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Experimental Research on the Physics of Coal Combustion

by

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Outline

- Background
- Development of novel optical instrumentation
- Swirl stabilised Coal burner
- Results
  - ✓ Coal particle size, velocity and temperature
  - ✓ Mechanisms influencing coal particle behaviour
  - ✓ Effect of vitiated air and co-firing gas equivalence ratio on probability of coal particle burning
  - ✓ Coal particle Reactivity
- Summary

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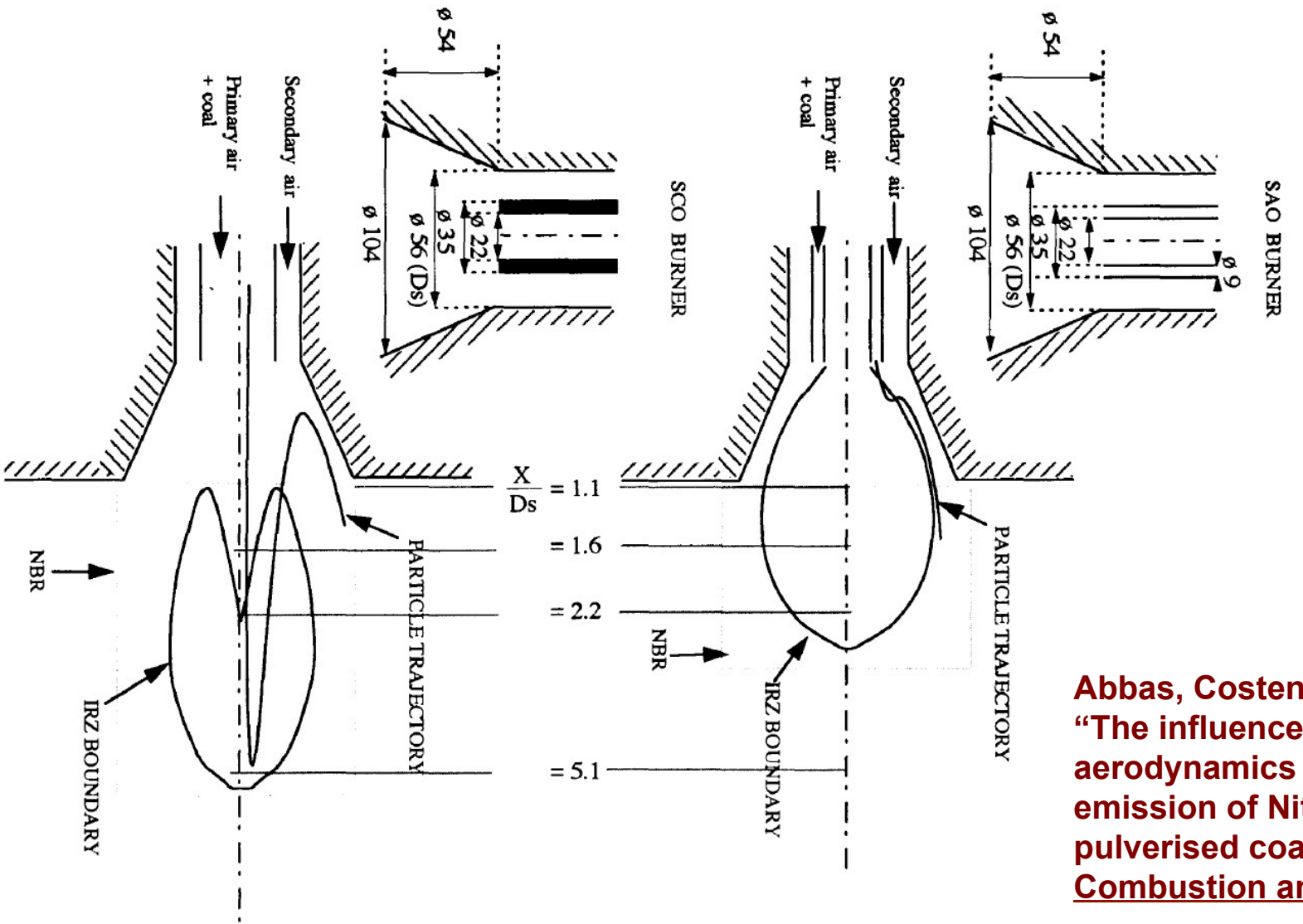
Evidence of effect of coal particle trajectories in the near burner region on low NOx Coal burners



Abbas, Costen & Lockwood (1991) "The influence of near burner region aerodynamics on the formation and emission of Nitrogen Oxides in a pulverised coal-fired furnace" Combustion and Flame 91: 346-363.

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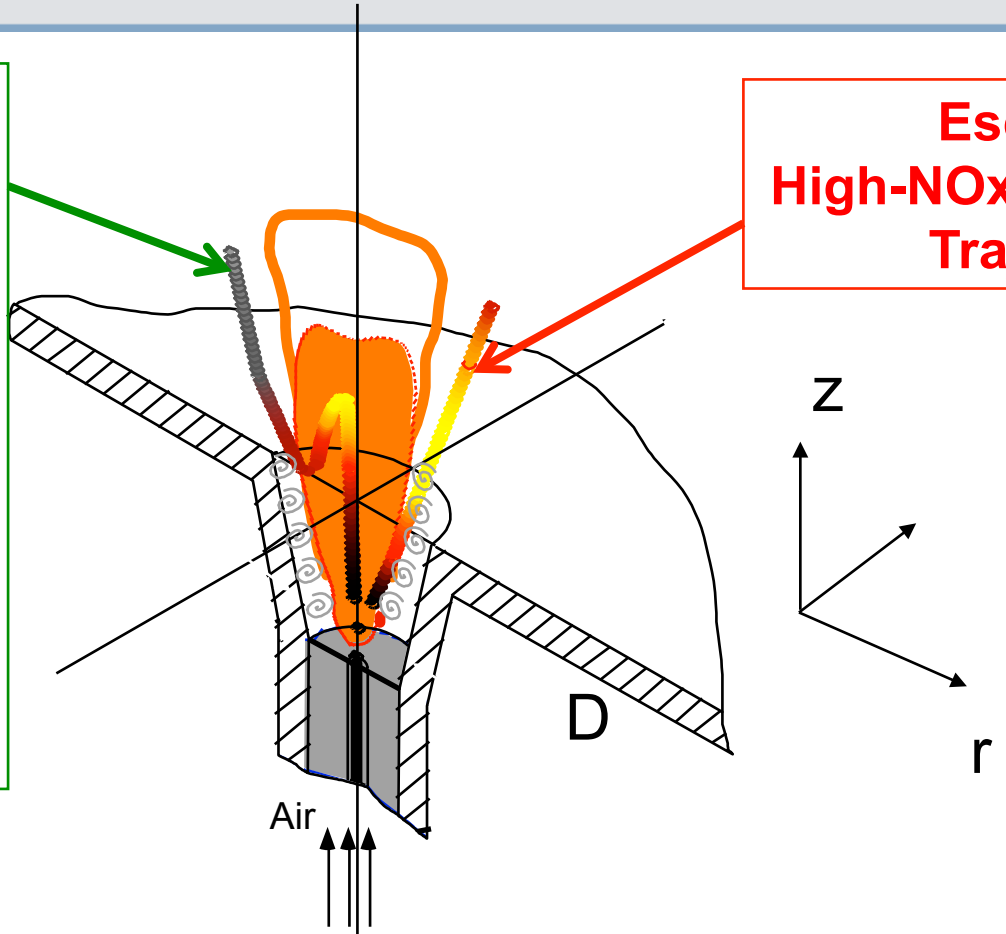
Low NOx Coal burners

Recirculating Low-NOx coal particle Trajectory:

Longer Residence time in the oxygen lean internal recirculation zone leads to reduced NOx emissions from fuel bound N_2

Escaping High-NOx coal particle Trajectory



DETAILED KNOWLEDGE OF THE MOTION AND TEMPERATURE OF A COAL PARTICLE IS IMPORTANT FOR THE OPTIMISATION OF OPERATION OF LOW-NOx BURNERS

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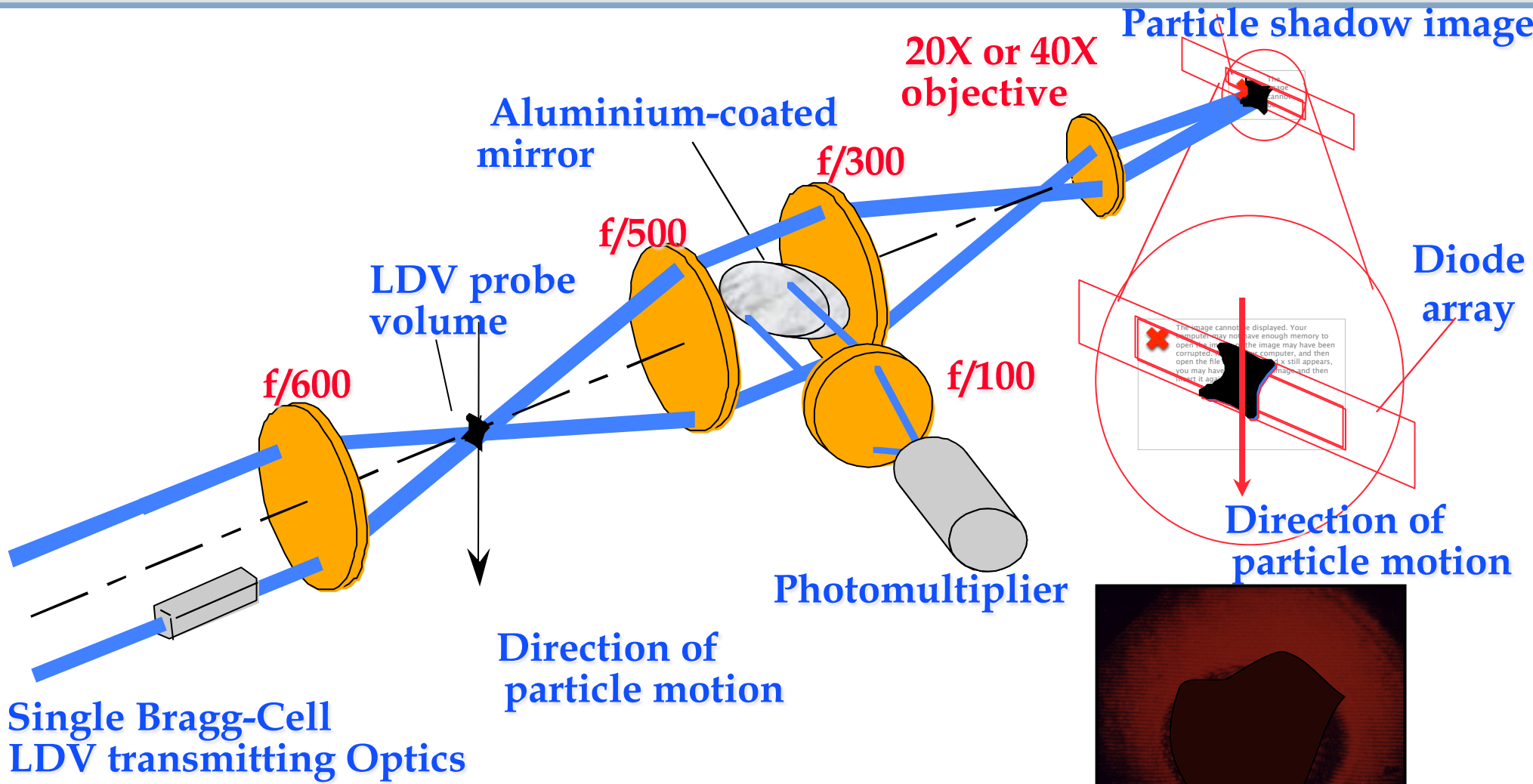
Shadow Doppler Anemometer for non-spherical particle size and velocity measurements at a 'point'



Patented and commercialised by Kanomax, Japan

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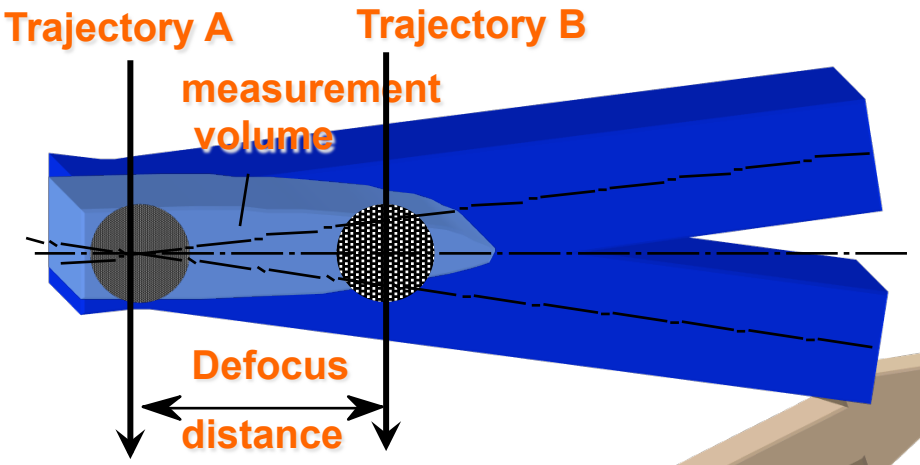
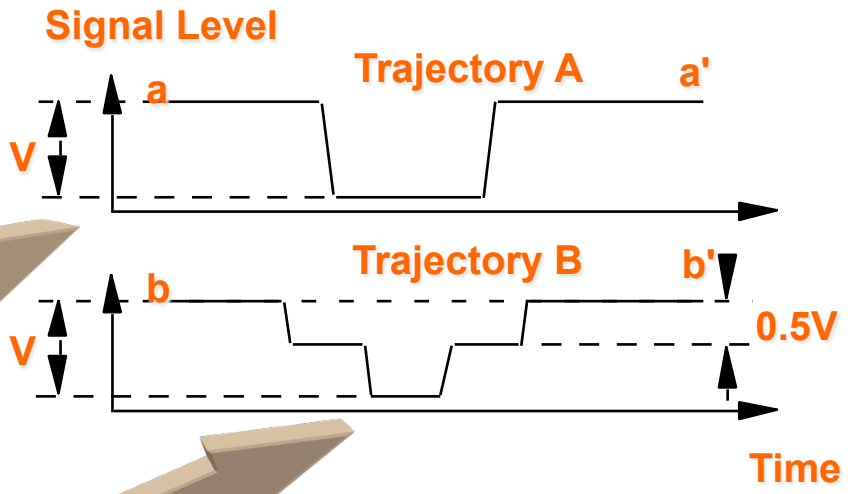
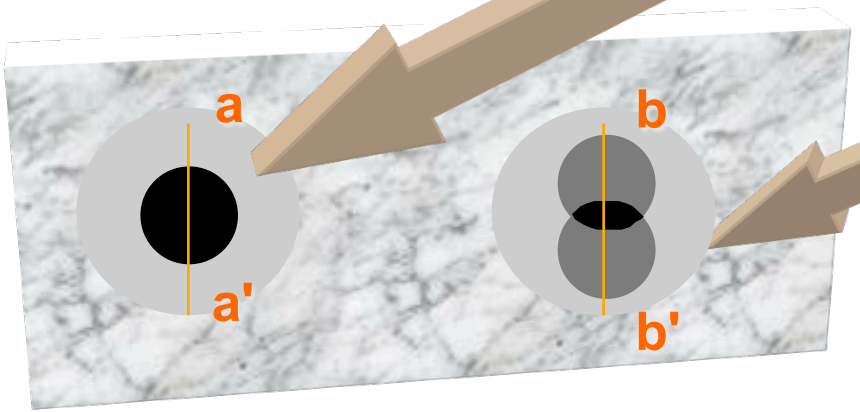
Appearance of Particle Images

