Combustion in Power Station Boilers – Advanced Monitoring Using Imaging

Report No.
COAL R264
DTI/Pub
URN 04/1797

November 2004

by

M.G. Abdul Rahman, J.R. Gibbins, A.K. Forrest

Imperial College of Science, Technology and Medicine
Mechanical Engineering Dept.
Exhibition Road, South Kensington,
London SW7 2BX

Tel: 0207 594 7036
Email: j.gibbins@imperial.ac.uk

The work described in this report was carried out under contract as part of the DTI Cleaner Coal Research and Development Programme. The programme is managed by Mott MacDonald Ltd. The views and judgements expressed in this report are those of the contractor and do not necessarily reflect those of the DTI or Mott MacDonald Ltd

First published 2004

REVISED SUMMARY – Project 121

Project title: Advanced Monitoring Using Imaging for Combustion in Power Station Boilers

Proposer: Imperial College of Science, Technology and Medicine

Address of registered office: Exhibition Road, South Kensington, London SW7 2AZ

Name of contact: Dr J Gibbins, Senior Lecturer

Address: Mechanical Engineering Dept.
Imperial College
Exhibition Road, South Kensington,
London SW7 2BX

Telephone: 0207 594 7036: **Fax**: 0207 823 8845

Other organisations formally involved in the project:

National Power (later Innogy)
TXU Europe (later Rugeley Power / International Power)
British Energy
Imaging & Sensing Technology (formerly IST-Rees)

Objectives of project

- To develop self-illuminated video (SIV) and image analysis techniques to identify adverse combustion conditions in utility PF boilers.
- To provide a number of quantifiable parameters from video images which can be used to evaluate flame stability and combustion.
- To develop PC software to transfer key parameters to existing data logging systems in real-time.
- To develop systems to transmit and integrate video data from a number of cameras, under actual boiler plant conditions.
- To determine optimum video probe designs and locations for quantitative SIV on utility boilers.

CONTENTS

1. TECHNICAL BACKGROUND	**4**
2. PROJECT OBJECTIVES AND ACHIEVEMENTS	**6**
3. TECHNIQUES AND RESULTS	**12**
4. CONCLUSIONS AND FUTURE WORK	**29**

1. TECHNICAL BACKGROUND

Video camera probes are widely used on UK boilers, mounted on the rear wall to observe oil gun flames on the opposing front wall during start up, as a safety measure. Once the boiler is under load, the much larger coal flames from the burners extend close to the rear wall and there is a high dust loading because of the ash in the coal. As a result, no distinct flame images are visible (Figure 1.1) but differences in the colour and pulsing frequency of the general 'fireball' are visible, and are sometimes used by operators as a qualitative guide to combustion conditions.

Previous work at Imperial (*Gibbins, J.R., Zhang, J, Afzal, H., Riley and Beeley, T., "Assessment of flame stability in swirl-stabilised burners and relation to coal properties", Proc. 10th ICCS, Li, B.Q. and Liu, Z.Y. (ed), Shanxi Sci. & Tech. Press, China, 1999, 459-462.*) had shown that quantitative flame stability parameters could be derived from digital processing of series of flame video images from a pilot-scale 0.5 MW single burner combustion test facility. In this case the images were well-resolved images taken from the side of a flame (see Figure 1.2 below) but it was recognised that in principle, provided meaningful information was present in the rear wall video camera probe images, the great flexibility in choice of the processing algorithms available would allow it to be extracted.

The challenges for the project would to verify whether or not rear wall camera images did indeed contain useful information, and if so to develop hardware and software to process this data in real time under power plant conditions.

Figure 1.1 ~750MWth 'fireball' image from rear wall furnace camera

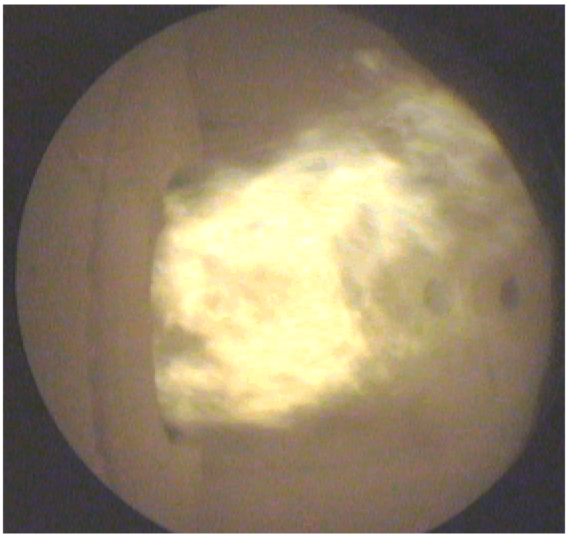


Figure 1.2 0.5MW test facility burner image *(from Gibbins et al above)*

The spatial and temporal fluctuations of full scale wall-fired burners had also been examined in detail using video methods (*Gibbins, J., Lin Y-M, Bowden, S. and Cameron, S., "Video observations of full-size pulverised coal flames", Comb. Sci. Tech. 162 (2001) 263-280.*) to process short term video observations in a 37 MWth single burner test facility. Well-resolved images of the burner flame could be obtained (see Figure 1.3) but conditions at full scale are obviously much more difficult than in a 0.5MW test rig. The radiant heat flux is a great deal higher so probe design is more challenging, particularly for extended operation. Furnace slagging is also like to be more of a problem. The optical paths are also much longer, by at least a factor of 10. The dust loading always present from ash in the coal therefore inevitably makes images at full scale much less clear; under some circumstances it might even be impossible to get satisfactory images due to dust obscuration on actual boiler plant.

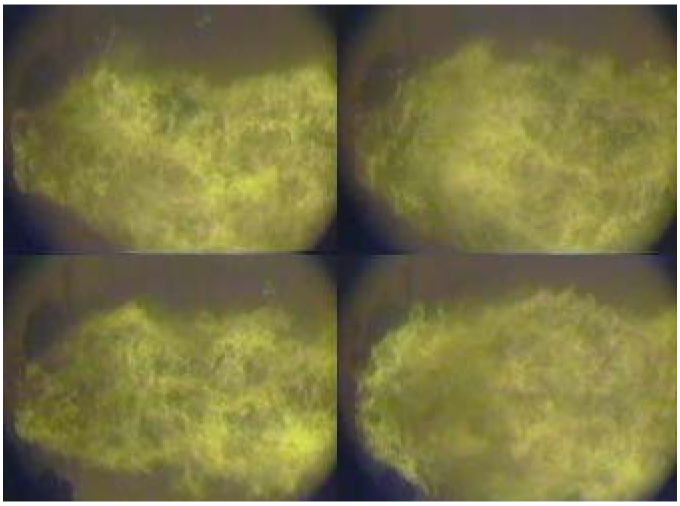


Figure 1.3 Wall fired burner flame images from 37 MWth burner test facility
(same burner under four different firing conditions)

While it was considered likely that useful data on the combustion performance of individual flames could be obtained from the sort of images shown in Figure 1.3, as well as requiring a suitable video processing computer platform for use on boiler plant, for this application new types of video probe would be required. For commercial viability, a compact probe would be required that could provide an appropriate field of view and good image quality, has high reliability, but yet is designed so that the costs associated with catastrophic air supply failure are not excessive. This last criterion is essential since, while plant air supplies will usually be reliable, large numbers of cameras would be affected by air supply failure if a significant number of burners were to be monitored. It was anticipated that wing burners could be observed through corner doors, although these would have to remain accessible for manual inspections. Other methods to view inner burners would also be desirable.

In summary, at the start of this project it was recognised that self illuminated video (SIV) techniques had considerable potential for routine monitoring of full scale power plants, but also that significant development work and experience would be required to provide the basis for utilising this potential in routinely-applied commercial systems. The key project objectives to provide this basis, and their fulfilment, are described in the next section.

2. PROJECT OBJECTIVES AND ACHIEVEMENTS

(original project objectives shown in italics)

All project objectives have been achieved. As planned, video capture and processing equipment was installed and tested on actual boiler plant early in the project and the results of practical experience used progressively to inform and refine developments.

This experience has confirmed the importance of proving techniques under actual PF combustion techniques. Work by Imperial on a number of other video projects involving observations in small-scale furnaces has shown that the technical challenges involved in acquiring satisfactory video data are much more severe in full scale plant. Different combustion-related phenomena are also encountered in practice.

Self-illuminated video (SIV) techniques and equipment will be developed and tested in real environments. The SIV techniques will be used to generate quantifiable performance parameters of utility boilers which can then be used for combustion improvement.

A key feature of this project is the early installation of video equipment and a prototype system to derive quantitative combustion performance information on a 500MW boiler. The need to implement an actual system and to address real plant problems from the outset will ensure close and meaningful collaboration between all partners and provide strong and realistic feedback for development activities. Development will proceed from this first prototype system with the following specific project objectives:

(a) Develop the SIV and image analysis techniques to identify adverse combustion conditions. Early detection of these, including during load changes, will help to avoid increase in carbon in ash and short term increase in dust emissions. There is the potential to pick up these events earlier than from existing instrumentation and this will aid operators.

An example of long-term combustion monitoring trends obtained using the prototype system is shown in Figure 2.1 below. The plant performance characteristics and combustion quality index (CQI) values for a utility power station are shown for three weeks of operation. The CQI values are shown only for periods of full load (>90%) and for the two most commonly-used mill patterns over this period. Changes in CQI during operating periods are evident, probably indicating that some aspects of combustion have still not completely stabilised over the relatively short periods at full load.

