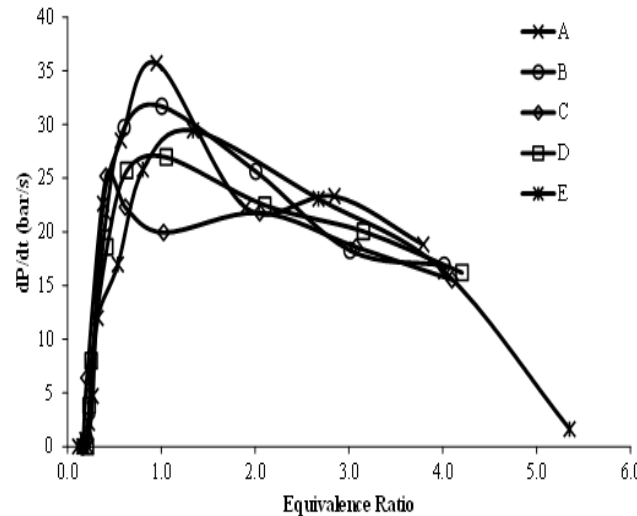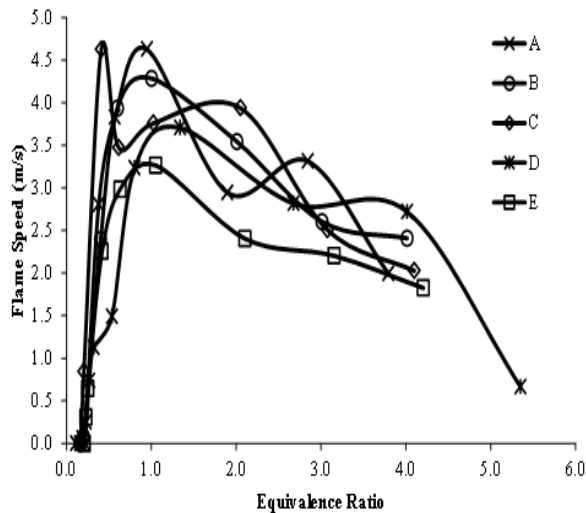

Hartmann
max. dP/dt
reactivity

Hartmann
MEC Ø

TORREFACTION SEVERITY

**Most reactive
mixture was the least
torrefied.**

