FLAME DEVELOPMENT IN PULVERISED BIOMASS FOR FINE AND COARSE PARTICLES.

David J.F. Slatter, Muhammad Azam Saeed, Gordon E. Andrews*, Herodotos N. Phylaktou and Bernard M. Gibbs.

Fire and Explosion Research
School of Chemical and Process Engineering,
University of Leeds, Leeds, LS2 9JT, UK.
<profgeandrews@hotmail.com>

11th ECCRIA (European Conference on Coal Research and its Applications)
5th-7th September 2016, University of Sheffield, UK

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Pulverised biomass is a significant source of renewable electricity and hence plays an important role in carbon reduction strategies. In the UK pulverized woody biomass burning in existing coal fired power stations generated 5.7% of electricity in 2014.

This biomass is burned either co-fired with coal or increasingly as 100% pulverised biomass. The biomass particle size fed to burners is relatively coarse as pelletised wood is feed to the coal millers which break the pellets into the size of the original wood from which the pellets are formed, which is not very fine. Also any fines in the storage and transport of the pellets are removed prior to transfer of the pellets to the burners (this can be up to 10% of the total pellet mass).

Little of the pulverised wood is <63µm and most in the 63 to 1000µm size range. There is little information on how these relatively coarse biomass particles propagate flames in boilers.

Also, their associated dust explosion hazards is not known.

This work presents high speed videos of flame propagation in coarse particle biomass dust clouds as a means of deducing the mechanism of flame propagation.

In the UK there is 3 GW of bioenergy plants generating renewable electricity (2 GW at Drax, Yorkshire).
4 GW of bioenergy plant is in planning and in addition Drax is planning to upgrade to 4 GW.

Biomass stores at Drax are the largest material stores in the world and are two orders of magnitude bigger than any dust explosion test has been carried out.
It is Government policy to phase out coal through a carbon tax only on coal and the industry is fighting to keep the power stations in business by converting to biomass.
The fuels are pellets (mainly from wood at Drax), miscanthus, straw, poultry litter, food recycling, paper mill residues, waste construction wood and agricultural residues. The dominant biomass is wood, sourced from anywhere in the world that can provide it sustainably. Little data on explosion risks exist!

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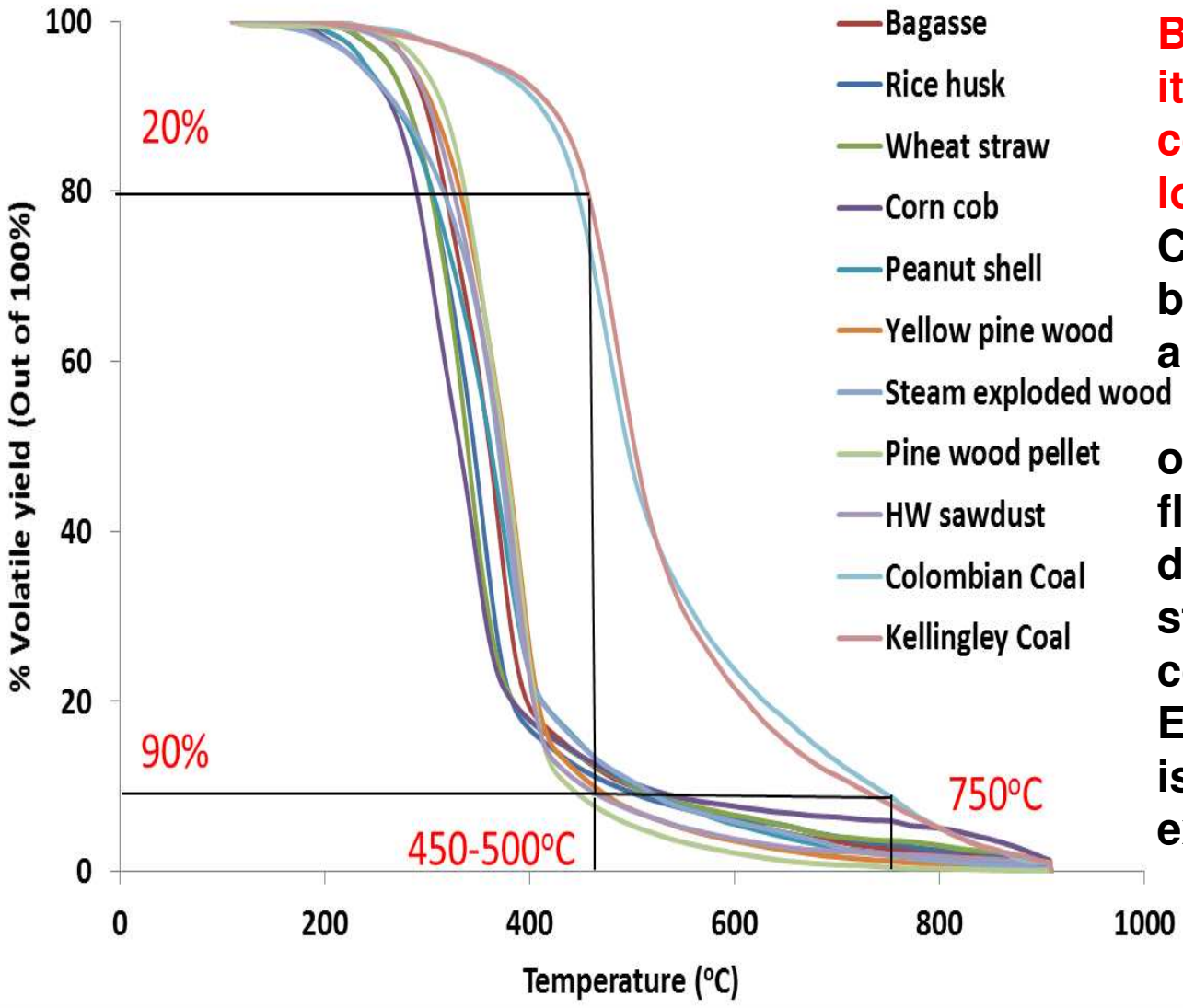

Biomass has lost 90% of its volatiles by 400°C compared with only 10% loss of volatiles for coal.

Combustion air in coal burners is preheated to around 300°C where there is typically 30% volatile of volatiles in biomass flames will make a large difference in the flame structure compared with coal flames.

Early release of volatiles is also crucial in the explosion hazards and in the biomass reactivity.

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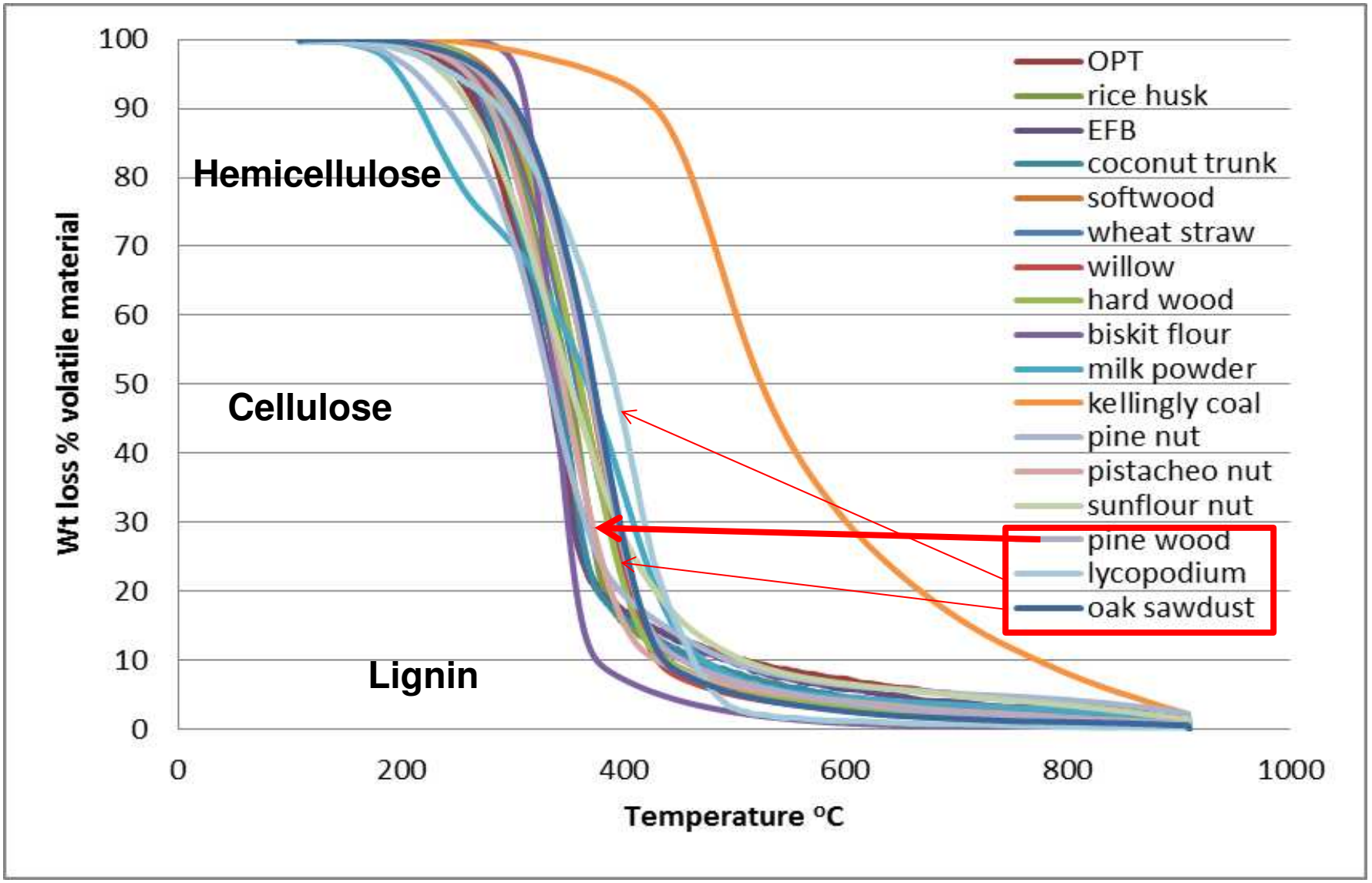

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A summary of existing data for wood and cellulose – ISO 1 m^3.

Source	Dust	MEC g/m^3	P_m bar	K_{st}	Size µm
Bartknecht	Cellulose	55-60 Ø = 0.14- 0.15			
NFPA 68	Cellulose		9.7	229	
NFPA 68	Lignite	60	10.0	151	32
Field	Wood	20-70			
Eckhoff	Chipboard wood dust	60 Ø ~ 0.30	9.2	102	43
Eckhoff	Wood cardboard jute	30 Ø ~ 0.15	5.8	26	
Eckhoff	Wood cardboard jute resin	30 Ø ~ 0.15	8.4	67	
Eckhoff	Lignin dust	15 Ø = 0.12	8.7	208	18
Eckhoff	Paper dust		5.7	18	<10
Eckhoff	Paper tissue dust	30 Ø ~ 0.15	8.6	52	54

VTT Publication 394 Finland 1999 ISO 1 m^3

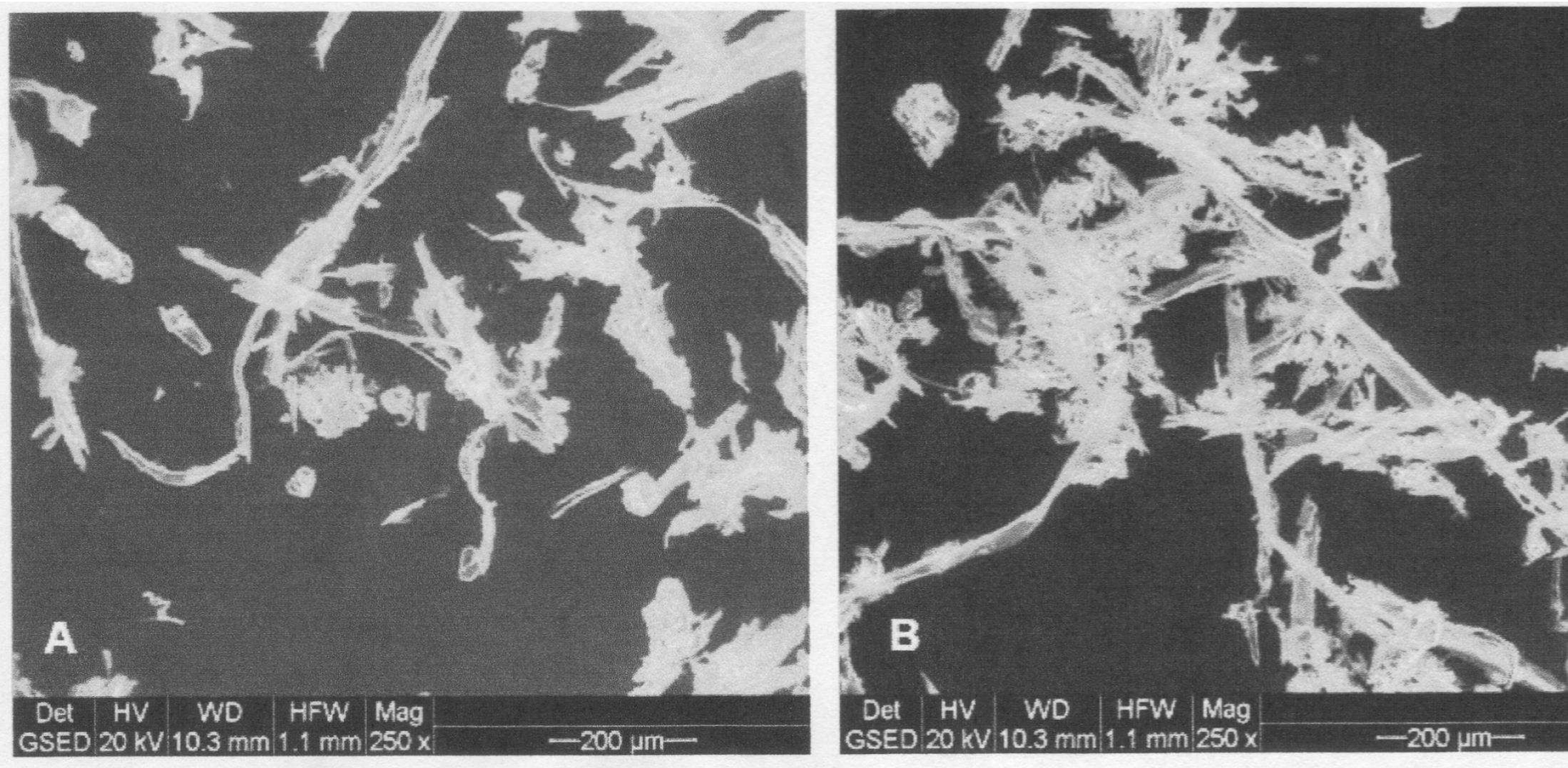
Biomass	MEC_{daf} $1m^3$	0/C z	H/C y	Stoich A/F	Stoich g/m^3	MEC $Ø_{daf}$	Mean Particle Size µm	VOF daf
Wood	29.4	0.731	1.59	5.63	213	0.138	95	83.6
Bark	27.8	0.637	1.42	6.03	199	0.140	57	74.1
Forest Residue	55.3	0.672	1.53	4.78	251	0.220	102	79.5
Spanish Pine	83.1	0.729	1.63	5.69	211	0.394	247	85.0
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	59.6	0.826	1.42	4.88	246	0.242	40	55.3

Energy from Biomass 2014

Prof. Gordon E. Andrews, ERI, SCAPE, Univ. Leeds, UK

D. Wong, S. Huntley, B. Lehmann (All FPInnovations)and O. Zeeuwen (Chilworth Tech)
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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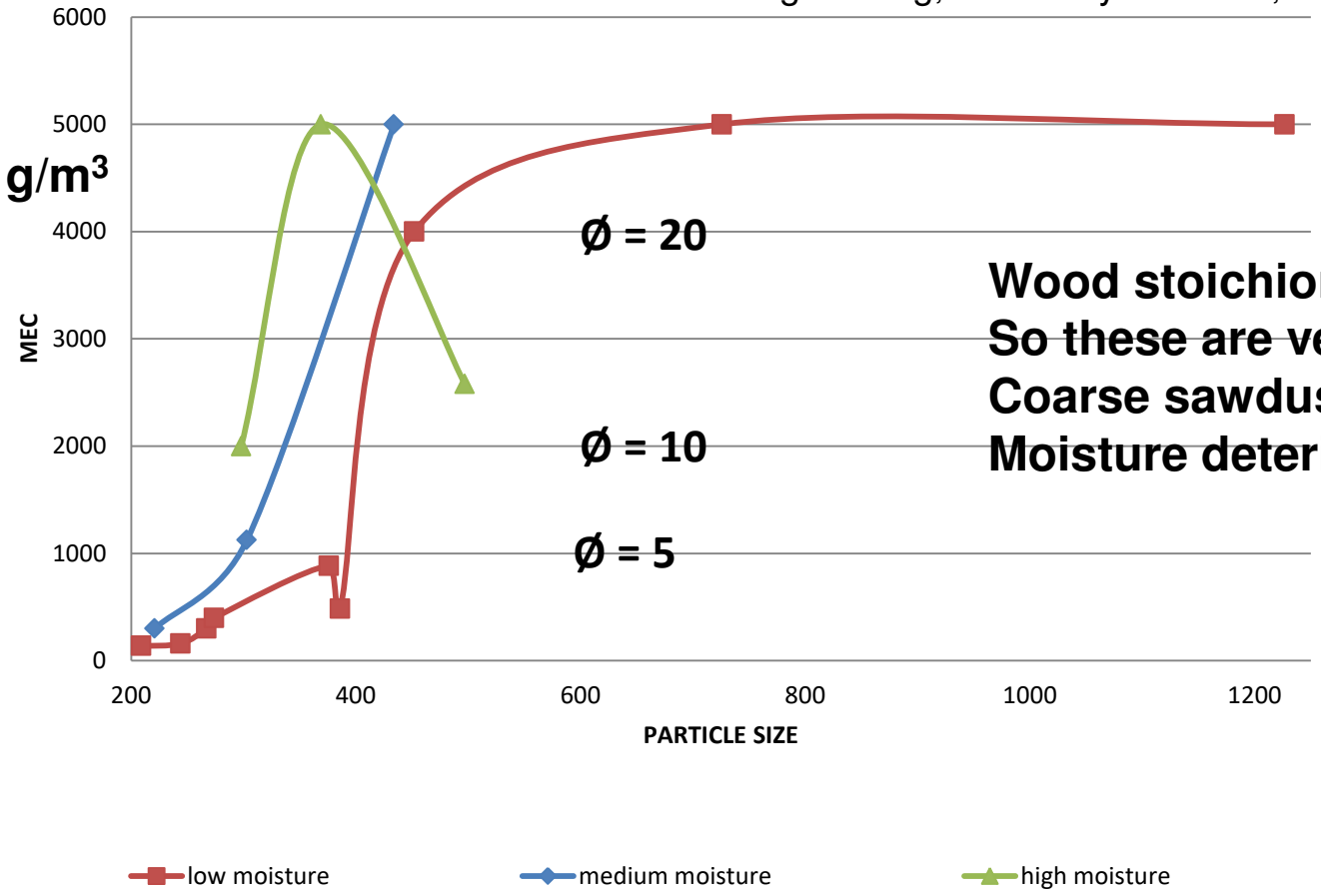

Wood stoichiometric ~ 200 g/m^3
So these are very rich MEC for Coarse sawdust particles.
Moisture deteriorates the MEC

MEC data for sawdust for large particles. MEC as high as 5000 g/m^3.
If 200 g/m^3 is assumed to be stoichiometric for the sawdust, then this is >25 Ø which is extremely rich. (Darrell Wong et al., 2013).