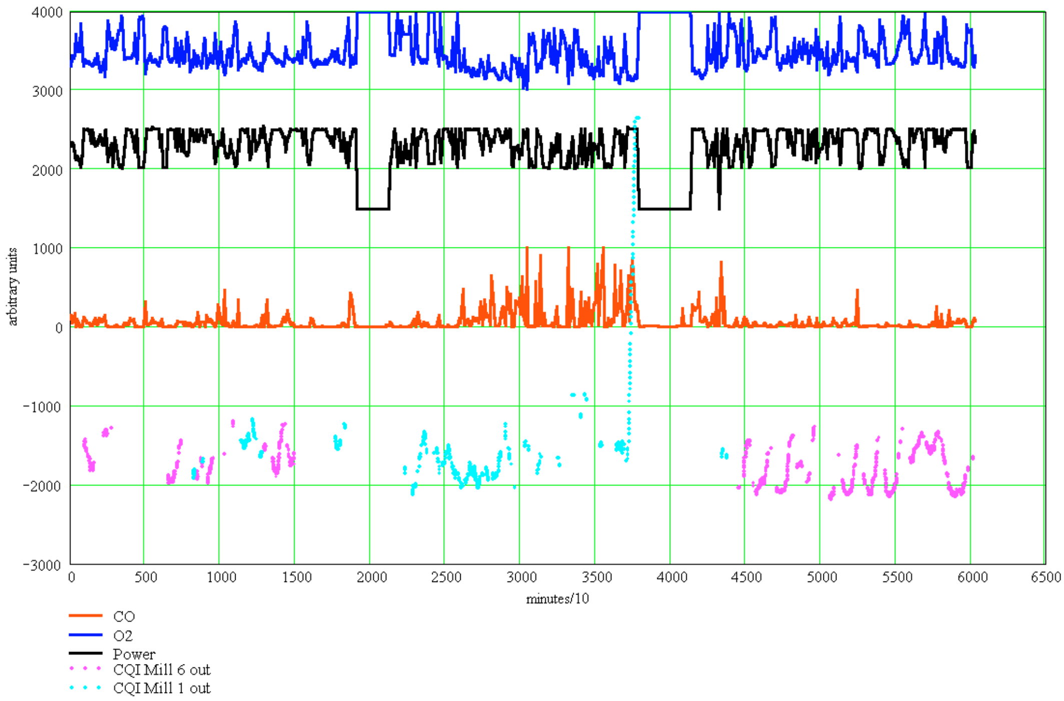


Figure 2.1 Combustion quality index for 500 MW unit over 3 weeks

(b) To provide a number of quantifiable parameters from video images which can be used to evaluate flame stability and combustion. This will include: flame fluctuation magnitude and frequency, availability of oxygen/fuel in specific flames and flame pattern. Locating the area of instability will help operators identify problematic burners.

A range of video processing options have been demonstrated. The combustion quality indices in Fugure 2.1 above were obtained for the amorphous images obtained from cameras on the furnace rear wall.

A method of classifying flame images into known categories using Principal Value Decomposition (PVD) has also been developed and used to identify flame images from four different combustion conditions (using earlier data from a full scale flame operating under well-defined conditions in a burner test facility). Applying a similar technique to that employed in the field of face recognition, eigenimages of the flame images defined the *eigen space* used to classify the images. The errors involved in the classification process were measured and compared with varying number of eigenimages defining the *eigen space*. It was shown that the number of eigenimages used to classify the flame images did not affect the classification accuracy greatly.

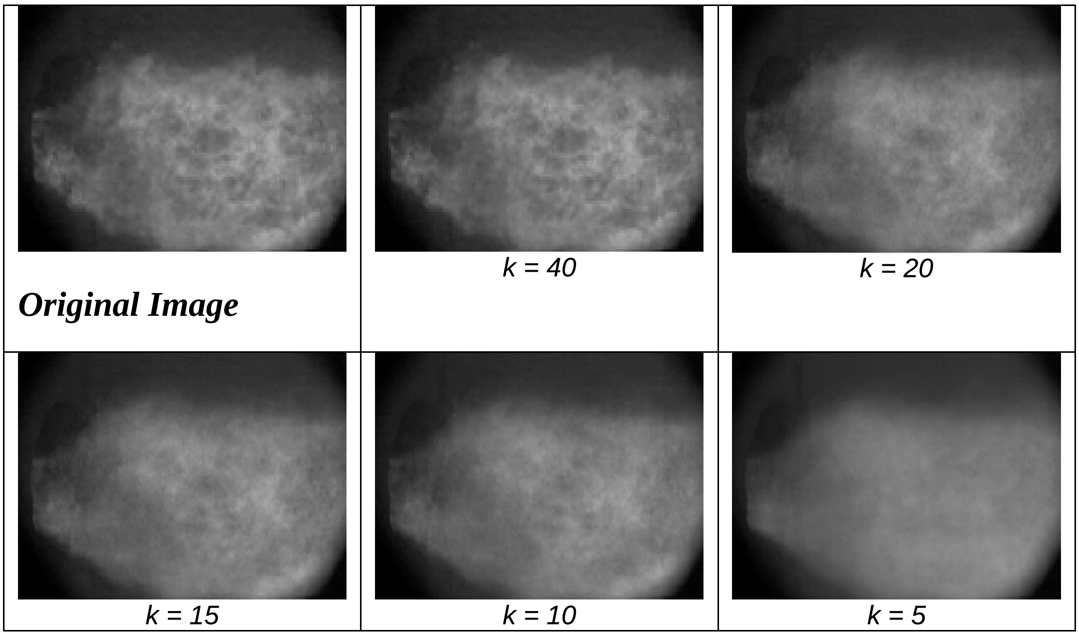
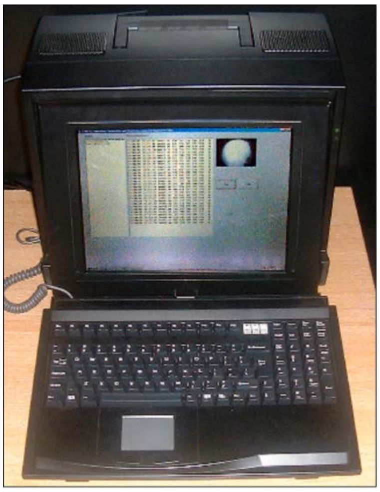


Figure 2.2 Flame images reconstructed using different number of eigenimages, k, compared to the original image. Setting k equal to the number of training images (k=40) results in a perfect reconstruction

Additional algorithms were developed and applied to quantify localised instability in the flame root for single burner observations when suitably-detailed images became available in the last phase of the project. These were run off-line using recorded data, but could be mounted on the existing data processing system using modifications to the current software for rear wall camera images.

(c) *To develop software to run on a stand-alone PC system to provide the above information in real-time and transfer key parameters to existing data logging systems.*



The final version of the video processing was operated continuously and reliably at a utility power station for over a year, using rear wall camera images. The system provides feedback of the SIV processing and measurements in real-time, on screen, as well as providing analogue (4-20 mA) signals for the power plant's data logging system.

Figure 2.3 Final system PC platform

(d) To develop systems to transmit and integrate video data from a number of cameras, under actual boiler plant conditions.

Figure 2.4 below shows data from four rear wall cameras integrated using a commercial video quad multiplexer, together with the individual images and combustion data values obtained by the processing software.

This data was transmitted using existing coax video cable connections. Commercial equipment was also set up to give reliable video transmission over existing plant twisted pair connections. This was used to transmit corner door video back to the plant control room and shown to perform reliably under plant conditions by an extended trial lasting approximately 9 months.

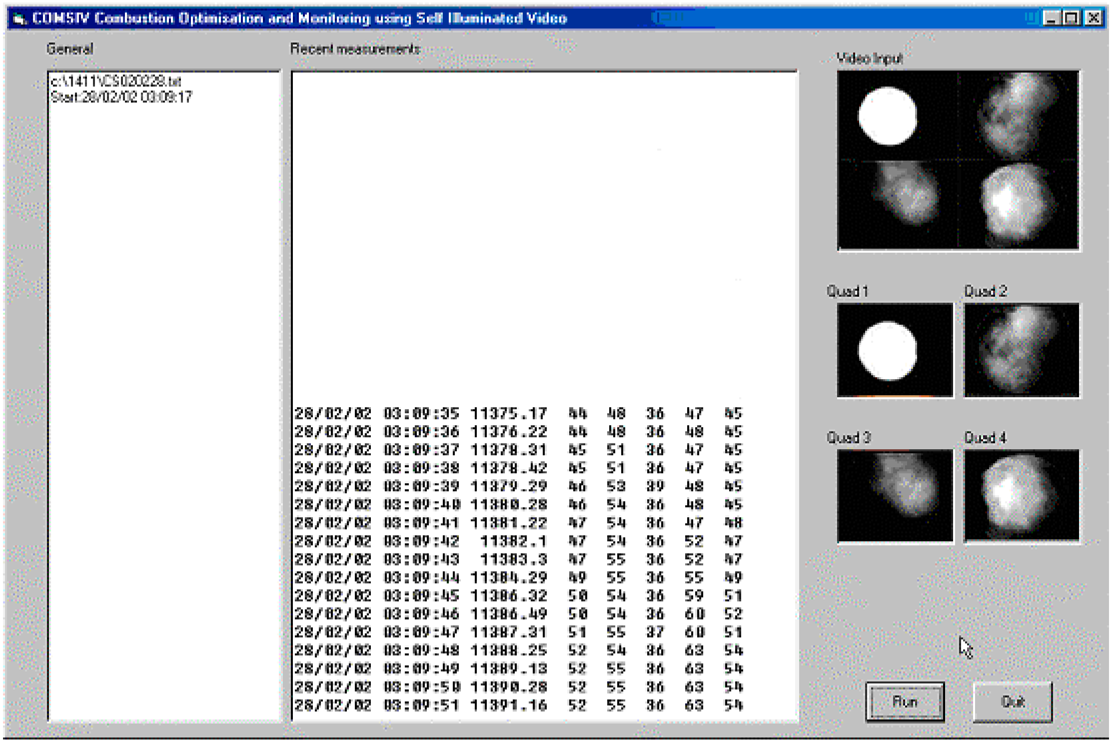


Figure 2.4 Screen display from video processing software reading four camera inputs

(e) To determine optimum video probe designs and locations for quantitative SIV. Initial development work will concentrate on systems with cameras observing multiple burners. Later work will investigate the use of individual cameras for each burner.