Particle Trajectory



Output Signal





Shadow at the detector plane

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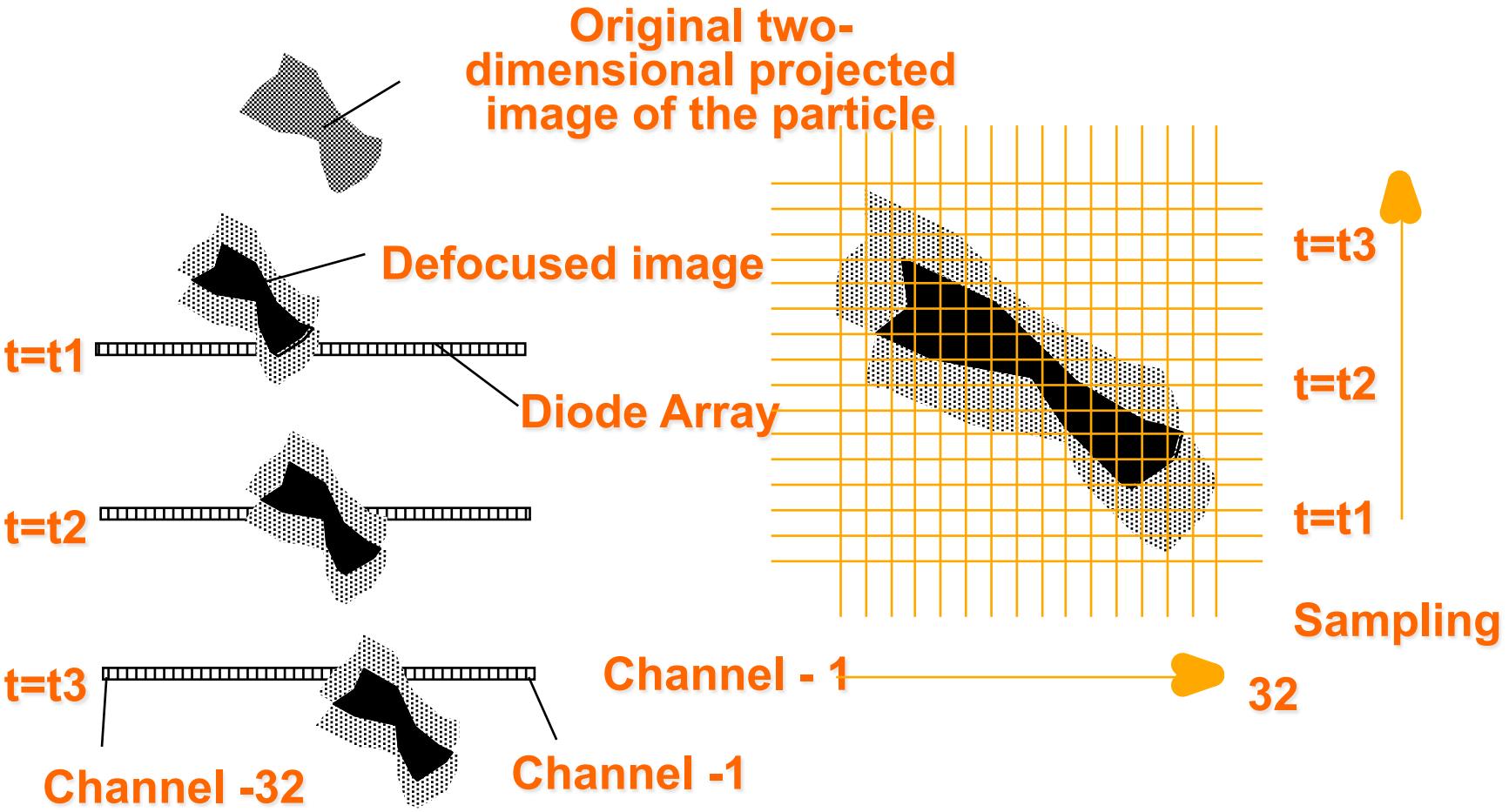
Recording & Reconstruction of Particle Image



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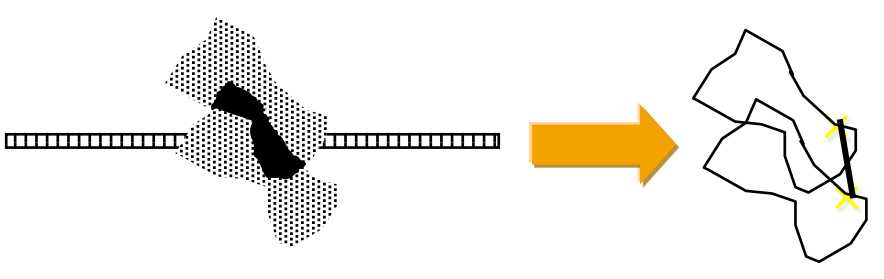
Additional Information obtained by SDV



$$\phi = \tan^{-1}\left(\frac{D_h}{D}\right) = \tan^{-1}\left(\frac{v}{u}\right)$$

Displacement between the shadows → Trajectory Angle, ϕ → Transverse velocity component, v

Particle Volume Flux, G →

$$G = \frac{1}{T_s}\sum_i \left[\frac{V_i}{A_i}\sum_{j=1}^{n_i}\frac{u_{ij}}{|u_{ij}|}\right]$$

Particle Volume

Sampling Time

Sampling Space

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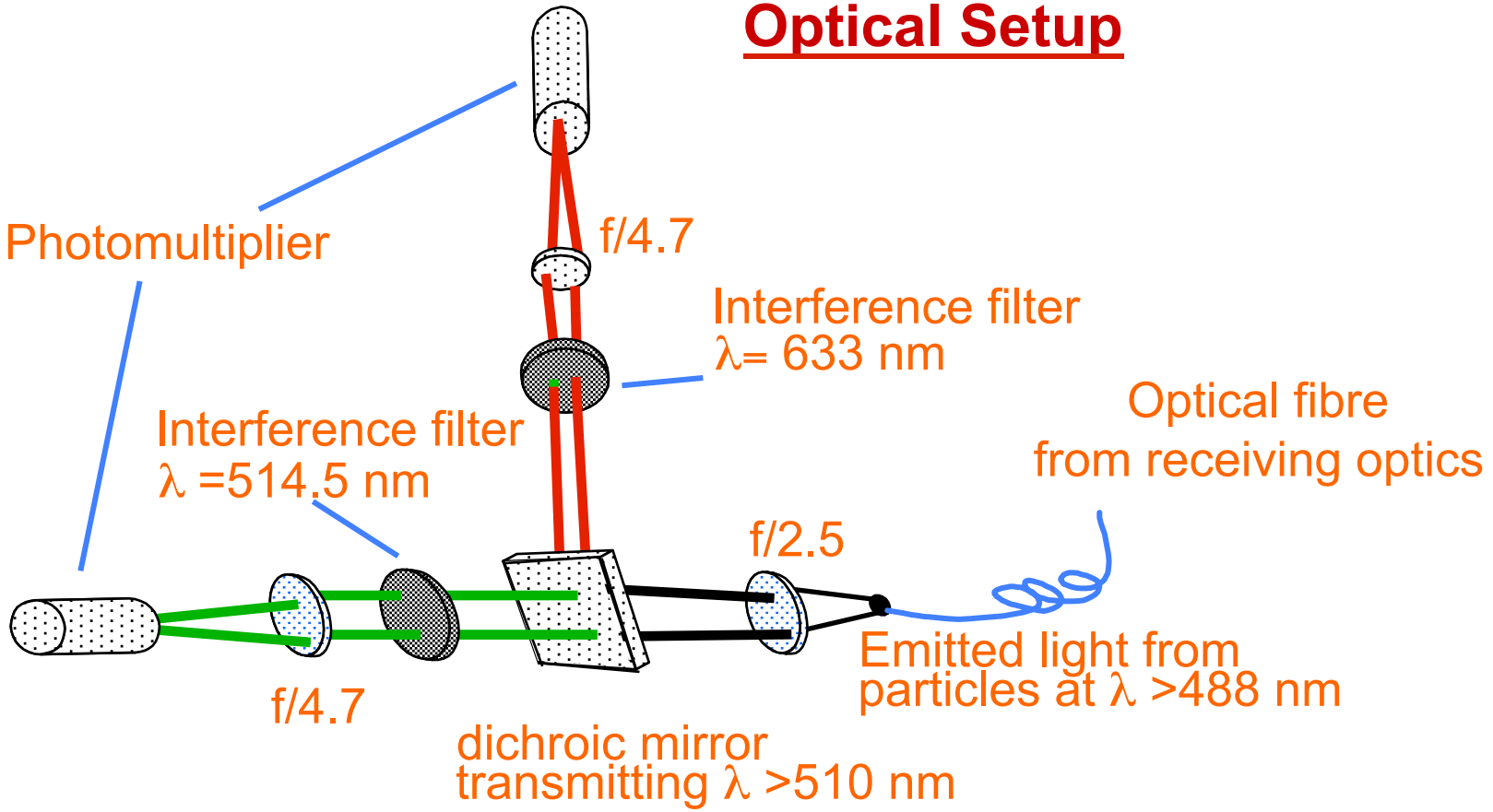
Particle Temperature Measurement with spatially resolved two-colour pyrometry

Optical Setup



OPERATION IN THE VISIBLE SPECTRUM ALLOWS USE OF STANDARD GLASS OPTICS AND PHOTODETECTORS

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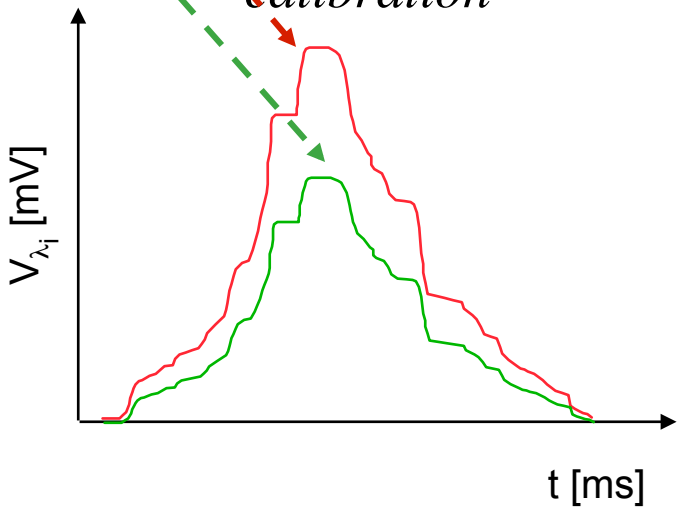
Particle Temperature Measurement

$$T_p = \underbrace{\left(C_{\lambda_2} - C_{\lambda_1}\right)}_{\text{from calibration}} \left\{ \underbrace{\ln\left(\frac{V^p_{\lambda_1}}{V^p_{\lambda 2}}\right)}_{\text{From measurement}} - \underbrace{\ln\left(\frac{X_{\lambda_1}}{X_{\lambda 2}}\right)}_{\text{from calibration}} - \ln\left(\frac{\varepsilon^p_{\lambda_1}}{\varepsilon^p_{\lambda 2}}\right) \right\}^{-1}$$

$\to 0$

using grey-body assumption for char particles



PARTICLE TEMPERATURE IS DETERMINED FROM THE RATIO OF THE MEASURED AMPLITUDE OF THE EMITTED INTENSITY SIGNALS AT THE TWO WAVELENGTHS