Clara Huescar-Medina et al. U. Leeds. Proc. 7th Int. Sem. Fire and Exp. Haz. 2013
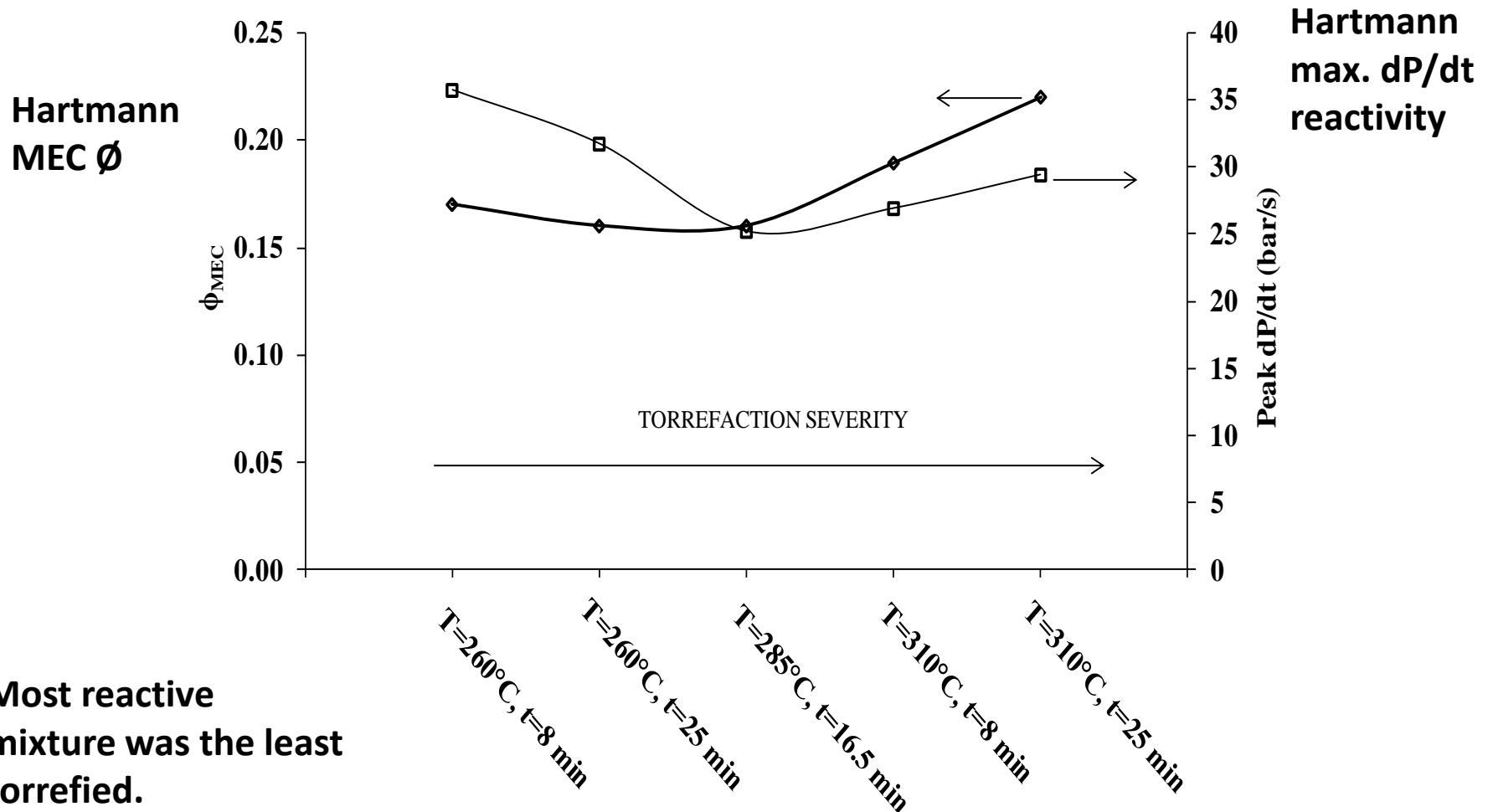**Torrefaction effects on the reactivity and explosibility of woody biomass. p.876-885**