It was demonstrated that quantitative SIV data could be obtained from cameras conventionally fitted in the rear wall of the furnace, principally to observe all burners on start up. Problems were, however, experienced when slag on the rear wall intruded into the field of view. This could generally be detected automatically, but during these periods valid SIV results could not be obtained. Extensive work was undertaken to improve video probe performance, but no solution could be found for very severe slagging – a jet of air from a camera could not be guaranteed to disperse heavy slag flows occurring at some distance from the camera over a sufficiently wide angle to keep the field of view clear. This camera position was also limited when firing coal because only the burners immediately opposite the camera could be observed – all other burners were largely obscured by their flames. Despite the attraction of using the video probes that are already fitted to many plant, later development work therefore concentrated on finding alternative camera positions. Plants burning weakly-slagging coals might still be suitable candidates for this type of installation, but cannot be relied on for UK plants which all source a wide range of coals.

The most viable alternative observation point was considered to be in the corner doors that are fitted at or around burner centreline height on all PF units for manual observations. Trials were undertaken on two plants, with single boiler doors modified with a camera port. These proved successful and towards the end of a project all corner doors were modified on a 500 MW unit. Specialised probe designs for this application were built and tested and are currently close to commercial status. Work has shown that excellent results can be obtained, although access to individual burner images has emphasised the inevitable complexity of multiple burner installations when single parameters are manifestly not able to represent the actual range of combustion characteristics that may be encountered in practice.

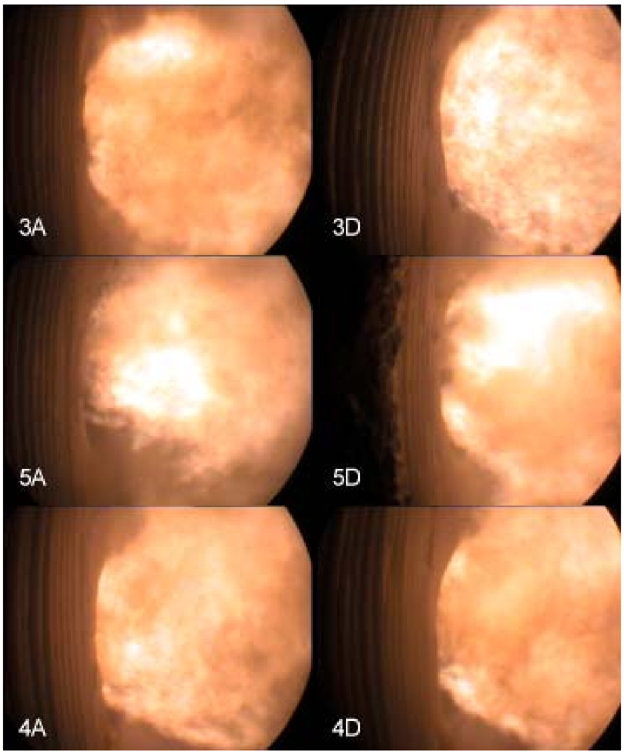


Figure 2.5 Composite view of six wing burners from a single 500 MW unit
(taken using a moveable wing burner camera probe during a short period while at steady firing conditions and processed into a single video file for comparison)

Trials were also undertaken to examine the feasibility of making short-term video observations through the oil gun tube in out-of-service burners. Two prototypes were tested, using different design approaches, but both were only partially successful due to the intense radiant heat load from adjacent burners, the long insertion length of 5 metres, and the small probe diameter required of 35 mm. Useful experience was gained, however, which it is expected will contribute to a successful design in the future.

Figure 2.6 View from an 'oil burner' video probe prototype (note the slag eyebrow on the adjacent burner).

3. TECHNIQUES AND RESULTS

In this project, techniques to acquire and process video data that have been tested under actual in power plant conditions are also the principal results. The techniques and sample data obtained will be described in phases corresponding to project milestones.

3.1 Rear wall camera video processing offline

3.1.1 Equipment

Pre-installed IST video camera probes on a 500 MWe boiler were used for this preliminary video processing activity. The camera was fixed in the usual position on the rear wall of the furnace, determined by the need for all burners to be observed on boiler startup. Trial video data was recorded for off-line processing, using time-lapse video recorders to allow full 24 hour periods to be monitored. Plant parameters (CO, O_2, NOx, SOx and load) were logged during this period for comparison with video observations.

Using this recorded data Imperial demonstrated a robust software algorithm for real time self illuminated video (SIV) image processing of multiple-burner flame images. This was suitable for implementation in a prototype system incorporating real time video capture and processing techniques that was subsequently progressively upgraded during the project, taking into account feedback from tests and progress in other technical areas.

3.1.2 Comparison between video image processing offline and plant performance data

Recorded video images were digitised under computer control and the resulting images processed using an algorithm based on a weighted combination of flame intensity and the frequency of different intensity levels to give a combustion quality index (CQI).

The results from this algorithm for three separate 24 hour periods of operation on a 500MW boiler unit are shown in Figure 3.1.1. The most significant factor is that carbon monoxide levels can be related to CQI at periods of full load when all available burners are in use and oxygen is at ‘typical’ levels. At reduced loads groups of burners may be taken out of service, giving different flame patterns. CQI levels under reduced load conditions would require additional calibration for each burner pattern.

Since significant improvements were likely to be achieved in the quality of the video data available for CQI calculations, and image processing algorithms were also undergoing development, the demonstration of a meaningful relationship between a CQI and actual combustion performance at this stage was extremely encouraging and allowed potential applications to be considered.

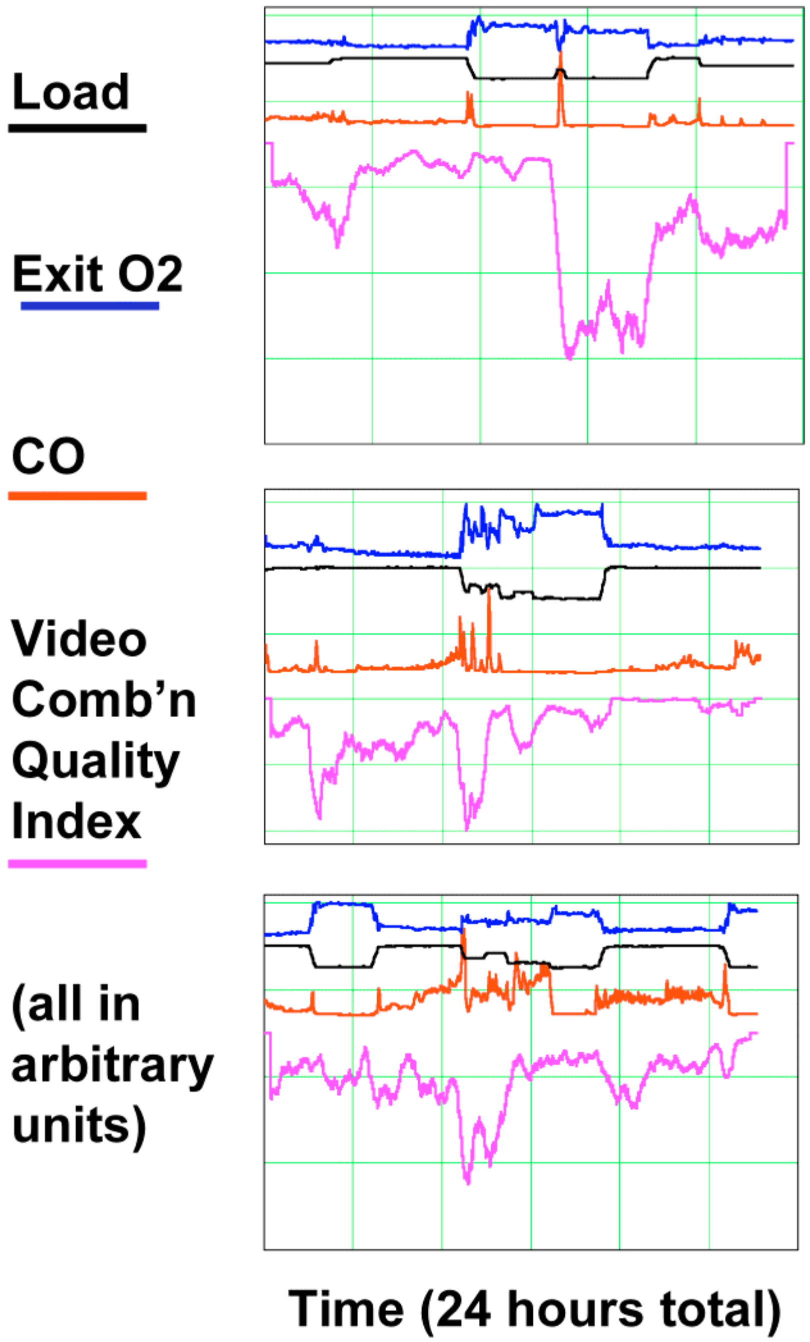


Figure 3.1.1 Comparison between video Combustion Quality Index and combustion performance – note that burners may be taken out of service at lower loads so that full load CQI trends will not necessarily apply.