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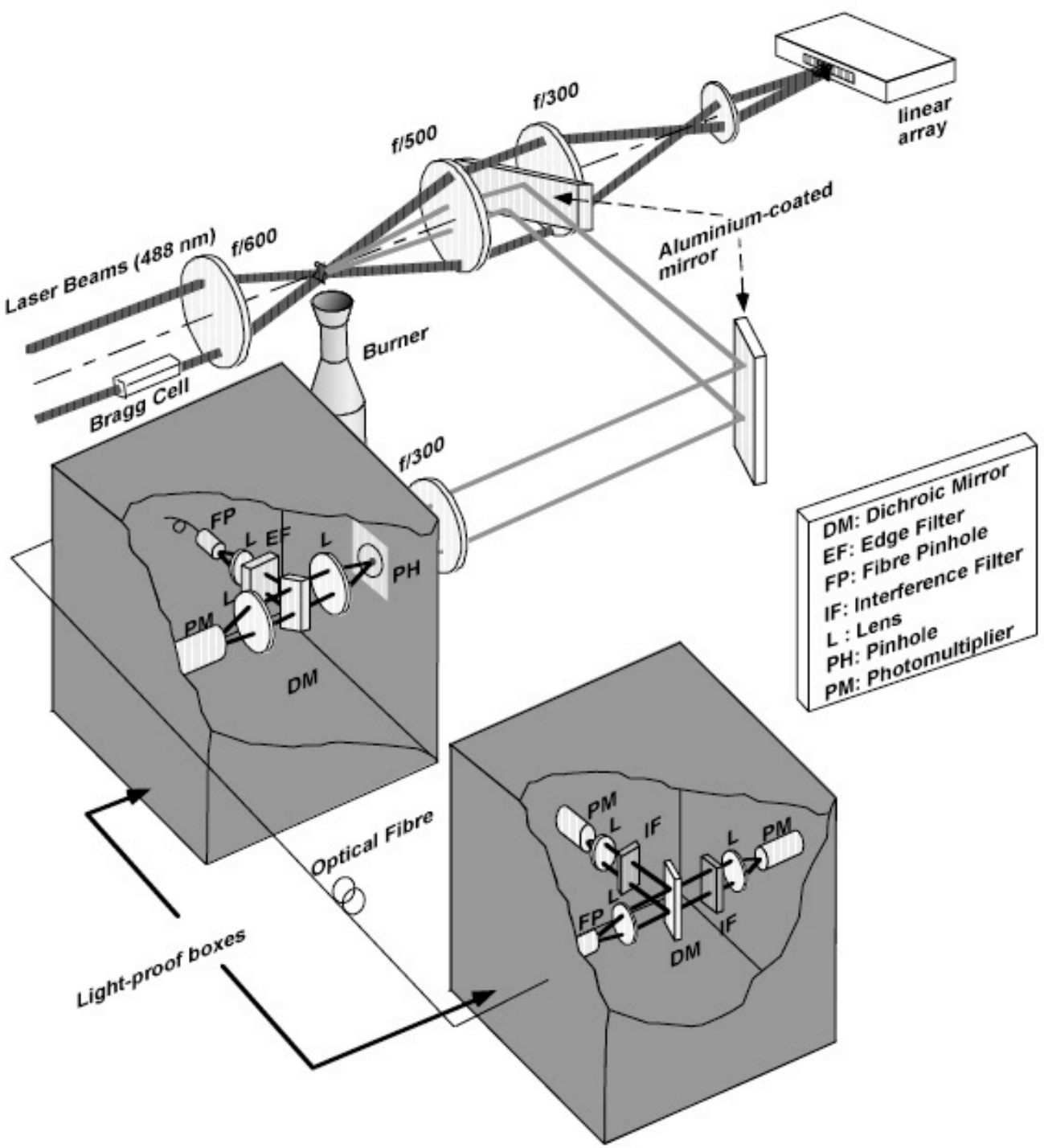
Combined Measurement of Velocity, Size & Temperature of Coal Particles



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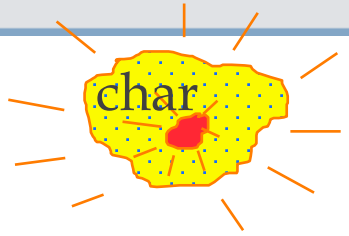
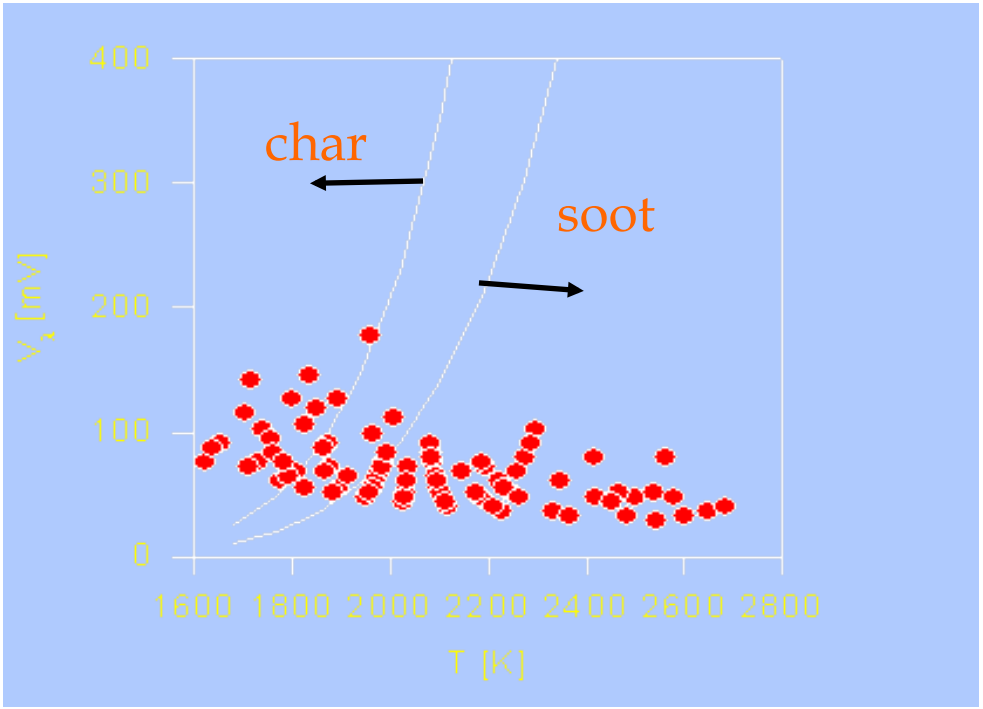
Was it char particles or soot?



Volatile flame surrounding char



Discrimination Criterion

$$V_{\lambda,\min} = \underbrace{X_\lambda}_{\substack{from \\ calibration}} \underbrace{d_{ph}^2}_{\substack{optics \\ pinhole}} e^{-\left(C_\lambda / \overset{measured}{\overbrace{T}}\right)}$$

$$V^s_{\lambda,\max} = \underbrace{X_\lambda}_{\substack{from \\ calibration}} \underbrace{d_{ph}^2}_{\substack{optics \\ pinhole}} \varepsilon^s_{\lambda\max} e^{-(C_\lambda / T_s)}$$

DISCRIMINATION BETWEEN CHAR AND VOLATILE FLAME IS POSSIBLE

A MORE RELIABLE TECHNIQUE IS REQUIRED!

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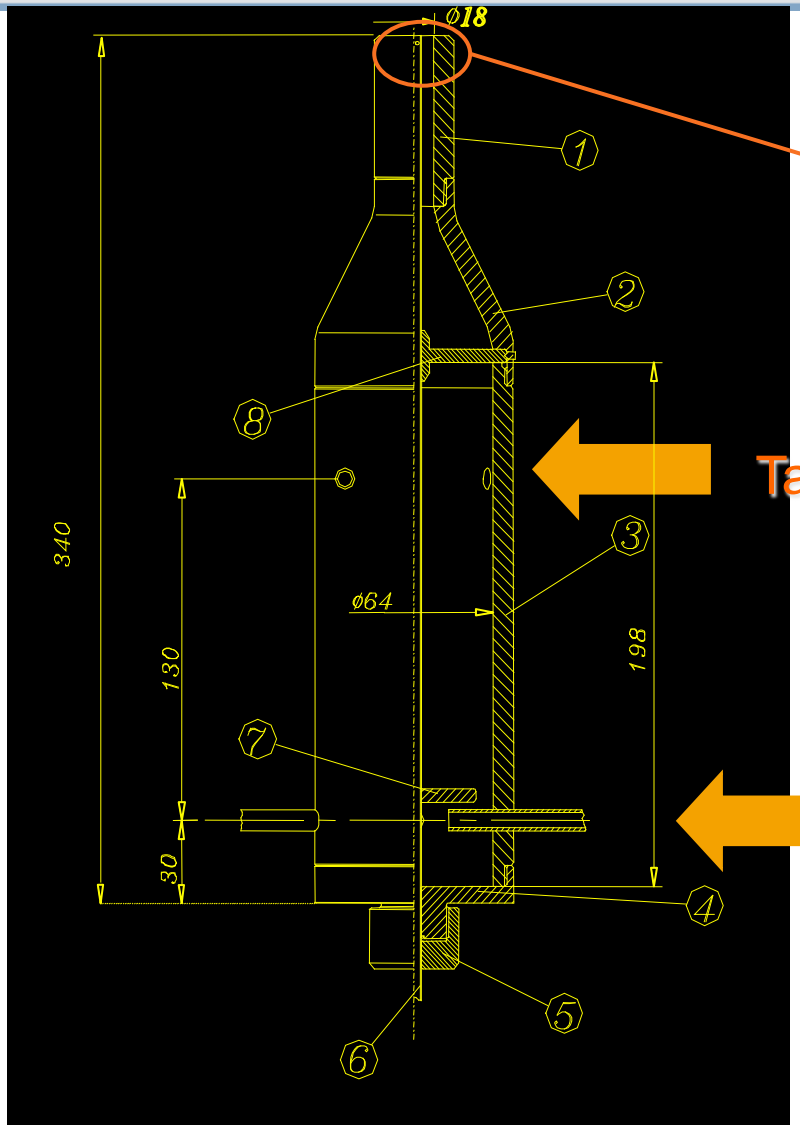
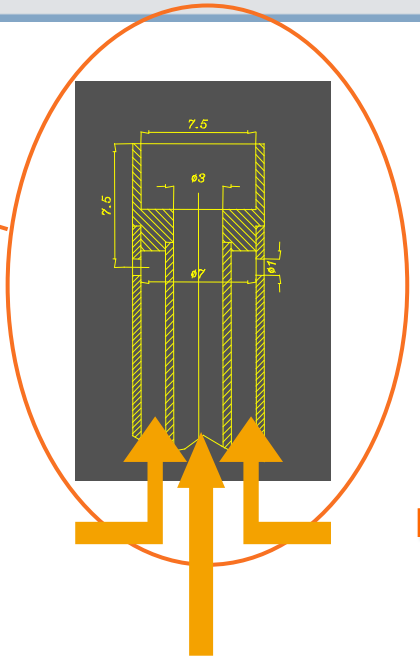
Swirl Stabilised Coal Burner Geometry



Tangential



Natural Gas

Pulverised Coal

Axial

Momentum Flux Ratio of Coal fuel to air streams

$$MR = \frac{(\dot{m}_{air,p} + \dot{m}_{coal})U_{0,p}}{\dot{m}_{air,s}U_0}$$

Variable Swirl was Generated by Combination of *Axial* and *Tangential* Entry of Air

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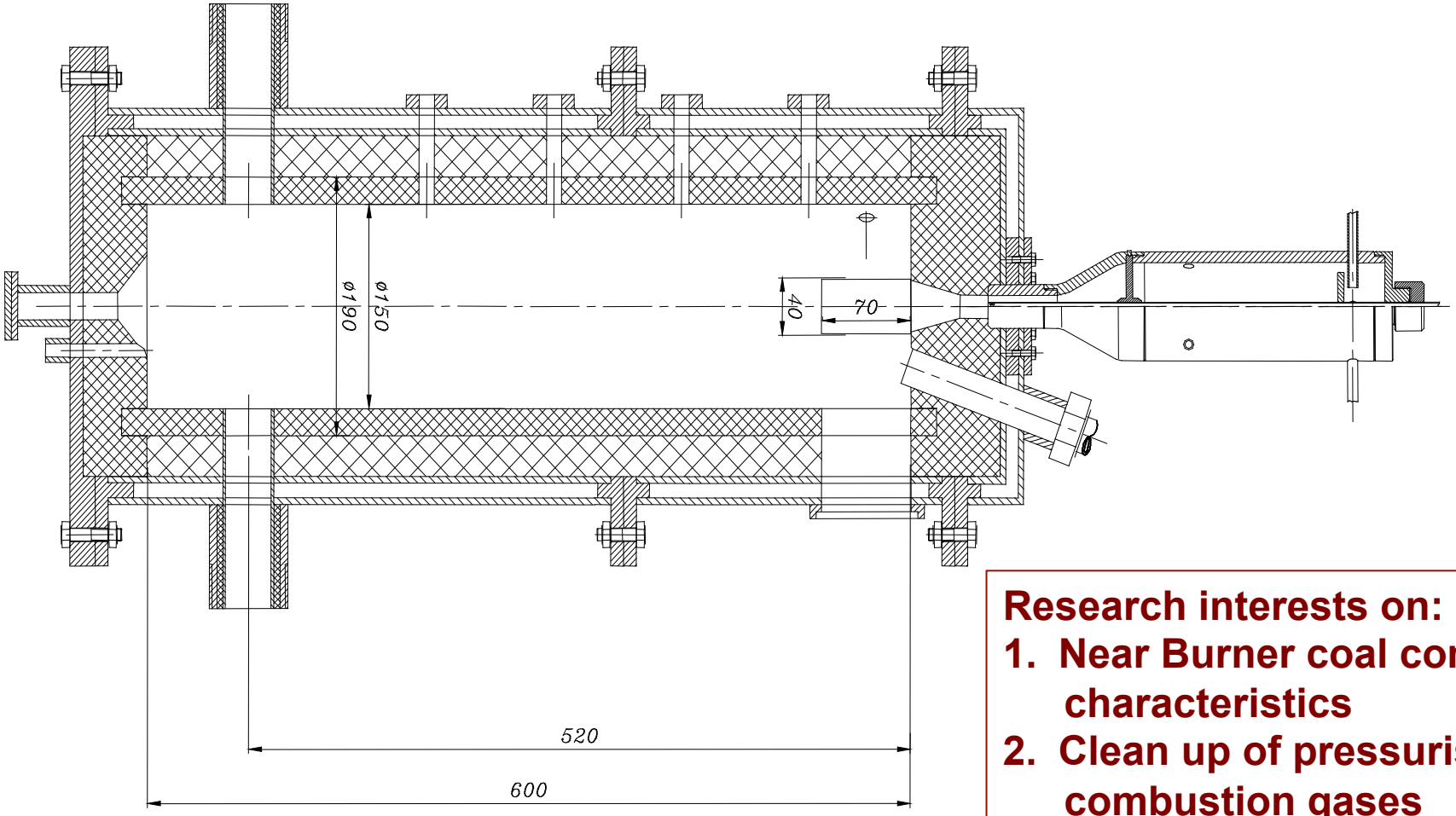
Furnace Design for pressurised coal combustion



Research interests on:

1. **Near Burner coal combustion characteristics**
2. **Clean up of pressurised combustion gases**

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Coal Particle Size and Velocity in Swirl stabilised Flames: Does Particle Size matter?