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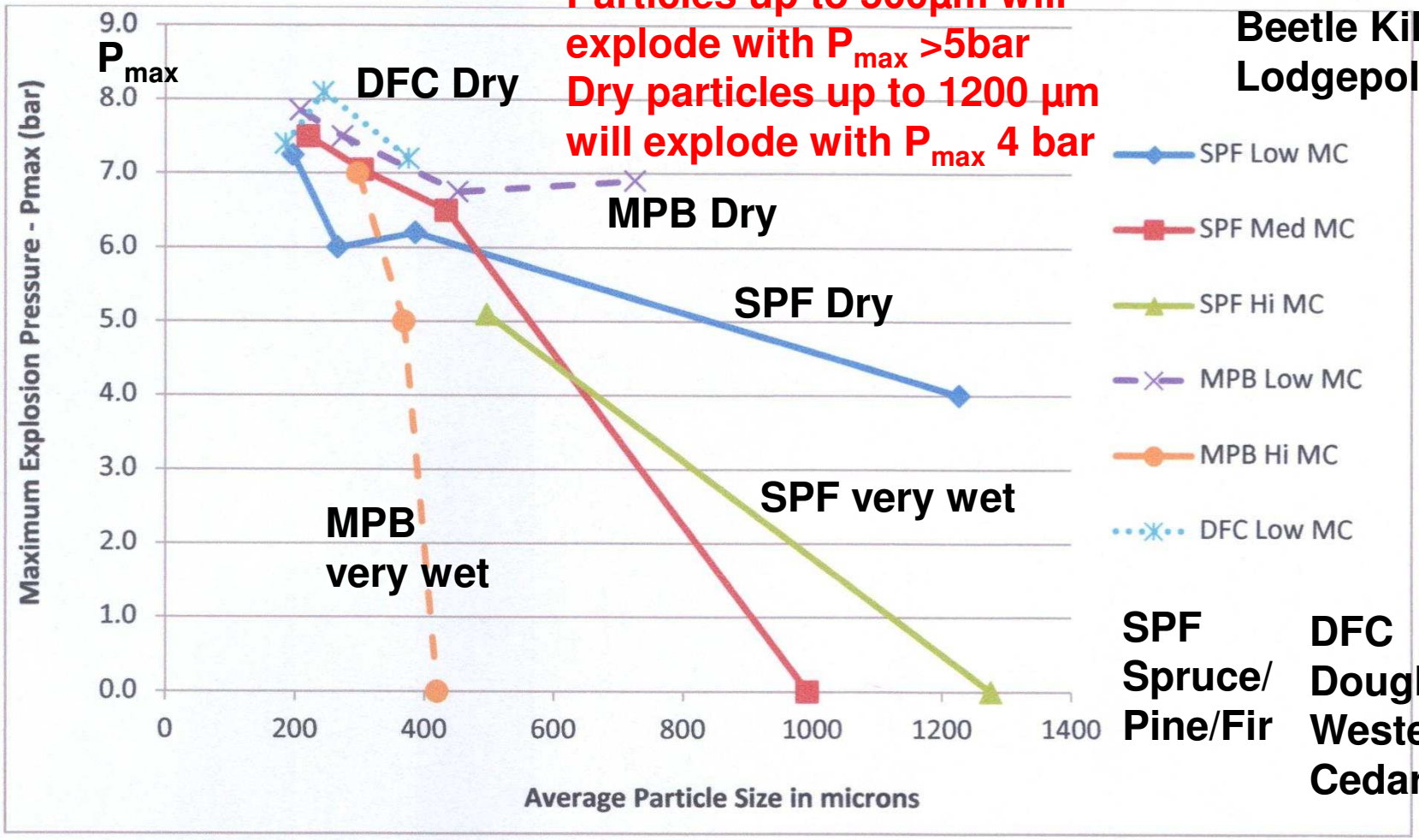

MPB Mountain Pine Beetle Killed Lodgepole Pine

MC Moisture Content

SPF Spruce/ Pine/Fir

DFC Douglas Fir and Western Red Cedar

Figure 30 Maximum explosion pressure as a function of the average particle size

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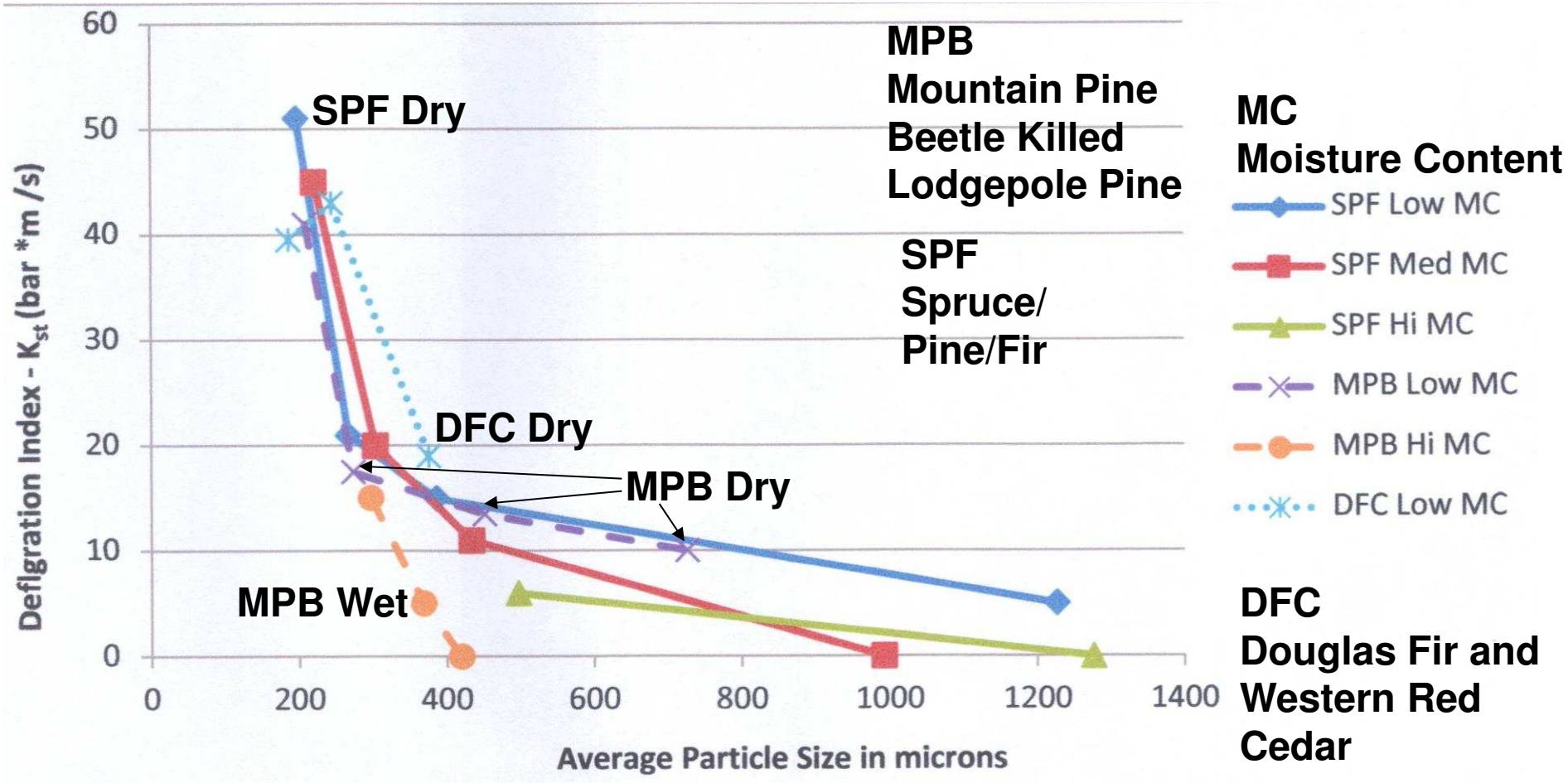
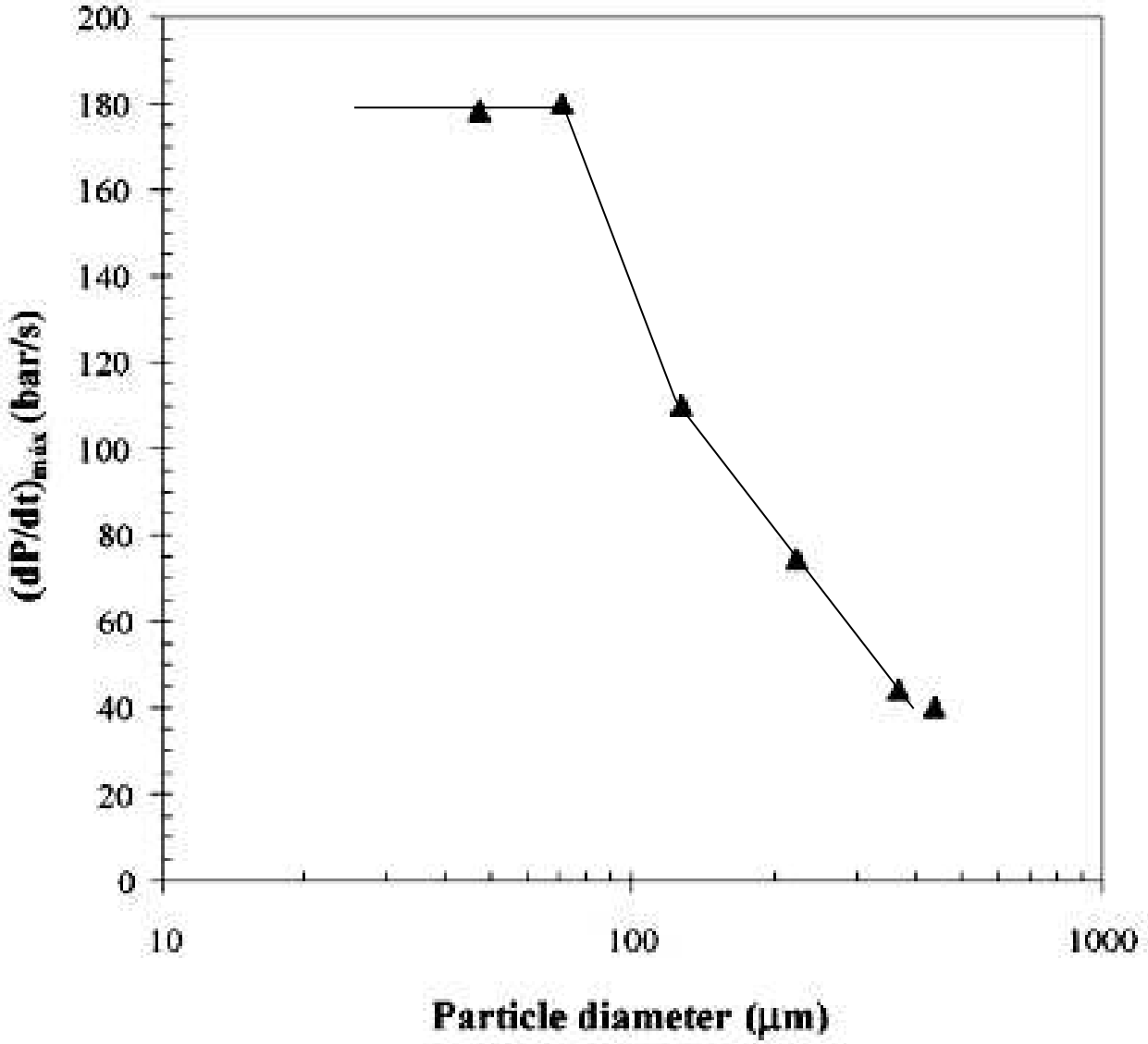


$K_{st} = dp/dt_{max}V^{0.33}$ bar m/s which is a measure of the dust reactivity



R. Pilao et al. (2006)

Cork dust

Note that particles of 400 μm will still explode. This will not happed for coal dust or hydrocarbon aerosol sprays. Consequently coarse biomass particles can explode.

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Oak sawdust from a furniture manufacturer.

Property	Oak	Pine
C	51.4%	54.9%
H	6.5%	6.3%
O	41.8%	37.1%
N	0.2%	1.9%
S	0	0
Water	8.9%	4.3%
Volatile	72.7%	80.2%
Fixed carbon	13.3%	11.1%
Ash	5.1%	4.7%

$CH_{1.53}O_{0.61}$ Oak
Stoichiometric A/F 6.37 kg/kg
Stoichiometric 188 g/m^3
Both on a dry ash free basis.
The actual stoichiometric A/F taking into account the ash and water was 5.50 kg/kg.
219 g/m^3 actual.

Pine $CH_{1.37}O_{0.51}$
Stoichiometric A/F 6.98$_{daf}$
172 g/m^3. Actual A/F 6.37
188 g/m^3 actual.

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Oak sawdust

Sieved Size fraction	<63 µm	63 – 150 µm	150 – 300 µm	<500 µm
$D_{0.1}$	12.8 µm	62.7	181	62.8
$D_{0.5}$	44.7	141.2	357	381
$D_{0.9}$	110	299	713	845
$D_{0.32}$ Size with same surface area	23.9	82.2	303	109.3
MEC Hartmann	0.20	0.4	1.4	0.6

The oak dust sieve size had a laser light scatter size that had a wide range of sizes with >50% larger than the sieve size. This indicates cylindrical shaped particles with the diameter passing through the sieve and the length greater than the sieve size, as shown in the SEMs.

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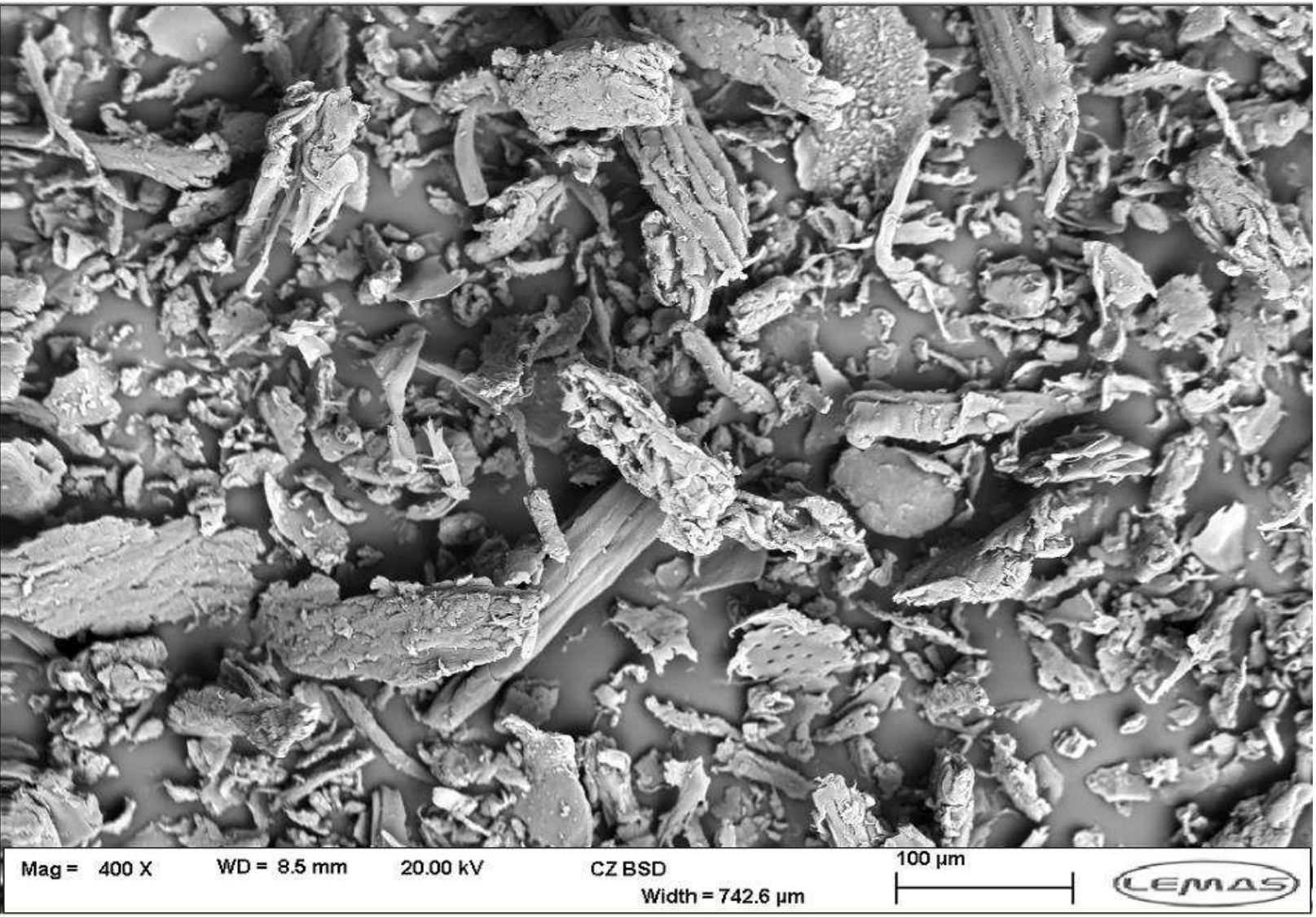

Oak sieved <63µm

Sizes can be Seen from 10 - 150µm Big particles are long and thin cylinders That pass Through the sieve vertically