3.2 Prototype real-time video processing system for rear wall camera data

Prototype versions of the real-time video data processing system were installed at utility power station in mid-August, 2001. The system was used to log information about the flame images in real-time, as well as being a platform for testing new algorithms. Two slightly different versions of software were installed and tested. The first version captured and analysed flame images at a constant rate of one frame per second. The second version analysed a series of flame images in one-second bursts. This enabled the monitoring and analysis of short-term variations in the flame images, and results from both systems could be compared to the plant performance data.

The system consisted of software developed in Visual C++, running on a standard PC with a commercial 'multimedia' video capture card installed. Figure 3.2.1 below shows a block diagram of the flame video processing software.

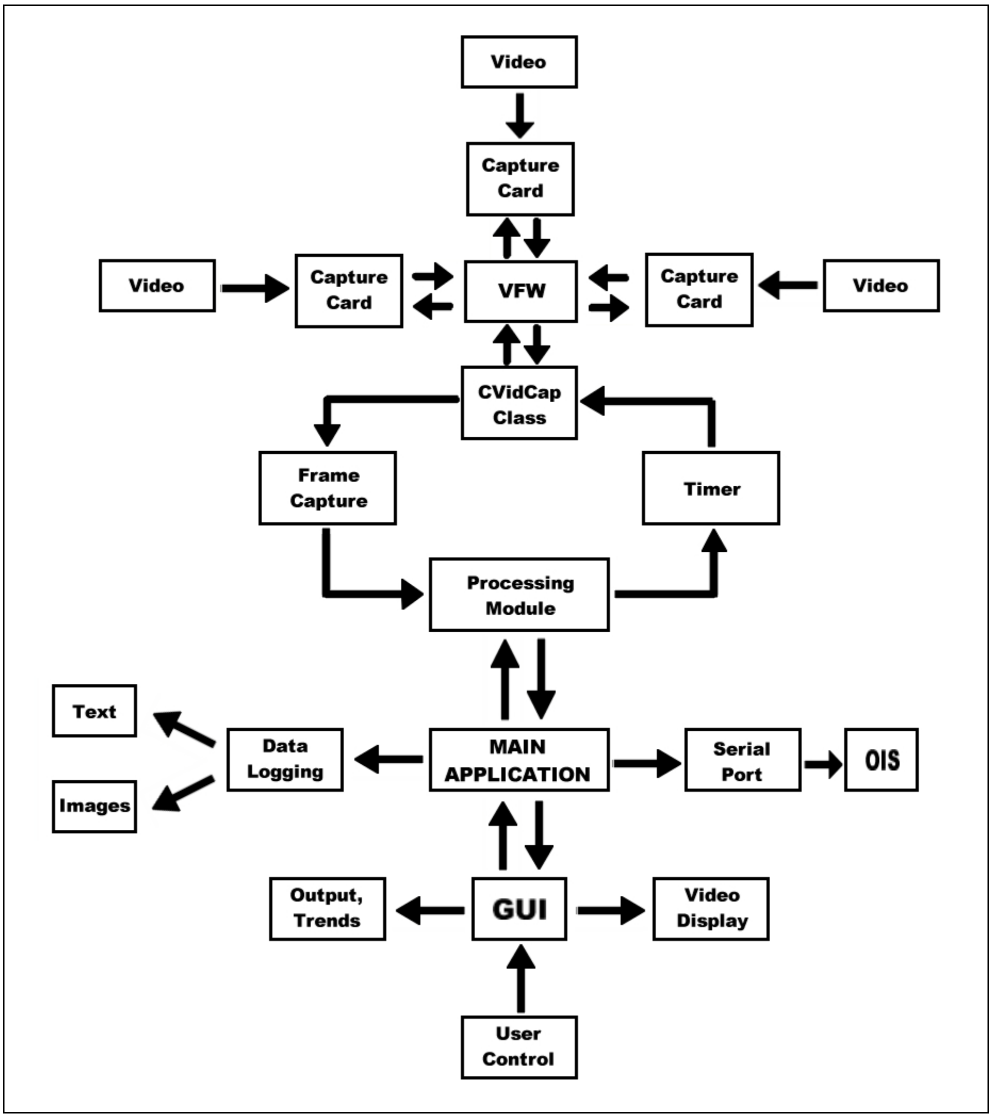


Figure 3.2.1 – Block diagram of software

The software can be divided into three main components:

(a) **Graphical User Interface (GUI) –** provides user control with the software and displays video output and results
(b) **Processing Module** – main part of the software that capture flame images, processes the data and return results
(c) **Data Logging Module** – logs the results and images
(d) **OIS Interface** – interfaces with the power plant data logging system

The Graphical User Interface (GUI) provides real-time information about the flame image and outputs the results of the image processing algorithm as graph on screen. Figure 3.2.2 below shows a screen display of the software running, processing images from four different cameras. At the same time, the data logging module recorded the information onto the computer's hard disk so that the data could also be used for offline experimental video analysis.

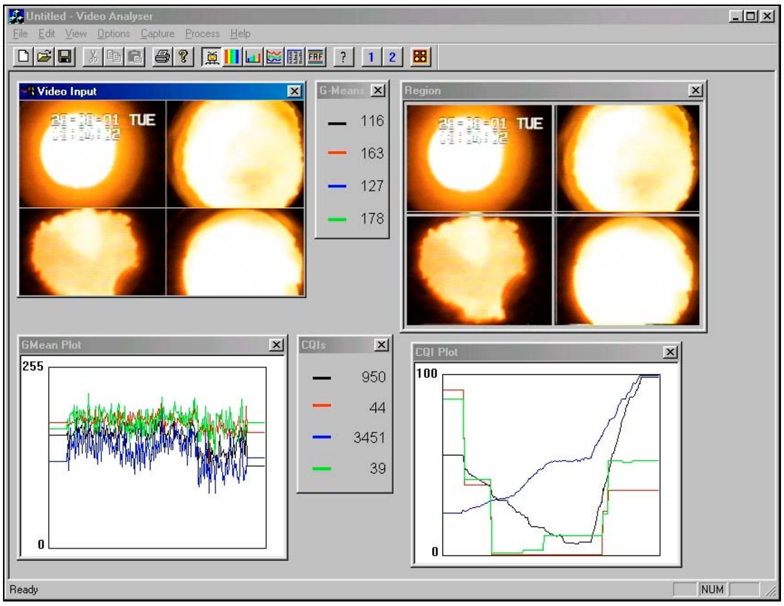


Figure 3.2.2 – Screen display from the operating prototype real time software

Results could also be sent to the plant data logging system, OIS, using a digital-analogue converter connected to the serial port of the computer. The processing module, interacts with the video capture card through a "wrapper-class", obtaining and processing a single image every second. The software is Video for Windows (VFW) compatible, therefore most video capture cards can be interfaced by the software to obtain flame images.

The prototype video processing systems were proven to be operate reliably over a period of approximately six months, up to the installation of the final version of the video processing system, although issues with video image quality due to slag intrusions affected the validity of the derived combustion quality parameters.

An example of long-term combustion monitoring trends obtained using the prototype system is shown below. The plant performance characteristics and combustion quality index (CQI) values for a utility power station are shown for three weeks of operation. The CQI values are shown only for periods of full load (>90%) and for the two most commonly-used mill patterns over this period. Changes in CQI during operating periods are evident, probably indicating that some aspects of combustion have still not completely stabilised over the relatively short periods at full load.

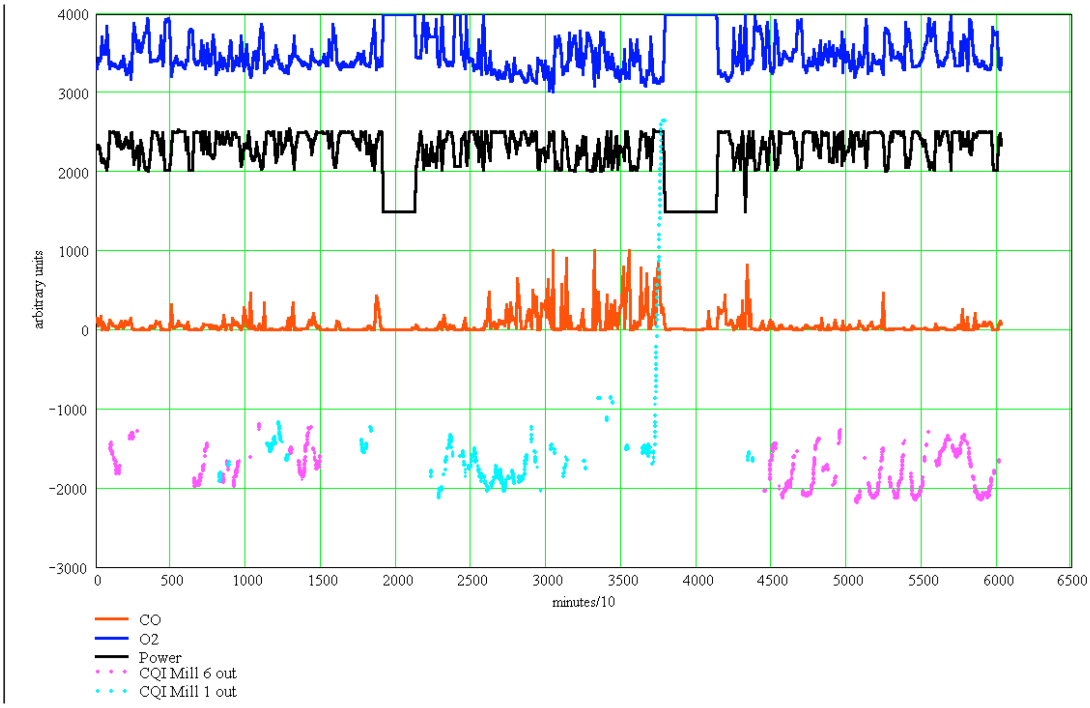


Fig. 3.2.3 Combustion quality index for 500MW unit over 3 weeks

3.3. Final version of SIV capture and analysis system

A final system for real time video processing was developed based on the previous two prototype systems. The system provides feedback of the SIV processing and measurements in real-time, on screen, as well as providing analogue (4-20 mA) signals for the power plant's data logging system. A screenshot of the software is shown in Figure 3.3.1 below.