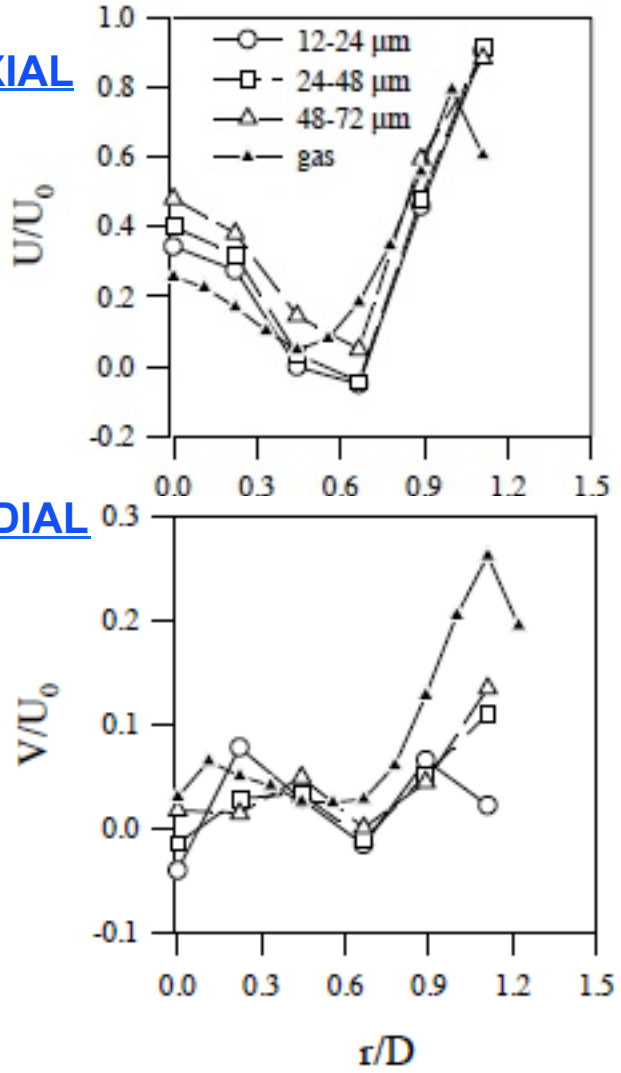
Coal fired flame with gaseous fuel support
Swirl number: 0.57
Gas Equivalence Ratio: 0.69

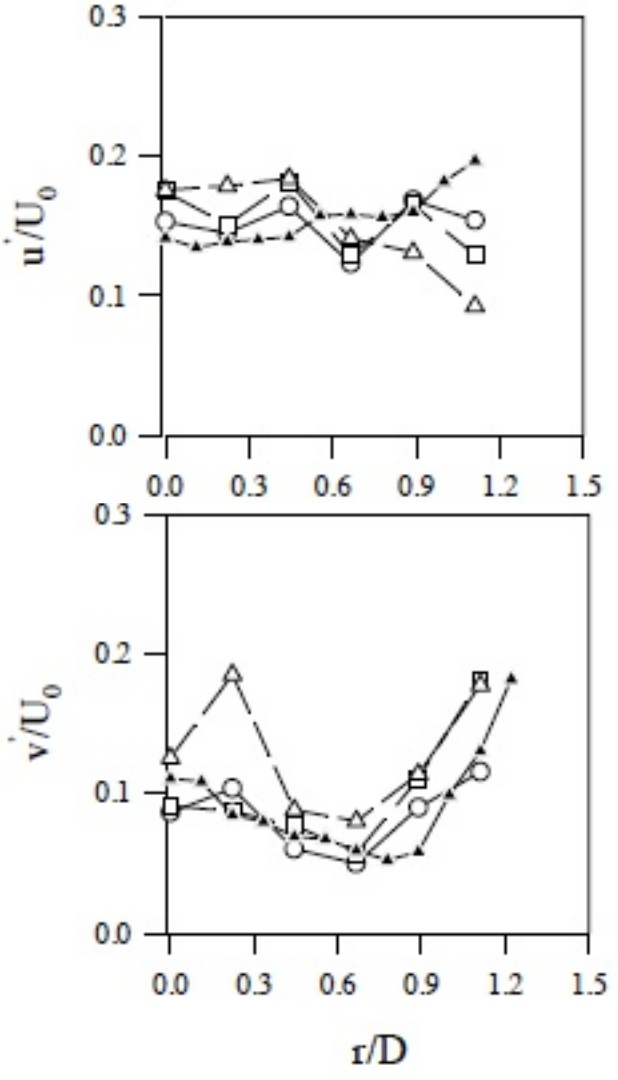
MEAN VELOCITY

RMS OF VELOCITY FLUCTUATIONS

AXIAL

RADIAL





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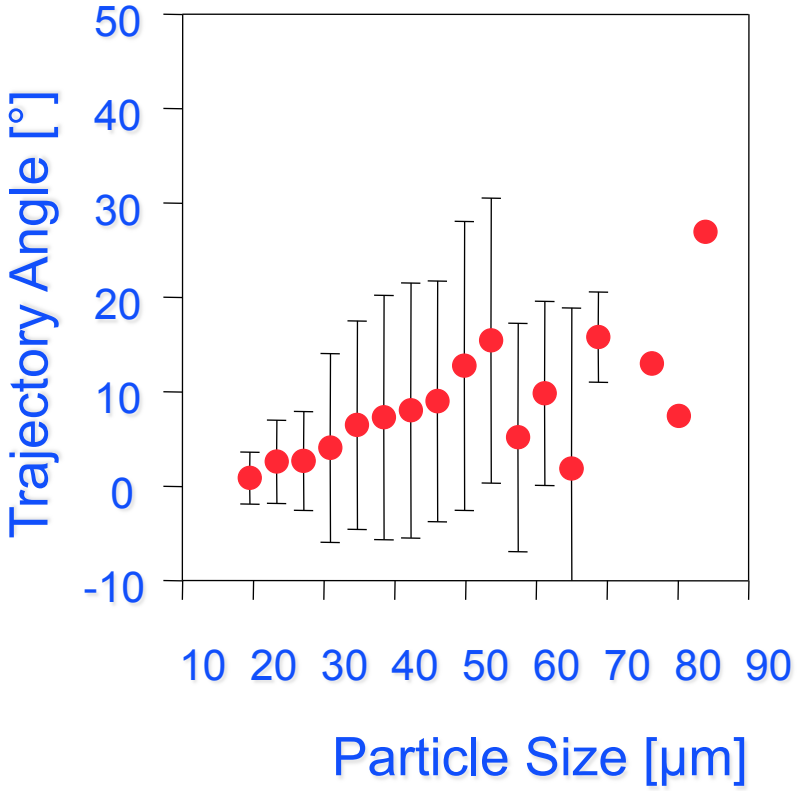
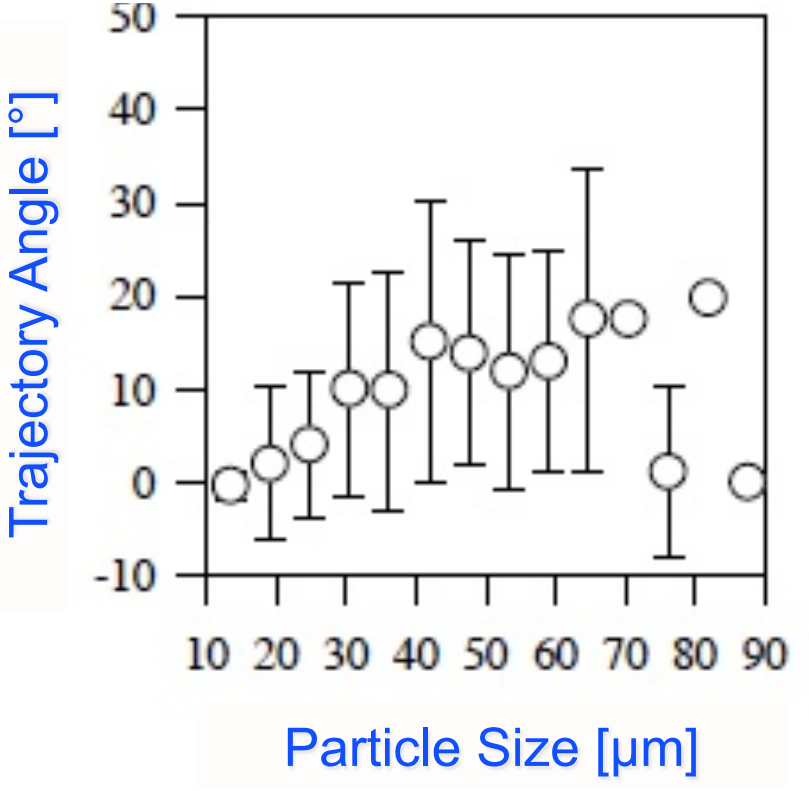
Coal particle Trajectory angle and its fluctuations as a function of particle size

The trajectory angle indicates deviation from burner centreline:

Larger Angle ➡ Larger Deviation



Swirl number 0.41 at r/D=0.9



Swirl number 0.57 at r/D=1.2

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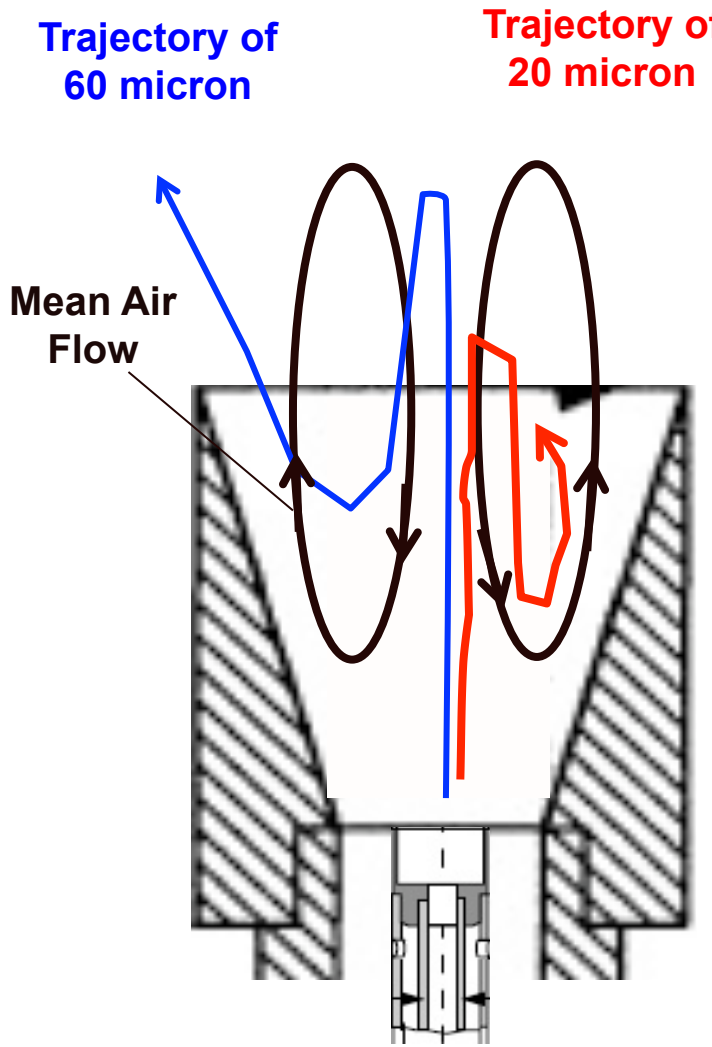
Coal Particle dispersion in Swirl stabilised Flames: Does Particle Size matter? – "Fountain Effect"



Different particle sizes reverse their motion at different distances from the burner exit, leading to different residence times in the recirculation zone.

Therefore, different sizes contribute differently to NOx emissions.

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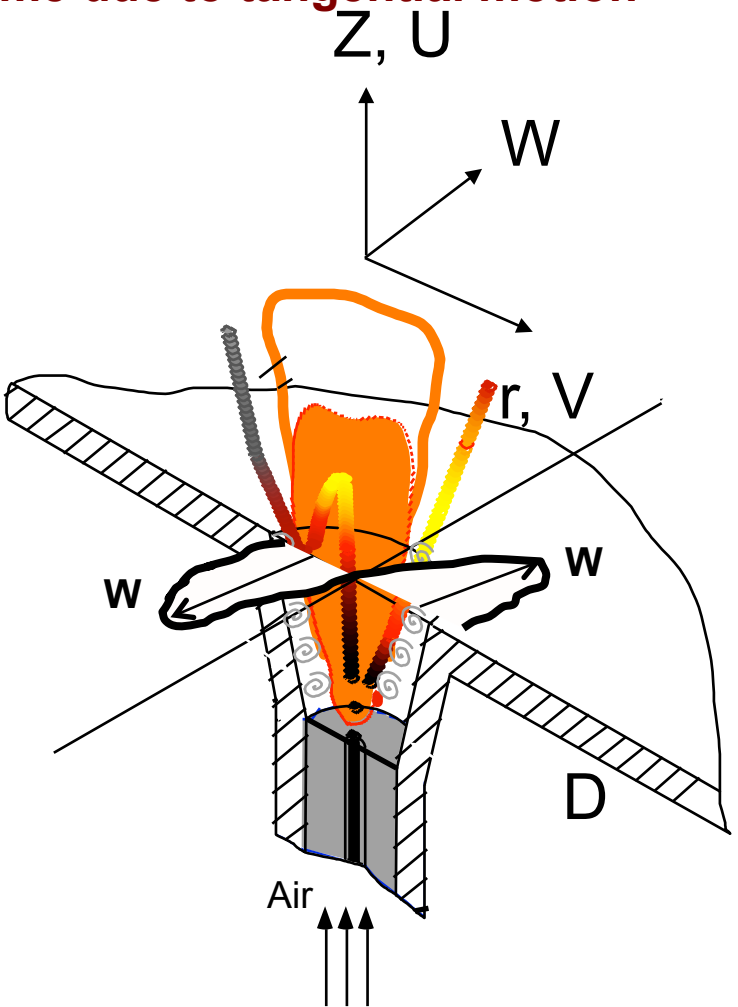
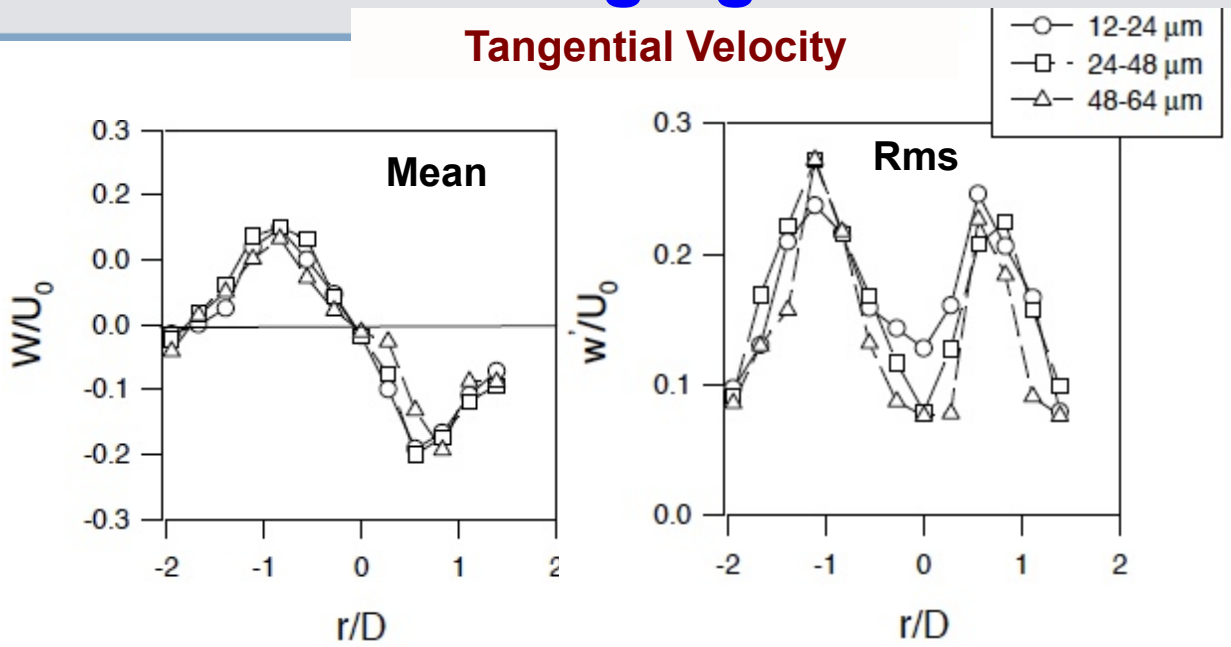
Coal Particle dispersion in Swirl stabilised Flames: Does Particle Size matter? – "Centrifuging Effect"