$y = 7.2x$
$R^2 = 0.83$
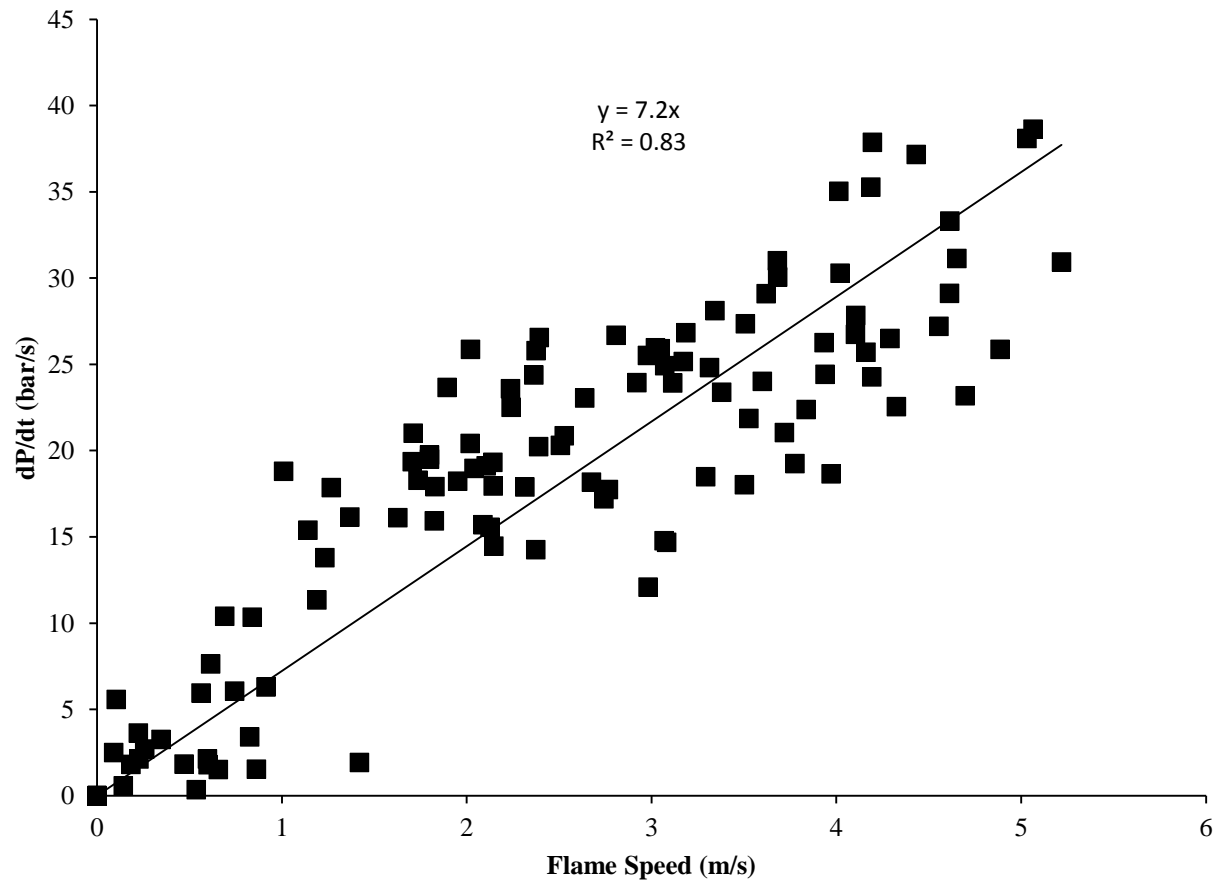
Hartmann

Torrefied biomass

Huescar et al. U. Leeds, IX ISHPMIE, Krakow, 2012

Biomass and torrefied biomass are extremely reactive with very low MEC

Torrefied biomass

Raw biomass

Particle of 150-300μm explode for raw and torrefied biomass. Aerosols will not explode at this size range!

The lean limit for fine particle Is 0.2 compared with 0.5 for gaseous HC. Only hydrogen will burn this lean!

Minimum Explosible Equivalent Ratio

Particle Size Range (μm)

<38   38-75   75-150   150-300

0.0 0.2 0.4 0.6

Slatter, D.J.F., Huescar Medina, C., Satter, H., Andrews, G.E, Phylaktou, H.N. and Gibbs, B.M.
The Influence of Particle Size and Volatile Content on the Reactivity of HC and HCO Chemical and Biomass Dusts

Seventh Fire and Explosion Hazards, Providence, USA, May 2013   **112**

Pine wood raw- initial dP/dt results

Pulverised biomass flame propagation and explosion characteristics with comparison with coal combustion.
Prof. Gordon E. Andrews, Energy Research Institute, SCAPE, Univ. Leeds, UK