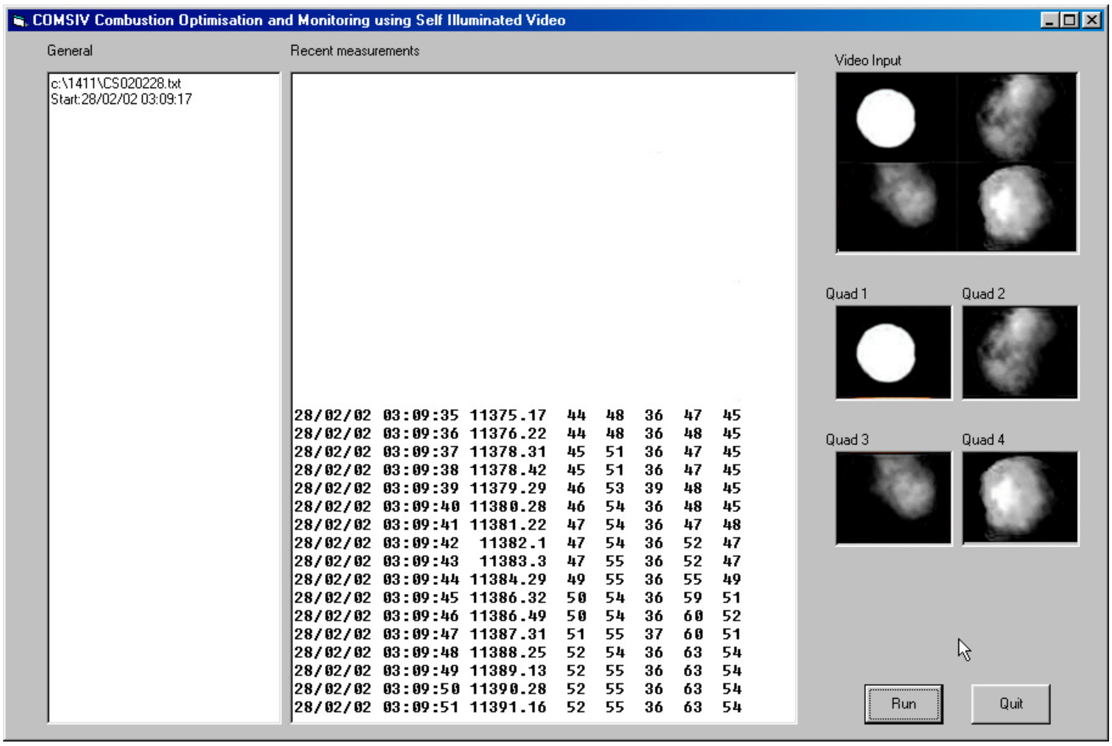
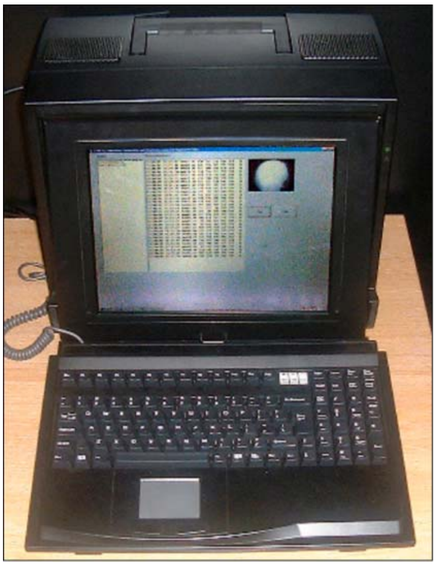


Figure 3.3.1 Screen output from final software



Utilizing a quad video processor or video multiplexer, the system is able to process flame images from four different sources simultaneously. Results from the processing software are also recorded onto the computer's hard drive for further processing and validation.

The 'black box' computer package used as the hardware platform for the final version of the SIV monitoring system is entirely suitable for use in an industrial environment, with the same footprint as a video monitor. The keyboard can be removed if required to limit program access to supervisory staff.

Figure 3.3.2 Final system PC platform

The final algorithms previously implemented in the prototype system for calculating the combustion quality index (CQI) were used in the new processing software for processing furnace rear wall camera data. The system provides the results on screen in real-time as well as feeding it into the power plant's data logging system. This final platform for video processing has operated reliably for approximately 12 months. While processing based on furnace rear wall cameras is likely to be superseded as a commercial application by processing based on corner door cameras, the software changes required are considered to be straightforward to implement once validated by offline testing – the main factor is having a proven video processing and data output hardware platform with flexible software implementation options.

3.4 Advanced image processing methods

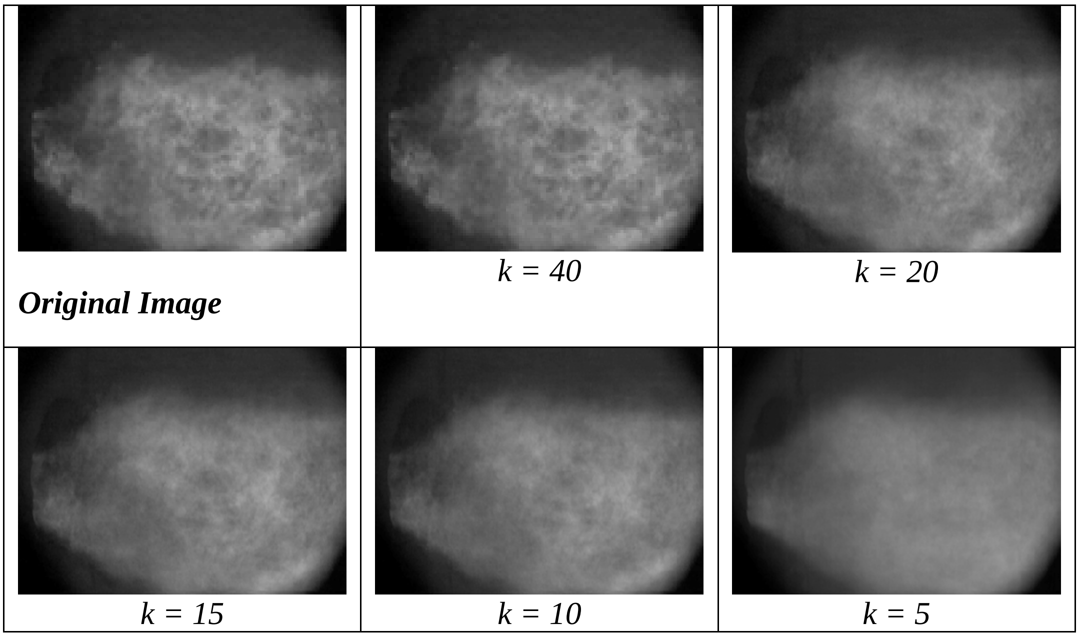


Figure 3.4.1 Flame images reconstructed using different number of eigenimages, k, compared to the original image. Setting k equal to the number of training images (k=40) results in a perfect reconstruction

A method of classifying flame images into known categories using Principal Value Decomposition (PVD) has been developed and used to identify flame images from four different combustion conditions. Applying a similar technique to that employed in the field of face recognition, eigenimages of the flame images defined the *eigen space* used to classify the images. The errors involved in the classification process were measured and compared with varying number of eigenimages defining the *eigen space*. It was shown that the number of eigenimages used to classify the flame images did not affect the classification accuracy greatly.

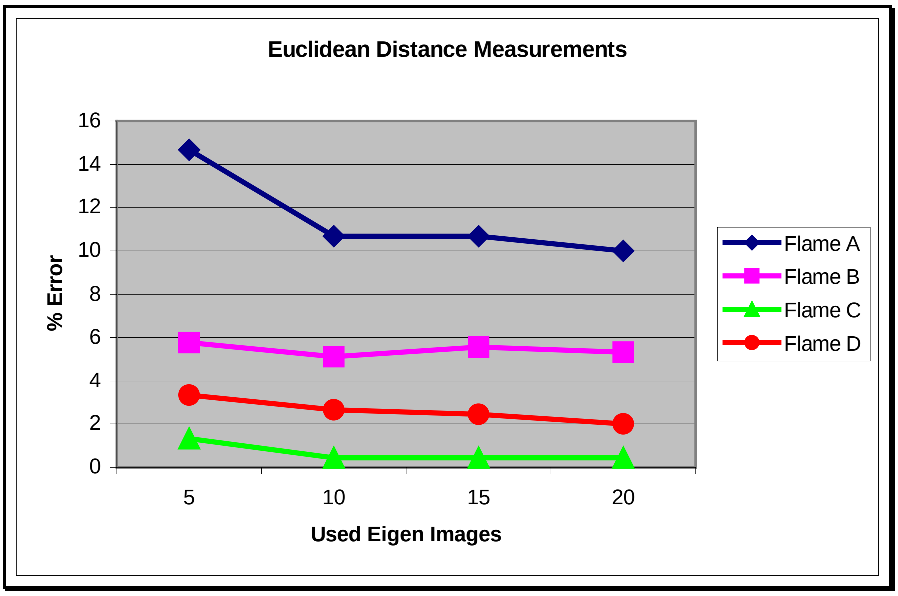


Fig 3.4.2 PVD Flame classification error based on Euclidean distance.