Particles Centrifuge away from the flame due to tangential motion



Tangential Velocity



Centrifuging Stokes Number

$$St_\omega = \frac{T_f}{\tau_p} = \frac{1/\omega}{\rho_p d_p^2 / 18\mu_g} \qquad St_\omega = \frac{18\mu_g}{\rho_p \omega d_p^2}$$

where $\omega = \frac{W}{r}$

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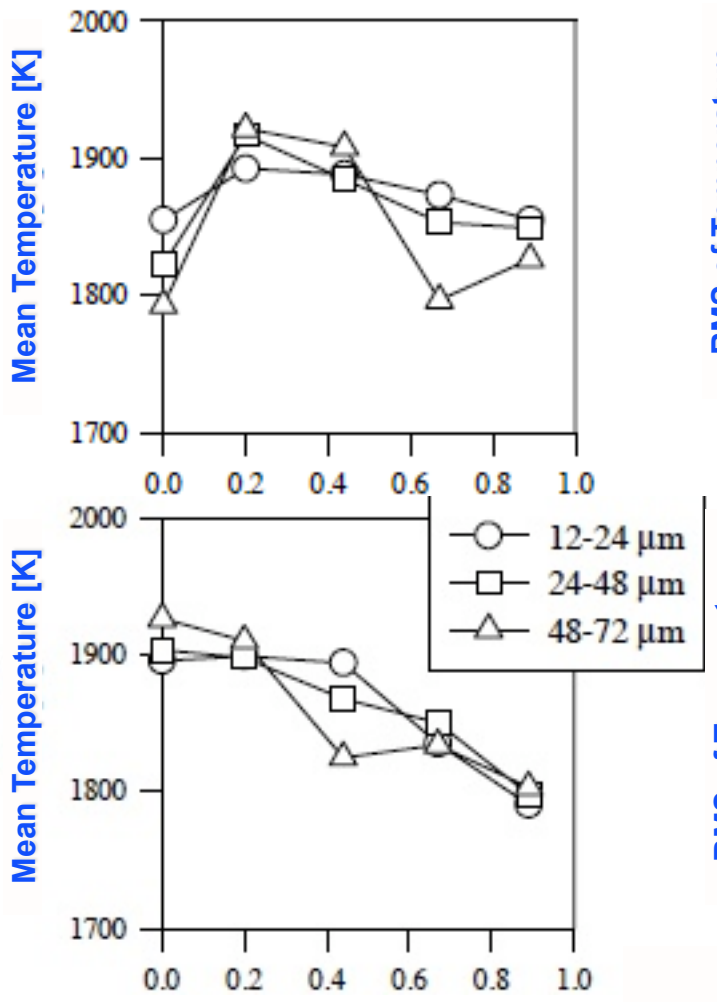
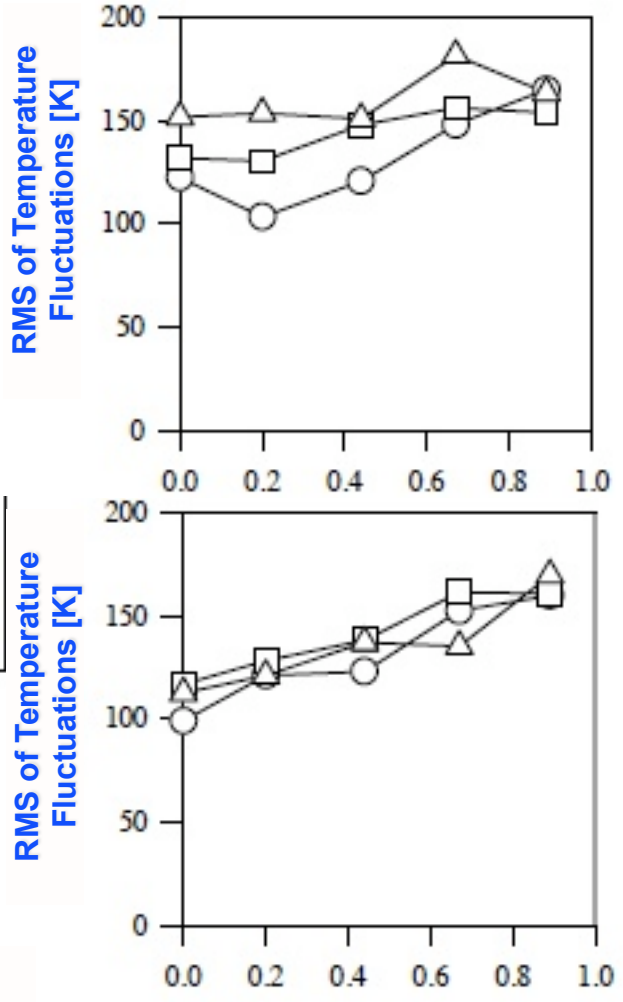
Radial Profiles of Mean and RMS of fluctuations of (Char) Particle Temperatures

- Mean Temperature was Size-Independent and Varied by about 100 K across Radial Profile
- Rms of Temperature fluctuations increased with Increasing Radial Distance





z/D=2.7

ϕ=0.69
MR=1/30

z/D=3.1

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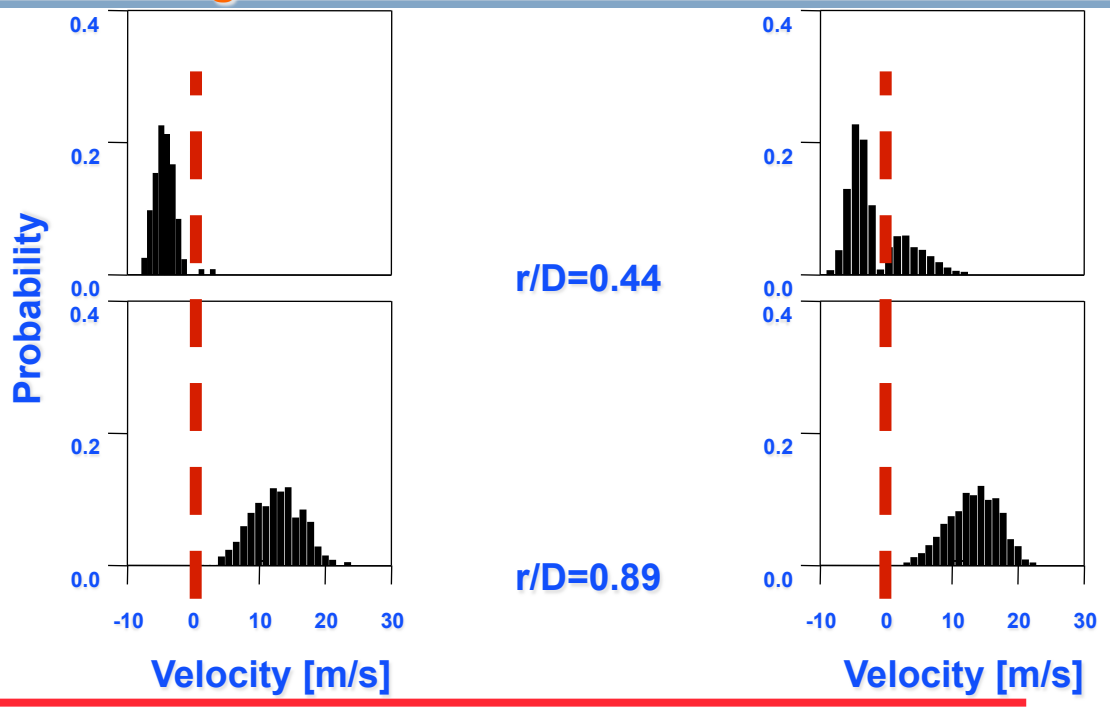
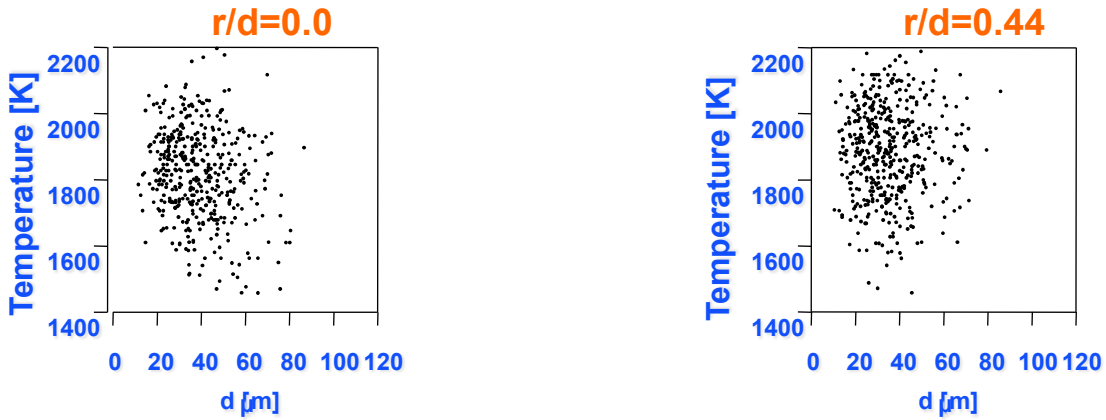
Comparison of behaviour of burning and non-burning Coal Particles

Size distributions of coal particles in a gas-piloted swirl-stabilised flame

(Swirl number=0.57; Φ=0.69)



Scatter plots of CHAR temperature as a function of coal-particle size at two radial locations



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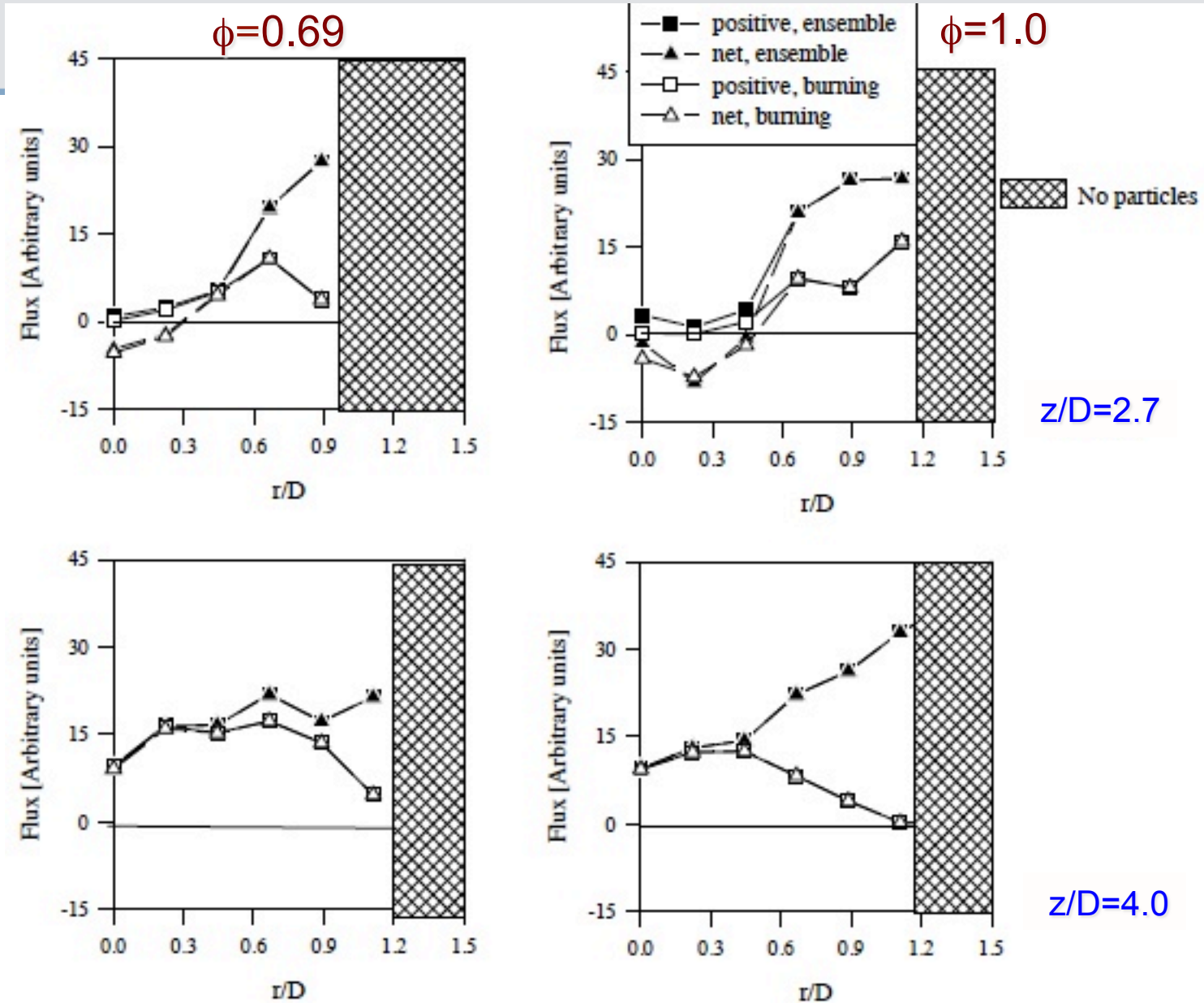
Radial Distribution of Particle Volume Flux