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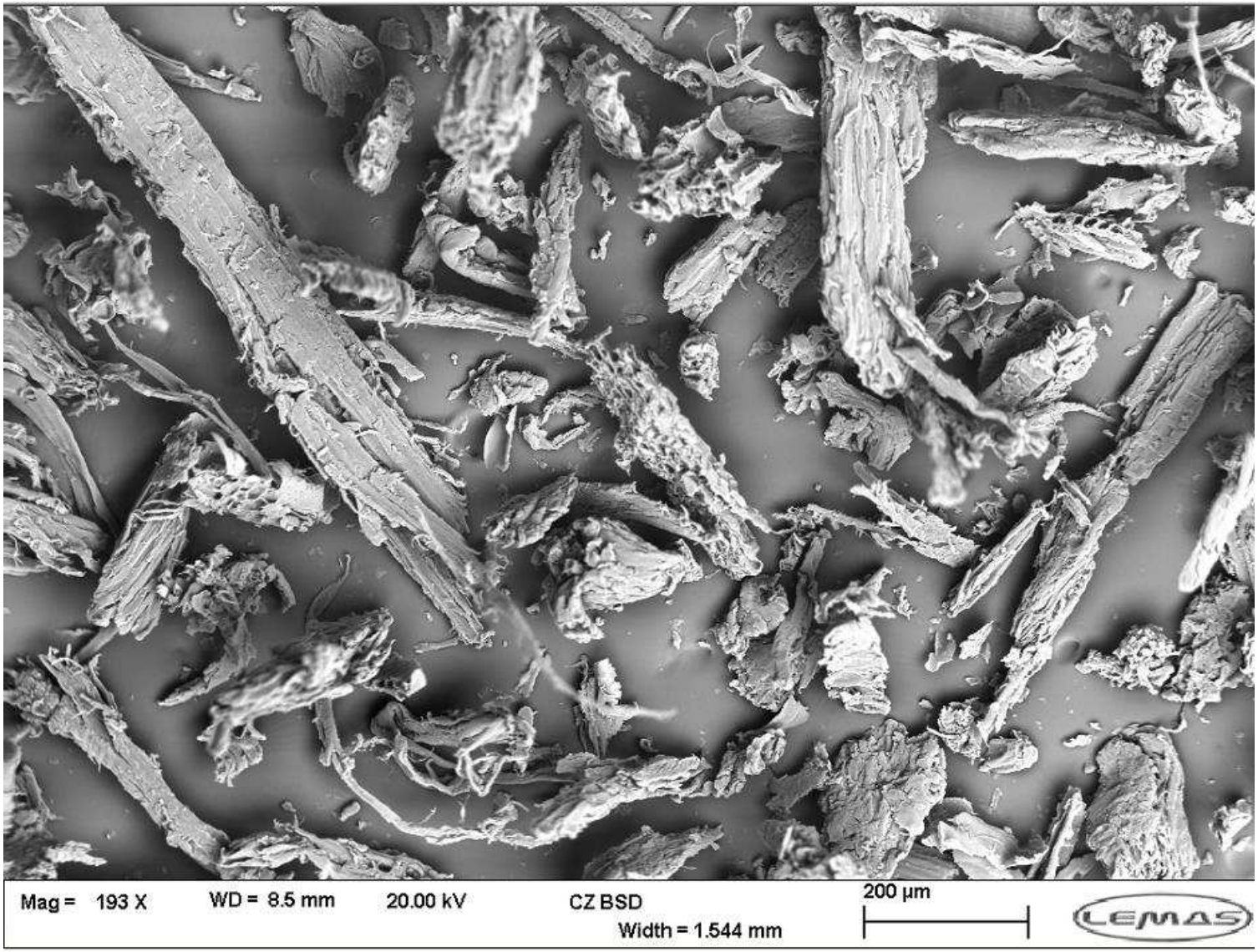

Oak sieved
63 – 150 µm

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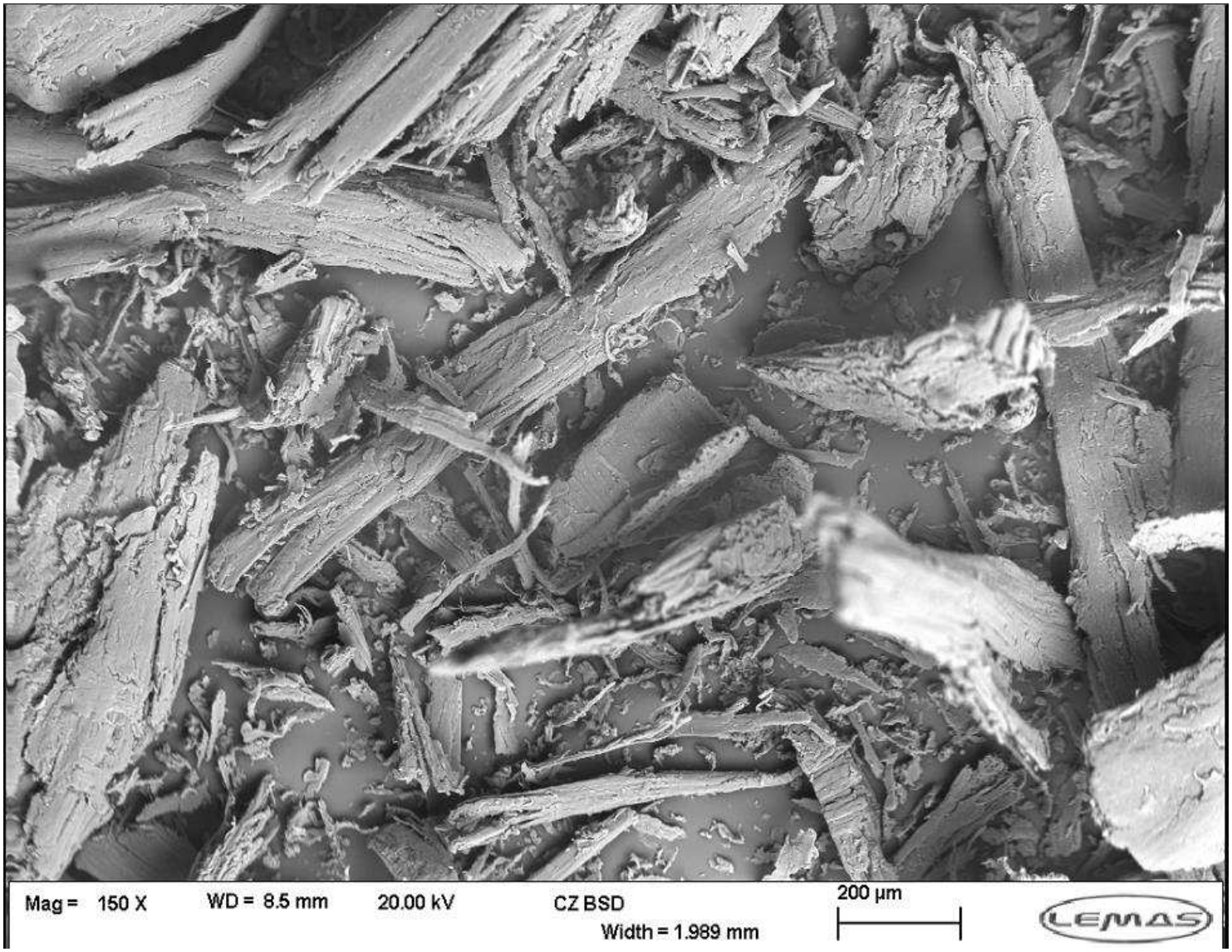

Oak
sieved < 500µm

Most of the mass is large particles but there is a significant fraction of fines.

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Initial equipment was for the A/B dust explosion classification apparatus with a perspex tube.

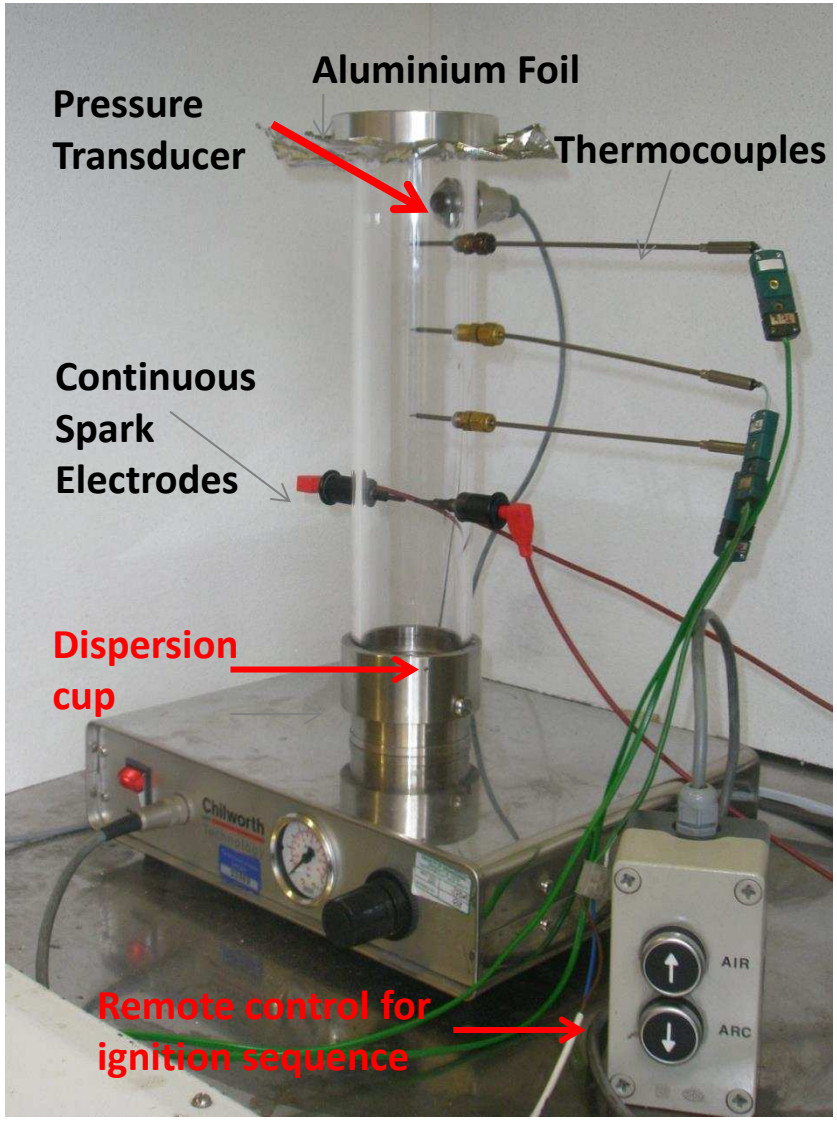
Visual determination of a flame is difficult and dependant on the observer's criteria, therefore the apparatus was modified to enable pressure rise and flame speed measurement (as in EU gas lean limit tests).

The combustion chamber is a 1.04L vertical polycarbonate cylinder (L=322mm, D=61mm 1.04L + 0.06L in cup) into which a 7 barg blast of air is introduced at the base from a 0.05L vol. This gives 1.5L of air in total at STP, which is used to convert the g of dust used into g/m^3.

Ignition is achieved by an arc ignition source, which is continuous.

The top of the tube is covered with aluminium foil secured with a locking ring that closes the tube. This bursts at 0.45 barg

The modified tube has a pressure transducer and three thermocouples have been fitted at 50mm, 100mm and 150mm for flame speed measurements. High speed video is also used to record the flame.



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Huescar et al. IX ISHPMIE, Krakow, 2012

A minimum pressure rise of 50mb above the burst pressure is used to determine the MEC.

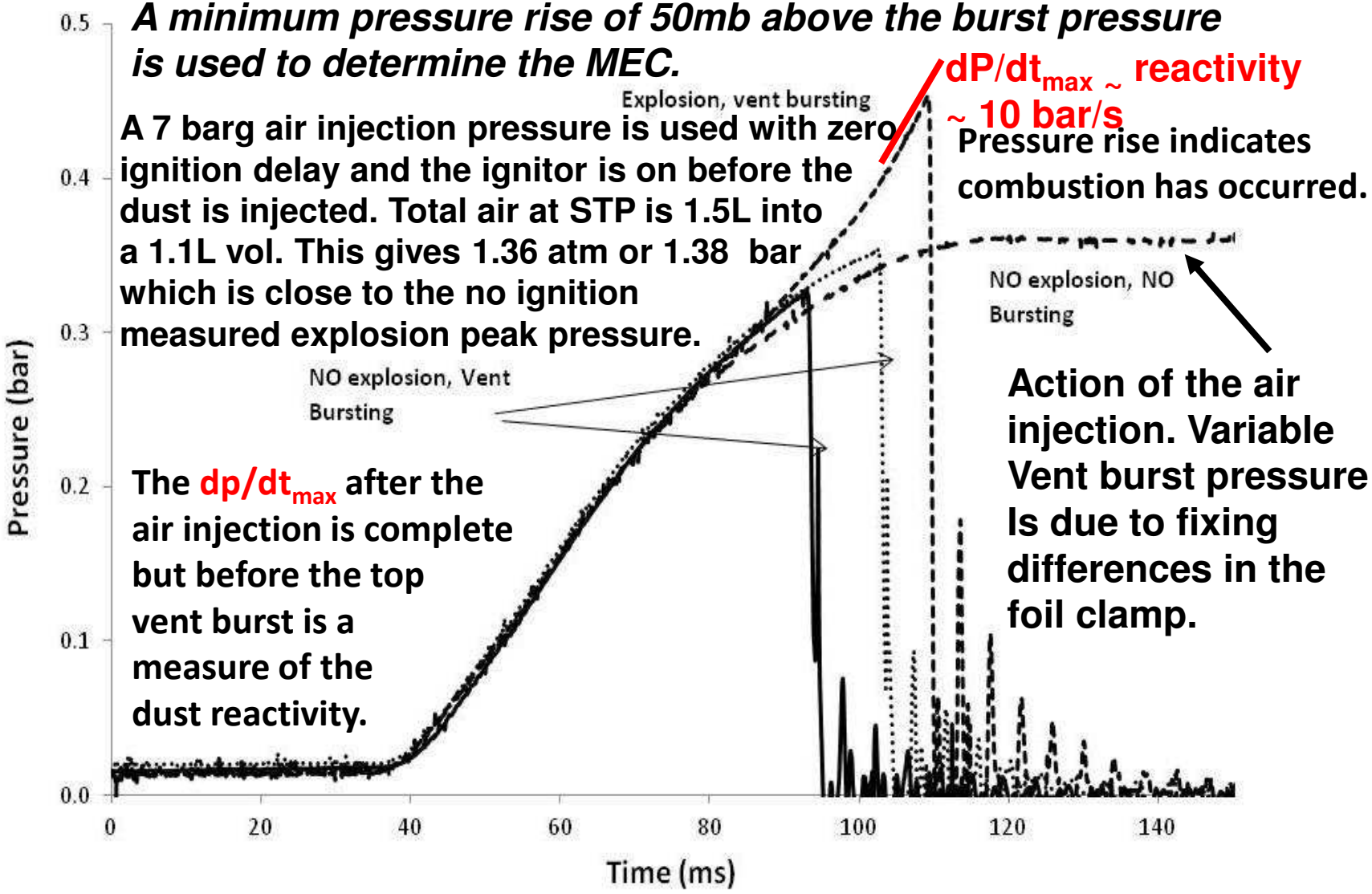
A 7 barg air injection pressure is used with zero ignition delay and the ignitor is on before the dust is injected. Total air at STP is 1.5L into a 1.1L vol. This gives 1.36 atm or 1.38 bar which is close to the no ignition measured explosion peak pressure.

The dp/dt_{max} after the air injection is complete but before the top vent burst is a measure of the dust reactivity.

dP/dt_{max} ~ reactivity ~ 10 bar/s

Pressure rise indicates combustion has occurred.

Action of the air injection. Variable Vent burst pressure Is due to fixing differences in the foil clamp.



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$D_{0.1}$	12.8 µm	62.7	181	62.8
$D_{0.32}$ Size with same surface area	23.9	82.2	303	109.3
< 100 µm	~85%	~30%	~ 5%	~ 15%
MEC Hartmann Ø	0.20	0.4	1.4	0.6

The oak dust MEC was very lean for the size sieved to <63 µm where the measured particle size was ~85% <100µm. As the proportion of fines (<100µm) decreased the MEC increased and was 1.4 for the most coarse dust.
This indicates that the flame propagated in the fine dust and the larger particles were heated by the post flame gases and then released volatiles that burnt.
For coarse powders the MEC was for rich mixtures and this would gasify the post flame coarse particles.

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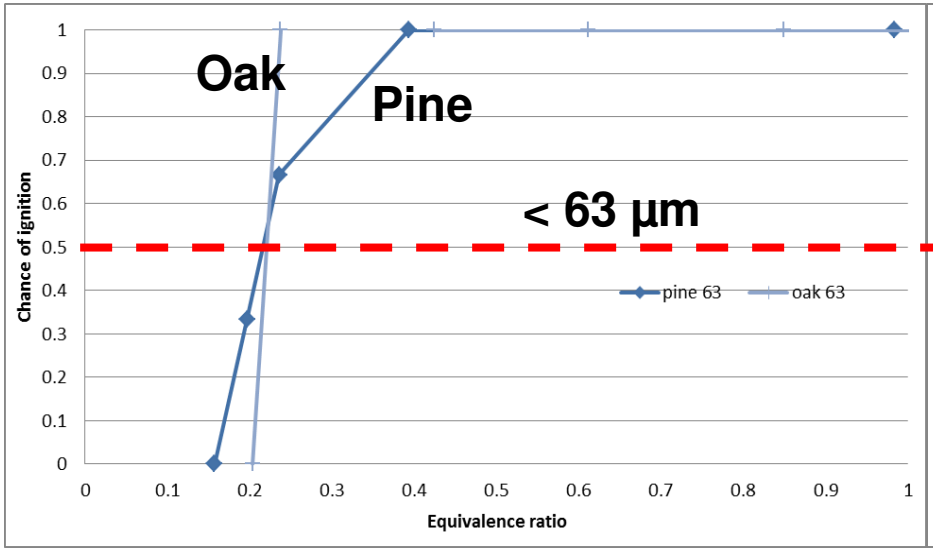

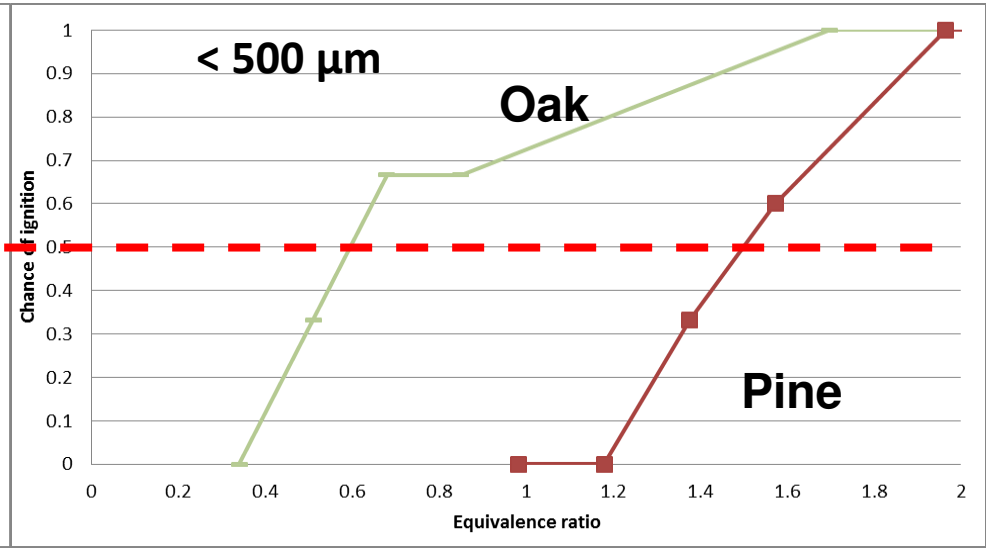

The differences in MEC between oak and pine dusts was due to differences in the actual particle size distribution for the same sieve size. It was not due to any chemical differences in the particles.