The flame images used to develop this processing method were obtained from previous single burner observations at Mitsui Babcock test facility, but correspond to the type of view that can be obtained from a probe placed in a corner door and viewing a wing burner. Being able to recognise flame conditions by rigorous statistical analysis potentially offers the capability to add a continuous classification of flame 'type' to program outputs, or possibly to provide automatic suggestions for the causes of 'problem' conditions in a flame. The techniques developed may also be used to achieve very high digital image compression ratios.

Site specific trials are required to assess the viability of PVD (and other) methods for flame video analysis, since flame image details will depend on such factors as probe siting, field of view, burner performance etc.. PVD methods are, however, likely to offer a valuable option for future commercial applications based on the proven real time processing platform with site-specific software.

3.5 Single burner observations using corner door and oil burner tube access

3.5.1 Preliminary observations

Early observations at Drakelow Power Station (Figure 3.5.1 below) and elsewhere demonstrated that useful views of wing burners could be obtained through corner doors, but also highlighted the difficulties of moving from short-term observations using hand-held temporary probes and mobile video recorders to long-term observations using robust permanent facilities.

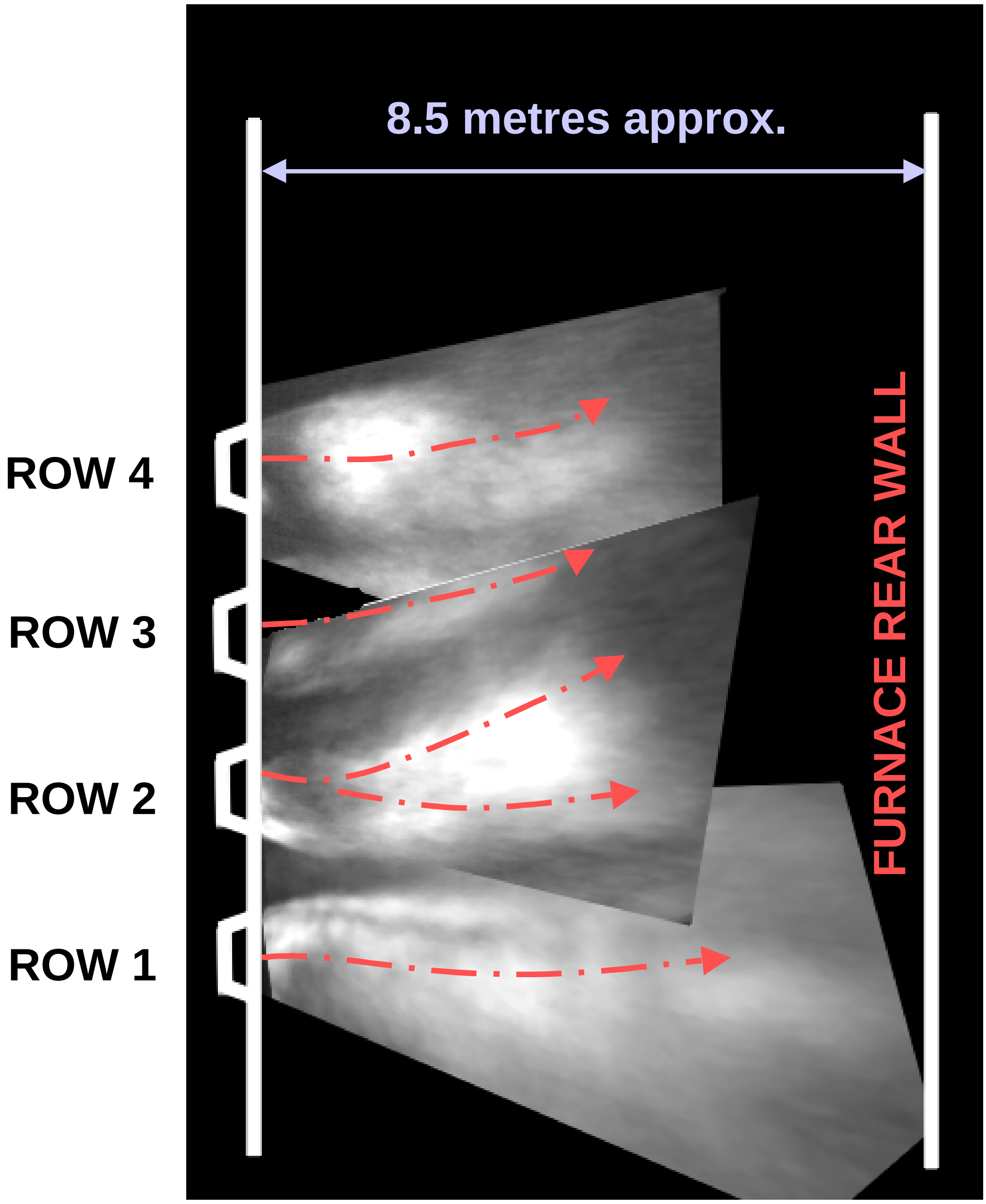


Figure 3.5.1 Volatile flame envelopes in full-scale utility boiler
Map of point fluctuation in instantaneous brightness, with approximate corrections for camera perspective, based on 3 sets of video observations at burner rows 2 and 4.

3.5.2 Video observations on a tangentially fired boiler

3.5.2.1 Background

This work was undertaken when an opportunity arose in another DTI CCT project, CC226. Video images of near-burner combustion during coal trials on a tangentially fired boiler were to be used to assess relative combustion stability as operating parameters were varied. Video probe technology and video analysis software had already been developed for use on wall fired burners in DTI CC121 and 207, and it was expected that these could be adapted to tangentially (corner) fired plant without excessive additional work.

The principal objective for these trials was to examine the effect of pulverised coal fineness on burnout. Coal particle size would conventionally be expected to impinge on burnout in the later stages of combustion, when insufficient time is available to complete combustion of the large particles. It was recognised, however, that any changes occurring in PF ignition patterns at the start of combustion might also be important, principally by delaying the start of combustion and hence further reducing combustion time. Video observation allowed these possible differences in ignition/stability between test runs to be assessed relatively accurately and cheaply.

Demonstration of video techniques on corner-fired plant would also increase the potential applications for the output from CC121 (and possibly CC207, also involving Imperial).

3.5.2.3 Video image analysis for combustion stability measurements

The term ‘combustion stability’ rather than the more commonly used phrase ‘flame stability’ is used to describe qualities of the PF combustion processes taking place in the tangentially-fired unit at Kingsnorth. No individual flames can be identified, with the ultimate stability of combustion (i.e. what stops it going out!) being ensured by internal feedback of the heat required for fuel ignition in the central fireball. In this respect it differs very significantly from wall-fired units where ultimate flame stabilisation (i.e. heat feedback) must be achieved in each individual burner. It is interesting to note, however, how stabilisation at the individual burner scale has inherently much greater turndown capabilities before ultimate stability is affected.

All power plants are, however, operated well away from the limits of ultimate flame stability (except perhaps occasionally in error) for obvious safety reasons. While ultimate stability limits are therefore sometimes considered in laboratory studies of ‘flame stability’, the more realistic concept for flame or combustion stability in the context of actual power plant operation is the consistency/and or the spatial distribution of combustion processes that are in no danger of extinguishing. Measures for this type of flame stability have been developed at Imperial College in previous industrially-sponsored work (*Gibbins, J.R., Zhang, J, Afzal, H., Riley and Beeley, T., "Assessment of flame stability in swirl-stabilised burners and relation to coal properties", Proc. 10th ICCS, Li, B.Q. and Liu, Z.Y. (ed), Shanxi Sci. & Tech. Press, China, 1999, 459-462.*) The spatial and temporal fluctuations of wall-fired burners have also been examined in more detail using video methods (*Gibbins, J., Lin Y-M,* *Bowden, S. and Cameron, S., "Video observations of full-size pulverised coal flames", Comb. Sci. Tech. 162 (2001) 263-280.*)

Throughout the period of the trials at Kingsnorth video data was captured on 24 hr time-lapse tapes at approximately 4 frames/sec. These tapes were digitised and stored as AVI files offline. Individual video frames were processed using proprietary algorithms based on techniques developed in CC121 to give two combustion quality indicators. CQI1 is a measure of the time-weighted intensity of the combustion images (as shown in Fig. 3.5.4), CQI2 is a measure of the consistency of combustion (i.e. how much of the time a characteristic amount of volatiles combustion can be observed in the field of view). Both factors are clearly directly related to combustion stability, and therefore generally correlate with each other. Values for CQI1 and CQI2 can be compared directly to give relative combustion stability ranking, although it would be meaningless to take the ratios directly and to consider that a doubling of CQI indicated combustion was ‘twice’ as stable for example.