For r/D>0.6
an increasing amount of particulate mass escapes without burning



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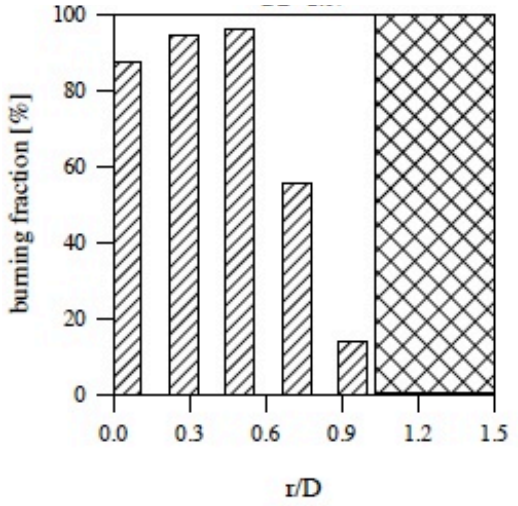
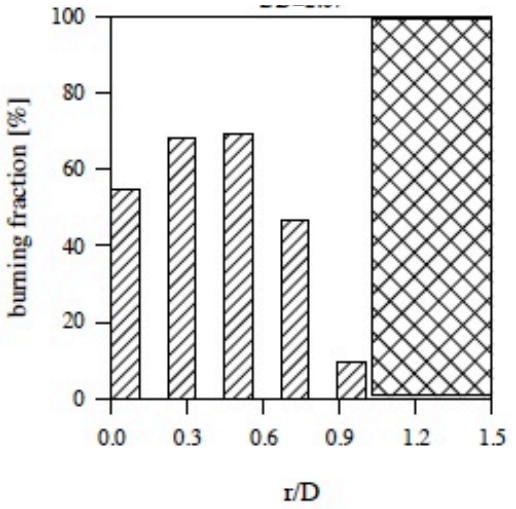
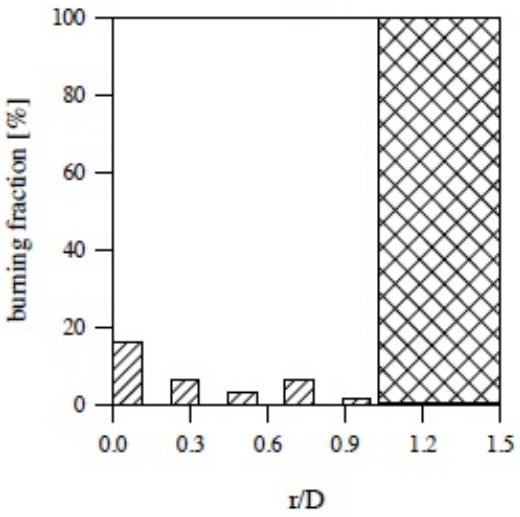
Radial Distribution of Burning Particle Fraction

BURNING FRACTION=NO OF BURNING PARTICLES/TOTAL COUNTS

z/D=2.7

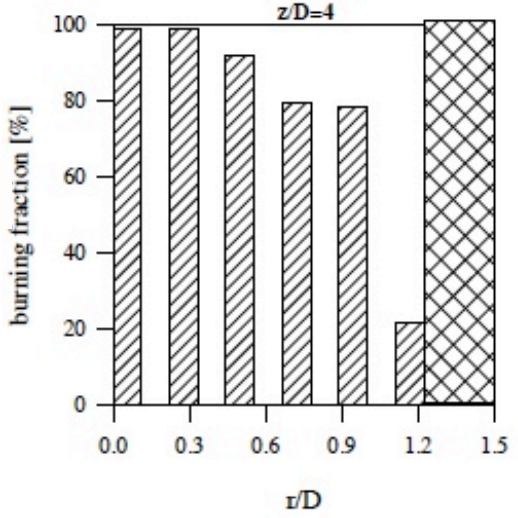


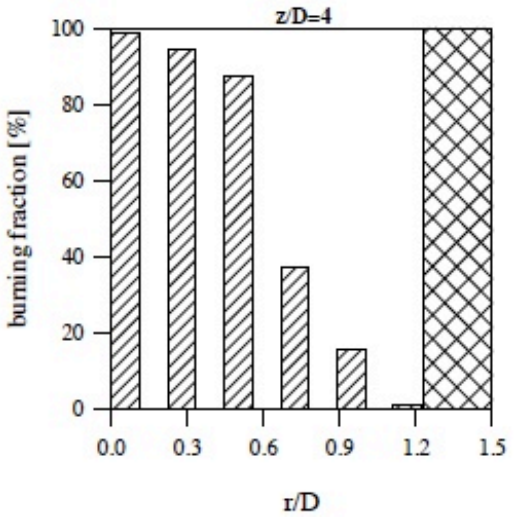




ϕ=0.69, MR=1/40

z/D=4.0





ϕ=0.69, MR=1/30

Φ=1.0, MR=1/30

Increase of the Gas Equivalence Ratio by 45% or Reduction of the Momentum Ratio (MR) by 25% result in reduction of the burning fraction

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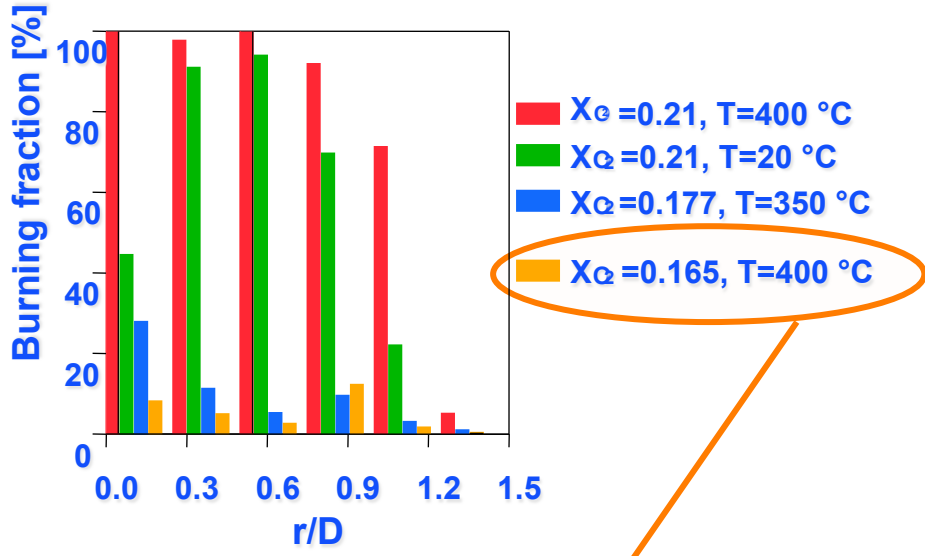
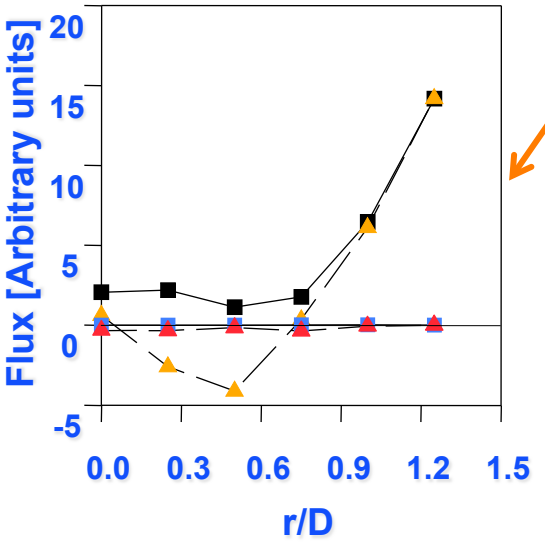
Coal Particles in swirl stabilised burner with Vitiated Air

Measurement of coal particles in swirl stabilised gas-piloted VITIATED-AIR flames

Distribution of Burning fraction of coal particles as a function of oxygen concentration / temperature of oxidant ...



… and the associated particle flux distribution for one of the cases.



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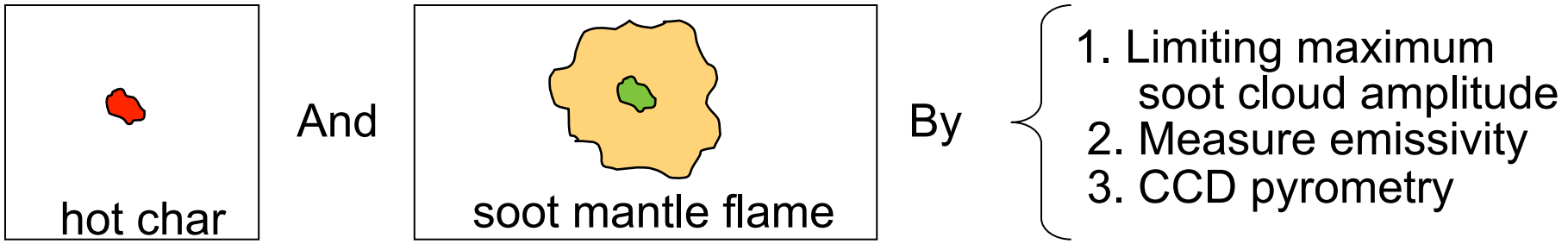
Evaluation of reactivity of coal particles

- **It is important to evaluate the reactivity of Individual Combusting Coal Particles, especially those of low rank coals, which are generally wet and need drying**
- **Difficulty:**
  - **Need to assess heterogeneous and homogeneous combustion phases in a controlled environment**
- **Objective: need to assess optical discrimination between**



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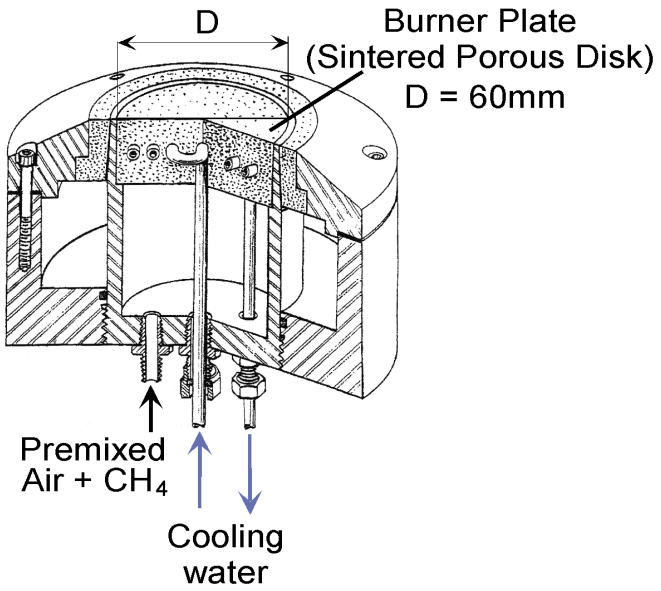
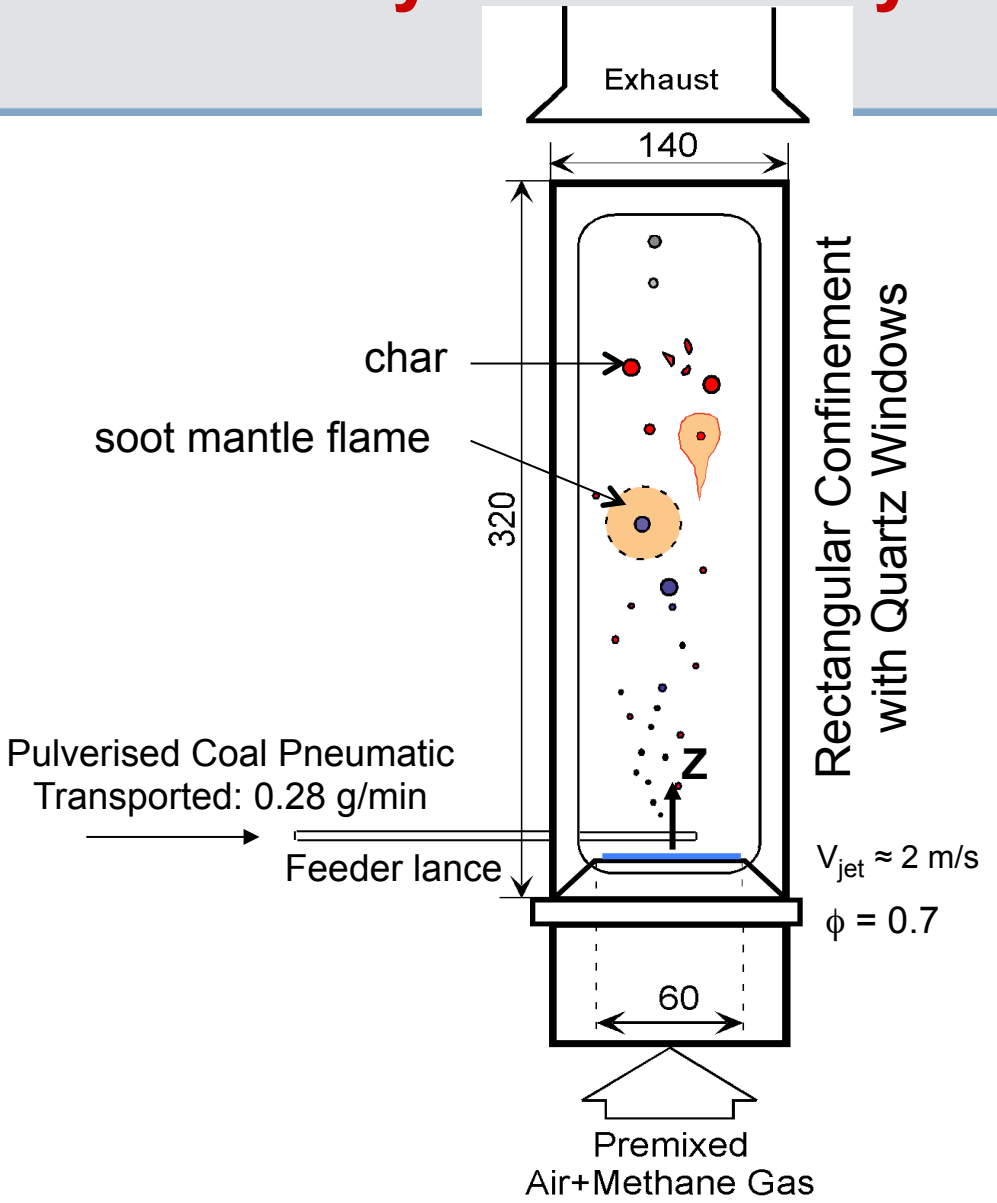
Transparent Wall Reactor for study of reactivity of coal particles