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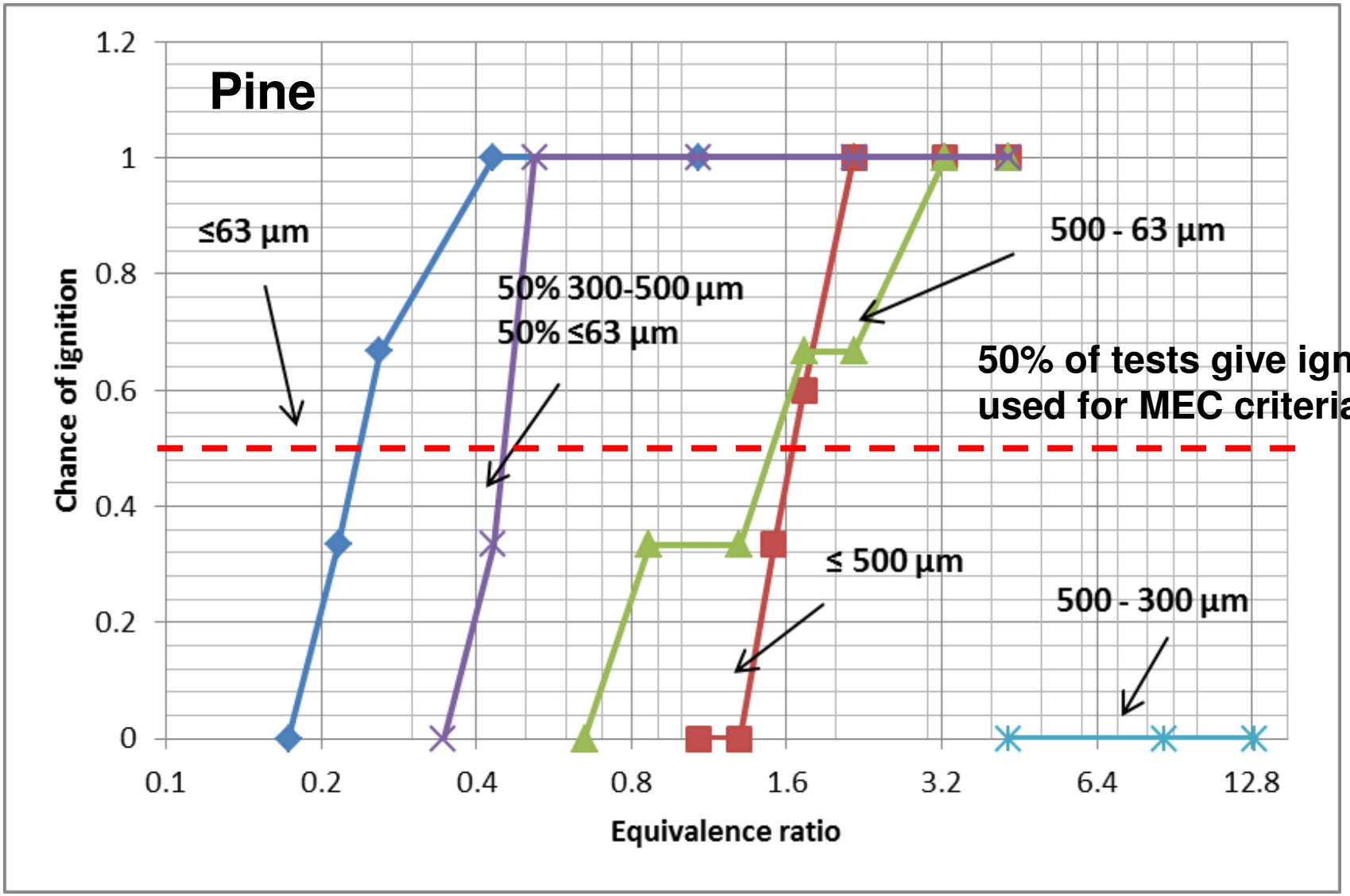

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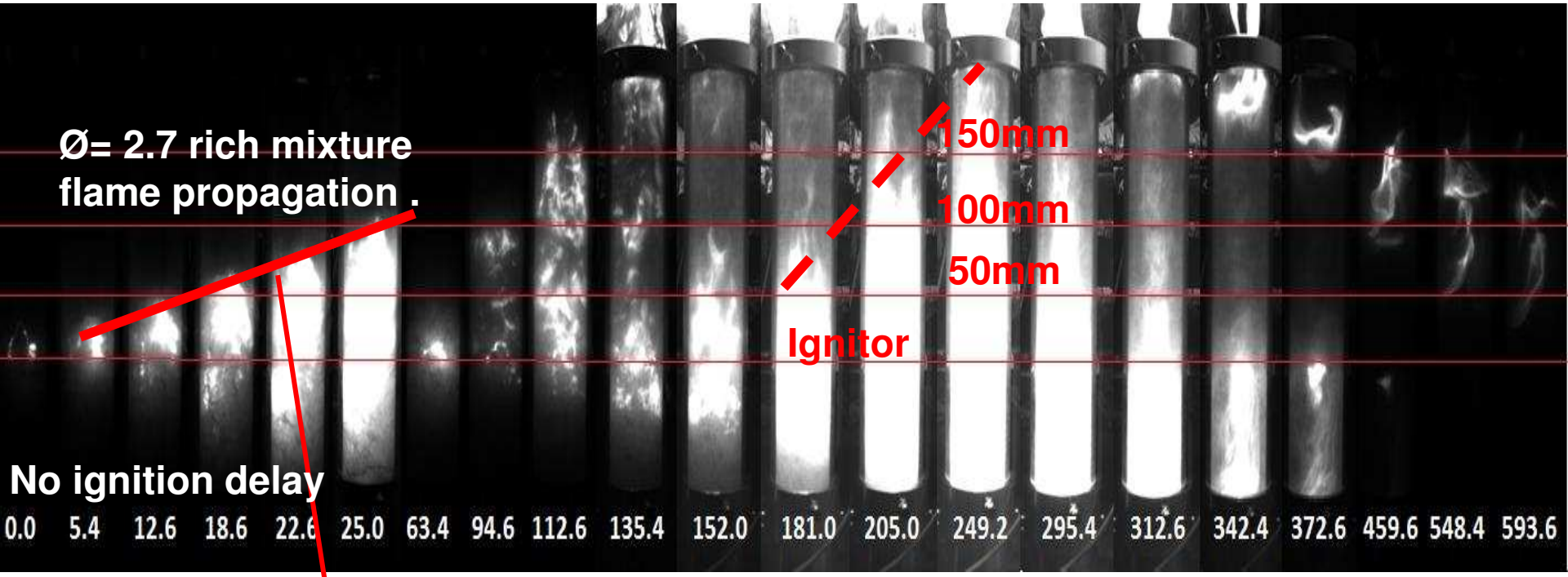
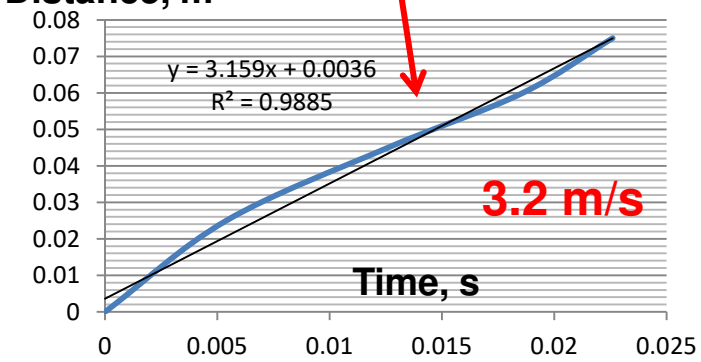
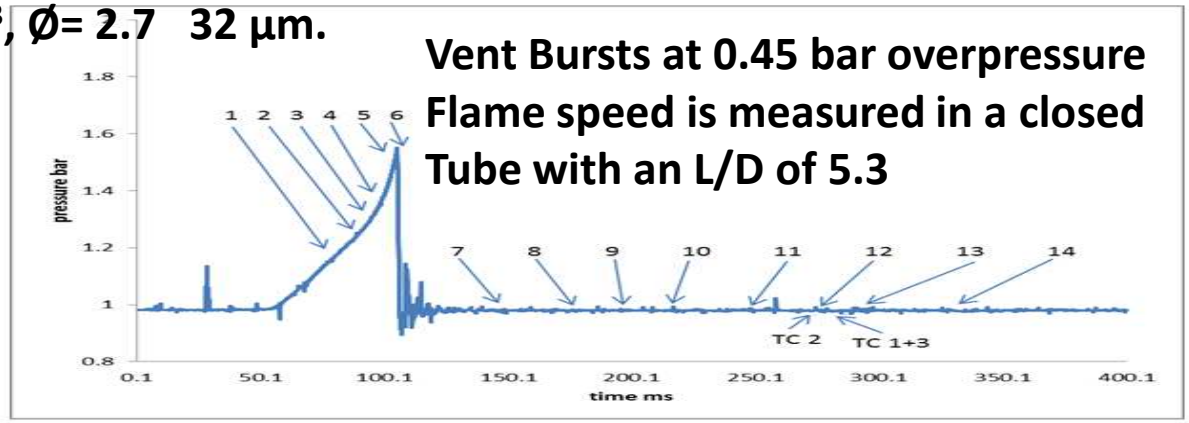
100mm 29



lycopodium 0.5g 333g/m³, Ø= 2.7 32 µm.





Vent Bursts at 0.45 bar overpressure
Flame speed is measured in a closed Tube with an L/D of 5.3

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For rich mixtures the initial flame front before the Hartmann vessel vent burst is the only flame that propagates at the injected concentration.

Once this flame bursts the vent, the flame exits the top of the tube and then there is a second flame in the tube that is burning dust not burnt in the first flame due to the lack of air. This flame was faster than the first flame. This second flame is leaner than the first flame due to the air flow into the explosion tube after the vent bursts.

Air then continues to diffuse in and mix with the unburnt dust until there was a third flame and this has a lower flame speed due to leaner mixtures.

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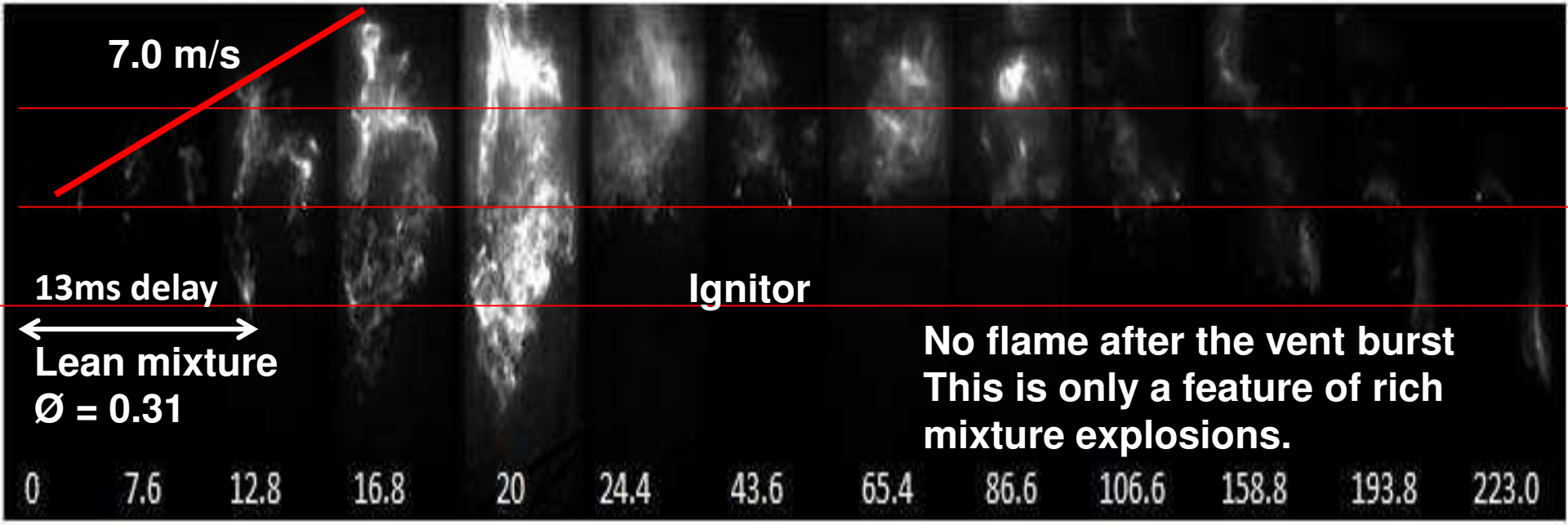

Lycopodium powder, flame propagation (Ø=1= 122.1g/m^3) 0.05g, 37.5g/m^3, Ø= 0.307, mass mean particle size 32 µm.
Note that in the ISO 1 m^3 we have measured spherical turbulent flame speeds for the same lycopodium powder at Ø = 0.31 of 3 m/s.
Here the flame speed is 7 m/s.
The higher value is due to the effect of the tube configuration with an L/D of 5.3, where it is known that the flame preferentially expands in the axial direction.

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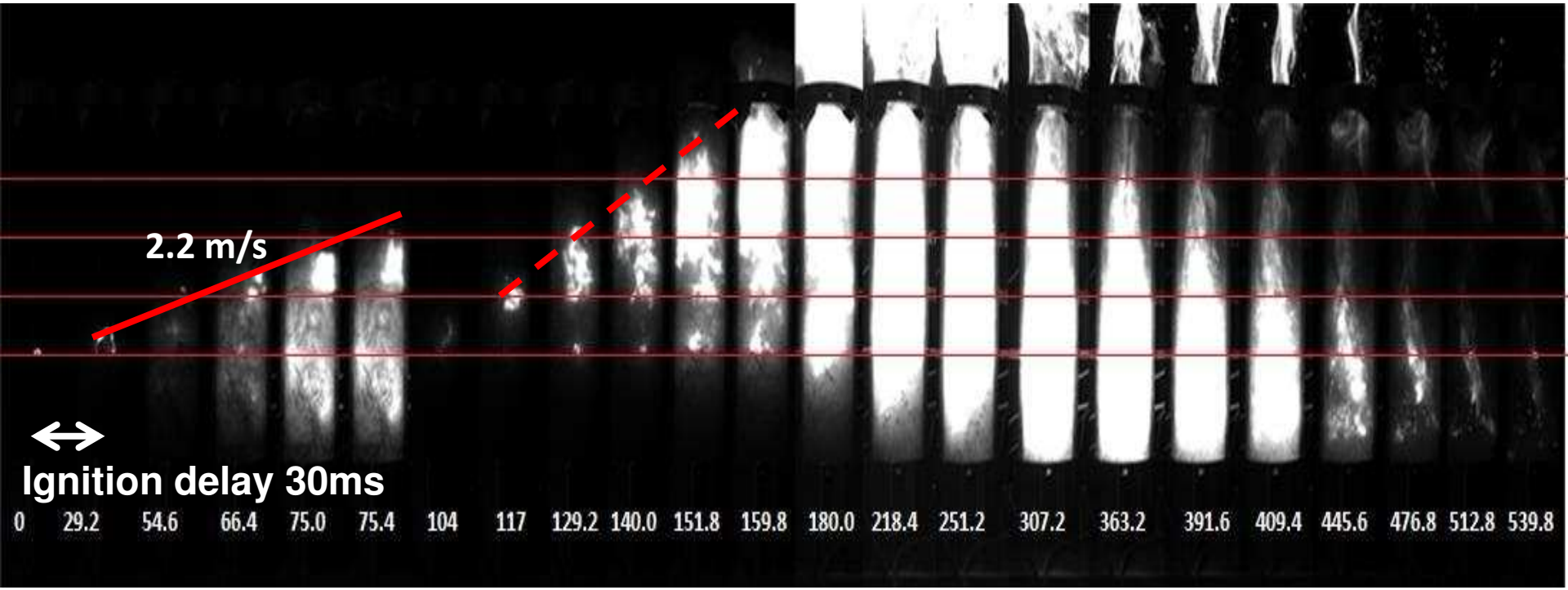

Oak dust sieved < 63µm (Ø=1= 218.9 g/m^3) 1 g, 750g/m^3, Ø=3.44

Rich mixture shows a second faster flame after the vent has burst and air Mixes with the unburnt oak dust.