3.5.2.3 Video probes

The video probes used for this project were based on the ‘long reach’ probe using a board camera developed for CC207. Preliminary trials showed that the heat flux on the corner fired unit was higher than near a wall-fired burner, so the probe design had to be modified to include an additional thermal shield tube. The final probe was 42 mm OD and approximately 1 m long. The tips of two probes are shown in Fig 3.5.2 below. The camera views at 90º to the probe axis through a small rectangular port, cooled and kept clean by a jet of air flowing out through it. Additional air flows through the baffle in the tip of the tube.

Figure 3.5.2 Probe for corner door observations in T-fired furnace

Figure 3.5.3 Corner door probe in use.

Probes were mounted in a stainless steel blanking plate fixed in burner inspection doors (Fig. 3.5.3). The lowest door level was used, allowing a view up of all the burners. Fig. 3.5.4, looking up a corner of the furnace from below, shows how the probe was positioned to view all of the oil burners, although obscuration from entrained solids reduced the visibility of the upper rows when firing coal (Fig. 3.5.5). In this case, the darker jets of unignited PF are visible against the brighter ‘fireball’ (the coal image area has been reduced slightly to avoid interference form the ash ‘stalactite’ visible on the right of Fig. 3.5.4).

Figure 3.5.4 Oil burners during start up sequence

Fig. 3.5.5 Coal jets and edge of fireball

3.5.2.4 Results and conclusions

Flame stability was observed to vary between runs, see Figure 3.5.6, but predominantly due to changes in oxygen level, Figure 3.5.7. Some secondary effect due to firing rate may also have been occurring, with higher power outputs appearing to give slightly lower stability during otherwise fixed test periods.

Video techniques developed in CC121 and CC207 were thus proved to be transferable to corner fired furnaces and the results appear to be robust and reasonable. The video observation results were available to contribute to the assessment and interpretation of burnout measurements in CC226.

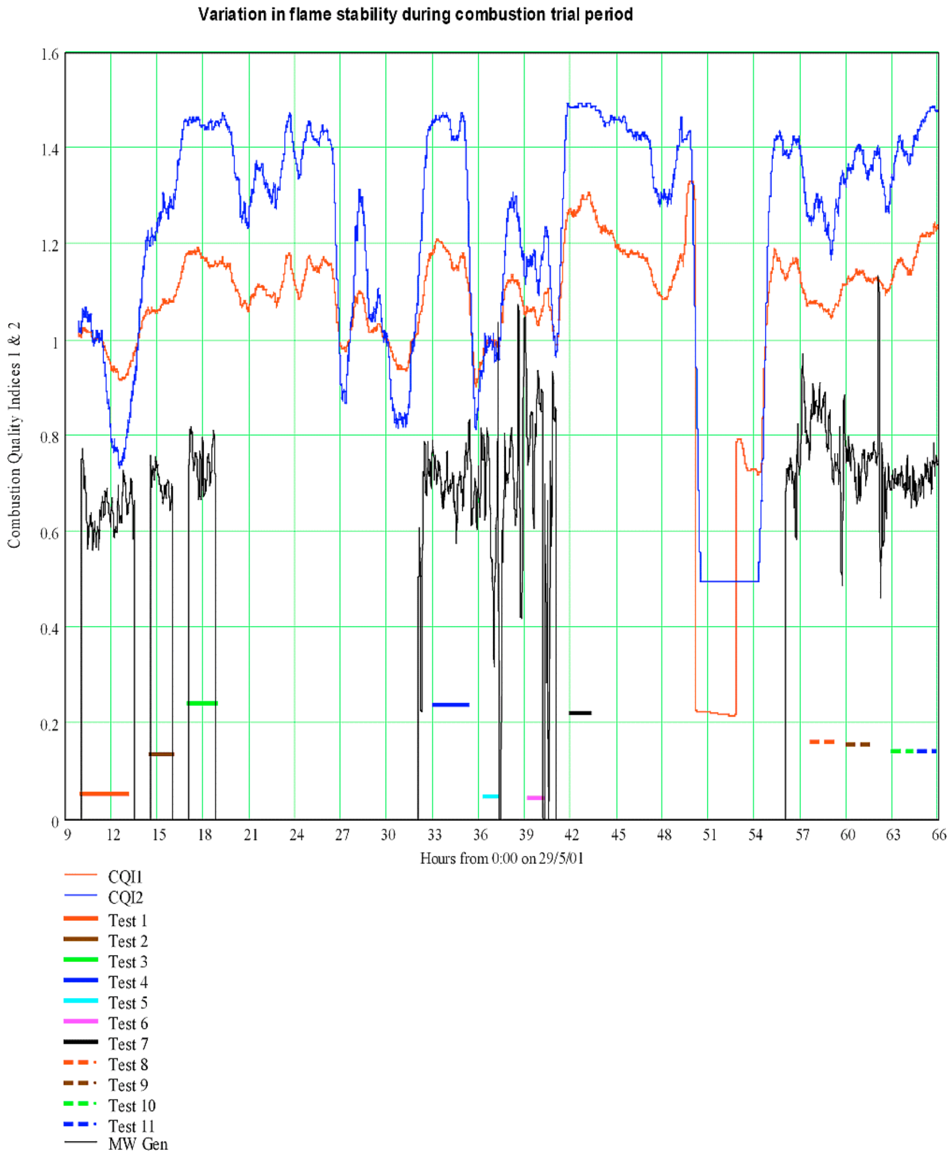
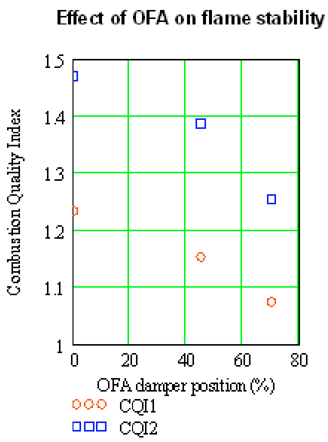


Figure 3.5.6 Combustion quality indices for corner door observations in a T-fired furnace

Figure 3.5.7



3.5.3 Long term use of corner door probes on a wall fired unit and oil gun tube probe trials

3.5.3.1 Video probes and mounting

Furnace corner doors on a 500MWe unit boiler were fitted with 3 inch BSP spigots to provide a permanent mount for corner door cameras. The original alignment of a trial spigot was found to be in need of adjustment – this was corrected for subsequent installations.

Twisted pair connections between the furnace and control room were used for real-time viewing and recording, with video decoders at each end. After some adjustments, these were found to perform well.

Video probes for corner door applications were developed through prototype and pre-production stages by Imperial and IST, with a number of options being tested under actual combustion conditions. For commercial viability, a compact probe is required that can provide an appropriate field of view and good image quality, has high reliability, but yet is designed so that the costs associated with catastrophic air supply failure are not excessive. This last criterion is essential, since while plant air supplies will usually be reliable large numbers of corner door cameras would be affected. Protection methods, such as a reserve air supply and automatic retraction, cannot be deployed on corner door installations, partly because of the cost for a large number of such units but also because bulky equipment cannot be installed in the corner doors which must remain accessible for manual inspections.

Fig 3.5.8 Root of wing burner viewed with prototype camera probe
(Distortion at the top of the frame is due to interaction between the twisted pair connection and the local DV camera used to record this image)

The provision of a full set of corner door camera probes was not feasible due to the cost of the probes themselves and because this would have required that additional permanent air and power supplies to be installed. When a full set of corner doors was available in September 2003, however, the effect of using multiple camera probes was simulated by moving a single probe between doors over a short period during an extended period of stable plant operation. The resulting views were processed into a single 6-way video – a typical frame is shown below.

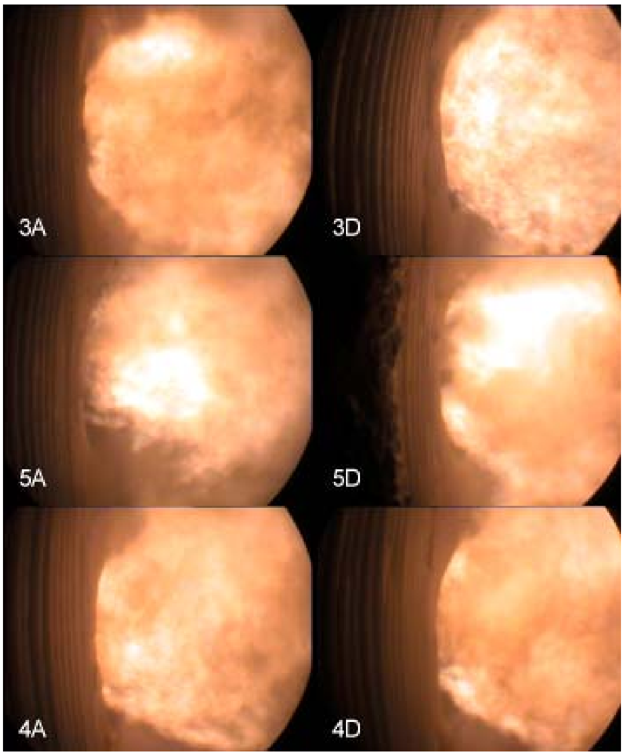


Figure 3.5.9 Composite view of six wing burners from a single 500 MW unit
(taken using a moveable wing burner camera probe during a short period while at steady firing conditions, processed into a single video file with one wing set of images mirrored for direct comparison between flames)

The differences between individual burner flames visible in Figure 3.5.9 confirmed previous observations (Figure 3.5.1) and illustrates the importance of obtaining specific information from individual burners where possible to characterise overall combustion performance. This supports reservations about not being able to view most burners using rear wall furnace cameras. It also raises the possibility of tuning burners individually or as mill and/or furnace groups to optimise performance as well as making adjustments to the whole unit.