Conference on Green Transport, Renewable Energy and Environment (ICGTREE 2014), August 23-24, 2014, Tianjin, China
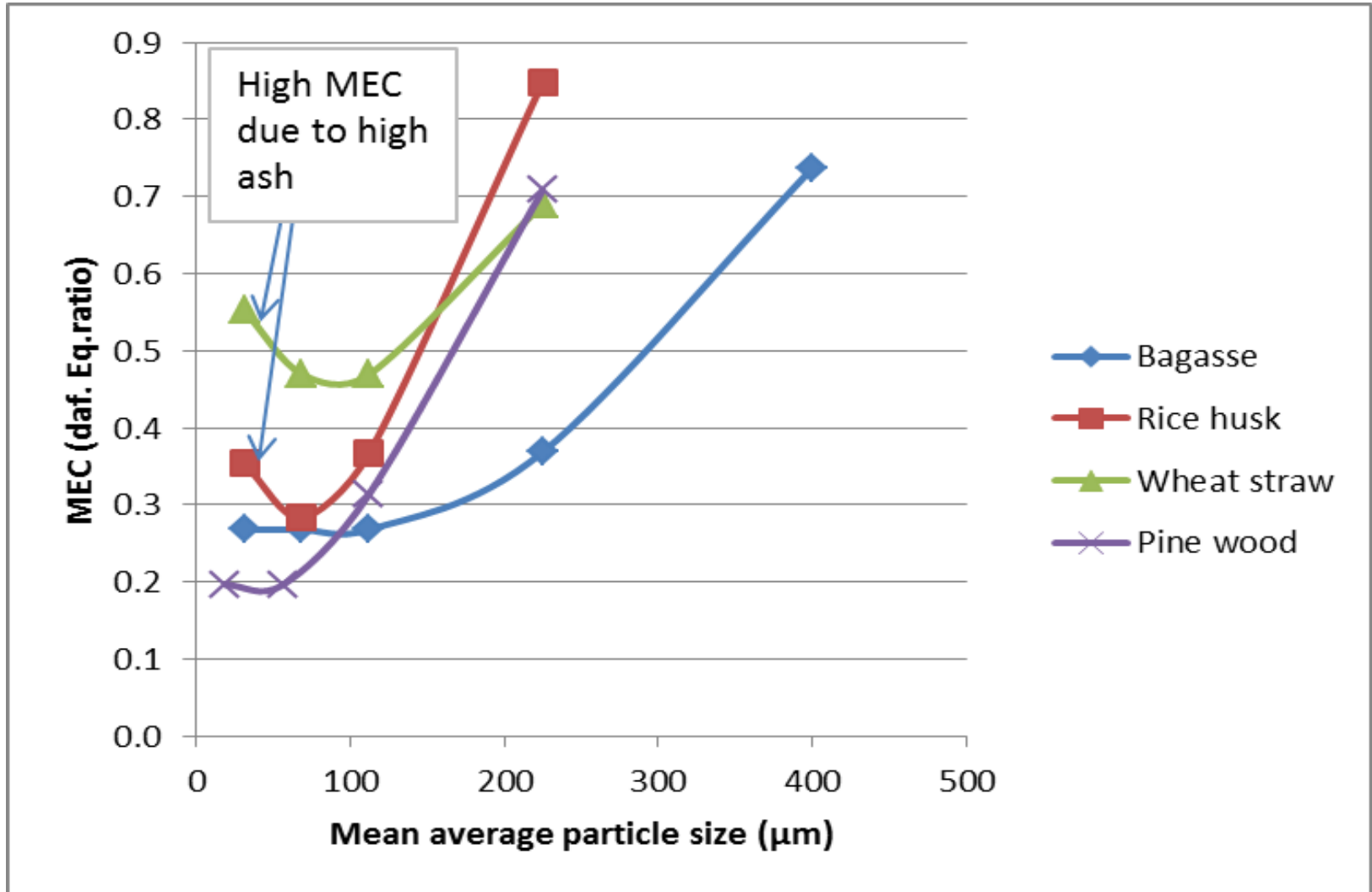
Conclusions

1. Biomass is extremely variable in its composition, ash fraction and water content – all of which affects its stoichiometric ratio and MEC. Explosion data must be expressed in equivalence ratio terms as for gas explosions, particularly the MEC.

2. The 1 m^3 ISO standard dust explosion equipment is the minimum size for reliable flame speed and K_{st} measurements.

3. Measurement of flame speeds in biomass explosions will help explosion modelling and in burner design as the flame front conditions are similar to furnace flames.

4. The ISO method has to be modified to work with fibrous biomass with practical particle size ranges and putting the biomass inside the vessel is the key to this. A method to do this with calibrated agreement with the standard technique has been demonstrated.

5. The Hartmann 1L cylindrical tube equipment is a useful technique for biomass as it works without modification on fibrous biomass.

6. Large biomass particles will propagate an explosion.

Some research questions – need for more research!

1. Is the measurement of the MEC using the Hartmann and 1 m³ equipment reliable?

2. If it is then why can biomass burn so lean if the particle size is <63μm. No gas other than hydrogen burns so lean.

3. What is the mechanism that enables large biomass particle sizes to burn, when liquid sprays of that size will not propagate a flame?