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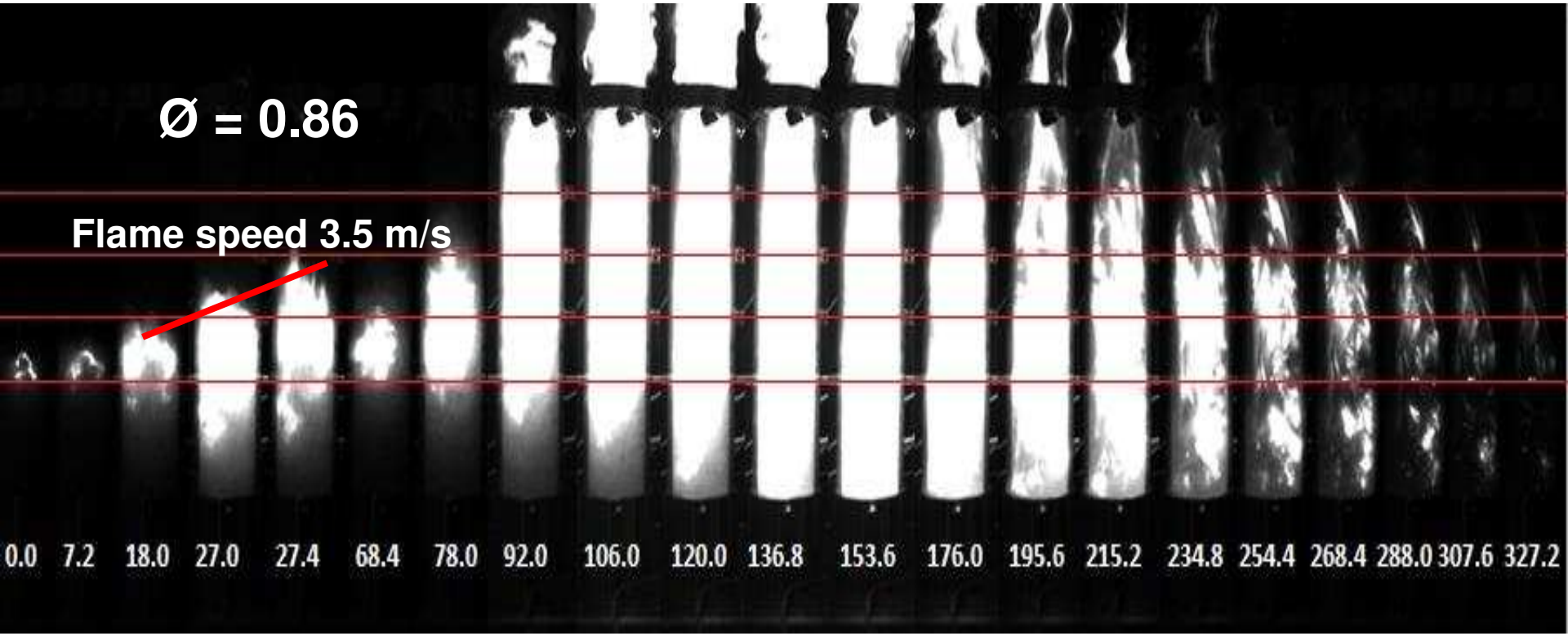

Oak sieved to < 63µm (Ø=1= 218.9) 0.25 g, 187.5g/m^3, Ø=.86

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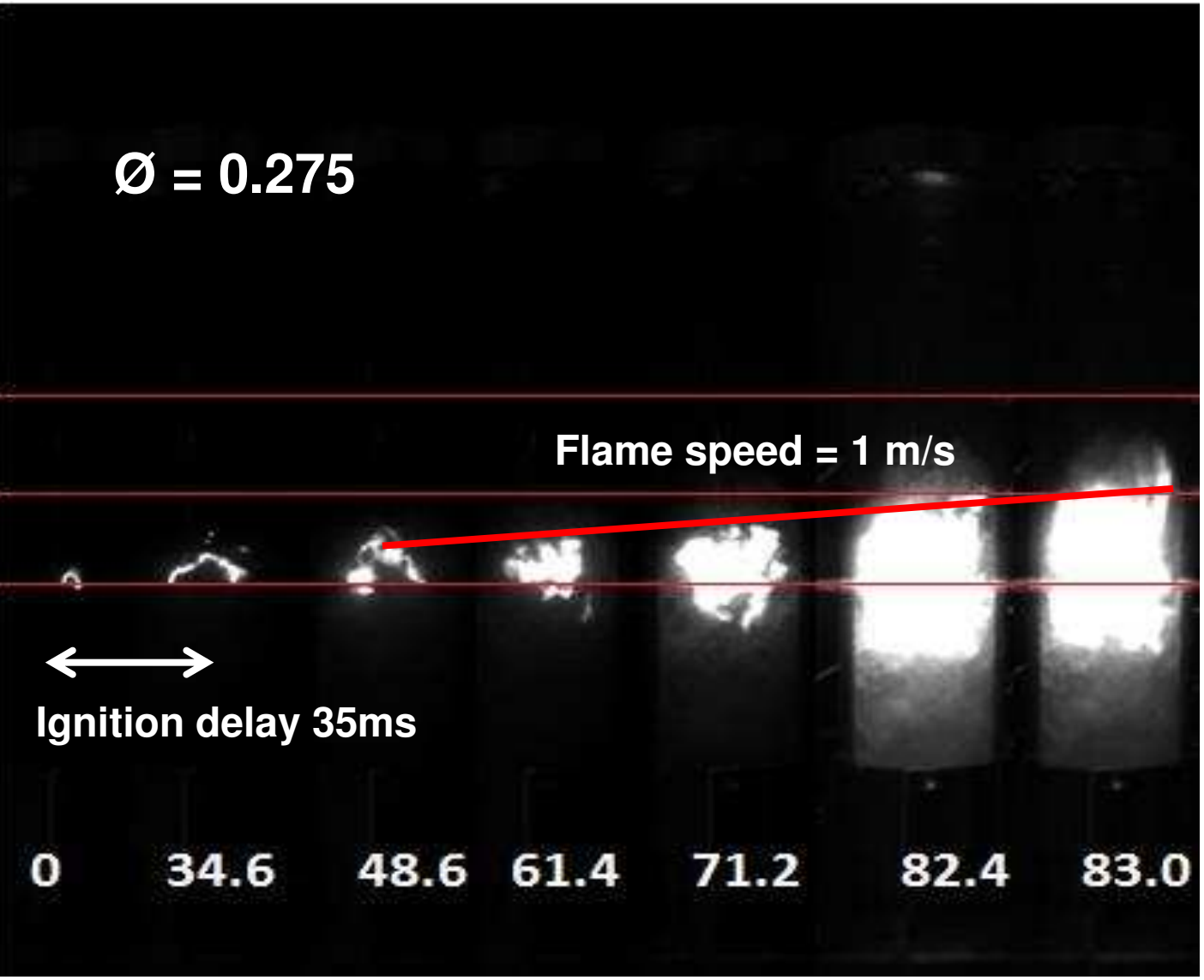

Oak <63µm
(Ø=1= 218.9)
0.08 g, 60g/m^3,
Ø=0.275

This is close to MEC

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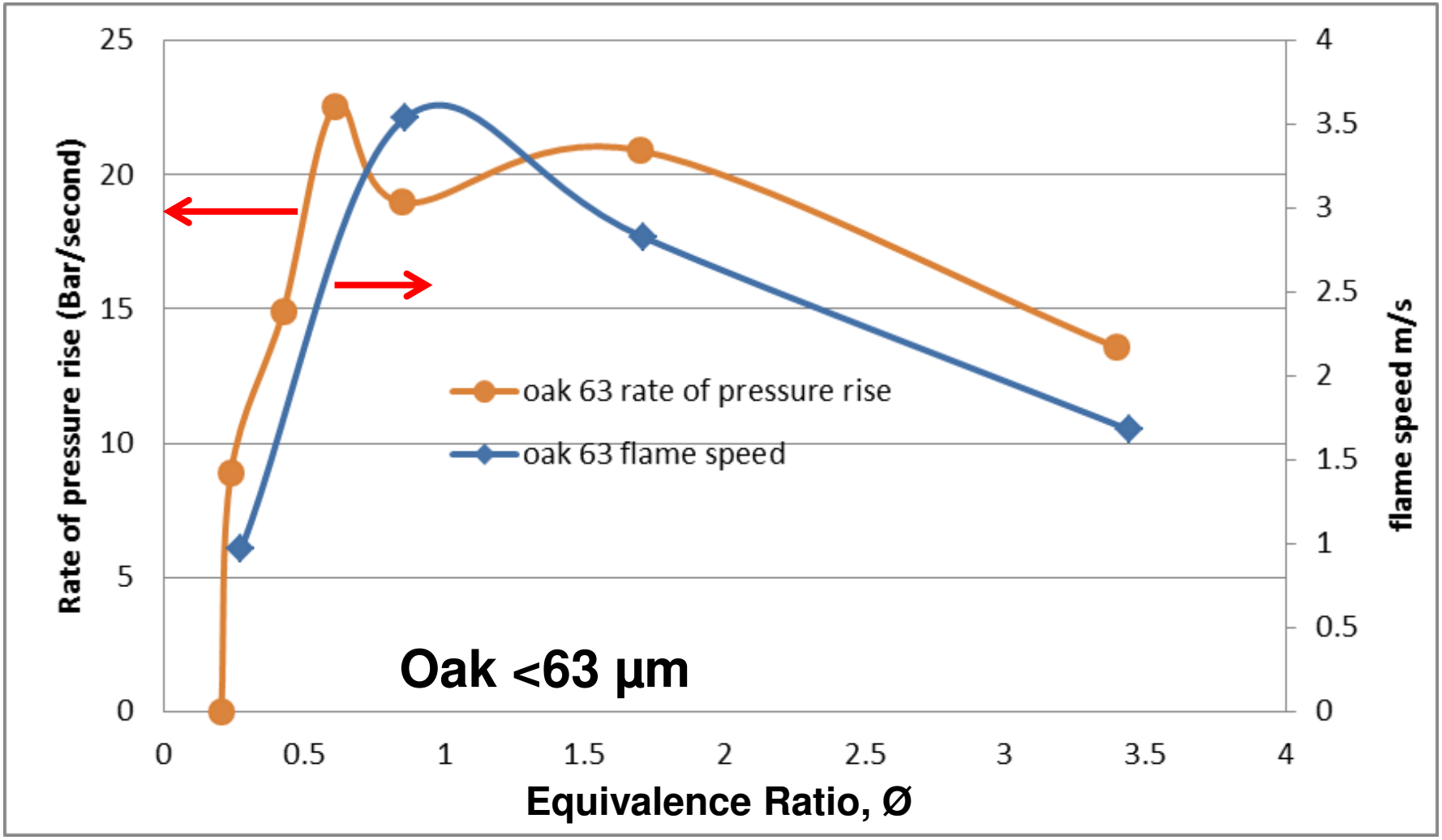

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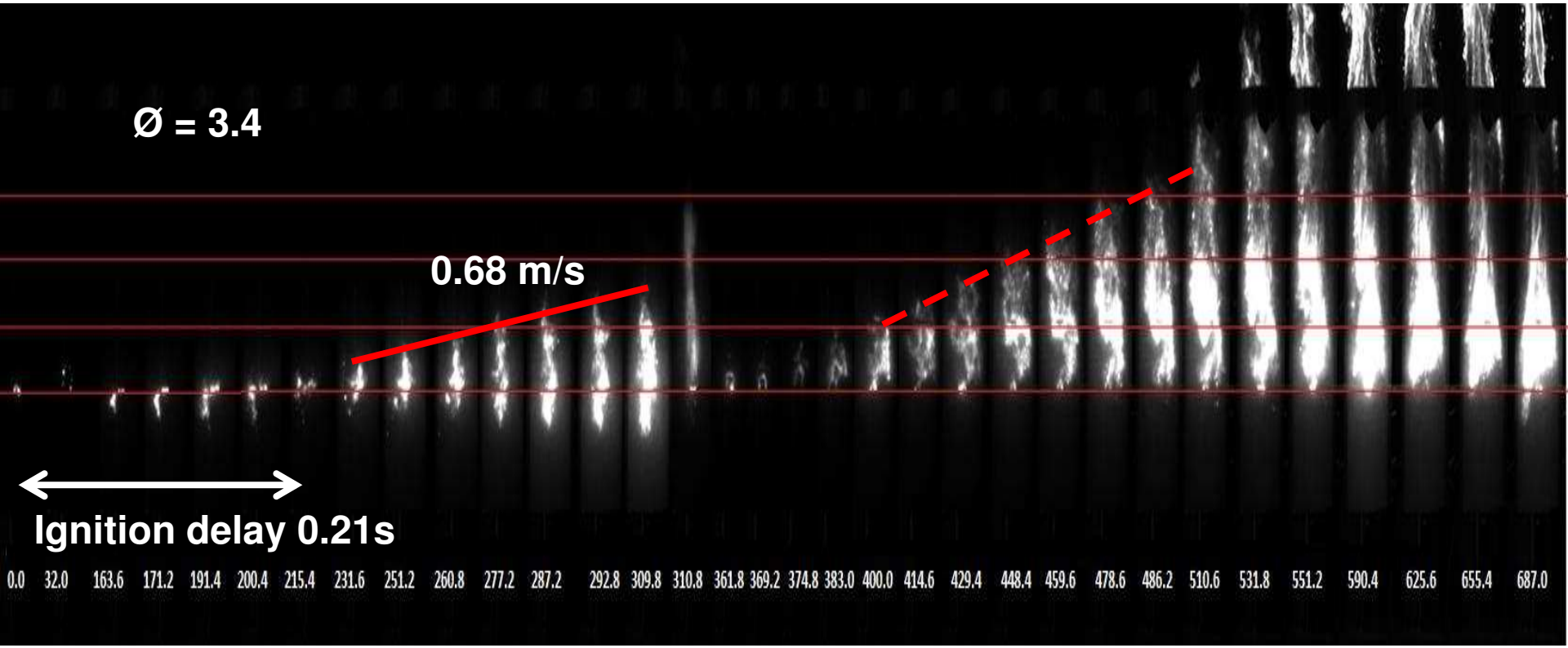

Oak dust sieved to <500µm (Ø=1= 218.9) 1 g, 750g/m^3, Ø=3.44

Note the faint leading flame front from the fine particle flame followed by the more intense luminous radiation from the large particles heated behind the flame front.

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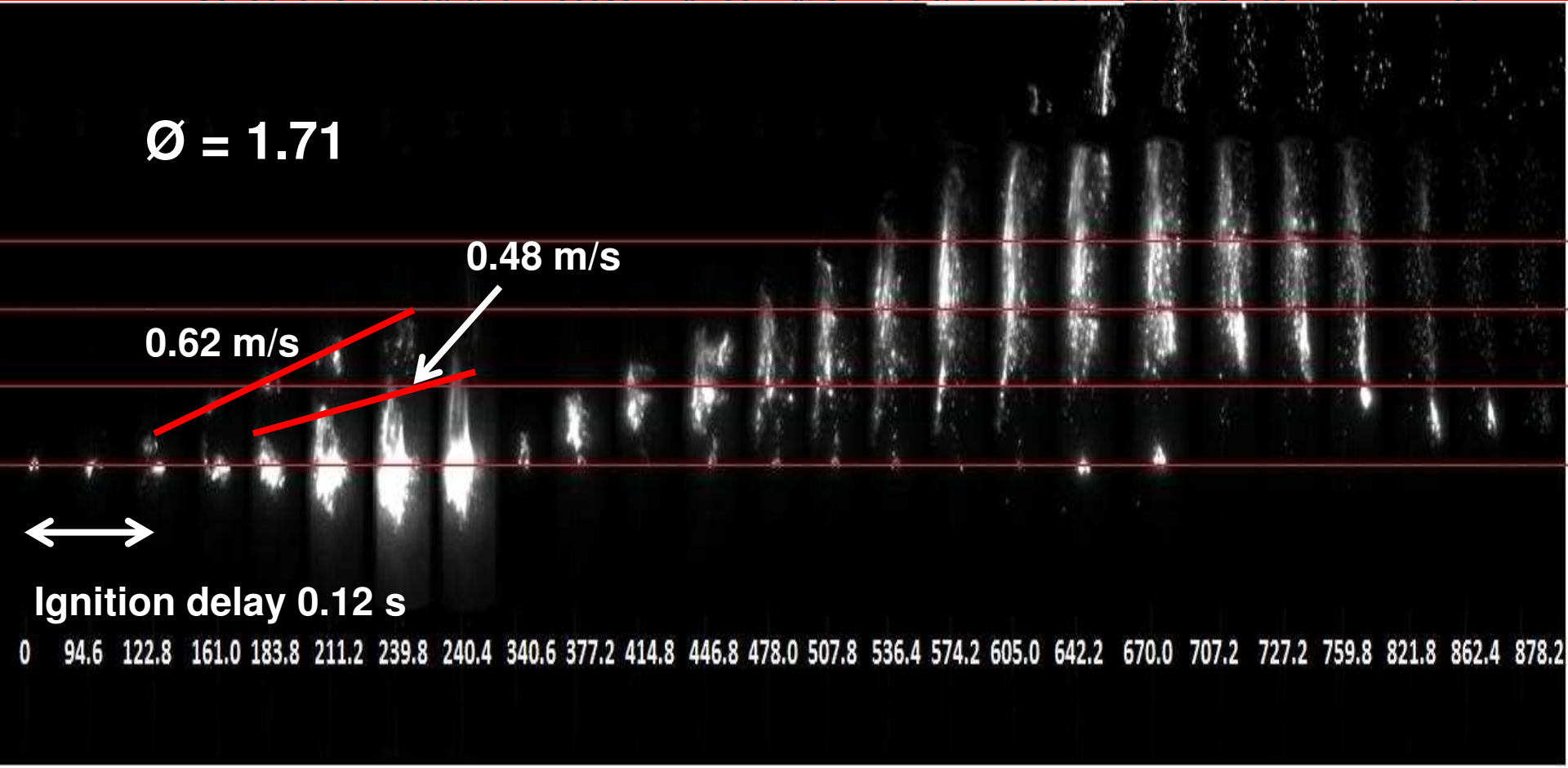

Oak less than 500 (Ø=1= 218.9) 0.5 g, 375g/m^3, Ø=1.71

Evidence of a faster flame front ahead of a slower most luminous region. The difference may be the flame thickness and this may grow as the flame propagates. However, this was not present for all equivalence ratios.