Since only wing burners are visible, however, measures would ideally be taken to relate inner burner performance to wing burner performance. Permanent installations to view inner burners would be extremely costly, if technically feasible, but previous experience with long reach probes in DTI CC 207 suggested that it would be possible to construct a probe long enough to be inserted approximately 5m through the central oil gun burner tube on an out-of-service burner. A view at approximately 90 degrees to the probe axis would allow up to four adjacent burners to be observed. The trials with this type of probe are described in section 3.5.3.3.

3.5.3.2 Video processing results from wing burner probes

Video data from the latest version of the corner door video probe has been recorded and processed off line. Since limited time was available to validate processing methods, implementing real time processing, with only the final result being recorded, was not considered to be justified. Recorded data allows different processing methods to be assessed for the same period. As discussed earlier, no fundamental problems are anticipated in modifying the existing processing system to implement the final algorithms.

Typical results are shown in Figure 3.5.10 below. Two methods have been used to derive a flame stability index for the visible root of the flame – as might be expected they give similar trends. Also shown in Figure 3.5.10 is coal flame stability index data derived from characterisation tests. Reductions in flame stability appear to follow the delivery to bunker of coals predicted by characterisation tests to have properties likely to result in lower flame stability.

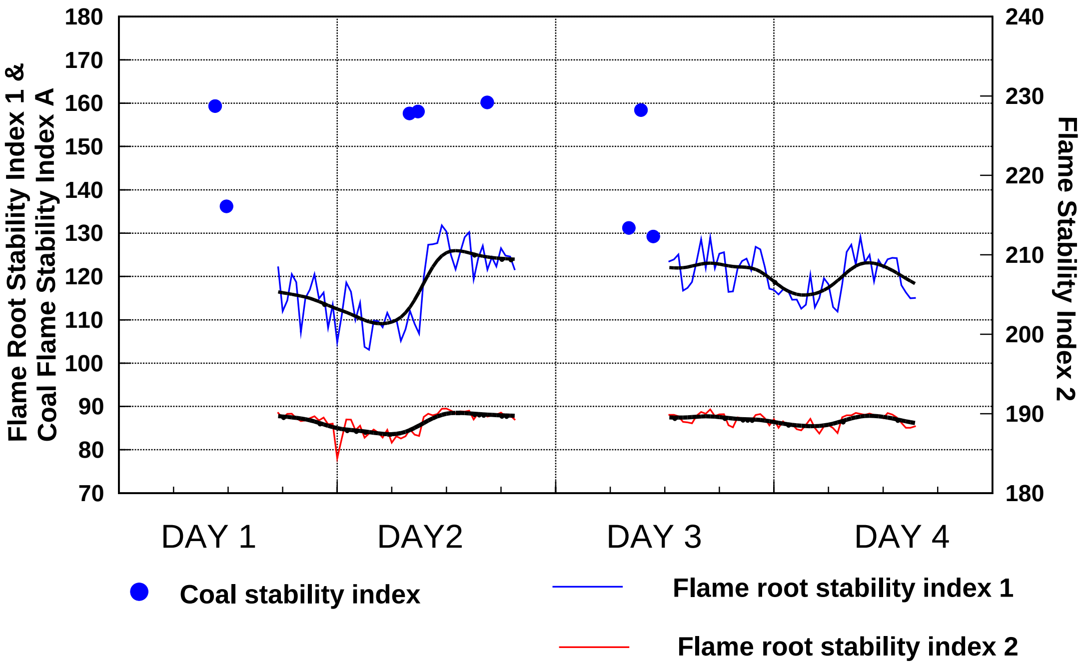


Figure 3.5.10 Flame root stability indices for corner door video processing

3.5.3.3 Oil gun tube video probe trials

Two long reach probe prototypes, using different design approaches, were tested but both were only partially successful due to the intense radiant heat load from adjacent burners and the long insertion length of 5 metres. Useful experience was gained, however, which it is expected will contribute to a successful design in the future.

Figure 3.5.11 View from an 'oil burner' video probe prototype, note the slag eyebrow on the adjacent burner.

The first probe design tested used a miniature board camera, looking at right angles to the tube axis. This design was similar to the 'Kingsnorth' probes shown in section 3.5.2.3, but the outer diameter of the probe was severely constrained, at just 35 mm OD instead of 45 mm OD. The miniature board camera required mounting in a tube 28 mm OD, leaving an annular gap of approximately 2 mm for cooling air to flow around the camera tube. This was found to be inadequate. The cooling air flow through the inner tube kept the itself camera cool enough, but the outer tube became red hot (estimated 800ºC) and thermal expansion caused the viewing apertures in the inner and outer tubes to become misaligned. As well as obscuring the view this also disrupted the air flow over the camera lenses and out through the viewing apertures, and the heat-reflecting filter on the camera eventually failed (optically, but still providing some thermal protection). This camera probe did, however, demonstrate the principle of viewing from this position, as shown in the image in Figure 3.5.11.

In the second probe design a 14 mm endoscope was used for optical access. This allowed a 22 mm OD inner tube to be employed, giving an adequate cooling air annulus about 5 mm wide. This probe was found to have adequate cooling, but unfortunately the large air pressure drop along such a long probe was sufficient to force condensing water from the compressed air supply into the endoscope optics. Insufficient dry instrument air supplies were available to avoid this problem.

No suitable alternatives could be developed within the scope of the present project, but based on the experience obtained it appears that two alternative approaches could be successful:

(a) Use a larger diameter (45 or 54 mm OD) probe inserted through a 'flame eye' port. This would be at an angle to the burner axis, however, which might affect the view in some directions.

(b) Use a smaller-diameter camera – advances in camera technology make it likely that smaller cameras will be available in the near future. A suitable camera (i.e. for a 22 mm OD tube) was not, however, identified in the course of this project.

4. CONCLUSIONS AND FUTURE WORK

4.1 Conclusions

1. Video probe location is the key factor for quantitative Self Illuminated Video observations on utility boilers. The single furnace rear wall video probes widely fitted to observe multiple oil burners on start up are not well-suited to continuous video analysis because of inherent limitations:

a) They have a limited view – predominantly of the flames from burners immediately opposite – once coal is firing.

b) The image varies with firing pattern and quantitative results would have to be calibrated for all permutations of firing pattern (and firing rate).

c) The high temperatures on the rear wall of the boiler lead to unavoidable intrusions of slag into the camera field of view from time to time. Although this has no adverse effects on normal operational use of the cameras it precludes reliable automatic video image analysis. No totally effective solution to the problem of slag intrusion under adverse operating conditions could be developed.

2. Corner door cameras have been demonstrated to give reliable and useful images for quantitative combustion quality assessments. Special designs are required, however, to accommodate the need for a large number of probes that can be reinstated after a cooling air supply failure at an acceptable cost. Corner door modifications for probe mounting and satisfactory low-cost video connections under boiler plant conditions via twisted pair wires have also been demonstrated.

3. Progress has been made towards a design for a novel probe to view any burner through the oil burner tube of an adjacent out-of-service burner.

4. A PC-based video processing platform has been developed and demonstrated for extended periods under plant conditions. Video data from a number of sources can be processed and appropriate 4-20 mA signals generated for simple interfacing to existing plant data logging systems. Any software-based processing algorithms can be implemented.

5. A range of processing algorithms to derive quantitative combustion quality data from flame video images have been developed and tested. These include advanced principal value decomposition methods that may also be used to store flame images for later inspection with very high compression ratios.

4.2 Future work

A sound basis for the development of commercial systems has been established, although since the inception of the project the UK electricity industry has been under severe financial pressure and the immediate market for all types of advanced combustion monitoring equipment has therefore been reduced.

Depending on commercial interest, scope exists to develop both the new video probe concepts and image processing and systems methods into commercial products. This may be either individually, or as a combined system. Video monitoring is now also established as a technique that is routinely available to complement other combustion research studies on full scale plant.

Two classes of commercial application are envisaged, for continuous monitoring and combustion optimisation respectively. In both cases it is likely that the video probes and processing methods will require some degree of tailoring to suit individual plant requirements. Continuing progress in video technology (e.g. reduced cost digital video cameras) may also mean that commercial designs may advantageously be offered as updated, site-specific systems rather than employing the same 'fixed' approach in all cases. Features of commercial systems for these two classes of application are suggested below.

a) Continuous monitoring

- Permanent probes are installed on all corner doors to monitor wing burners.
- Probe technology allows refurbishment of multiple probes at a reasonable cost in the event of cooling air failure.
- Operators are able to gain useful information from real time video display in control room.
- Digital recording is required for retrospective performance analysis – essential to be able to go directly to view at any time (i.e. tapes not adequate except possibly for archiving).
- Numerical processing to derive one or more combustion quality indices would be an advantage, to provide objective measures to supplement operator subjective judgements. A number of options have been demonstrated in this project although all of them would need 'calibrating' against actual plant performance.

b) Burner adjustment

- Burner viewing is required from all corner doors (i.e. gland mounts required on all corner doors), it would be advantageous if this viewing was simultaneous but not essential.
- Temporary air, power and video connections would probably be adequate.
- Additional probes to view inner burners through oil burner probes or other ports on the rear of the burners would be a great advantage, although some additional views could be obtained by taking appropriate mills out of service.
- Numerical processing to give a limited number of numerical parameters is technically feasible, but it may be more useful to employ image processing techniques to generate complete images that highlight aspects of the flames that cannot be seen by eye (e.g. *Gibbins, J., Lin Y-M, Bowden, S. and Cameron, S., "Video observations of full-size pulverised coal flames", Comb. Sci. Tech. 162 (2001) 263-280*).