4. Why does the most reactive mixture occur for very rich mixtures, quite different from the behaviour of a gas mixture.

5. What is the controlling mechanism for pulverised biomass reactivity?

6. Is the mechanism of flame propagation for rich mixtures, where the reactivity is a maximum, the same as for the slightly lean mixtures used in pulverised furnaces for thermal efficiency reasons. Do lean flames have a different flame propagation mechanism?

7. The evidence from lean flammability measurements (MEC) is that biomass dusts are more reactive than hydrocarbons. However, the evidence from flame speed and laminar burning velocity measurements is that they are less reactive. How can these two findings be reconciled?

8. What is the role of turbulence in biomass dust flame propagation. Experimentally it is difficult to establish a laminar dust flame, could it be that the very reactive dust flames are only reactive through the action of turbulence?

9. What is the flame thickness of biomass flames? We are currently using the rise time of the thermocouples to estimate the flame thickness from the flame speed times the time the temperature takes to reach a maximum. The initial results suggest that the biomass flames are very thick - >10mm compared with 1mm for gas flames.

10. Why does all the biomass burn and there is no evidence of enhanced char in the debris. Coal has a char burning phase but it appears that biomass does not – why?

11. Why does a mixture of biomass and coal show a higher reactivity than coal or biomass alone?

12. Extending the data base to a wider range of biomass so that correlating parameters can be looked for. The aim is to determine a method of predicting the flame speed and reactivity from the biomass composition and volatile content.

13. Our results to date indicate that there is a strong variation in the flame speed and laminar burning velocity with biomass composition, about a factor of 5 difference has been seen up to now. In contrast hydrocarbon flames have a quite narrow range of burning velocities of 0.35 – 0.45 m/s (apart from acetylene and ethylene which are more reactive). Why is there such a difference and can it be correlated and understood. Currently we think the rich mixtures that are most reactive undergo flame front gasification with very high heating rates that gasify all the mass including the char. This produces a mixture of CO, hydrogen and methane which is what propagates the flame. All of this needs validating and fitting to a model.

14. For dusts, flame thickness is greater than for gases and this makes the minimum vessel size potentially larger than that for gas flames.

Do we need even larger experimental vessels for dust explosion flame speed and burning velocity measurement?

We have a 10m³ vessel that could be adapted for this purpose in Leeds.

The modification of this vessel for dust explosion would be worthwhile in my opinion – but costly and would need significant funding!

Most of the rest of these research questions can be done on existing equipment.

15. What is the influence of explosion vessel size on the flame propagation in biomass dust clouds. Do biomass dust flames have a self acceleration mechanism similar to gas flames.

Some biomass stores are being built larger that current knowledge on biomass or gas explosions. Can existing design guides be applied to volumes much larger than that they were validated for.

Is there a need for large scale dust explosion research?

16. Why does methanol, which has the same elemental composition as wood, have lean limits in terms of equivalence ratio closer to that of hydrocarbons than wood?

17. Liquid aerosols or sprays.

The question about methanol leads to the more general area of liquid sprays. There is currently no accepted experimental method to test for flame propagation in aerosols. We think that the equipment used for dusts could be adapted for liquids, particularly the Hartmann equipment for the lean limits and the 1 m³ for flame propagation. This would involve putting the liquid of known mass inside the equipment and then blasting air at it, which will atomise and disperse the liquid.

Contents

1. **Introduction**
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4. **Problems with biomass explosion characterisation.**
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>   **Hartmann for MEC**
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>   **20L sphere**
>
>   **ISO 1 m^3**

5. **Modifications of the ISO 1 m^3 vessel for woody biomass.**
6. **Leeds MEC results for woody biomass**
7. **Leeds ISO 1 m^3 vessel results for biomass (Clara Huescar Medina will present this in the next lecture).**

Pulverised biomass flame propagation and explosion characteristics: problems and solutions.
Prof. Gordon E. Andrews, Energy Research Institute, SCAPE, Univ. Leeds, UK

United Kingdom Explosions Liaison Group, UKELG, meeting on Biomass Dust Explosions
University of Leeds, 23.9.2014