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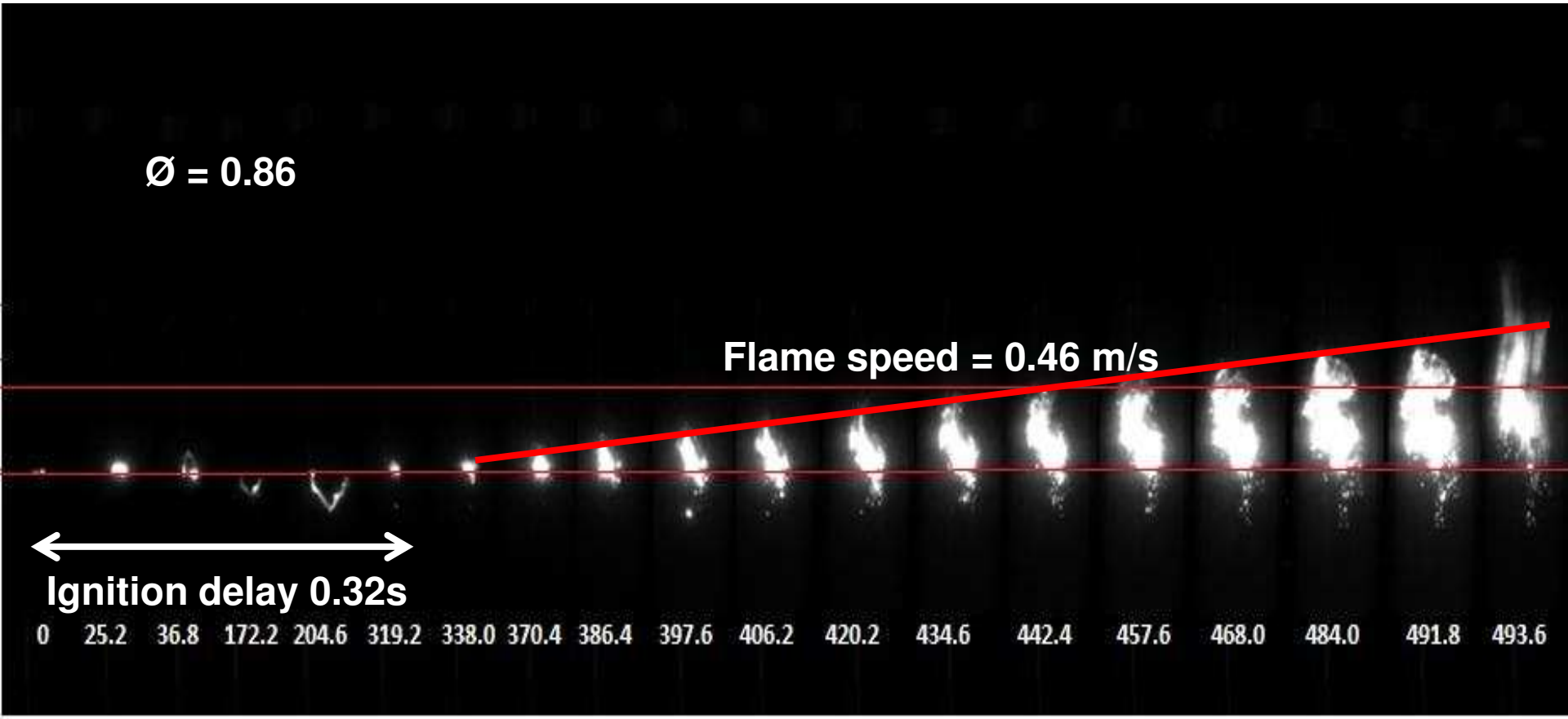

Oak <500µm (Ø=1= 218.9) 0.25 g, 187.5g/m^3, Ø=.86

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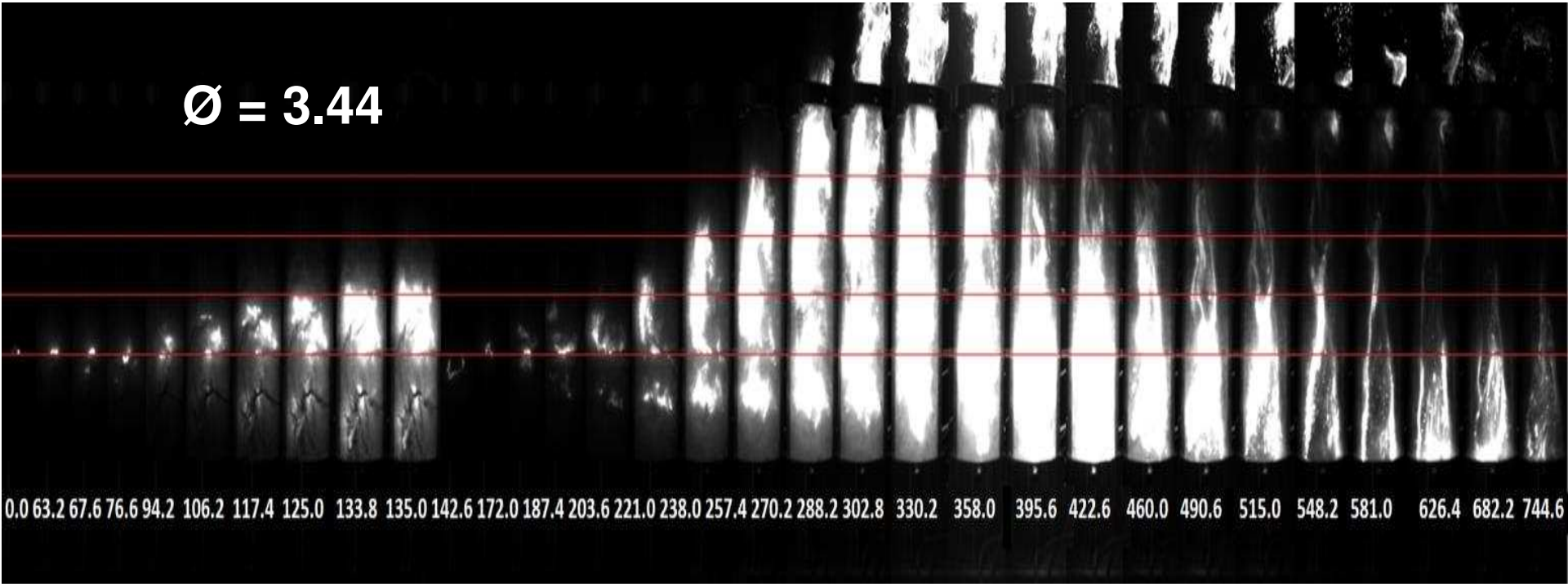

Oak sieved to give the size range 63 - 150µm (Ø=1= 218.9) 1 g, 750g/m^3, Ø=3.44
Aim was to investigate coarse particles with the fines removed.
Flame speed 1.0 m/s

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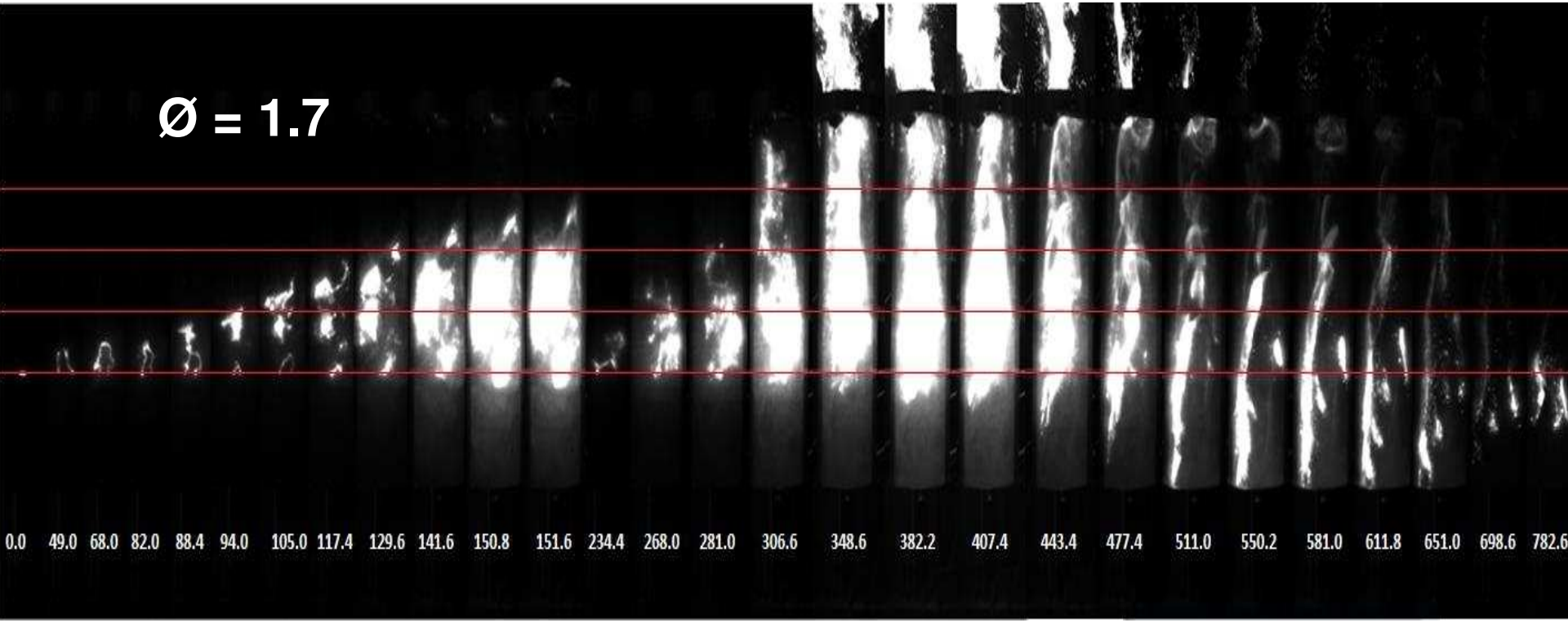

Oak 63 – 150 µm (Ø=1= 218.9) 0.5 g, 375g/m^3, Ø=1.71
Flame speed 1.7 m/s

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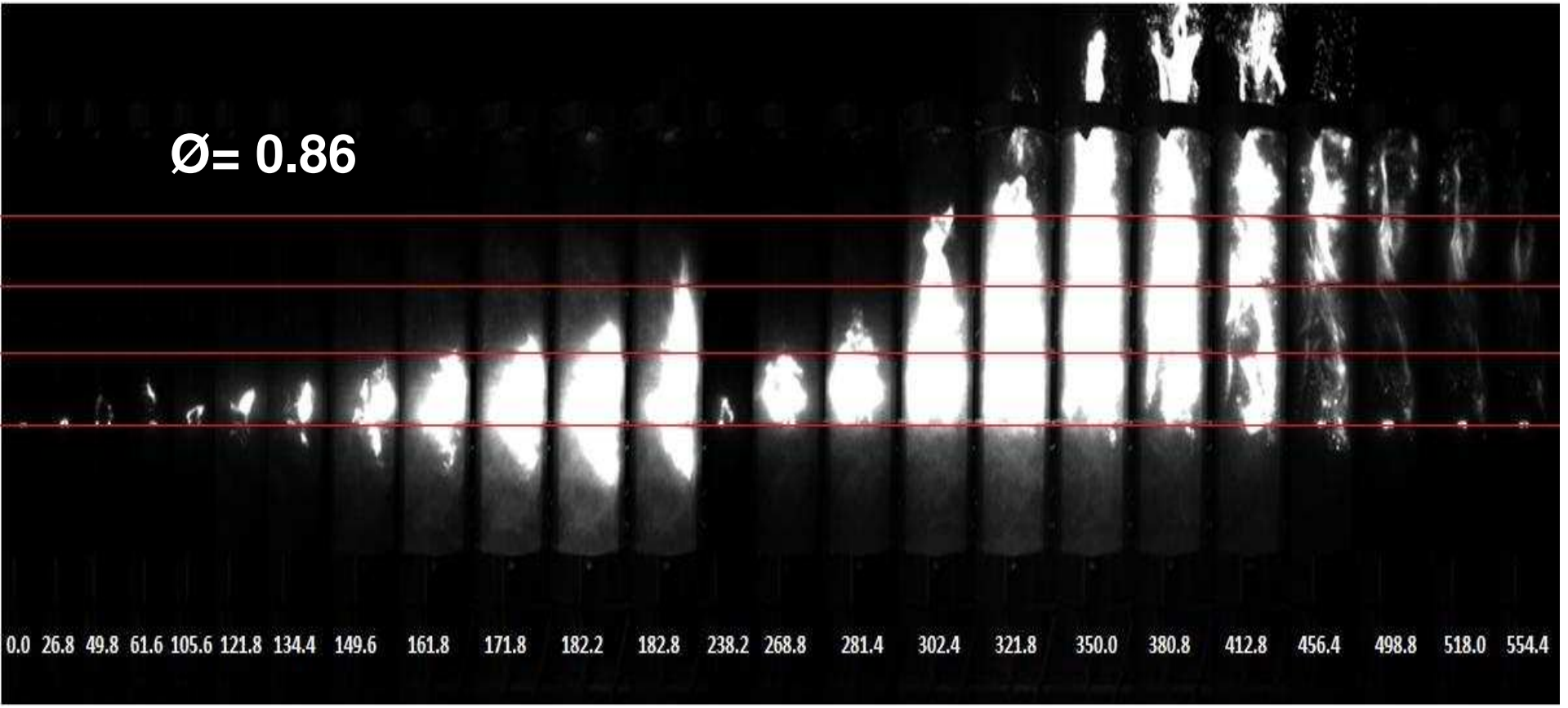

Oak 63 – 150 µm (Ø=1= 218.9) 0.25 g, 187.5g/m^3, Ø=.86
Flame speed 0.9 m/s

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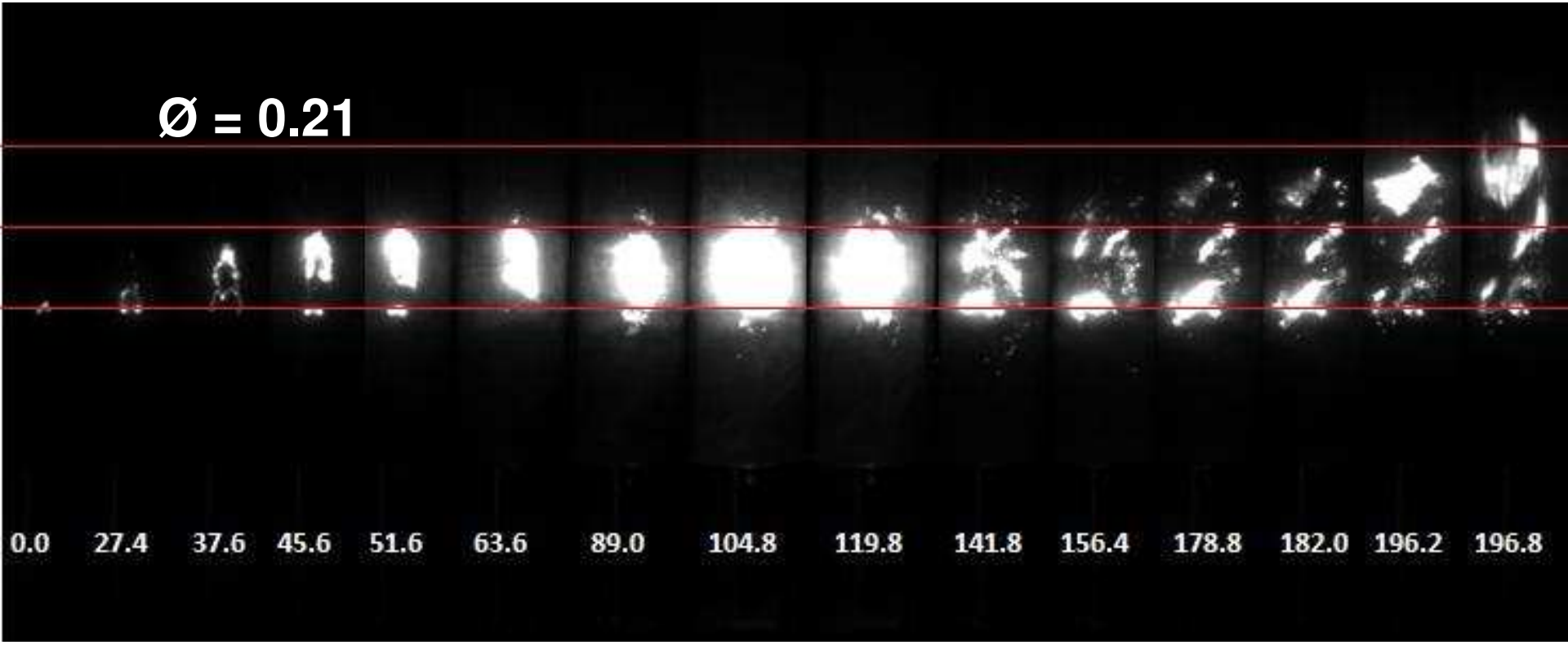

Oak 63 – 150 µm (Ø=1= 218.9) 0.06 g, 45g/m^3, Ø=0.206
Close to lean limit – flame propagates >100mm from spark and hence Satisfies the 100mm flame propagation criteria for the EU gas flame lean limits.
Flame speed 0.4 m/s

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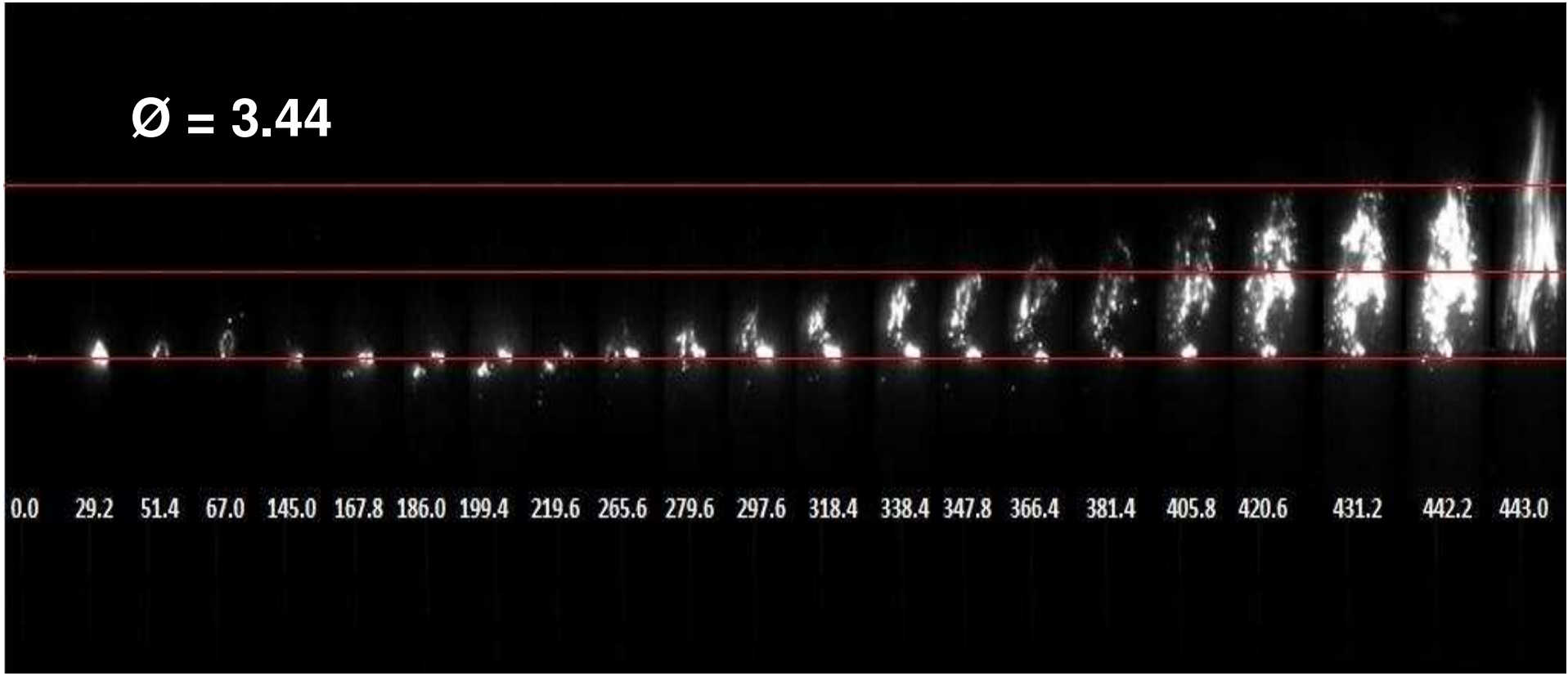