Measuring Region
Z=20-80 mm (t=15–30ms)
Temperature: 1700-1800K
O2: 6-8mol %

McKenna flat flame burner





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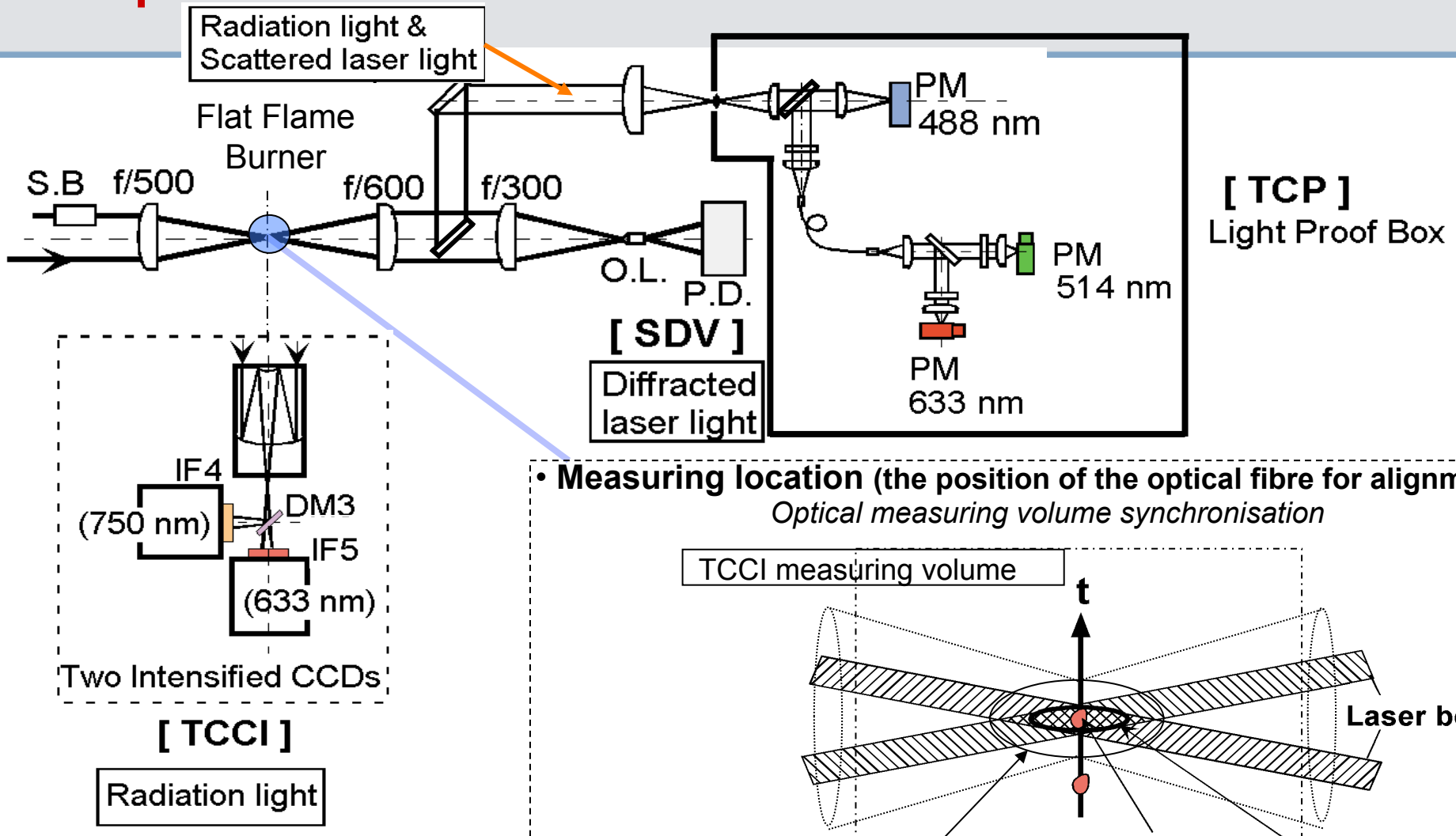
Combined measurement of particle size/shape, velocity and temperature and discrimination between 'char' and 'soot'



- **Measuring location** (the position of the optical fibre for alignment)

Optical measuring volume synchronisation

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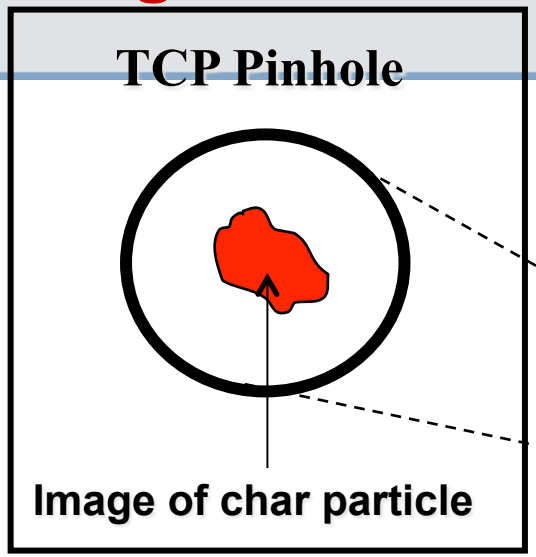
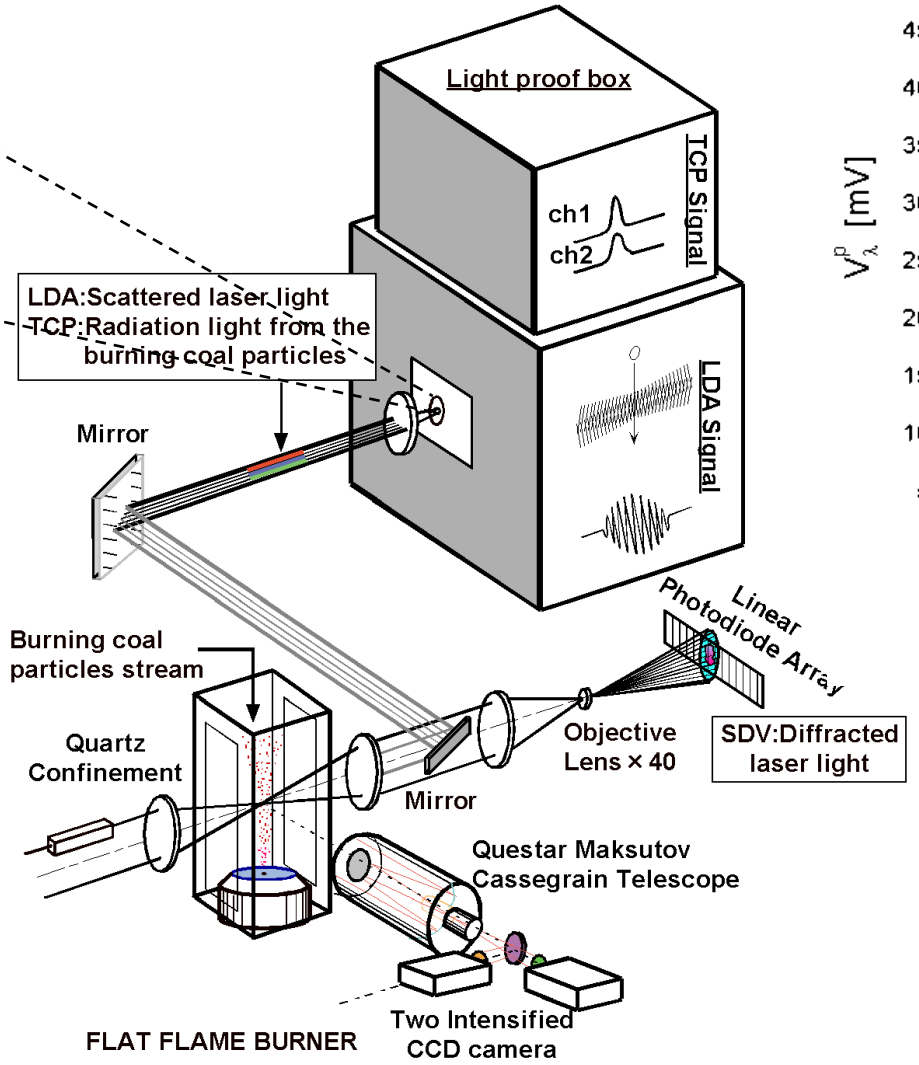
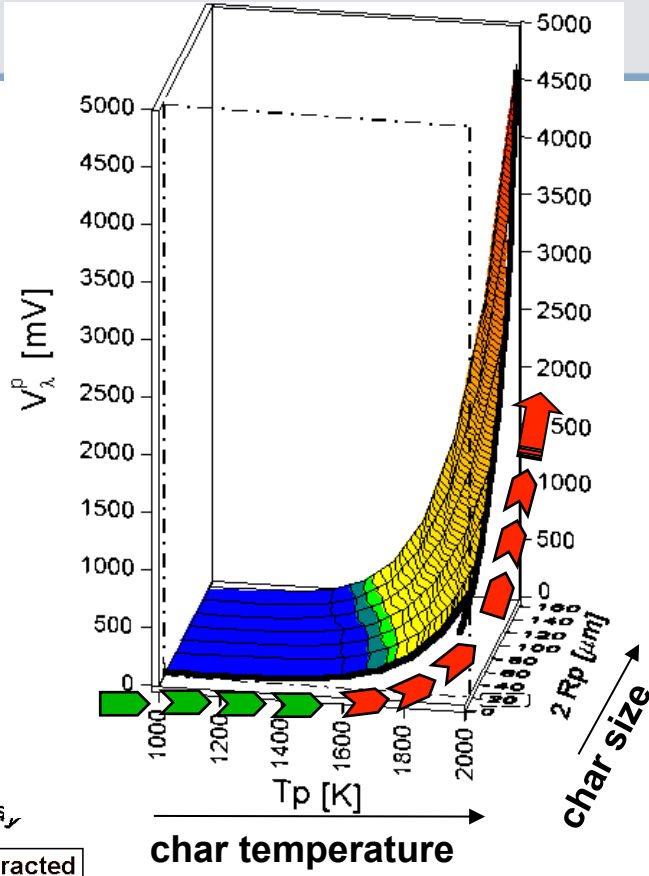
Vignette Criterion to identify 'char'







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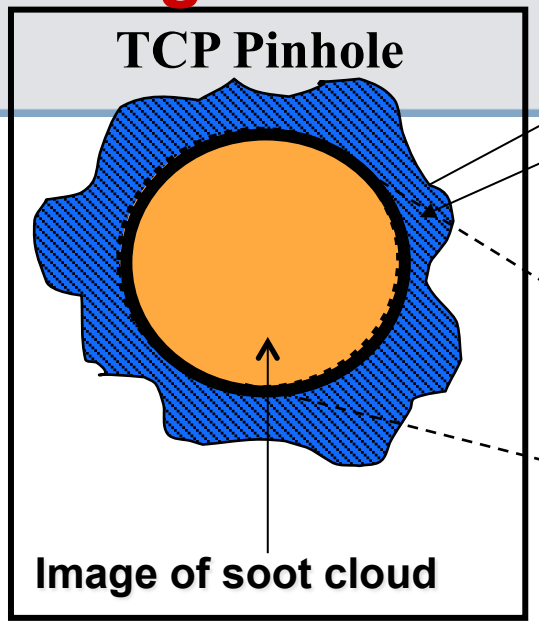
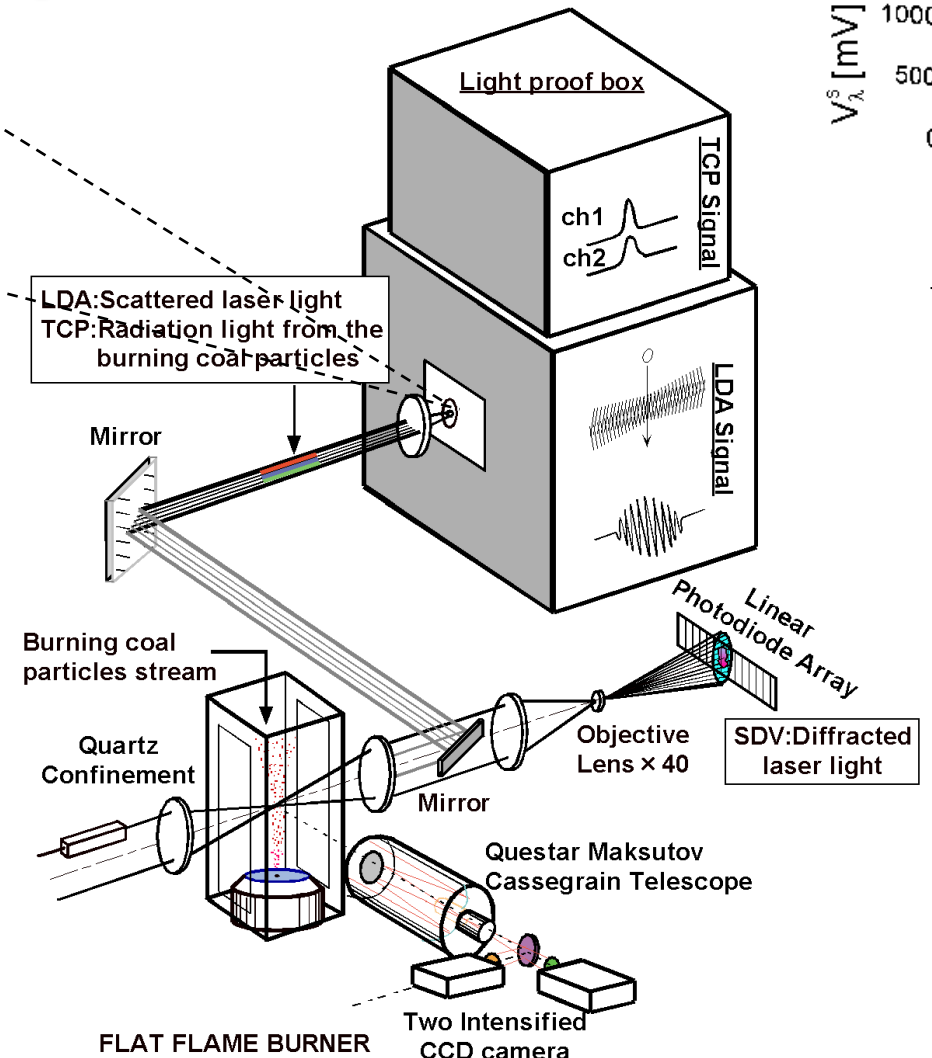
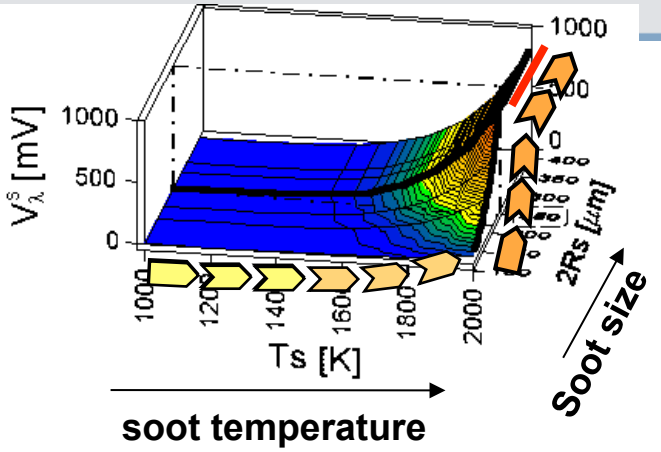
Vignette Criterion to identify 'soot'