Oak 150 – 300 µm (Ø=1= 218.9) 1 g, 750g/m^3, Ø=3.44
Flame speed 0.45 m/s

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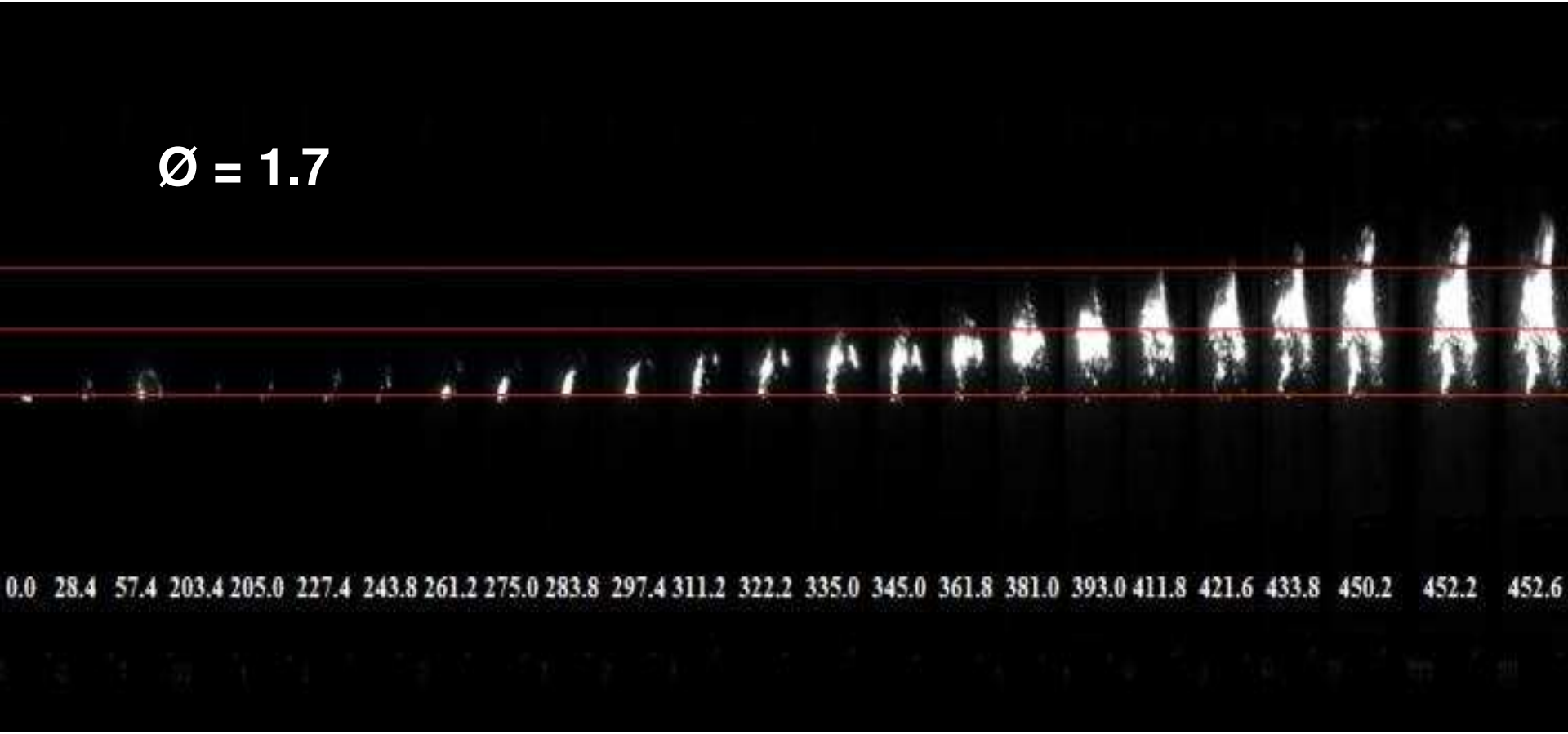

Oak 150 – 300 µm (Ø=1= 218.9) 0.5 g, 375g/m^3, Ø = =1.71
Very coarse particles with no fines still propagate a flame, but there is a long ignition delay. Flame speed 0.61 m/s

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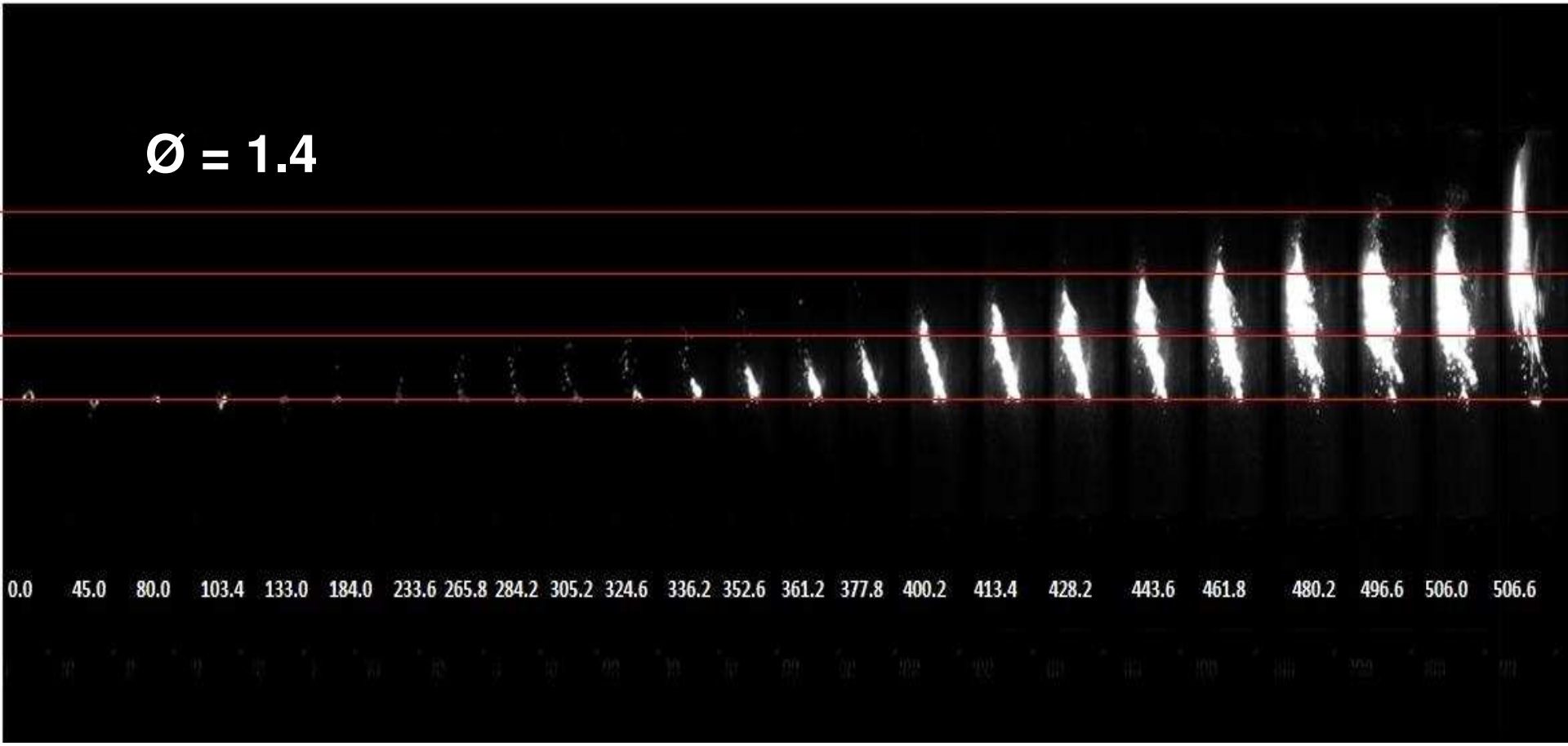

Oak 150 – 300 µm (Ø=1= 218.9) 0.41 g, 300g/m^3, Ø=1.37
Flame speed 0.70 m/s

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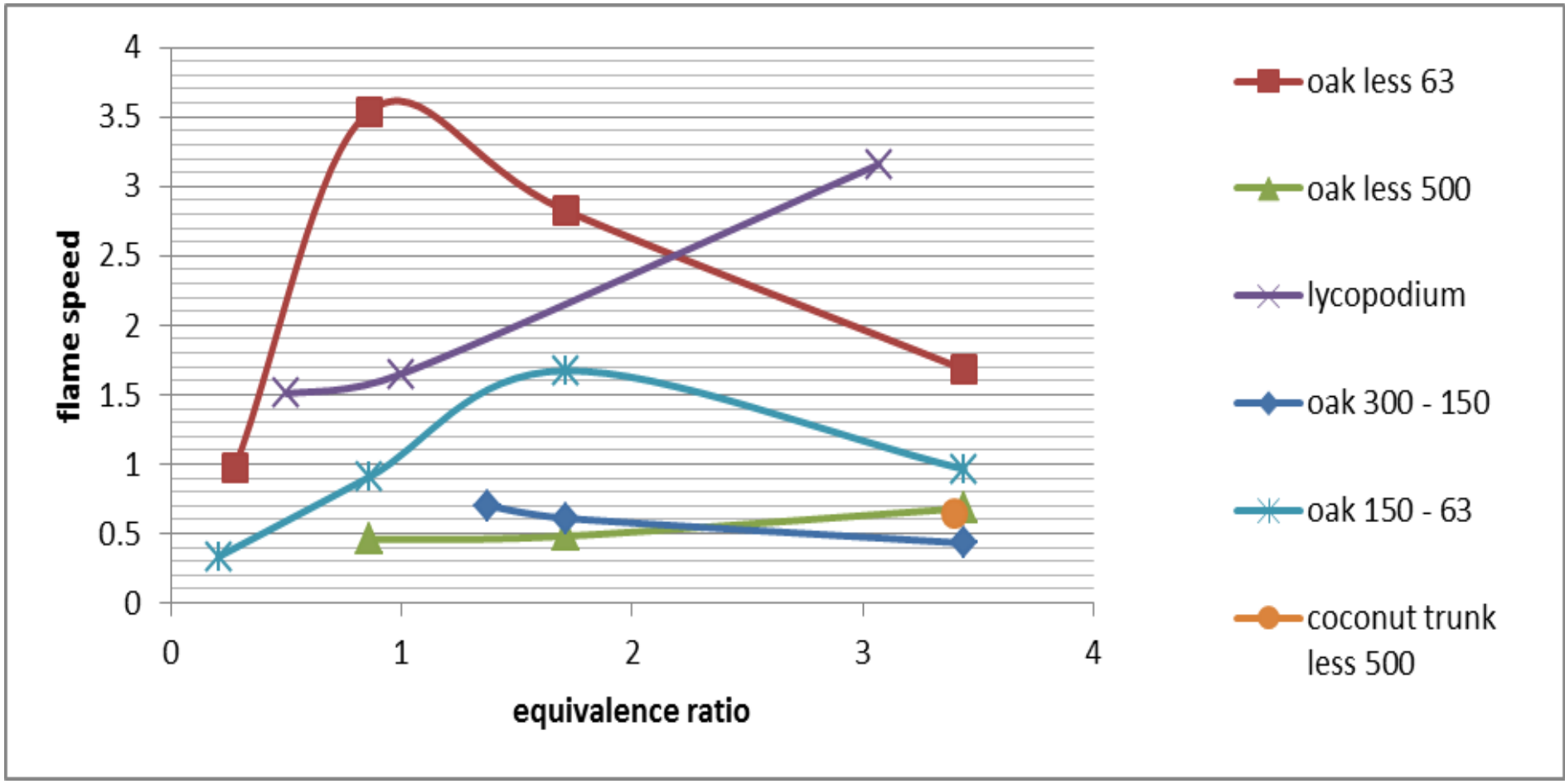

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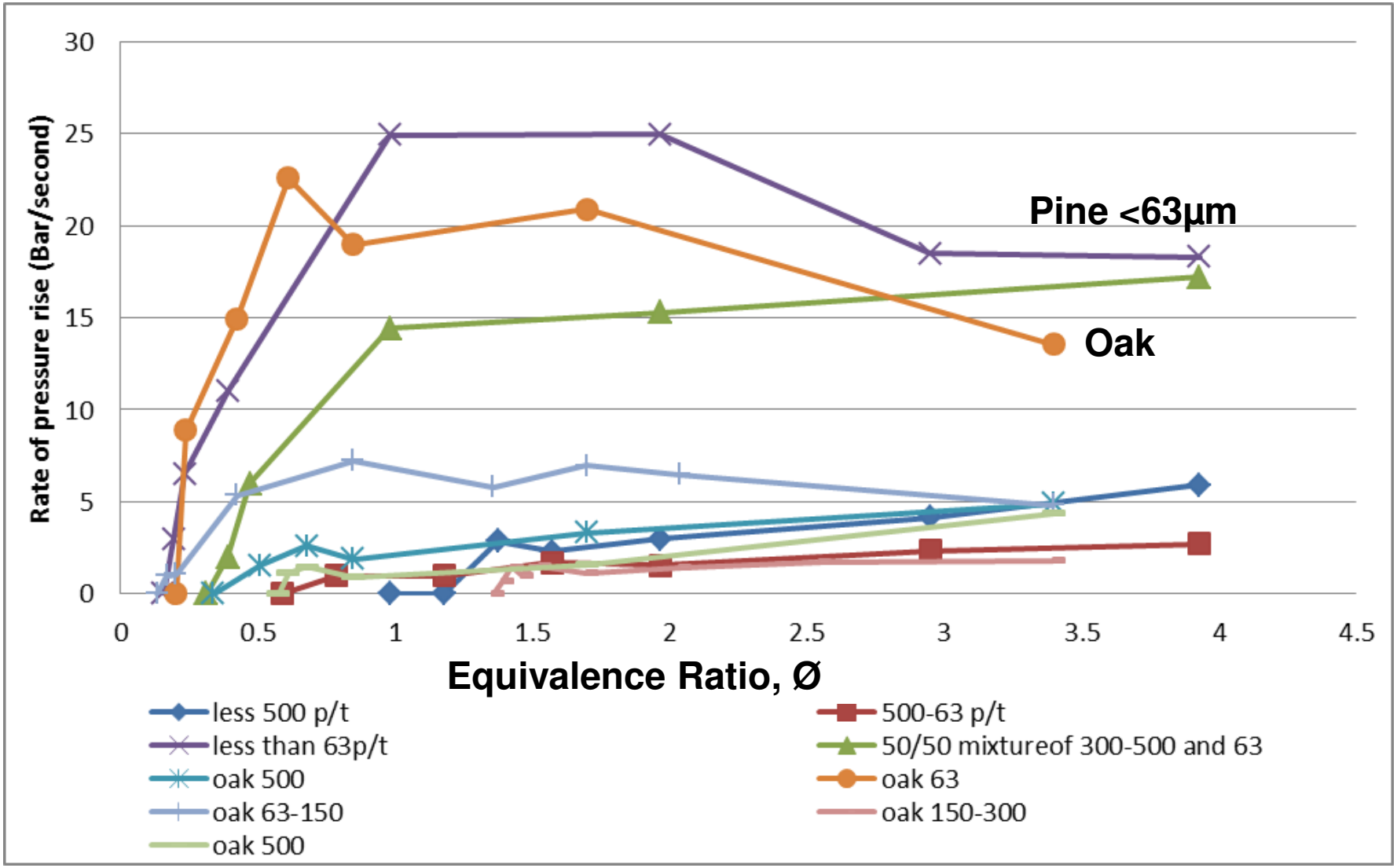

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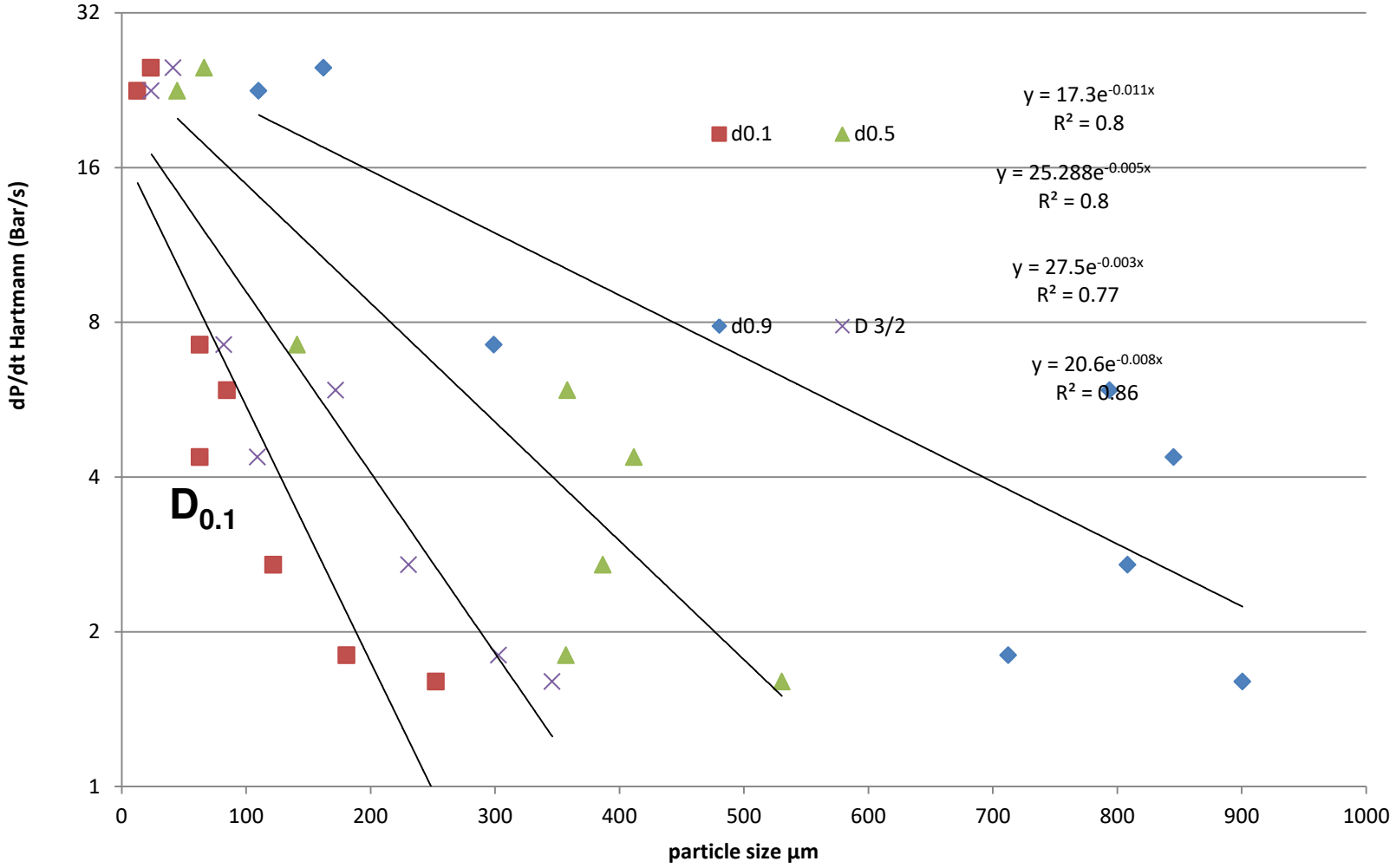

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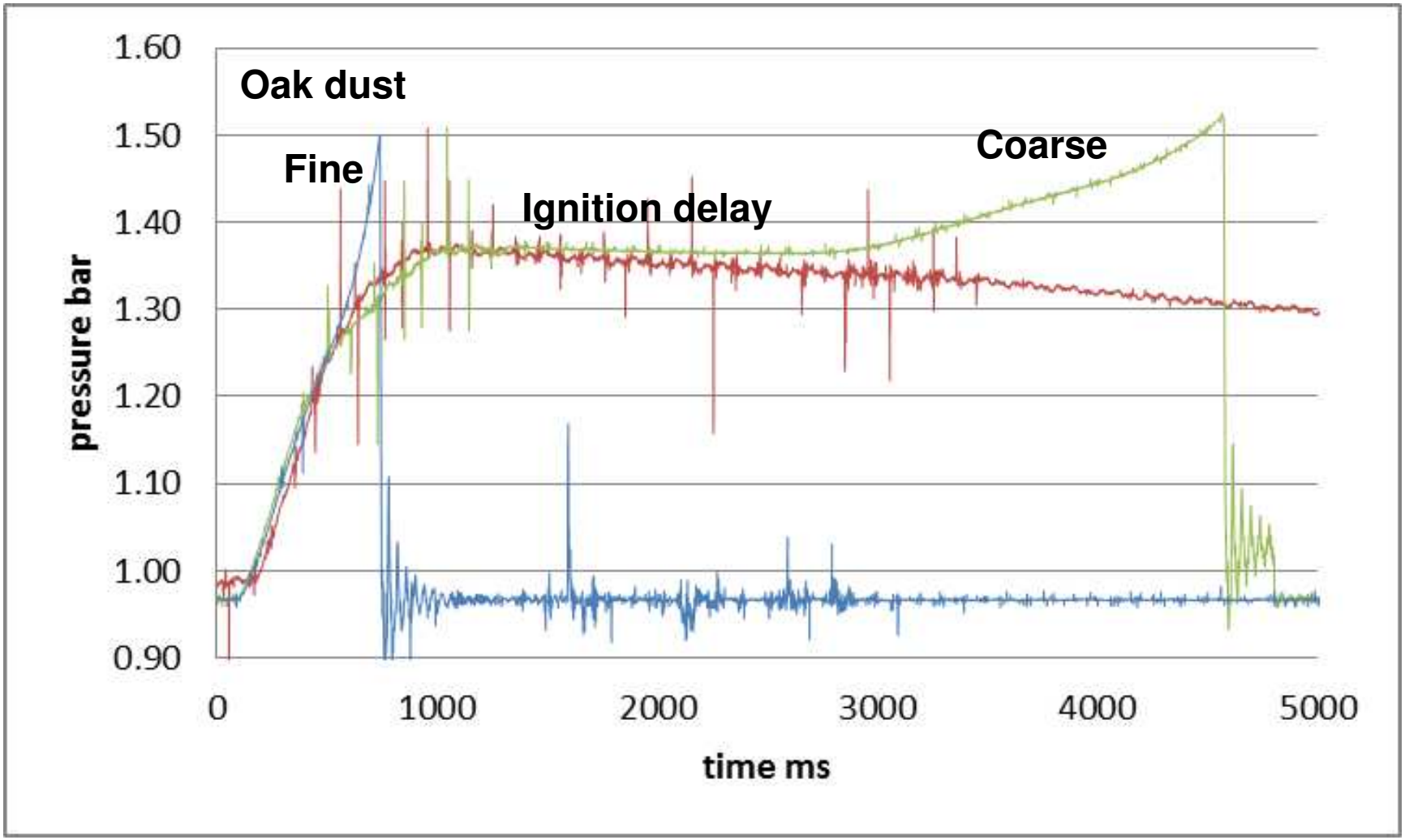

Without dust (red), With dust - coarse and ignition (green) and With dust - fine and ignition (b

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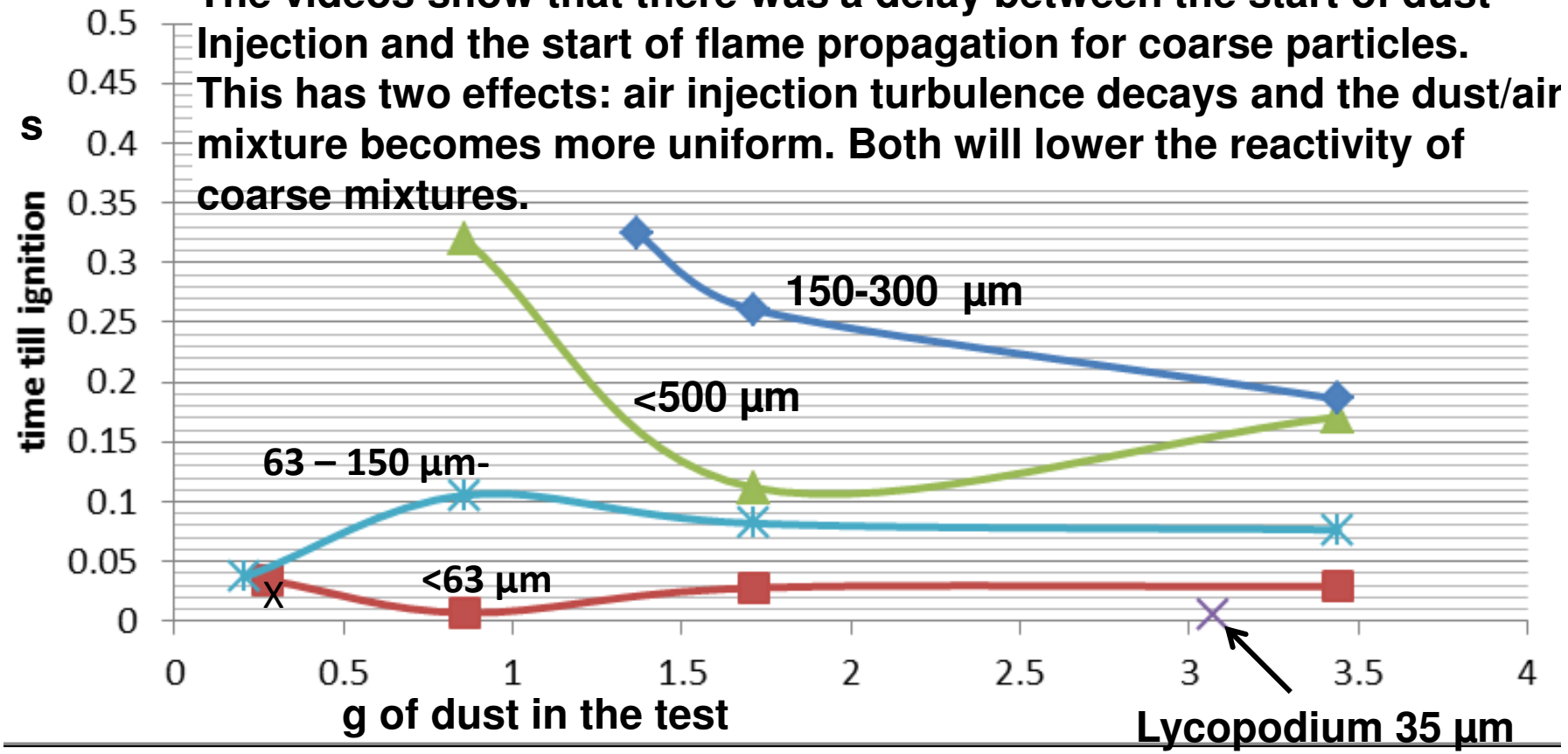
The videos show that there was a delay between the start of dust Injection and the start of flame propagation for coarse particles. This has two effects: air injection turbulence decays and the dust/air mixture becomes more uniform. Both will lower the reactivity of coarse mixtures.



The time from the start of injection to the video observation of the start of flame propagation for oak sawdust. The size fractions were achieved by sieving. Fine particles have the lowest delay and the presence of fines with coarse particles reduces the overall ignition delay.

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For fine particles <63 µm sieve size the ignition delay was small.

A consequence of this is that there is little time for the injected dust and the air in the Hartmann tube to mix.

Also the turbulence decays with time from start of injection and hence fine particles will propagate at a higher turbulence level than for coarse particles.

The long ignition delay for coarse particles will lead to greater mixing time and hence the injected equivalence ratio could be close to the flame propagation equivalence ratio.

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It was noted that all of the videos showed greater obscuration (caused by dust) ahead of the flame propagation.

Also observations of the dust dispersion using scattered light indicates that at the time of ignition the dust has not penetrated the full volume of the vessel and these videos indicate that the dust may have only penetrated 2/3 of the vessel length. This makes the mixture locally richer.

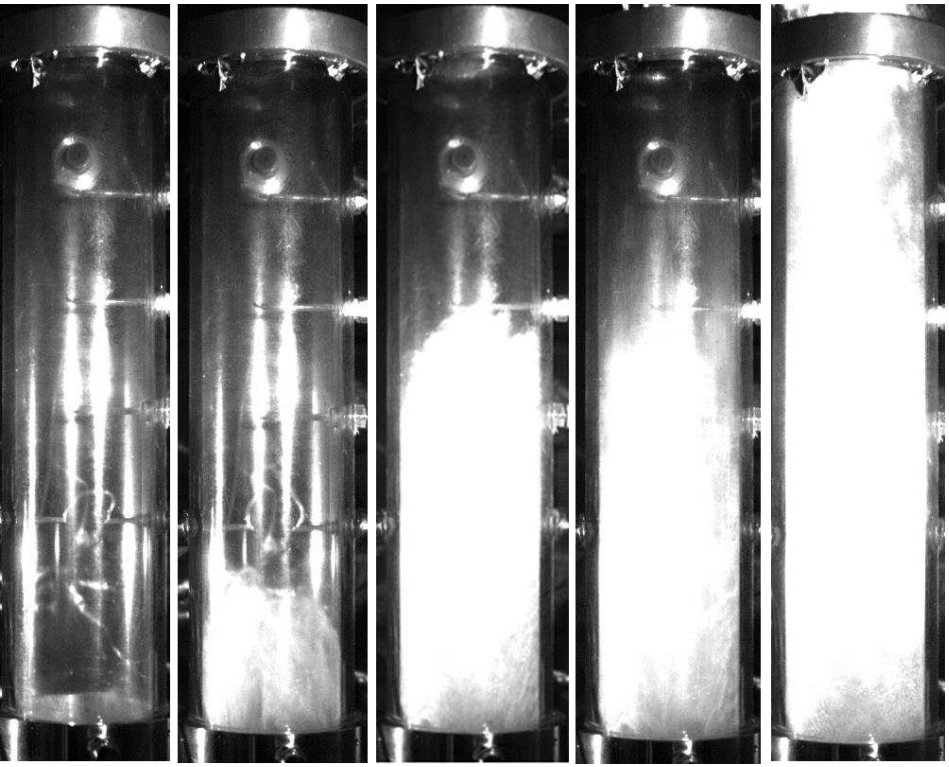
As this only occurs for fine particle size, due to the short ignition delay, it may be that the very lean MEC for fine particles is an experimental error and that for fine dusts an artificial ignition delay should be imposed. The authors have shown that 60 ms delay gives a richer MEC for fine mixtures.

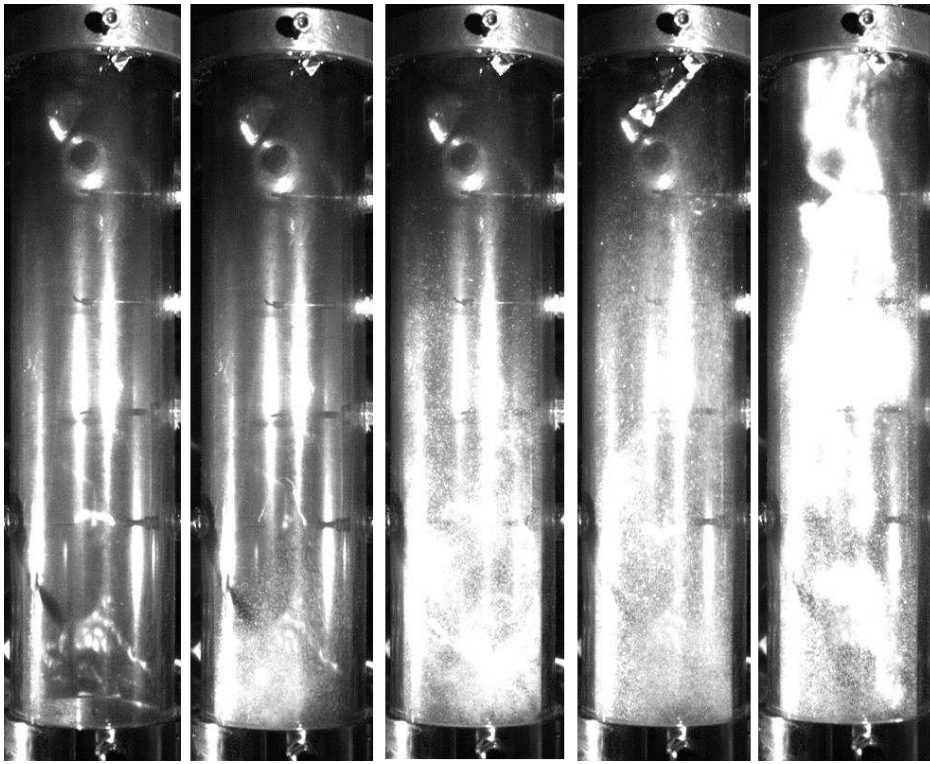
Thus there are two opposing effects and the local equivalence ratio at the flame front need direct obscuration measurements to resolve these issues.

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? But why would this only be a problem for HCO dusts?

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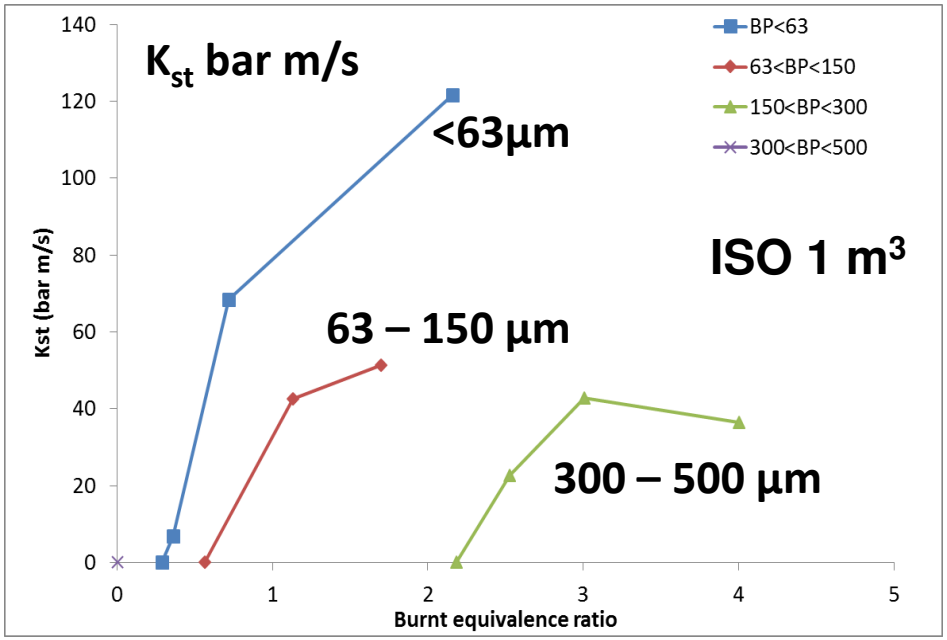
Flame propagation mechanism for coarse dusts.

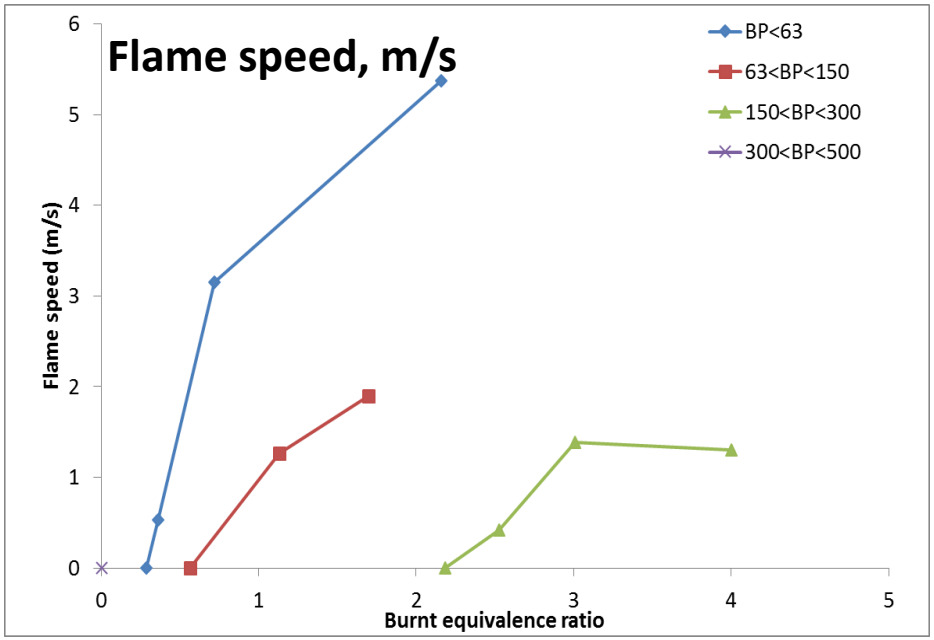
The MEC data indicates that the lean limit becomes richer for increase in particle size.

The explanation for this is that the flame front propagates in the fine particles, so that if the proportion of fine particles is low, as in dust with large mean particle size, then richer mixtures are required to give a flammable mixture in the fine fraction.

The explosion induced wind ahead of the flame cause the fine fraction and coarse fractions to separate and this leaves the coarse particles behind the fine particle flame front, where the dust is heated and gasified when the overall mixture is rich.

Experiments by the authors on the ISO 1 m^3 dust explosion vessel also support this mechanism.





K_{st} vs. burnt equivalence ratio for different sized fractions steam exploded pine wood (BP)

The lean limit becomes richer as the particle size increases, as shown for work on the Hartmann equipment. The reason is that the mixtures have a wide range of sizes with around 10 – 20% fines (<100µm). The flame propagates in the fine particles and the larger particles burn in the post fine flame hot gases. However, the fines are ~ 10 - 20% of the mass and so the overall mixture is rich for the fines to be flammable. This is the mechanism of combustion of coarse biomass.

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Conclusions

1. **Coarse particles of oak and pine will explode. The main reason is the presence of a wide size distribution with a significant fine fraction in all the coarse fractions.**
2. **The reactivity of coarse particles is very low relative to fine particles. They act mainly as a heat sink that lowers the flame temperature, which lowers the reactivity.**
3. **The mechanism of coarse particles propagating a flame is for the fine fraction to propagate the flame and for the coarse fraction to lag behind the flame front and be heated and gasified by the initial flame front.**
4. **Flammability is then controlled by the fine fraction so that the overall mixture has to be very rich to generate sufficient fine fraction mass for the fine fraction to be flammable.**
5. **Coarse fractions have an ignition delay which gives time for the dust and air to mix. Fine fractions ignite immediately and may propagate in a mixture that is locally rich and thus to have an artificially low MEC.**