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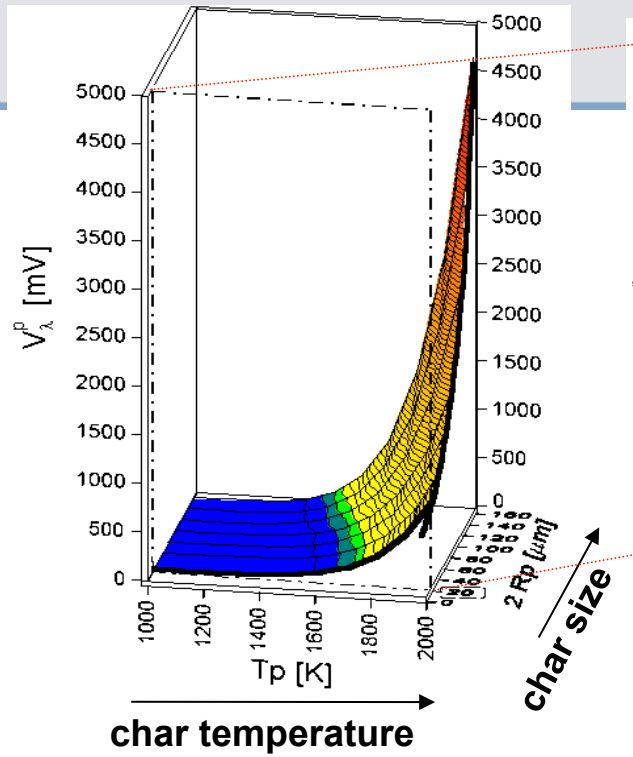
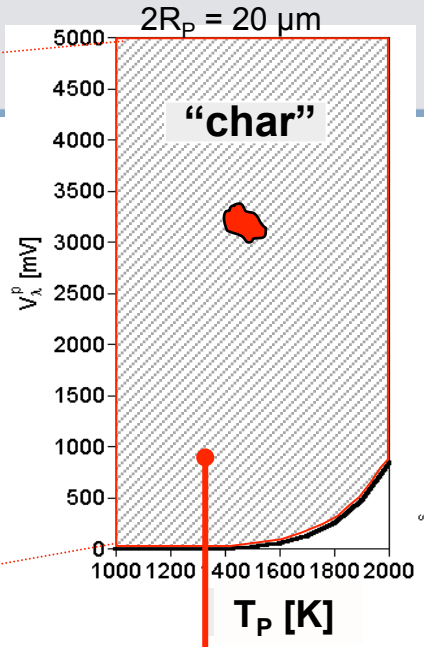
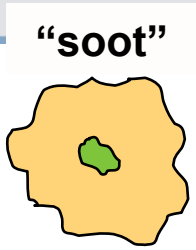
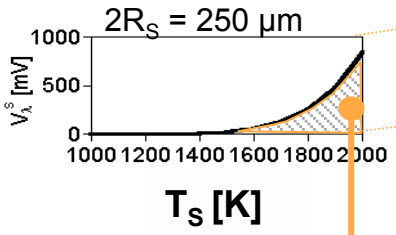
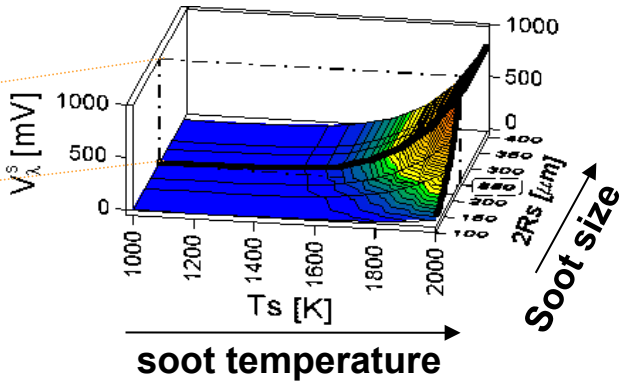
Discrimination between ‘soot’ & ‘char’

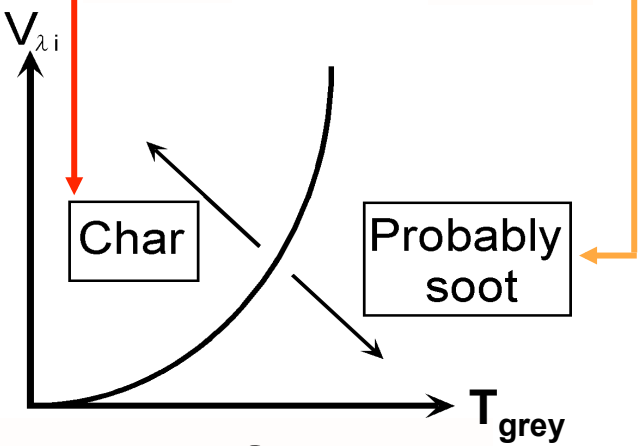












- $T_p \Leftrightarrow T_{grey}$

Grey Body Assumption

$$T_p = T_{grey}$$

$$\because a_{e1}/a_{e2} = 1$$

- $T_s \Leftrightarrow T_{grey}$

Optically thin flame assumption

$$T_S = \frac{C_2 T_{grey}\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right)}{C_2\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right) - T_{grey}\ln\left(\frac{\lambda_2}{\lambda_1}\right)}$$

$$\because a_{e1}/a_{e2} = \lambda_1/\lambda_2$$

Vignette Criterion

$$V_{\lambda i}\left(T_{grey}\right) = X_{\lambda i} d_{ph}^{'\,2} \varepsilon_{\lambda i}^{s}\Big|_{\max} \exp[-C_2/\lambda_i T_{grey}]$$

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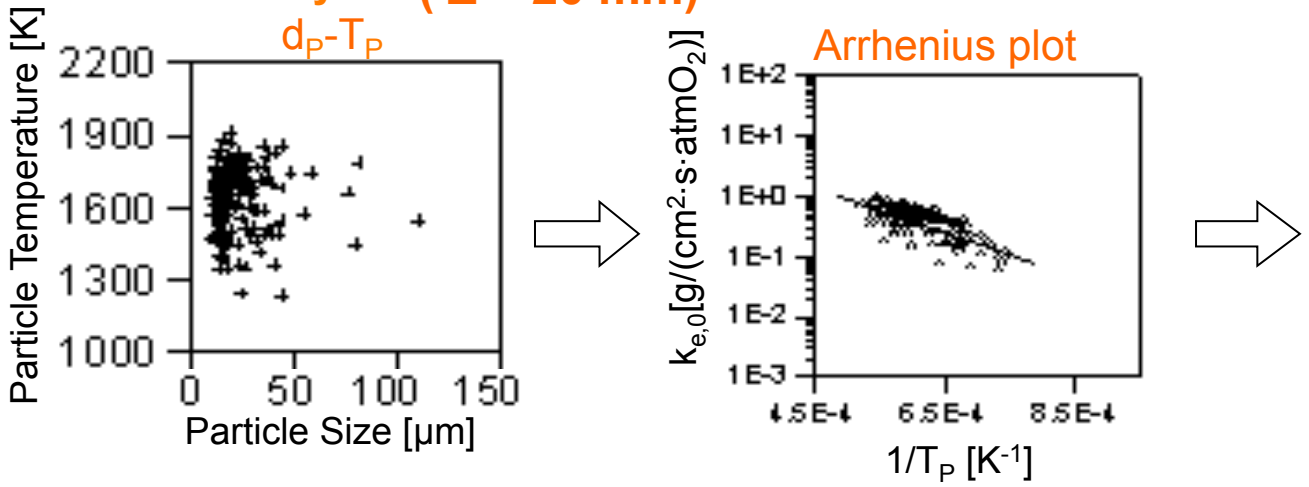
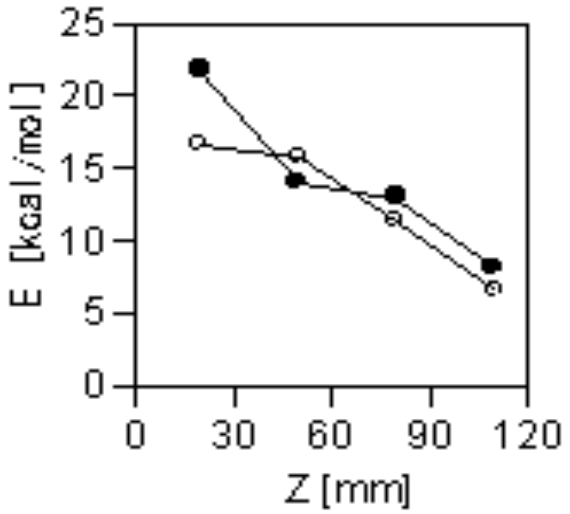
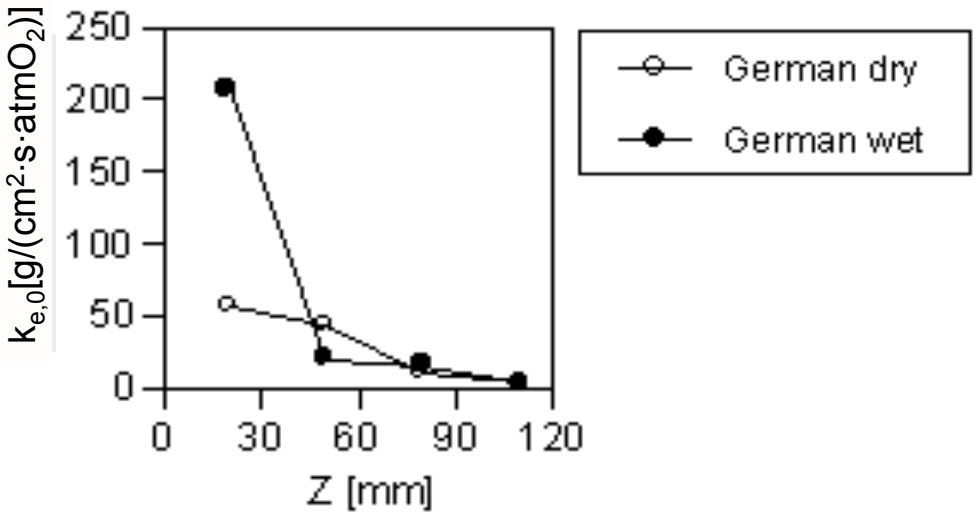
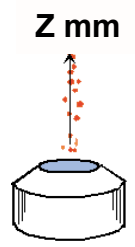
Reactivity plots

German Rhenish Dry (Z = 20 mm)









Φ = 0.9

Concluding Remarks [1]

Shadow Doppler Velocimetry

Novel Imaging technique for sizing non-spherical rough particles

Advantages

- High spatial accuracy
- Particle shape resolved *(although currently 2-D)*
- Minimal Calibration
- Robust Technique: Can be Applied to Confined Environments
- Can be Extended to Obtain More Particle Info

Disadvantage

- Maximum Particle Density is Limited due to Forward Scattering

Concluding Remarks [2]

INSTRUMENTATION for combined coal particle size/shape, temperature and velocity

- Combined Shadow Doppler Velocimetry (SDV) - Two Colour Pyrometry (TCP) can provide …
  - ✓ size/velocity/temperature correlations in coal burners
  - Amplitude-based criterion for TCP improves accuracy of measurement dramatically but…
    - ✓ is based on empirical observations not deterministically identifiable during experiments
  - CCD-based TCP can help resolve type of flame when used with SDV but...
    - ✓ suffers from lower sensitivity

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Concluding Remarks [3]

RESULTS FROM SWIRL STABILISED BURNER

Measurements in the Near-burner Region of Swirl Stabilised Gas Supported coal particle Flames With Equivalence Ratios ϕ=0.69 & 1.0 and Momentum Ratios of 1/30 and 1/40 showed that:

- 45% Increase of the Gas Equivalence- and 25% Decrease of the Momentum Ratio Resulted in Reductions of the Burning Fraction by 25% and 80% Respectively.
- Most Particle Volume Flux Escaped From the Region r/D>0.6 where a Large Fraction did not Burn.
- The Mean Char Temperature Decreased, on average, by about 100 K Across a Radial Profile and Showed no Size-dependence.
- The Previous Observation Was Confirmed by Scatter Plots of the (Char) Particle Size and its Instantaneous Temperature.
- Coal particle reactivity was quantified as a function of residence time